Water management in Curaçao: A case study of the Swaen area

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Water management in Curaçao: A case study of the Swaen area

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Preface

This report presents the findings of our research on water management in the Swaen area of Curaçao, conducted as part of the Multi-Disciplinary Project for the Delft University of Technology.

This document is primarily intended for policy makers, engineers, researchers, and other stakeholders involved in the Swaen project or similar water management initiatives. Due to the inclusion of advanced 2D hydrodynamic modeling, and biochemical water quality assessments, we assume the reader has a foundational understanding of civil engineering, spatial planning, or environmental sciences.

To assist in navigating this report, the chapters are structured to separate distinct elements of our research. Readers seeking historical context, geographical characteristics, and the social stakeholder framework should start with Chapter 2. Engineers and hydrologists focusing on stormwater can consult Chapter 3, which details the HEC-RAS computational mesh, design storm selection, baseline inundation results, and proposed spatial mitigation strategies. Those focused on sanitary infrastructure should review Chapter 4 for the baseline wastewater assessment and system design principles, followed by Chapter 5 for the empirical evaluation of the horizontal subsurface flow constructed wetland at the University of Curaçao. Finally, Chapters 6 and 8 consolidate the overarching conclusions, project limitations, and recommendations for future research.

We would like to express our gratitude to the people and organizations who made this project possible. Special thanks go to our TU Delft supervisors, dr. Begüm Tanis, Poonam Taneja, and dr. Henk Polinder, as well as our local supervisor, Ergün Erkoçu, and the *Even Groene Vrienden* initiative for connecting us with real-world sustainability challenges and providing guidance, insights, and support throughout this endeavor.

Willemstad, 06 november 2026

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Abstract

Curaçao faces critical water management challenges, specifically inadequate rainwater retention that leads to urban flooding and insufficient wastewater treatment that causes severe marine and groundwater pollution. Using the Swaen neighbourhood in Willemstad as a focus area, this report investigates how a decentralized spatial and technical water management plan can be designed to integrate and improve both rainwater and wastewater systems.

The research employs a multifaceted methodology to address these issues. For rainwater management, 2D hydrodynamic modeling (HEC-RAS) was utilized to simulate a 10-year design storm (30-minute duration, 92 mm/hr intensity) and assess the effectiveness of various spatial retention interventions. For wastewater management, a Multi-Criteria Analysis (MCA) evaluated potential decentralized treatment options to formulate a conceptual neighbourhood-scale design. Additionally, empirical testing was conducted on an existing horizontal subsurface flow constructed wetland at the University of Curaçao (UoC) using two plant species (Typha domingensis and Ruellia simplex) to determine its real-world efficiency in treating household wastewater under local semi-arid conditions.

The hydrodynamic baseline model revealed significant local flooding in Swaen. The most effective mitigation strategy that was found, combining 114 m^3 of distributed household storage tanks with a 290 m^3 centralized storage basin, successfully reduced the local inundation volume from 215 m^3 to 144 m^3 and decreased total downstream outflow. For wastewater, the MCA identified a centralized neighbourhood gravity collection system paired with a communal septic pretreatment unit and a 58.37 m^2 subsurface-flow constructed wetland as the most effective design for the area's 149 residents. Experimental wetland tests confirmed this approach's viability, demonstrating substantial reductions in chemical oxygen demand (up to 58%), total suspended solids (100%), and fecal indicator bacteria (E. coli and Enterococci), although additional polishing is required to fully satisfy local irrigation standards.

Decentralized systems present a highly effective and adaptable solution for upgrading Swaen's infrastructure. To move from conceptual design to implementation, future work must prioritize on-site hydrological observations during major storm events to calibrate the rainwater model, parameter sensitivity analyses, and detailed topographical surveys to finalize the wastewater sewer alignment. Additionally further research is necessary on the constructed wetland technology in the context of Curaçao, including testing more water quality indicators and improving design for more efficient treatment.

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1 Introduction

The island of Curaçao, which has a long history of colonial rule and rapid development, consists of a rocky island formation laying in the southern Caribbean sea, about 65 km to the north of the coast of Venezuela. The island runs roughly from northwest to southeast and is traditionally divided into three areas. The urban area of greater Willemstad, the northwest (called *Bandabou*) and the southeast (called *Bandariba*) [2]. The area of Willemstad is concentrated around the natural harbor in the *Schottegat* bay, with densely populated urban areas stretching out in all directions around the bay and along the southern coast. The northwest (usually referred to simply as 'west') features more natural areas, beaches and smaller villages. The southeastern (referred to as 'east') part of the island consists of mostly privately-owned protected land [2]. Throughout the 20th century, and into the 21st century, population on the island has been increasing steadily from about 100.000 in 1950 to almost 160.000 in the year 2026 [3]. The tourism sector, one of the island's main sources of income, is expected to grow in the future [4], putting increasing pressure on infrastructure systems.



Figure 1.1: Map of Curaçao [5]



Figure 1.2: View of the Christoffelberg, the highest peak on the island [6]

Due to its unique geographical and climatological conditions, Curaçao has had a long history of challenges and solutions with regard to the management of both rain- and wastewater. In the next sections, the most important water management related challenges are identified and introduced, the scope and method of this research are introduced and a case is made for using decentralized solutions to solve the problems in a focus area, which is also introduced.

1.1 Water-Management problems in the modern era

In the present time, the island of Curaçao faces challenges with regards to the management of rain- and wastewater. In this section, the most important challenges are identified and explained.

1.1.1 Rainwater Management

The following main challenges were identified with regard to rainwater management in Curaçao:

- The focus of rainwater management is placed on quickly transporting all of the water to sea, missing the opportunity for infiltration and replenishment of the groundwater.
- Rainwater management is insufficient in many areas of Willemstad, leading to flooding events in the wet season.

Curaçao has traditionally had an extensive rainwater management system designed for the retention and subsequent infiltration of rainwater to replenish the groundwater, making use of channels or *rooien* and dams [7]. Afterwards, the groundwater, which was accessed by wells, could be used for many different purposes, including as drinking water. Curaçao has 48 watersheds, which means 48 different paths for the water that falls on the island to follow [8]. Traditionally, these were all extensively dammed to enforce the infiltration of the rainwater into the ground. Many of these dams have since fallen in disrepair, or were destroyed to make room for housing. Some *rooien* are still in use today, which carry water towards the sea when heavy rain falls. However, without adequate retention measures, this creates a situation where water is quickly carried out to sea, instead of replenishing the groundwater. Furthermore, water is able to concentrate faster because there is little retention. This is more likely to cause floods when compared to a system where water is retained at multiple levels; never allowing it to concentrate in one place.

1.1.2 Wastewater Management

The following main challenges were identified with regard to wastewater management in Curaçao:

- The wastewater treatment plants of Klein Hofje and Klein Kwartier will not be able to keep up with future demand for treatment capacity.
- There is evidence suggesting that the effluent from Klein Hofje is not sufficiently clean for discharge on surface waters.
- Groundwater quality is low due to salt intrusion from the sea and high levels of human contaminants in urban areas.
- High rainfall in the wet season regularly causes overflows in the sewer system, leading to further contamination of terrestrial and marine environments.

In the year 2018, only about 16% of wastewater was being treated on the island [9], almost all of which was treated in the two main wastewater treatment plants (WWTPs) of Klein Hofje and Klein Kwartier. These plants are not able to keep up with the demand for wastewater treatment [10]. This is not only because of growing demand, but also because the plants themselves are not able to run at full capacity due to the deteriorated state of the facilities[1]. The effluent from the WWTPs is widely being used for the purpose of irrigation for farming and gardening in the area. However, a recent study has linked the use of WWTP effluent to higher concentrations of human-made compounds in coastal waters [11], leading to the conclusion that using effluent for irrigation purposes near-shore may also lead to contamination of marine environments [10].

[1] Source: from talks between the project team and personnel at these facilities

However, most of the wastewater on the island is not treated but directly infiltrated into the ground through cesspits, or discharged into the sea, either through *rooien* or directly [12], [13], [14]. Pollution of the marine environment has caused major problems for marine life. The state of coral reefs around Curaçao has shown rapid deterioration, with around a 50% cover loss over just 4 decades [14]. While many factors play a role in this process, it has been indicated that pollution has major effects on marine life [11], [15]. This effect can be observed in Curaçao, where reefs that are situated near urban areas are the ones most affected. Apart from the effect of wastewater that is directly discharged into the sea, there is also the contamination of groundwater by cesspits, having potentially harmful effects for public health through wells [13] and, via infiltration in aquatic systems on the island, for aquatic life [16]. There is also evidence suggesting groundwater borne contaminants can find their way into the marine environment [11], which is a process called subsurface groundwater discharge (SGD). It has been shown that heavy rainfall can increase the effects of SGD, in addition to causing extra direct surface water runoff to the sea [17], which causes an increase in human pollutants in the marine environment.

1.2 Decentralized Solutions

The challenges that are described above are of a complex and multivariate nature, making the finding of a fitting solution a difficult task. Moreover, it is likely that no single solution exists but rather a combination of many smaller interventions will be necessary. Within the scope of this study, attention will be paid mostly to decentralized, local solutions to the above-mentioned problems.

Decentralized water management infrastructure, which as opposed to centralized water infrastructure has its focus on local solutions near the source of generation, could be an attractive option for Willemstad. With a shift to more sustainable cities, these solutions offer some advantages over more traditional systems [18], [19], [20]. Decentralized solutions are not likely to fully replace centralized infrastructure in the future. Hybrid strategies have shown promising results, showing that centralized and decentralized systems can work together to create an optimal system [19], [20]. For Willemstad, the main advantages of a decentralized system are listed below.

1. Depending on the type and scale of the system, decentralized solutions can offer a cheaper alternative when compared to a centralized system [18], [19]. In Willemstad, this is expected to be the case because ground conditions make laying pipes an expensive endeavor.
2. Decentralized solutions can offer a greater level of water resource management efficiency, through reuse practices of both rain- and wastewater [18], [19]. Within the arid climate of Curaçao, the advantages of this are especially great.
3. The reuse and local capture of water can additionally improve the water independence of the area, making the system more robust.
4. Localized rainwater management practices promote infiltration and capture of rainwater at the source, preventing high runoff and spreading of pollution over the streets, in addition to recharging the groundwater [18].

1.3 Focus area

The problems described in the previous sections are generally present across Curaçao, and are especially present in the greater Willemstad area. However, to limit the scope of this study, a focus area is defined. This will allow for the creation of a comprehensive decentralized water management design, which is the main aim of this project. The focus area is a small, relatively underdeveloped neighbourhood in Willemstad, known as *Swaen*. Being situated between the neighbourhoods of *Scharloo* and *Sint Jago*, its location is rather central in Willemstad, making it all the more remarkable that development has stayed behind. Figure 1.3 shows the location of the Swaen area within Willemstad.



Figure 1.3: Location of the Swaen neighbourhood within Willemstad [21]

The neighbourhood is situated next to the Scharlooweg road, which runs in northwest-southeast direction. It extends perpendicularly to this road, ending in a hillside some 150 meters further. There are two large open spaces, with trees growing in and around these spaces. Cars are able to drive here to get to the back of the neighbourhood. In the middle, there is a historic town hall, dating to around 1879 [22]. Around the perimeter of the area, and next to the town hall, lots of small, informal houses have been built over the years by the inhabitants of the area. The town hall is in a dilapidated state but also houses people. In total, the population is around 100 people [23].



Figure 1.4: An overview of the neighbourhood of Swaen [24]



Figure 1.5: Historic Town Hall Swaen [25]

Recently, the neighbourhood has come under increasing pressure owing to its combination of low

development and a high-value location [24]. This, in combination with the problem of deteriorating housing and facilities, is posing a major threat for Swaen. However, the area has since been recognized for its cultural value and heritage and is enjoying a new influx of investment as part of the Dutch 'Heritage Deal'. The project Swaen investigates how a culturally-inclusive approach can be applied to improve the living conditions and facilities without a loss of identity [24]. Part of this project is also about finding solutions to the water management issues that present themselves in Swaen. Swaen faces the same challenges that are present in many other urban areas on the island: a lack of a formal stormwater and wastewater management system is causing problems of flooding during rain events, and pollution due to wastewater all throughout the year. Swaen, therefore, can serve as an excellent focus area for this study. The solutions proposed in this report for Swaen can serve as an example for other areas of Curaçao with similar problems.

1.4 Research Questions and Scope

Within the frame of water management and specifically in the Swaen area of Curaçao, the following main research questions has been set up:

> *How can a spatial and technical water management plan be designed for the Swaen area to integrate and improve rainwater management and wastewater treatment?*

To answer the main research question, a few subquestions have been identified. These are listed below:

1. What decentralized retention measures can be selected and spatially integrated to effectively mitigate local street flooding and reduce total downstream outflow?
2. How can an effective wastewater management system be developed for the Swaen area, considering the local conditions and existing infrastructure limitations?
3. What is the effectiveness of a constructed wetland system on the island of Curaçao for the purpose of treating household wastewater to reach irrigation level standards?

In light of the research questions established above, the scope of this study is now defined. The study will focus on two main facets of water management: rainwater and wastewater. The report is also split into three parts: rainwater, wastewater and constructed wetland. The research was carried out over a period of 10 weeks on location in Curaçao, from the 31st of August to the 6th of November of the year 2026. For both parts, the research focused on first defining the current situation in the Swaen area, with the study approach consisting of mainly stakeholder meetings and literature review. Afterwards, for the design of a working rainwater management system, a GIS map was made of Swaen, which was used in combination with a flow modeling software (HEC-RAS) to find and simulate solutions and come up with a system design for the Swaen area. For the topic of wastewater, the methodology consists of literature review and weighing multiple options for a decentralized wastewater management design. This research also encompasses an experimental investigation into an existing constructed wetland system on the campus of the University of Curaçao (UoC). This part of the research focuses on getting the constructed wetland in operating order and measuring first results of filtering capacity for the treatment of household wastewater. This is done in order to help validate the technology in a Curaçao context, and investigate the potential effectiveness of this system in Swaen.

The intention of this research project is to apply a multifaceted approach, consisting of literature review, modeling, MCA and practical experimental work, in order to give advice on the design and spatial layout of a decentralized, sustainable water management system for the Swaen neighbourhood of Willemstad. The target audience is policy makers, engineers, researchers and other interested parties that are involved in Swaen or similar projects.

1.5 Report Structure

This report opens with a small investigation into the Swaen area to give the necessary context. This is done in Chapter 2. After this, in Chapter 3, the methodology and results of the rainwater management investigation are presented, as well as an advice on what has been identified as the best course of action. In Chapter 4, the same is done for the wastewater management investigation. In chapter 5, the constructed wetland system is introduced and test results are presented. Finally, in Chapter 6 the conclusion is given, in Chapter 7 the discussion and in Chapter 8 the recommendations.

2 Background

In this chapter, all relevant history of the water management situation on Curaçao will be outlined. This will provide the context that will give insight into how current day problems came into existence. Thereafter, a current stakeholder analysis will be done.

2.1 Brief History of Rain and Drinking Water Management in Curaçao

The island has a semi-arid climate, with most of the year remaining practically dry, except for a wet season around October, November and December [26]. This has been a challenge for as long as people have inhabited the island and has led to a long history of water management and water-related culture and problem-solving [27]. The original population, consisting of several different indigenous groups, likely used local water supply in the form of simple wells [8], [28]. Colonial rule on Curaçao started in the year 1499 with the Spanish period, which lasted until the year 1634, when the Dutch conquered the island. Throughout the colonial period up until the modern era, the land was transformed through many deforestation efforts, agricultural practices and urban development [28]. During this long period, many different water management practices were developed and used that are now considered traditional. Early practices include the building of dams and channels (called *rooien*), used to prevent quick runoff of rainwater, and provide storage of water for local use on plantations and as drinking water [7], [8], [27]. Examples of these traditional structures can be seen in Figures 2.1 and 2.2 (although the the structures in these images are more modern examples, they use the same principles as the older ones). This system ensured that rainwater had time to infiltrate into the earth, thereby replenishing the groundwater.



Figure 2.1: Old spillway, which was part of the water management system at the historic plantation Hofi Rooi Catootje [7]



Figure 2.2: Historic dam near Santa Martha, with an outlet door that could be opened and closed [8]

Rising needs led to the establishment of 'water plantations' [29] around the *Schottegat* bay [28], [30], which consisted of large colonial-style manors featuring a system of basins and dams used for catching and storing rainwater. This water was then transported using canoes to nearby Willemstad, where it was sold [29], [30], [31]. As water demand in the urban Willemstad area kept increasing, water had to be brought from plantations further from the city. This water was transported in barrels by mule [30], [31]. Another practice, popularized around this time is the rainwater catchment basin (or *regenbak*). These were eventually built with every new house, for personal use and also to sell the water to others. The number of these catchment basins increased steadily throughout the 18th and 19th centuries, reflecting

the constant battle against water shortages on the island [30]. These practices stayed mostly the same throughout the 17th, 18th and 19th centuries [30]. In the late 19th century came another development in the form of windmills of American design, that greatly increased the efficiency with which water could be extracted from wells [28], [30]. This allowed water plantations to keep up with growing water demand at the time.

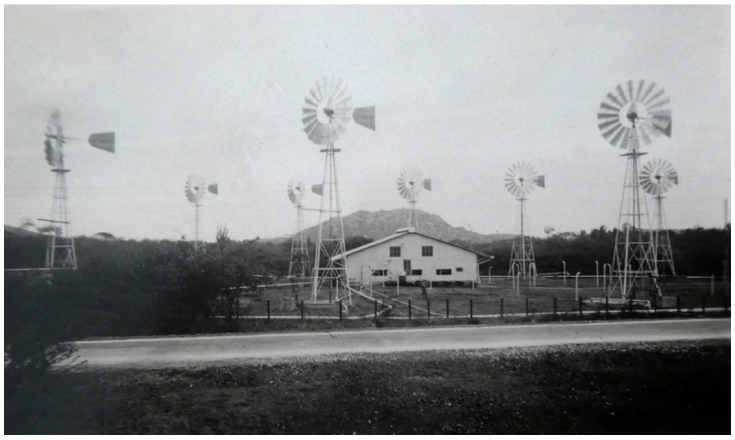

Figure 2.3: American windmills at Julianadorp and pumping station and filtration plant (Photo likely taken in the 1930s) [8]



Figure 2.4: Historic picture of the oil refinery [32]

The establishment of a large oil refinery on the island in the year 1918 was a major turning point for water management on the island [7], [28]. The refinery had a large water demand itself and, along with other factors such as a further increases in population and an increase in wealth, put ever growing-pressure on the water management system [28], [30]. The refinery kept expanding throughout the 20th century, which meant that the water demand kept increasing. The eventual establishment of one of the first desalination plants in the world in 1928 was a big shift [7]. The plant was expanded multiple times until, by the early 60s, all of the drinking water on the island was supplied from it [7], [29]. This then led to a decline in attention to many of the traditional water management systems; the retention dams, wells and *rooien* [7]. The modern era of water management in Curaçao had started, where ground water was still sometimes used for irrigation, but all drinking water was supplied using desalination. The system consisted of a centralized water supply from the desalination plant, with water moving through pipes to every household. Around 70% of households were connected in 1960 and 97% in 1985, showing the rapid expansion of the network [27].

2.2 Brief History of Wastewater Management in Curaçao

In parallel with the issue of rain and drinking water, the island has also had to deal with the issue of wastewater treatment. Although both related to water, this latter issue has presented the island with a different set of challenges. Sanitation and wastewater management practices are much less documented on the island. This is likely because the traditional solution was a relatively simple one: to discharge wastewater into open water or into the ground. Up until the rapid urban development in the 20th century, which started when the oil distillery was established in Curaçao in 1918, it is likely that most wastewater treatment practices were localized and simple. In the 40s of the 20th century, the first sewer pipes were installed in the urban Willemstad area [33]. These were not part of a centralized sewage system but rather had the task of collecting the wastewater from a neighbourhood and transporting it to open water in the area. This system expanded gradually in the next decades. Later on, when ground and coastal

waters started to become significantly contaminated by waste water seeping into ground, the country made plans for the construction of multiple wastewater treatment plants [34]. Particularly, the largest installation at Klein Hofje [33] was intended to relieve contamination in the nearby Piscadera Baai, so that it could be used for touristic exploitation [34]. Currently, there are four treatment plants on the island, two of which treat almost all of the water. These are the plants at Klein Hofje and Klein Kwartier, intended for the treatment of respectively the western/central and eastern parts of the Willemstad [33] urban area, with respectively a contribution of 62.2% and 34.1% to the total wastewater treatment [35]. All urban areas outside Willemstad, with the exception of the village of Tera Kora, are not connected to any wastewater treatment plant [33].



Figure 2.5: Aerial view of the wastewater facility Klein Hofje [36]



Figure 2.6: Wastewater truck dumping its contents into the sea [37]

The problem of wastewater treatment is only growing however. In May 2018, it was reported in a broad study on the infrastructure of Curaçao that only about 16% of wastewater was being treated, while the remaining 84% is discharged into the terrestrial or marine environment [9]. Furthermore, only 33% of the population is connected to the network. The most widely-used solution to the problem of wastewater is the traditional practice of the cesspit, or *beerput*, which consists of a hole in the ground to which the wastewater is pumped from the house and left to infiltrate into the ground. This cesspit then needs to be emptied of sludge once in a few years. The cesspit has one main advantage: it does not deplete the ground water table [33]. The cesspit is an example of a localized, traditional solution to the problem of wastewater which has survived up until the modern era because it is relatively cheap and easy to implement. However, it should be noted that this solution only has a very limited treatment capacity.

2.3 Social Context and Stakeholdernetwork

For the future realisation and acceptance of rain and wastewater management in Curaçao is dependent on social factors. Their acceptance determines whether solutions such as the constructed wetland move beyond the design stage and can be maintained in the long term. This section describes the stakeholders relevant to this project and their roles, as listed in Table 2.1.

2.3.1 Stakeholder overview

Several government bodies shape the project's technical and regulatory boundaries. Openbare Werken (OW), under the Ministry of VVRP, manages public infrastructure and drainage. The Klein Hofje wastewater treatment plant, the island's largest, shows the capacity and limits of the existing system.

For this project, their lab was used. The second used lab is that of Analytisch Diagnostisch Centrum (ADC). They can provide water quality analyses on bacteria to verify treatment performance. Because the site includes the protected historic town hall in Swaen, Stichting Monumentenfonds Curaçao (MFC) and UNESCO also matter: they provide restoration funding and protect heritage value, which constrains how far the terrain can be changed.

Knowledge institutions bring expertise and continuity. The alumnus who designed and built the base of the constructed wetland explained the original design choices and their implications. The University of Curaçao (UoC), with its close links to the local job market, is a central partner for collaboration. The Caribbean Research and Management of Biodiversity (CARMABI) adds ecological and biodiversity expertise and they benefit from better wastewater management. This helps their coral protection. Even Groene Vrienden on the other hand connects students to the projects that benefit businesses and the government on sustainability challenges.

Among companies, AWA Consulting is a direct client of this project and is water management advisor for the Swaen area. Aqualectra, the water and power company of Curaçao, is not always capable to produce enough clean water. Therefore, they benefit from more rainwater retention. Engineering contractors are key to building and integrating the systems, they benefit financially from the work.

At the local level, Unidat di Bario represents neighbourhood interests and can support community acceptance. The UoC gardener, who maintains the plants on the terrain, benefits directly from a well-functioning filter and pump system.

Table 2.1: Overview of stakeholders.

Type	Stakeholder	Description
● Population	Unidat di Bario	An umbrella organization in Curaçao that promotes well-being in neighbourhoods and to collaborate with all neighbourhood organizations.
● Government	Analytisch Diagnostisch Centrum(ADC)	Curaçao's leading national medical and analytical laboratory.
	Water treatment plant(Klein Hofje)	The wastewater treatment plant (WWTP) at Klein Hofje on Curaçao is the island's largest water treatment plant
	Openbare Werken(OW)	Department of infrastructure which operates under the Ministry of Traffic, Transportation, and Spatial Planning (VVRP).
	Stichting Monumentenfonds Curaçao(MFC)	Provider of restoration funding in the form of grants and loans to individuals and organizations that wish to restore or maintain their protected monuments.
	Alumnus	Designed and constructed the base of the constructed wetland. Informed us on design choices and their implications.
	University of Curaçao(UoC)	The national and public state university of Curaçao. It is greatly connected to the jobmarket of Curaçao, which gives it a central role of collaboration.

Type	Stakeholder	Description
● Knowledge Institutions	CARMABI	CARMABI (Caribbean Research and Management of Biodiversity) is a non-profit foundation on Curaçao dedicated to scientific research, conservation, and management of the island's natural resources.
	Even Groene Vrienden	A TU Delft initiative for interdisciplinary learning communities in which students collaborate with businesses and government agencies on real-world challenges related to sustainability and the energy transition.
● Companies	Aqualectra	The Curaçao water and power company.
	Engineering Contractors	Constructors of rain- and wasterwatermanagement systems.
	AWA Consulting	Client of this report and advisor water management.
● Other	UoC gardener	Caretaker of the plants on the terrain. He benefits from a filter and pump system that works well.
	UNESCO	protector of cultural and natural monuments of exceptional universal value to humanity. This includes the historic town hall in Swaen.

2.3.2 Stakeholder Matrix

In order to get an overview of where attention should go to, a stakeholder matrix was created, shown below in Figure 2.7. In order improve the water systems, the parties at the top should be convinced and become more interested and the parties with the most interest should get a say in this.

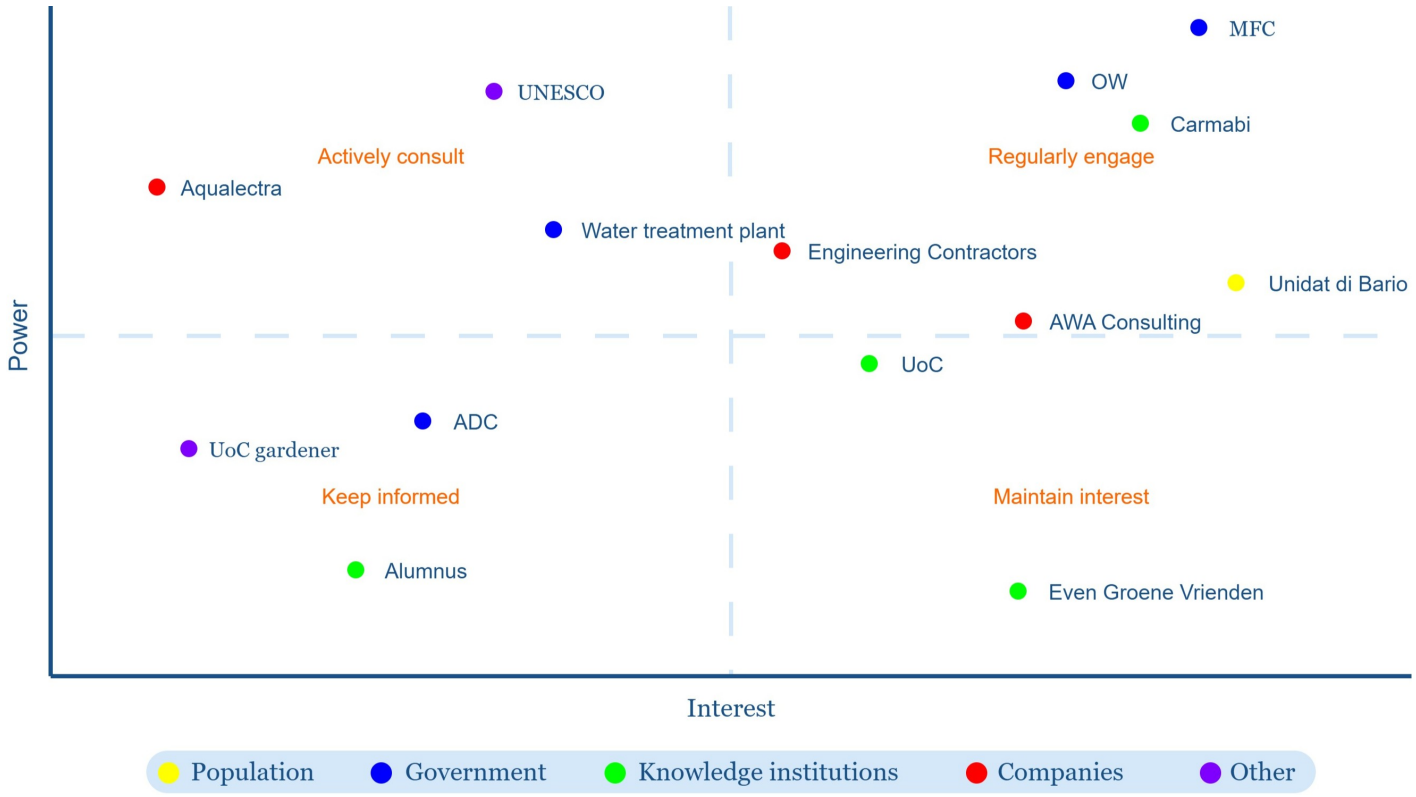

Figure 2.7: Stakeholder Matrix

3 Rainwater Management

This chapter presents the methods and results related to the core rainwater management subquestion: *What decentralized retention measures can be selected and spatially integrated to effectively mitigate local street flooding and reduce total downstream outflow?* In order to evaluate these potential stormwater interventions in Swaen, this chapter justifies and presents the 2D hydrodynamic modeling approach. The models are used to analyze the existing surface water dynamics in the Swaen catchment. The methodology begins by establishing the physical framework through the baseline model geometry and schematization. Subsequently, the meteorological and physical boundary conditions are defined via a comparative precipitation analysis, coupled with the appropriate surface parameterization of the local terrain. The unmitigated baseline hydrodynamic results are then presented to quantify current surface water vulnerabilities before any interventions are applied.

3.1 Software justification: 2D hydrodynamic modeling with HEC-RAS

To understand exactly how rainwater moves through the Swaen catchment during heavy tropical storms, the Hydrologic Engineering Center's River Analysis System (HEC-RAS) was selected over traditional models. While broad-area hydrological models estimate total runoff for an entire zone at once, and traditional 1D node-link models like *EPA SWMM* require predefined piped flow paths, both are insufficient for modeling unconfined surface water in complex suburban environments. HEC-RAS was chosen because it physically simulates how water flows across the actual, detailed shape of the land.

This modeling approach is driven by three specific capabilities:

- **Simulating direct rainfall:** Instead of assuming water instantly enters a river or pipe network, the software allows simulated rainfall to be applied directly onto a digital map. This is necessary to identify exactly where unconfined shallow water flows and where it naturally pools before reaching established drainage infrastructure.
- **Capturing fine terrain details:** Suburban water flow is heavily dictated by micro-topography like curbs, walls, and minor depressions. HEC-RAS efficiently processes high-resolution elevation data, allowing the model to recognize these small but critical features without exceeding computational limits.
- **Incorporating local soil variations:** Ground absorption is not uniform across the district. The model can seamlessly integrate localized soil data, such as specific Beerkan infiltration measurements, ensuring that the balance between ground absorption and surface runoff is grounded in actual site conditions.

By combining detailed surface topography, real soil permeability, and intense rainfall patterns, HEC-RAS provides the precise spatial resolution required to evaluate targeted flood mitigation strategies.

3.2 Baseline model geometry and schematization

This section outlines the physical framework underlying the hydrodynamic simulation of the Swaen catchment. Adjustments were made to translate the local topography into a computational environment. The following subsections detail the methodology for processing raw LiDAR elevation data into a continuous terrain model, the spatial discretization of the study area using a variable-resolution 2D computational mesh and the delineation of domain boundaries to mathematically govern the hydraulic limits of the simulated system.

3.2.1 Elevation data and terrain processing

For the surface elevation analysis, LiDAR data provided by the Ministry of VVRP via AWA-Consult was utilized as the foundational Digital Elevation Model (DEM). To accurately simulate local hydrological flow paths, manual terrain corrections were applied to the DEM using QGIS.

Because raw LiDAR data can smooth over or entirely miss narrow vertical features in the built environment, such as residential boundary walls, were manually digitized based on current Google Earth satellite imagery. This ensures the modeled surface accurately enforces physically realistic flow paths.

Moreover, in the northwestern corner of the Swaen area, the distance between several buildings in the DEM was artificially increased. Observations from local field investigations confirmed that the physical spacing between these structures was wider than depicted in the raw data, which had positioned them too closely together, creating an unrealistic blockage for water flowing over the intermediate road. The buildings themselves were otherwise left unmodified, retaining their original LiDAR elevation profiles.

3.2.2 2D computational mesh

While a formal mesh sensitivity analysis was not conducted, the two-dimensional computational mesh in HEC-RAS was optimized through an iterative refinement process based on initial hydraulic performance. A base grid resolution of 5 by 5 meters was initially applied to the overall catchment. However, preliminary simulations revealed that a uniform 5-meter resolution resulted in numerical leakage across narrow physical barriers. The coarse cells could not adequately enforce the containment provided by residential boundary walls and local micro-topography, causing water to unrealistically exit the defined flow corridors.

To resolve this without incurring prohibitive computational run times for the entire model, a targeted refinement region was implemented specifically within the primary area of interest. A localized cell size of 1 by 1 meter was applied to explicitly capture these critical physical barriers, ensuring realistic hydraulic routing. The surrounding macro-catchment was maintained at the 5-meter resolution to preserve computational efficiency while handling broader overland flow. As figure 3.1 shows, this is visually represented by the red grid structure within the larger blue model boundary.

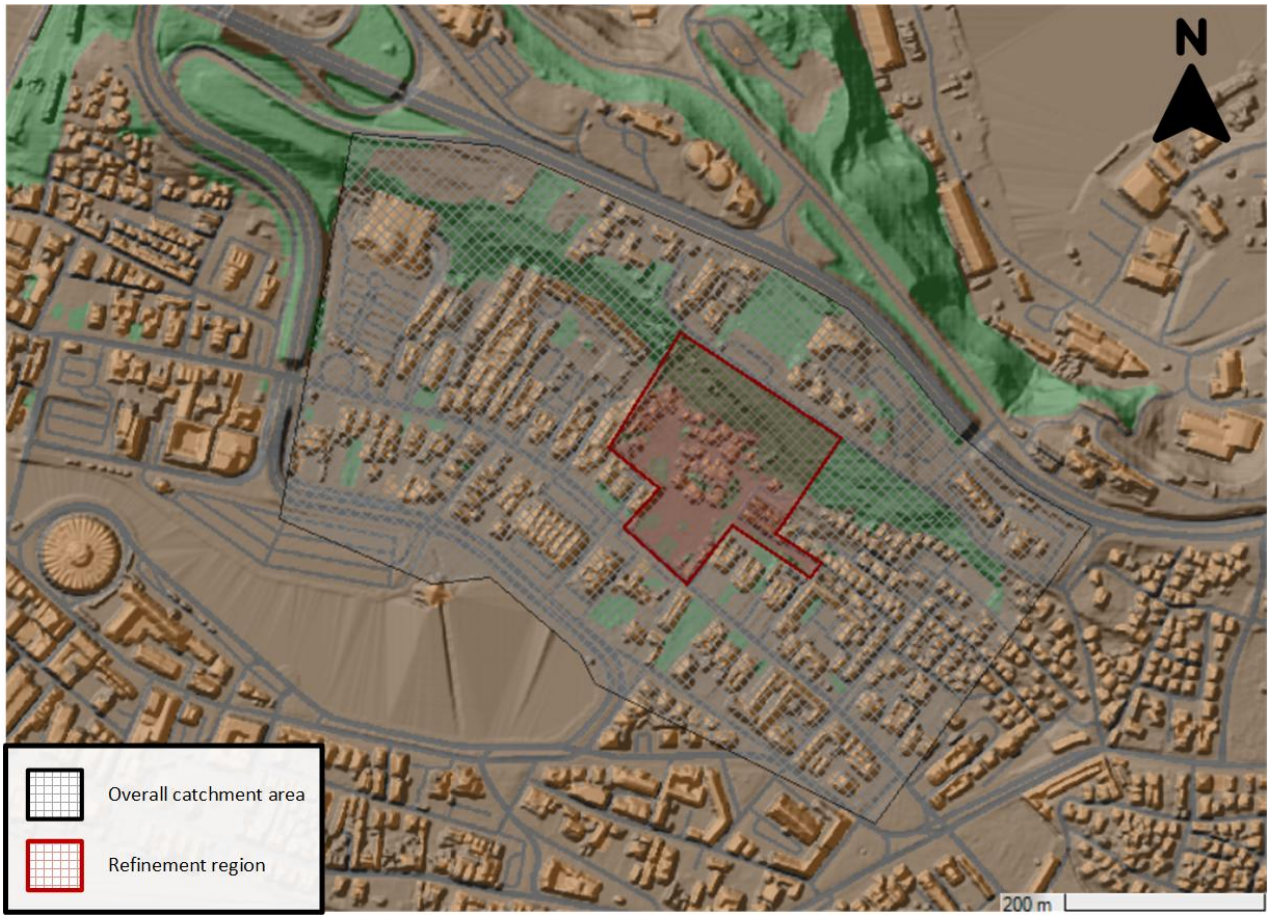

Figure 3.1: Topographic overview of the 2D computational domain in HEC-RAS

To minimize numerical errors and optimize the representation of water flow, breaklines were utilized. These breaklines force the cell faces of the computational mesh to align perpendicularly to the projected profile lines. In the model, these profile lines function as measurement points to accurately quantify flow rates. Additionally, storage areas were implemented within the computational mesh to measure the retained water volumes specifically for the Swaen region.

3.2.3 Land cover classification

To capture the physical environment of the Swaen district, OpenStreetMap (OSM) data was extracted and filtered into 2 primary land cover categories: Buildings and Paved Roads [38]. Green area's were hand marked in based on Satellite data and put into a new land cover category. All surfaces not yet annotated as Buildings, Paved Roads or Green areas were put into a new land cover category other. In the case of Swaen this mainly consists of permeable roads and the 'Other' land cover category is therefore treated as permeable road. After projecting the data to the model boundaries and resolving topological overlaps, this continuous land cover map (Figure 3.2) establishes the geometric baseline for assigning spatially varying parameters across the computational mesh.



Figure 3.2: Land cover classification of the model

3.2.4 Domain delineation and boundary conditions

The extent of the model domain was broadly defined to capture the complete influence of the upstream catchment area on the Swaen region. The model boundary follows natural and infrastructural topographic divides. On the north and west sides, the road situated on top of the hills serves as a natural boundary. On the east-side, the domain boundary was derived from the DEM analysis, enclosing all areas that drain towards Swaen. At the southern boundary, the system drains towards the Waaigat.

To correctly simulate the physical outflow of water from the model domain, a normal depth boundary condition of 0.006 was applied to all four outer edges of the 2D flow area. This ensures that surface water can exit the modeled catchment in a controlled manner without causing artificial backwater effects at the boundaries.

3.3 Precipitation analysis and design storm selection

This section establishes the precipitation boundary conditions by first examining established Dutch urban drainage standards and comparing them against the high-intensity rainfall characteristics typical of the Caribbean region. By synthesizing these geographical and methodological differences, a specific design storm is formulated and justified as the primary meteorological input for the Swaen catchment simulation.

3.3.1 Dutch design storm standards and performance criteria

In the Netherlands, urban surface water management and drainage design rely on universally accepted sector guidelines established by Stichting RIONED, rather than strict national legislation. Municipalities legally anchor these standards by adopting them into local policy [39]. For urban drainage design, Dutch engineers utilize predefined design storms with specific performance criteria for surface runoff. The baseline standard is *Bui 08*, a two-year return-period event delivering 19.8 mm of rainfall over 60

minutes. Under this standard, drainage systems must fully process the runoff to prevent any surface water accumulation. To accommodate a changing climate, new developments increasingly apply *Bui 09*, a five-year return-period storm dropping 29.4 mm over 60 minutes. During this event, water levels in the network may rise to ground elevation, but must not overflow onto the street. Finally, *Bui 10* serves as a critical above-ground stress test. Because this ten-year return-period storm delivers 35.7 mm over a concentrated 45-minute period, standard underground drainage capacities are expected to be exceeded. During this intensive event, the design philosophy shifts entirely to surface water management. Temporary flooding on streets and green spaces is utilized as a deliberate storage strategy, provided the surface water remains strictly below building floor elevations to prevent water ingress and property damage [40].

3.3.2 Caribbean precipitation characteristics and local practices

In contrast to the moderate-intensity frontal systems typical of the Netherlands, the Caribbean hydrometeorological regime is heavily influenced by tropical convective systems. Convective precipitation is triggered when the sun intensely heats the Earth's surface, causing the warm, moist air directly above it to rise rapidly, expand, and cool until its water vapor condenses to form large cumulonimbus clouds. As a result, convective rainfall in tropical regions is characterized by its high intensity and short duration, typically covering small, localized areas [41]. Even outside of the primary hurricane season, the Caribbean experiences severe rainstorms that generate extreme precipitation totals over highly concentrated periods, rapidly overwhelming initial soil infiltration capacities.

In the absence of publicly formalized municipal drainage codes in some local territories, the wider Caribbean region relies on standardized engineering practices to manage its distinct hydrometeorological risks. National bodies, such as Jamaica's National Works Agency (NWA), have formalized these practices into comprehensive development guidelines, establishing a robust regional framework for hydrologic and hydraulic infrastructure design. Central to this framework is a dual-drainage philosophy structured around specific recurrence intervals [42]:

- The Minor Drainage System: Roadside gutters, curb inlets, swales, and underground culverts are dimensioned to collect and convey runoff from frequent storms with return periods up to 1-in-10 years without causing localized inundation [42].
- The Major Drainage System: Overland flow paths, natural gullies (roois), retention corridors, and structural relief waterways are designed to accommodate extreme, less frequent events up to a 1-in-100-year return period when the capacity of the minor system is exceeded [42].

For small catchments ($\leq$ 100 ha or 1 km^2) without significant internal flood storage, peak discharge (Q) is commonly computed using the Rational Method [42]:

$$Q = \frac{1}{3.6 \cdot 10^6} \cdot C \cdot I \cdot A$$

where C is the composite runoff coefficient, I is the rainfall intensity in mm/hr derived from localized Intensity-Duration-Frequency (IDF) curves for a storm duration equal to the catchment's time of concentration (T_c), and A is the drainage area in km^2. To account for the extreme peaking characteristics

of tropical cloudbursts and the limitations of T_c formulations in steep or compact terrain, guidelines establish a minimum design duration: if the calculated T_c is less than 10 minutes, a 10-minute intensity is adopted. For larger watersheds or developments involving detention storage, designers transition to hydro-numerical modeling tools such as TR-55 or 2D simulations in HEC-RAS [42]. Even in these advanced models, the time of concentration remains a foundational parameter; establishing a simulated precipitation duration that matches the basin's T_c ensures the model captures the critical event generating the maximum peak discharge.

3.3.3 Selected design storm for the swaen simulation

For the hydrodynamic evaluation of the Swaen catchment area, a design storm with a 10-year return period (T10) and a duration of 30 minutes was selected. This rainfall has a intensity of 92 mm/hr, which is extracted from figure A.1 in appendix A.

Because specific hydrologic design mandates for micro-catchments are limited for Curaçao, this study adopts the formal guidelines published by the Jamaican NWA as a robust, geographically comparable Caribbean standard. The sufficiency of a 10-year return period is justified by two specific NWA design criteria that align directly with the Swaen site conditions:

First, the NWA explicitly prescribes a 10-year design return period for "minor drainage systems," which encompass the street gutters, roadside ditches, swales, and small channels that characterize the unconfined overland flow in the Swaen district. Major drainage systems, which require 100-year frequency evaluations, are strictly defined as large natural waterways and rivers, which are not present within this specific project scope.

Second, for the sizing of retention and detention solutions, the NWA guidelines mandate a 10-year frequency storm for inflow calculations whenever the contributing watershed area is smaller than 250 hectares. Because the Swaen catchment falls well below this 250-hectare threshold, evaluating the network against a T10 event provides a technically sufficient and regionally compliant baseline for sizing the surface water management solutions.

To accurately determine the critical storm duration, the time of concentration (T_c) for the catchment was established through a steady-state simulation in HEC-RAS. Rather than relying solely on empirical formulas, constant rainfall intensities were applied over a prolonged period of 60 minutes. The resulting hydrographs demonstrated that the outflow reaches a constant plateau at approximately 33 minutes, as shown in Figure 3.3. At this steady-state point, the catchment is fully contributing, meaning runoff from the hydraulically most remote areas of the 2D computational mesh has reached the measurement profile.

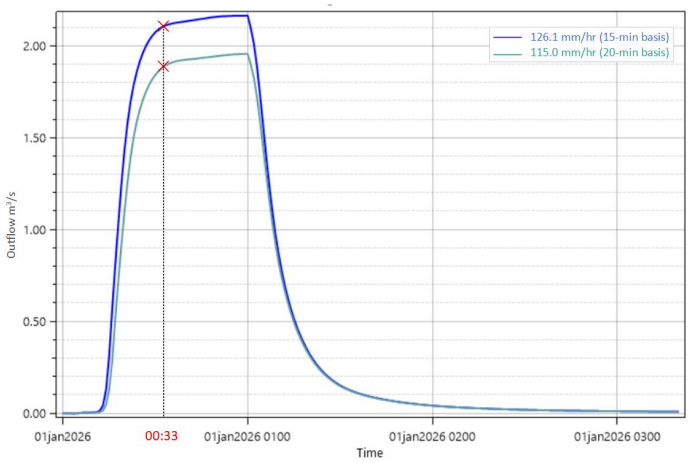

Figure 3.3: Catchment response to 1-hour constant rainfall simulations

Since the physical concentration time is approximately 33 minutes, as illustrated in Figure 3.3, a T10 storm with a 30-minute duration was selected as the governing scenario. This duration closely aligns with the actual concentration time, ensuring that the simulated peak flow and total runoff volume accurately represent the critical conditions required for sizing the retention and drainage solutions.

Lastly, evaporation was intentionally neglected throughout the hydrodynamic modeling process. During short-duration, high-intensity rainfall events, the volume of water lost to evaporation is negligible compared to precipitation rates. Furthermore, omitting evaporation serves as a conservative, safe design assumption. By assuming no water is extracted from the system via evaporation, the model slightly overestimates the total surface runoff and peak flow. This builds a natural margin of safety into the catchment analysis, ensuring that the final volumetric capacity of the retention solutions is robust enough to handle extreme conditions.

3.4 Surface parameterization

This section details the assignment of surface roughness coefficients across various land-use classifications and the definition of soil infiltration parameters. By integrating localized field measurements, such as in-situ infiltration tests, these parameters ensure the computational model realistically represents the physical interactions between the precipitation and the Swaen catchment terrain.

3.4.1 Manning value

Manning's roughness coefficient (n) represents the hydraulic friction and resistance that a surface exerts on moving water, directly determining flow velocities and inundation depths across the terrain. Higher values indicate rougher surfaces that slow water down and cause higher water levels, whereas lower values represent smoother surfaces that allow runoff to flow more quickly. The values assigned to the study area, as presented in Table 3.1, are based on the benchmark classifications from Australian Rainfall and Runoff (ARR) Project 15 (Table 10-1 and Table 10-3) [43]

Table 3.1: Land-cover roughness parameters

HEC-RAS classification	Literature category	Manning's n ($s/m^{1/3}$)
Impervious Roadways	Paved roads	0.02
Unconsolidated Granular Surfaces	Open pervious area, minimal vegetation	0.035
Vegetated Terrain	Open pervious areas, moderate vegetation (shurbs)	0.06
Urban Structures	Residential area – high density	0.3

3.4.2 Infiltration rates

To establish the infiltration rates for the HEC-RAS model, a single field measurement was conducted in the Swaen area using the Beerkan-test [44]. Due to the exceptionally hard clay soil present at the site, testing yielded prolonged infiltration times, concluding with a stabilized field observation of 200 milliliters of water infiltrating over a 15-minute period. Utilizing a measurement ring with an inner diameter of 15.9 centimeters, this volume translates to a raw, steady infiltration rate of 79.4 mm/hr, which is equivalent to 0.0221 mm/s.

This raw field rate (b_1) does not represent the final design value and must be mathematically corrected to determine the true saturated hydraulic conductivity (K_{fs}) of the soil. This adjustment accounts for the geometry of the testing equipment and the specific physical properties of the clay. The correction is calculated using the following formula[45]:

$$K_{fs} = \frac{b_1}{0.467\left(\frac{2.92}{r\times\alpha^*}+1\right)} \tag{3.1}$$

The calculation incorporates the raw steady infiltration rate (b_1) of 0.0221 mm/s, the testing ring's radius (r) of 79.5 mm, and a standard soil sorptive number for clay (α^*) of 0.004 mm^{-1}. Applying these specific parameters yields a saturated hydraulic conductivity of 0.00465 mm/s. Converting this result from seconds to hours provides the definitive infiltration rate of 16.7 mm/hr, which was adopted as the final input for the HEC-RAS model.

3.5 Baseline hydrodynamic results

This section establishes the existing flood hazards, flow dynamics, and baseline system behavior in the Swaen district prior to the implementation of any mitigation measures.

3.5.1 Inundation extents and temporal dynamics

The baseline 2D hydrodynamic simulation reveals pronounced spatial variations in water accumulation, driven by the local topographic gradient of the Swaen district. At peak inundation (figure 3.4), surface water predominantly accumulates in a localized depression in the central-western region, reaching a

maximum depth of 0.46 m. The lower southern zone experiences pooling up to 0.15 m. As the system drains (figure 3.5), the central-western accumulation recedes to 0.27 m. Residual pooling in the southern zone diminishes to localized pockets of approximately 0.05 m, and the higher northern area transitions entirely to surface runoff with negligible standing water.

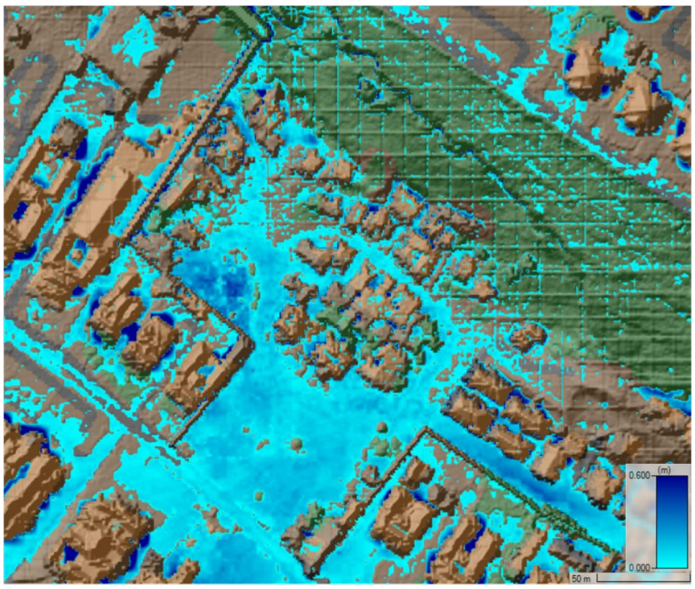

Figure 3.4: inundation depths during peak runoff ($t = 00{:}30$)

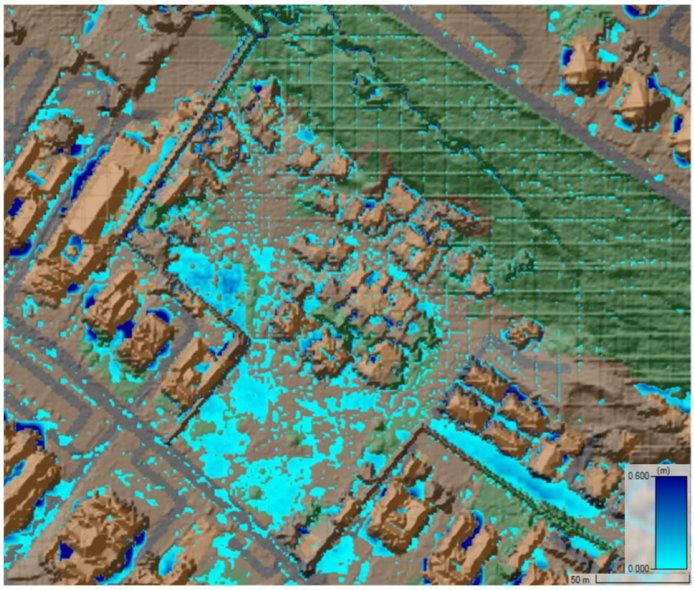

Figure 3.5: Residual water depths during the recession phase ($t = 03{:}30$)

3.5.2 Flow dynamics and velocities

Surface flow routing is heavily constrained by local topography and the geometric bottlenecks of the urban layout. As illustrated in figure 3.7, runoff predominantly originates from the higher northern and northwestern elevations. Additional surface water enters the domain from the eastern boundary. Together, these flows funnel southward through the residential grid. These diverse flow paths weave between structures and converge toward a pronounced localized depression in the central western region. The maximum observed velocity of 1.28 m/s occurs within a narrow, central flow path leading into the southern zone, as illustrated in Figure 3.6, indicating a highly concentrated route. Additional elevated velocities approaching 1.0 m/s are recorded in the northeastern section, as well as at the western domain boundary where external runoff enters the Swaen region. Ultimately, unretained stormwater is routed out of the district via pathways directing flow to the south.

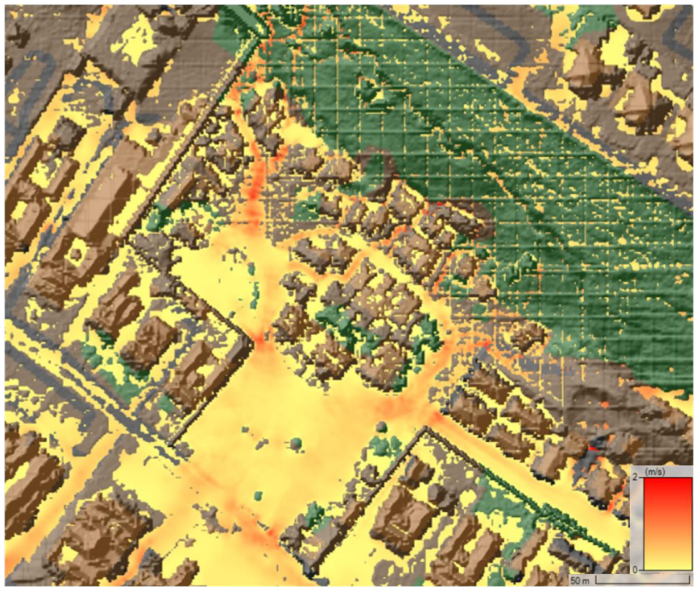

Figure 3.6: Surface flow velocities at peak discharge (t = 00:30)

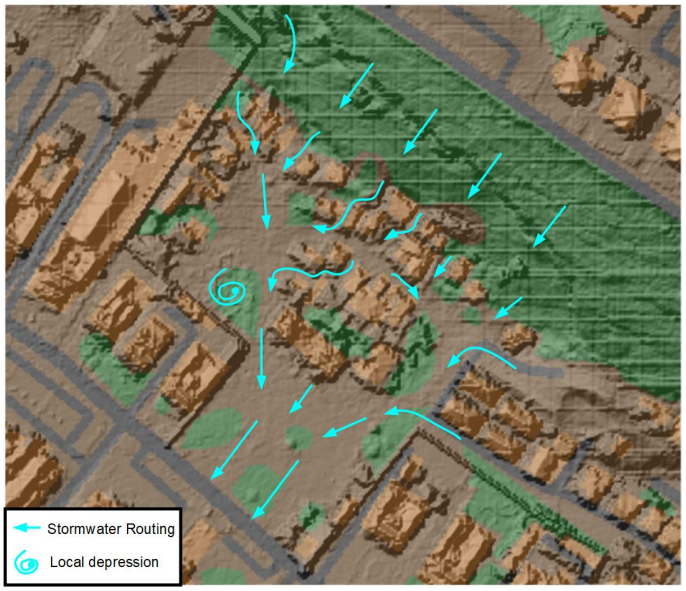

Figure 3.7: Flow pathways and local depressions areas

3.5.3 Hydrologic response and volume accounting

The catchment demonstrates a rapid hydrologic response, generating a peak discharge of 1.324 m^3/s at t=00:30, immediately preceding the time of maximum inundation depth. As is detailed in table 3.2, total precipitation introduces 824.32 m^3 into the specific Swaen storage area. This precipitation volume can be verified through a straightforward hand-calculation: applying a 92 mm/hr rainfall event over a 30-minute duration across a 17,920 m^2 area yields the total volume ($17,920 \times \left(\frac{92}{2\times1000}\right) = 824.32$ m^3).

The remaining parameters in the volume accounting table are derived directly from the HEC-RAS model outputs. The model shows the precipitation input is augmented by 1552.02 m^3 of boundary inflow. From this combined input, 212.925 m^3 is lost to total soil infiltration. The hydrodynamic system ultimately routes 1897.80 m^3 out of the domain as outflow, resulting in a total inundation volume of 215.00 m^3 within the localized Swaen district.

Table 3.2: Total volume accounting for Swaen

Parameter	**Volume (m^3)**
Inflow	1552.02
Precipitation	824.32
Outflow	1897.80
Total infiltration	212.925
Total inundation volume	215.00

3.5.4 Model stability and Swaen volume balance

Computational stability is robust across the simulation run. The global HEC-RAS computational log reports an excellent cumulative mass balance error of only 0.043% for the entire model domain. Localized

volume accounting for the specific Swaen sub-area yields a minor volume continuity error of 50.6 m^3, equating to a percentage error of 2.13%. Though this is higher then the expected global error of 1% in the HEC-RAS Manual, it also mentions that for sub-areas a higher tolerance should be allowed[46]. Thus captioning the main flows with 2.13% error is tolerated. For a comprehensive review of the governing equations, numerical tolerances, and iteration logs supporting this stability analysis refer to appendix B

3.6 Evaluation criteria

To assess the effectiveness of the proposed rainwater management solutions, the performance of each individual and combined solution is compared against the established baseline conditions. To ensure both local inundation within the project area and downstream flood risks are adequately mitigated, the evaluation is based on two Key Performance Indicators (KPI's):

- **Total outflow volume:** This criterion evaluates the cumulative volume of water (measured in m^3) discharging from the Swaen district over the entire duration of the design storm event. A successful mitigation strategy must significantly reduce the total outflow volume compared to the baseline to prevent overwhelming the downstream municipal drainage infrastructure.
- **Inundation volume:** This criterion assesses the total volume of surface water ponding within the Swaen project area boundaries. The primary objective is to minimize standing water in the public realm, thereby maintaining accessibility and enhancing the overall comfort and livability of the district during rainfall events.

3.7 Potential mitigation solutions

In this subchapter potential mitigation solutions are mentioned listed, including Key Performance Indicators and interpretation of these results. More extensive results and images of QGIS map layers is visible in appendix C.

3.7.1 Household-storage tanks

Based on the QGIS buildings layer, there are 40 buildings in the neighbourhood with a total area of $2,483$ m^2. Assuming all water that falls on the buildings is captured using storage tanks this results in a total storage of 114 m^3. This was used in the model though in reality this might be closer to 85% [47]

Table 3.3: Comparison of baseline and household-tanks implementation

Metric	Baseline	Household-tanks
Outflow m^3	1898	1813
Inundation volume m^3	215	189
Volume storage m^3	–	114

Table 3.3 presents the results for the household-storage tanks scenario. Implementing this decentralized storage successfully reduces the inundation volume in the Swaen area by 26 m^3, dropping from 215 m^3 to 189 m^3. Additionally, capturing this runoff leads to a direct reduction in the catchment's outflow,

which decreases by 85.08 m^3. By utilizing the total storage capacity of 114 m^3, the system demonstrates a tangible reduction in both critical evaluation metrics.

3.7.2 Centralized storage facility

Another possible intervention involves the creation of a centralized storage facility. Though the design of this storage area is outside the scope for this research potential configurations are underground storage tanks, rock storage systems, or traditional Curaçaoan *Rèn bak* (cistern).

This intervention also has the advantages of storing water for reuse; both in case of a rock storage where water slowly infiltrates into the surrounding soil, and in case of storing the water in a storage tank or cistern where it can be directly used again.

Table 3.4: Comparison of baseline and individual storage strategies.

Metric	**Baseline**	**Storage 1**	**Storage 2**	**Storage 3**	**Storage 4**
Inflow m^3	1552	1521	1614	1610	1615
Outflow m^3	1897	1611	1788	1293	1391
Inundation volume m^3	215	174	218	218	217
Volume storage m^3	–	311	186	674	578

Visible in Table 3.4, are different locations and sizes for storage areas in Swaen.

The table shows that storages 2, 3 and 4 have minimal results when adressing Inundation volume. As the volume is very similar to the baseline run. Storage 1 does show good results, as this does decrease the inundation volume by 41 m^3.

3.7.3 Permeable roads

To manage runoff and encourage infiltration, permeable roads were evaluated within the system. Due to software constraints that prevent directly modeling localized increases in surface infiltration, these permeable surfaces are modeled as local storage areas. This was achieved by lowering the terrain of the road network by 30 cm. To evaluate the scalability of this approach, three configurations were simulated:

- **Permeable roads (small):** The road elevation is uniformly lowered by 30 cm to act as local storage throughout the network.
- **Permeable roads (medium):** The lowered road network is combined with a dedicated storage basin (marked in yellow at the southern, lowest point of the catchment) designed to capture runoff. This southern basin has a capacity of approximately 300 m^3.
- **Permeable roads (large):** The lowered road network is combined with an expanded southern storage basin featuring a capacity of approximately 1100 m^3.

Although this solution effectively reduces the overall catchment outflow, it has a negligible effect on the inundation volume. The simulation results demonstrate that increasing storage capacity does not proportionally decrease inundation. Even the “small” configuration provides limited benefit; despite

Table 3.5: Comparison of baseline and permeable roads strategies.

Metric	Baseline	Perm. Roads (small)	Perm. Roads (medium)	Perm. Roads (large)
Outflow m^3	1898	1767	1477	1065
Inundation volume m^3	215	189	202	193
Volume storage m^3	–	168	451	865

capturing nearly 200 m^3 of runoff, the inundation volume drops by only 20 m^3. So, this intervention proves ineffective and is ultimately not considered a viable mitigation strategy for the catchment.

3.8 Combined system performance

Because single solutions were not enough, different combinations of measures and locations are tested. As shown in Table 3.6, combining Storage 1 with household tanks works very well and the two measures support each other.

Other combinations show little improvement to the *storage 1 + tanks* model on inundation volume in Swaen, with additional storages mainly capturing water that would otherwise flow out of Swaen.

Table 3.6: Results of combination mitigation strategies

Metric	Storage 1 + tanks	Storage 1 with small storage 2 + tanks	Storage 1 with large storage 2 + tanks	Storage 1, 3, 4 + tanks
Inflow m^3	1526.16	1598.46	1600.62	1604.4
Outflow m^3	1551.6	1615.14	1451.04	635.64
Inundation volume m^3	144	144	143	125
Total stored volume m^3	404.218	435.218	601.218	1424.218

3.9 Proposed mitigation strategy

The proposed mitigation strategy is a combination of area-wide storage and household storage tanks. As explained in subchapter 3.7.1, a total of 114 m^3 is stored in the storage tanks, and an additional storage area of 290 m^3 is created at the western edge of Swaen. The exact location is visible in Figure 3.8.



Figure 3.8: Proposed mitigation strategy. Storage area is shown in blue, with purple representing the houses within Swaen where water will be captured.

This specific configuration was selected as the optimal strategy because other combinations show little improvement to this strategy on inundation volume in Swaen. While the most extensive strategy evaluated (Storage 1, 3, 4 + tanks) yields the lowest total inundation volume (125 m^3), it demands a massive total storage capacity of 1424 m^3. In contrast, the chosen *storage 1 + tanks* strategy achieves a highly comparable reduction in street flooding but requires over 1000 m^3 less storage space (404 m^3 total). This makes it a substantially more efficient, cost-effective, and spatially realistic urban intervention. The hydraulic performance of this intervention is compared against the unmitigated baseline in Table 3.7.

Table 3.7: Comparison baseline and proposed mitigation strategy

Metric / Parameter	**Baseline (m^3)**	**Proposed Strategy (m^3)**
Inflow	1552	1526
Outflow	1898	1551
Total inundation volume	215	144
Storage area 1	–	290
Volume in the Rainbarrels	–	114

As visible in Table 3.7, the total volume of unconfined water on the streets in the Swaen area is significantly reduced from the baseline of 215 m^3 to 144 m^3, while the total downstream outflow is reduced from 1898 m^3 to 1552 m^3.

4 Wastewater Management

This chapter focuses on wastewater management within Swaen. Although plans for the development and improvement of the area have existed since the 1990s, more concrete actions and research have only been undertaken in recent years [48]. Given the urgency of addressing the existing infrastructural and environmental challenges, the coming years provide an important opportunity to establish a more sustainable and effective wastewater management system.

The objective of this chapter is to assess the current wastewater situation and present design considerations and spatial requirements for a future wastewater system in Swaen. An important attention point is that the domestic wastewater is aimed to be collected through a closed system and kept entirely separate from stormwater. This separation greatly improves the reduction of public health risks, it prevents wastewater from entering open drainage channels, and protects the quality of surface water and the surrounding environment.

The scope of this chapter is to develop a conceptual approach to wastewater management, identify a preliminary collection route, and define the spatial reservations required to create the proposed system. Although potential collection and treatment solutions are considered, the detailed engineering design of the sewer network and wastewater treatment facilities falls outside of the scope of this study. Instead, the chapter establishes a technical principles and spatial framework needed to guide future design and decision-making.

4.1 Technical analysis of the current situation and design principles

4.1.1 Data collection and baseline assessment

The baseline assessment of wastewater management in Swaen combines literature research, satellite imagery, site observations, and conversations with local residents. Since limited information is available in the literature describing the wastewater infrastructure in Swaen in detail, the assessment relies on multiple sources to establish the current situation. Information from Curaçao as a whole and comparable areas is used where area-specific data are unavailable.

Population numbers obtained from World Population Review [49] and Central Bureau of Statistics Curaçao (CBS) [50] indicate an estimated population of 107–127 inhabitants. However, the accuracy of these figures is uncertain, and more recent, verified population data for Swaen could not be identified. During conversations with residents, one long-term resident estimated that approximately 90 people live in the area. Although this estimate is somewhat lower than the figures obtained from the desktop research, it provides a broadly comparable indication of the population size.

The area's functions and land use must also be considered when establishing the design requirements. The spatial assessment in Figure 4.1 identifies residential buildings, nature, roads, and available space for wastewater infrastructure. In addition, the area's elevation differences are mapped in Figure 4.2 to assess

the feasibility of gravity-based wastewater collection. These aspects are particularly useful in the design of potential solutions for the area.



Figure 4.1: Land-usage of Swaen [38]

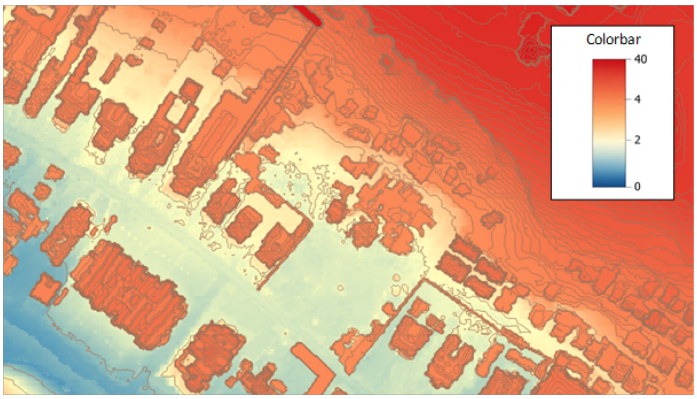

Figure 4.2: Elevation map of Swaen as described in subsection 3.2.1. Contour lines are added every meter.

Swaen is not connected to the central sewerage network in Willemstad, thus people are forced to install cesspits or septic tanks to process their wastewater themselves. In Curaçao 81% of people used either cesspits (77%) or septic tanks (3%) [51]. The assumption is that people in Swaen make use of self-installed cesspits, which is because of site observations and through conversations with residents. Septic tanks might also be used in the area, but most likely not up to standards with most conventional septic tanks. These tanks could therefore also be considered to be a form of cesspits.

Currently, domestic wastewater generated in Swaen is not subjected to any identified treatment process. The area is not connected to a centralized wastewater treatment plant in Willemstad, and no operational decentralized treatment systems have been identified. Consequently, wastewater is assumed to be discharged without effective treatment, potentially posing risks to public health and the surrounding environment.

Finally, the wastewater has to be disposed or reused. A large proportion of the domestic wastewater from Swaen seeps into the soil via cesspits and septic tanks and can subsequently reach the sea through the groundwater. Another disposal option often used on Curaçao is discharging the wastewater directly into the ocean after collecting it with tank trucks [51], although it is not entirely certain if this happens in Swaen. A good solution would be to reuse treated wastewater in the Swaen region, for example in irrigation practices, this way the valuable freshwater will not be wasted.

Table 4.1 provides an overview of the wastewater facilities and processes currently present in the Swaen area. It summarizes the existing wastewater management situation based on the available information and observations. Cells marked with both a cross (✗) and a checkmark (✓) indicate that the presence or use of a particular facility is uncertain or limited to specific locations within the area.

Table 4.1: Wastewater infrastructure elements used in Swaen.

Type	Element	Used in Swaen
Collection/conveyance	Sewer network	✗ / ✓
	Pumping station	✗
Decentralized systems	Cesspits	✓
	Septic tanks	✗ / ✓
Treatment systems	Centralized treatment	✗
	Decentralized treatment	✗
Wastewater disposal/reuse	Discharge into groundwater	✓
	Ocean dumping	✓
	Irrigation Use	✗
Control systems	Smart water meters	✓

4.1.2 Effluent and discharge standards

On Curaçao there are no actual legally binding effluent or discharge standards available. There is a proposal made by Werkgroep Milieunormering Nederlandse Antillen in 2007 talking about these standards for the Netherlands Antilles [52]. These were proposed environmental standards and the next step was to establish them legally through Lands- and Eilandsbesluiten. These guidelines were never actually applied, but they form the right overview about what the wastewater treatment process should accomplish. Besides, after this proposal there hasn't been any further proposed guidelines for effluent or discharge on Curaçao. For the wider Caribbean region there are more recent documents discussing regulations on wastewater quality. In 2025 a report from the United Nations [53] has set recommendations and standards for domestic wastewater discharges in the Caribbean region. Although this document is not specifically focused on Curaçao, the data in the report is very helpful as a guiding standard. In Table 4.2 the effluent standards for Curaçao are shown based on the two proposals. In Appendix D the different wastewater parameters are shortly explained.

Table 4.2: Guidelines for domestic wastewater discharges on Curaçao (max. values) [52] [53]

Parameter	Unit	1) On sewerage system (2007)	2) Irrigation (2007)	3) On surface water (2007)	4) On surface water (2025)
BOD_5	mg/l	n/a	50	30	30
COD	mg/l	n/a	125	150	n/a
N-tot.	mg /l	n/a	28	5	n/a
P-tot.	mg /l	n/a	5	1	n/a
Fecal Coli	x/100 ml	n/a	1000	200	200
E. Coli (freshwater)	x/100 ml	n/a	n/a	n/a	126
Enterococci (salt water)	x/100 ml	n/a	n/a	n/a	35
Oil / Grease	mg/l	200	–	10	15
pH	–	6.5 – 8.5	6 – 8	6 – 8	5 – 10
Electrical Conductivity	μS/cm	2250	2250	n/a	n/a
Chloride	mg /l	150	250	n/a	n/a
Suspended Solids	mg/l	350	50	30	30
Temp. Max.	°C	40	n/a	32/+1 °C	n/a
SO_4	mg/l	350	n/a	n/a	n/a

Note: n/a = not applicable or no standard is specified for this parameter. Standards are expressed as 24-hour samples.

4.1.3 Estimation of wastewater flow and loads in Swaen

The domestic wastewater flow in Swaen is estimated using the average per capita wastewater generation rate for Curaçao. Swaen is solely a residential area and thus only has wastewater contributions from residential purposes. According to the World Health Organization (WHO), the total volume of household wastewater generated in Curaçao in 2020 was approximately 6.652 million m^3 [54]. The total population of Curaçao in the same year was 156,223 inhabitants [55], according to the CBS.

The average annual wastewater generation per capita is calculated as:

$$Q_{\text{cap,annual}} = \frac{6{,}652{,}000}{156{,}223} = 42.58 \text{ m}^3/\text{person/year} \tag{4.1}$$

Using 366 days for the year 2020, the average daily wastewater generation per capita is:

$$Q_{\text{cap}} = \frac{42.58}{366} = 0.1163 \text{ m}^3/\text{person/day} \tag{4.2}$$

Therefore, the estimated average domestic wastewater generation rate is 116.3 L/person/day. This value is used as the basis for estimating the wastewater flow in Swaen.

The population in Swaen was earlier estimated at 107-127 residents. From this range the number of 127 inhabitants was chosen to get a conservative basis for further calculations. With this data, the estimated average domestic wastewater flow is calculated as:

$$Q_{\text{avg,2026}} = 127 \times 0.1163 = 14.77 \text{ m}^3/\text{day} \tag{4.3}$$

Future wastewater flows should also be estimated to account for population growth and change in the residential composition of the Swaen region. Two future population approaches were used published by CBS [56]. The first approach uses a population growth estimate, which projected a population increase of approximately 13% by 2050. The second approach uses the projected maximum population of Curaçao of 182,626 inhabitants in 2040, compared with the 2020 population of 156,223 inhabitants. These are the two approaches that are deemed the most likely to occur for Curaçao, thus the other approaches of the CBS report are discarded in terms of this research. Applying both these methods the following domestic wastewater flows are obtained:

$$Q_{\text{avg,2050}} = (127 \times 1.13) \times 0.1163 = 16.69 \text{ m}^3/\text{day} \tag{4.4}$$

$$Q_{\text{avg,2040}} = \left(127 \times \frac{182{,}626}{156{,}223}\right) \times 0.1163 = 17.27 \text{ m}^3/\text{day} \tag{4.5}$$

The second approach results in the higher estimated wastewater flow and is therefore adopted as the preliminary design basis. The resulting average domestic wastewater flow is 17.27 m^3/day. It should also be noted that these projections are indicative rather than definitive. The island-wide population growth rate may not reflect the actual development of Swaen.

Two other parameters to include in the flow rate calculations are the infiltration and inflow allowances. Infiltration and inflow are described as the extra water that enters a wastewater system from exterior sources other than the actual wastewater the system is designed for [57]. Infiltration is the groundwater that makes its way into the system, while inflow is the rainwater that gets into the system unplanned. The infiltration and inflow (l/l) should be accounted for since this gives extra load on the system. Infiltration, the groundwater entering the system, could infiltrate the system through cracked pipe joints, poor sealing or aging pipe material. The inflow, the rainwater entering the system, could penetrate the system through leaky manholes, illegal system connections or bad separation of rainwater and wastewater systems. Even a very well-designed separated wastewater system will never achieve zero infiltration and inflow, making it a must to include these parameters into the design.

No specific infiltration and inflow (l/l) allowance for the Curaçao wastewater system was identified in the available literature. Even the close Caribbean region does not provide exact information regarding the standards of how to apply certain l/l allowances. There is information available through a reference project on Jamaica. Jamaica provides a relevant regional reference due to its Caribbean climate and environmental conditions, making this assumption more representative for the Curaçao context than values derived solely from temperate regions. A Jamaican environmental-impact assessment submitted to the National Environment and Planning Agency (NEPA) gives the wastewater flow calculation for a proposed wastewater treatment plant. In this report, an allowance of 10% of the average wastewater flow is used, considering just the infiltration of the wastewater system [58]. The inflow is not taken into account in that report. Since also no Curaçao-specific value for inflow was identified, inflow is assumed to contribute an additional 10% of the average wastewater flow. Consequently, the total additional flow from infiltration and inflow is assumed to be 20% of the average wastewater flow, which is supported by literature review [59].

The last part of the calculation entails the contribution of a peak factor. The domestic water usage varies the whole day long and is higher or lower on certain times of the day. This is why there should be a peak factor applied to the produced wastewater, so the wastewater system is designed for the highest possible water usage of the area. The following formula is used to determine the wastewater peak factor:

$$PF = \frac{Q_{\max}}{Q_{\text{avg}}} \tag{4.6}$$

Where:

- PF = peak flow factor (dimensionless);
- $Q_{\max}$ = maximum wastewater flow rate;
- Q_{avg} = average wastewater flow rate.

Since there is no data accessible considering peak factors for Curaçao, the specific wastewater peak factor can be estimated using available wastewater flow data from Curaçao. The largest wastewater treatment plant, *Klein Hofje*, has a daily capacity of 3500 m3/day and a peak capacity of 350 m3/hour [60]. The average hourly flow corresponding to the daily capacity is:

$$Q_{\text{avg,h}} = \frac{3500}{24} = 145.83 \text{ m}^3/\text{hour} \tag{4.7}$$

The resulting peak factor is:

$$PF = \frac{350}{145.83} = 2.40 \tag{4.8}$$

This peak factor would be viable for Curaçao, but there is a special condition in Swaen since only about 100 people are living there. If the wastewater system for Swaen will only be designed for that specific region, the peak factor will likely have to be higher. There has been a study on small communities in

arid climates, which recommends to use a higher peak factor for these conditions [61]. This is the case because the variability in water usage will be very large for small areas, since fewer people make use of the system. As the number of users increases, individual household fluctuations tend to average out. In a small network, however, a relatively small number of simultaneous activities can cause a much larger variation relative to the average flow. The following formula can be used to estimate the peak factor for these communities, where P is the amount of residents in thousands [61]:

$$PF = 1 + \frac{14}{4 + \sqrt{P}} = 1 + \frac{14}{4 + \sqrt{0.127}} = 4.21 \tag{4.9}$$

This value is also consistent with the findings of Imam and Elnakar for a small near-arid residential community, where a 1-hour peak factor of 4.35 was obtained at a 99% probability of non-exceedance [61].

Finally the design flow rate for Swaen can be determined. The design flow rate is the wastewater flow rate with all factors and future approaches included, resulting in the highest possible flow rate for the system. This way, a wastewater management system can be designed that has a high enough capacity for all of the predicted future situations. The following formula describes the design flow rate:

$$Q_{\text{peak}} = Q_{\text{avg}} \times (1 + f_{\text{I/I}}) \times PF \tag{4.10}$$

Where:

- Q_{avg} = average wastewater flow rate;
- $f_{\text{I/I}}$ = infiltration and inflow allowance;
- PF = peak flow factor.

Using the selected design parameters:

$$Q_{\text{peak}} = 17.27 \times 1.20 \times 4.21 = 87.25 \text{ m}^3/\text{day} = 3.64 \text{ m}^3/\text{hour} = 1.01 \text{ L/s} \tag{4.11}$$

The value of 87.25 m^3/day represents the peak flow expressed as an equivalent daily rate. It does not represent the expected average wastewater production over an entire day. The actual average wastewater flow remains 17.27 m^3/day before the infiltration and inflow allowance.

4.2 Potential solutions for wastewater

Presently, the baseline of the area has been set, the effluent standards are known and the design flow rate has been determined. Next, solutions to improve the wastewater management in Swaen are investigated and designed.

The wastewater system and the stormwater system will be designed as two separate systems. It is strived for to keep the two networks disconnected as much as possible, with stormwater already handled in

Chapter 3.

4.2.1 Collection system

At first, an effective collection system should be determined for the area. The wastewater collection system is dedicated to the Swaen region and will be designed solely for this region. Centralized and decentralized options will be compared with each other. In the case that one of the centralized systems is preferred for the Swaen region it will be necessary to investigate whether connection to the main sewerage system is possible. Otherwise these systems will be out of the question for Swaen. It is also a possibility to combine the benefits of the various systems into one general design such that the optimal solution will be created. The following system types are considered to be viable options for the Swaen area.

Collection system options

Gravity sewer (conventional sewerage system) [62]:

Gravity sewerage systems make use of gravity to transport wastewater from one place to another. The network is often set up with primary and secondary pipelines connecting with each other. The pipes are laid at a continuous downwards slope towards a central collection point. With these systems there is no need for mechanical power to assist in pumping of the wastewater, which saves on the complexity and costs of this option. The system is also easy to operate and requires relatively low maintenance. The system has to be created, however, with such a flow that the self-cleaning velocity will be sustained. In Swaen this type of system could be applicable since the area consists of a continuously downward slope to one end of the region, well-suited for this type of network. This system does take a lot of space though in comparison to the other systems due to the need for wide pipelines and extra properties like manholes for the network.

Pumped/pressure sewer [63]:

In these types of systems the wastewater is pumped through smaller-diameter pipes and is not dependent on the downhill slope of the pipes. If necessary, each pipe section has an its own pump to get the wastewater to higher elevations in the system. One of the main advantages of this system is that the routing of the pipelines is very flexible and there are multiple different system configurations possible. In comparison to the conventional sewerage system the initial costs and running costs are higher and the system is dependent on external energy to function. Maintenance on the system is more complex and therefore also more expensive than a gravity sewer system, because of the mechanical components of the system. These systems can also be set up with a vacuum station, which pulls the water instead of pushing it.

STEP / STEG systems (solids-free sewer) [62]:

STEP (Septic Tank Effluent Pumping) and STEG (Septic Tank Effluent Gravity) are sewerage networks that make use of decentralized solutions to transport pre-treated and almost solids-free wastewater through the system. The difference between STEG and STEP systems is that the STEG systems use gravity flow to transport the wastewater, while the STEP systems use pumps for transport. One of the

requirements for this system is that there is primary treatment of the wastewater on household level before the water can be processed. The main solution can be found in the form of a septic tank, installed at the homes of the residents. Here, the main solids will be filtered out of the wastewater to prevent clogging of the pipes. In contrast to the other two systems, no minimum flow velocity is required because of this. Maintenance frequency on the pipe network is relatively low, because there is a low amount of solid particles present in the transporting pipes.

Decentralized treatment [62]:

In contrast to the other systems, decentralized treatment solutions process the water on-site where the wastewater is collected. These systems therefore make no use of a centralized sewerage system. Wastewater is transported in the local network on small scale in contrast to full city networks. Common decentralized technologies include upgraded septic tanks or anaerobic baffled reactors (ABR) for individual households, small package treatment plants serving a cluster of connections, and constructed wetlands that use planted filter beds to clean effluent before infiltration or discharge. Later in this report the different treatment options will be discussed in detail. The advantage of these systems is that they avoid the need for a big sewerage network and big diameter piping. Furthermore, these systems provide local solutions to the water problems in Curaçao, which makes the implementation easier accessible for small or isolated communities. Water is transported based on the preferred option for the local situation, with gravity flow or pumps. Depending on the applied solution, the required land area can be a lot bigger than other systems because of the designs being mostly above ground.

In Table 4.3 a comparison of the different systems is shown to give an overview of the characteristics of the collection systems. It should be noted that these characteristics are in comparison with each other and that they should not be viewed separately. Adding on to this, the characteristics of the decentralized options are very broad and could differ depending on the chosen variant.

Table 4.3: Comparison of wastewater collection and treatment systems [62] [63]

Parameter	Gravity Sewer	Pumped/Pressure Sewer	STEP/STEG system	Decentralized treatment
Driving Force	Elevation/slope	Pump/vacuum station	Elevation/slope or pump	Elevation/slope or pump
Terrain	Sloped	Any	Any	Any
Pipe diameter	Wide diameters	Small diameters	Small diameters	Small–medium diameters
Land requirement	Small/Medium	Small	Network: Small; Equipment: Medium	Low–High (Depends on system)
Initial Costs	Medium	High	Medium	Low/Medium
Operating Costs	Medium	High	Low	Low/Medium
Application level	Neighbourhood/ City	Neighbourhood/ City	Neighbourhood/ City	Household/ Neighbourhood
Complexity	Low	Medium	High	Low–High
Power requirement	None	High	Medium	Low

Choice of collection system

Next up, a choice has to be made between the different collection system options. The centralized wastewater treatment systems are a potential solution for improving wastewater management in Swaen, Curaçao. In these approaches, wastewater from individual households is collected through a sewer network and transported to a central wastewater treatment plant. The wastewater is treated at a single location before being discharged or reused, depending on the effluent quality and applicable requirements. The main advantages of centralized treatment are the potential to treat large wastewater volumes efficiently and centralize operation and maintenance. However, implementing such a system requires substantial investment in sewer infrastructure, including pipes and household connections. Furthermore, the technical feasibility and economic viability of a centralized sewer network in Swaen require further investigation.

To investigate this possibility, a visit was made to Openbare Werken (Public Works) at the relevant ministry in Curaçao. During this visit, the possibilities for implementing a connected sewer system in Swaen were discussed. Openbare Werken indicated that establishing a connected sewer system in the area is possible. However, several uncertainties remain regarding the costs and the locations of existing sewer connections to which a new network in Swaen could be connected. In addition, the sewer network in Willemstad is not comprehensively mapped, and detailed maps of existing wastewater infrastructure are only available for certain areas. For Swaen and much of its surrounding area, such information is not yet available, making it difficult to assess the feasibility and costs of a centralized system accurately.

During the consultation, a map was obtained from Openbare Werken showing parts of the existing wastewater infrastructure in the vicinity of Swaen. Figure 4.3 presents the interpretation gathered from this map and provides an initial overview of the possible connection points that could connect Swaen to the centralized sewer system of Willemstad. Depending on the exact location of existing sewer pipes, ground elevations, and the distribution of households, a new network could potentially connect Swaen to the existing infrastructure. Gravity-driven transport may be possible if sufficient elevation differences are available, otherwise, pumping infrastructure could be required. On the map, the two main connection points are visualized to give an indication of the possibilities within the region.



Figure 4.3: Potential sewer connection points for Swaen [21]

Although centralized wastewater treatment remains a potentially viable option for Swaen, this research will further focus on decentralized wastewater treatment systems. This choice is based on the uncertainties regarding a centralized system and allows for a more detailed investigation of treatment solutions that can operate close to the point of wastewater generation, either at individual households or at shared facilities serving a group of residences. Potential technologies include improved septic tanks, anaerobic baffled reactors, anaerobic filters, constructed wetlands, and compact aerobic treatment units.

Decentralized treatment offers several potential advantages for Swaen. Systems can be adapted to local conditions and implemented in phases, potentially reducing the need for an extensive sewer network. Depending on the selected technology, decentralized systems may also require relatively little energy and allow wastewater to be managed locally. These characteristics make them relevant alternatives to investigate for a residential area where the costs and configuration of a centralized sewer connection remain uncertain.

However, decentralized systems also have disadvantages. Individual installations can result in maintenance activities being distributed across multiple properties, while shared systems require clear arrangements for operation, maintenance, and responsibility. Treatment performance also varies between technologies, and some systems require electricity, specialist maintenance, or substantial land area. Furthermore, treated wastewater must still be managed safely to prevent environmental pollution, particularly groundwater contamination.

Centralized wastewater treatment is acknowledged as a potentially feasible solution, particularly given the consultation with Openbare Werken. However, because the available information is insufficient to establish the precise costs and technical requirements of connecting Swaen to the existing sewer network, the detailed assessment focuses on decentralized treatment alternatives. The aim is to identify solutions that can provide adequate effluent quality, protect groundwater, and remain technically feasible and financially manageable under the local conditions in Swaen. A centralized sewer connection remains an

alternative for future investigation if more detailed infrastructure and cost information becomes available. For now, a decentralized treatment solution will be further investigated and it has to be determined what kind of solution is optimal for the Swaen region.

4.2.2 Wastewater treatment system

The research will zoom in further on decentralized wastewater treatment options. A choice will be made using a MCA to find the best suited treatment alternative for Swaen specifically. First off, various different treatment options are discussed.

Decentralized treatment options

Cesspit [64]: A cesspit is a wastewater collection tank that is used for the temporary storage of sewage. It is one of the most basic methods to handle wastewater in residential practices. Most commonly the pit is not watertight and the liquids are leached into the ground below, leaving behind a solid mass inside of the cesspit and contaminating the groundwater. This volume of solids has to be emptied once in a while to prevent the pit from overflowing. Cesspits are not a wastewater treatment method, but function as a collection system. This solution is very cheap to implement and is the current situation for most residents in Swaen, but the quality of the wastewater flowing into the underground is not good enough for the goals of the project.

Septic Tank [65]: A septic tank is a wastewater filtering method that cleans wastewater through two steps. First off, the solids in the wastewater will settle in a settlement tank, while the grease in the water will float to the top. After this, biodegradation of the nutrients in the water will take place in a following chamber with the help of bacteria. This happens under low-oxygen conditions. The main solids and some nutrients will be filtered out of the wastewater, but it will still be of low quality. After the treatment in a septic tank the wastewater has to be treated further to get to a sufficient level. That is why this option is only seen as a pre-treatment solution for the Swaen area. The tanks also have to be emptied periodically and thus require some human labour. These solutions are already present in Swaen for some residents, but the current situation is not sufficient enough on water quality level to sustain for the future.

Constructed Wetland: A constructed wetland is an engineered system that treats wastewater by mimicking the natural purification processes of wetlands. Wastewater flows through a bed of gravel or other filter media, where microorganisms, plants and physical filtration processes remove pollutants such as organic matter, suspended solids and nutrients. The wetland provides a natural, low-energy treatment process that can improve water quality while creating a vegetated habitat. In Chapter 5 this treatment system is discussed in more detail.

Composting Chamber [66]: A composting chamber is used to treat residential black water. Under aerobic conditions micro-organisms decompose the biodegradable parts of the wastewater flow. This leaves compost and a separate wastewater flow exiting the chamber. One of the by-products of this method is compost, which can be used in function as soil amendment. The compost is not directly ready for use though in most cases and requires some extra treatment after extraction in most use cases. The system for a composting chamber is quite complex to build and maintain, thus training of the user is required to utilize the chamber to its full potential. The long service life and low operating costs of the

system are advantages that make this treatment option more viable.

Anaerobic Baffled Reactor (Improved Septic Tank) [67]: An ABR is an improved septic tank consisting of multiple compartments. The advantage this has over a conventional septic tank is that the wastewater stays longer in the system and flows slower. The longer stay duration results in a higher efficiency in comparison with a normal septic tank. Although this option is more efficient than a regular septic tank, the system mainly filters solids out of the wastewater and is limited in the filtering of nutrients and pathogens. The system is relatively simple and requires low maintenance. Adding on to this, the ABR does not require energy to function due to the application of gravity flow.

Anaerobic Filter [62]: The anaerobic filter is a wastewater filtering system which makes use of multiple filtration chambers placed in series. The system functions as a bio-reactor and makes the water flow through a filter, where solid particles are stopped and the organic matter is processed by the biomass in the filters. Some pre-treatment is essential for this system to work, otherwise the filters will get clogged and the system will stop working. The filters reduce the amount of solids and BOD in the effluent, but other contaminants are not efficiently filtered by this method. This option requires no energy to work and has low operating costs. On the other side, it requires some knowledge to operate the tank and is limited in the filtering of nutrients and pathogens.

Biogas Reactor [62]: A biogas reactor turns wastewater into 3 main products with an anaerobic process, namely a sludge, biogas and an effluent stream. The sludge produced by the reactor can be used as a fertilizer, while the biogas can be utilized as a renewable energy source. The system operates without an energy demand, but is more effective when the reactor is heated. The process works fastest when high temperatures (50-57 °C) are reached and is ineffective when the reactor is cooled down (< 15 °C). The biogas reactor has low operating costs, but the construction and handling of the system requires some advanced knowledge. The wastewater treatment is also limited and pathogen removal is not sufficient enough using this method.

Wastewater Lagoons [68]: Another wastewater treatment method utilizes wastewater stabilization ponds (lagoons) to treat the dirty water. The wastewater is cleaned using biological processes that occur due to optimal conditions in the pond. The lagoons are in direct contact with sunlight creating a warm environment with a large supply of oxygen. This supports the growth of beneficial bacteria and algae, which help break down the organic matter in the wastewater. The downside of this method is that it requires a large amount of space to store the water. Adding on to this, the wastewater is in direct contact with the outside air resulting in foul odor being emitted. It is therefore not recommended to create these lagoons close to the homes of residents. Seepage of the basins is a problem with this method that is hard to repair once the lagoons are filled. The method is relatively cheap, both in operating costs and the initial costs to install these lagoons. It is also very energy-efficient and requires low maintenance to operate.

Aerobic Treatment Unit [69]: Aerobic treatment units (ATU) can be utilized to treat wastewater in an aerobic manner. A pump inserts oxygen into a tank where the wastewater is collected. Here the oxygen creates natural bacterial activity used to treat the dirty water. The bacteria breaks down and removes nutrients from the water. The treatment unit cleans the wastewater relatively well in comparison to the other systems. To make sure the pathogens in the wastewater are removed fully up to standards, pre- and posttreatment tanks are required in the system. This will bump up the costs of the total system significantly. The benefit of the system is that it demands low space usage, because the tanks should be

fully submerged in the ground. In Curaçao this could also mean higher installation costs though, because of the hard and rocky underground.

Multi-Criteria Analysis

A Multi-Criteria Analysis (MCA) was used to compare the potential decentralized wastewater treatment options for the Swaen area in Curaçao. The method allows alternatives to be assessed against several criteria simultaneously, rather than evaluating them on a single factor. These criteria include land availability, energy demand, installation costs, operation and maintenance (O&M) costs, effluent water quality, reliability and robustness, and risk to groundwater. This is to find the most optimal decentralized wastewater treatment method specifically for Swaen. Every option will be rated from - - to + + based on its performance in the specific categories. Since the cesspit is not a wastewater treatment option, but rather a decentralized collection system, this option will be left out of the MCA and will not be used as a treatment solution in Swaen.

Since the criteria do not necessarily have equal importance, a weighting study was carried out before scoring the treatment alternatives. The five authors independently assigned an importance score to each criterion. The individual scores were then normalized by dividing each score by the sum of that person's scores and multiplying by 100%. This converted each researcher's scores into percentages that add up to 100%. The final weight for each criterion was calculated as the average of the five normalized scores.

The resulting weights were used in the MCA to calculate a weighted score for each treatment option and thus get to the most optimal treatment system for the Swaen area. In Table 4.4 the various criteria are explained, which are used to determine the most optimal solution.

Table 4.4: Criteria and explanations for the multi-criteria analysis (MCA).

Criteria	Explanation
Land availability	Land availability is assessed on how large the treatment systems are in size and the number of installations needed to serve Swaen in order to be functional. Some methods require only one centralized system for the whole Swaen, while others need an individual system at each residence.
energy demand	The energy demand entails how much electricity or other energy is required for the treatment systems to operate effectively.
Installation costs	Installation costs include the initial investment required to make the treatment system fully operational, including construction, equipment, excavation, and installation. The impact of Curaçao's rocky substrate is also considered in these costs.
O&M costs	Operation and maintenance (O&M) costs include the ongoing expenses required to operate and maintain the system such as labour, energy consumption, cleaning, repairs and monitoring.
Effluent water quality	The effluent water quality is the quality of the treated water that is leaving the systems. This water is filtered by the treatment methods and is of better quality than the wastewater entering the systems. The quality of the water is determined by the parameters explained in Appendix D, which have maximum values according to the guidelines in Table 4.2.
Reliability/robustness	For the reliability/robustness the consideration is based on the system's ability to provide consistent treatment under various conditions, the mechanical complexity of the systems and how easy it is to perform maintenance on the systems. The combined result of these options will determine how the methods score on this criteria.
Risk to groundwater	Groundwater risk is assessed based on the likelihood that pollutants from the treatment system will reach and contaminate groundwater. This depends on the water quality that infiltrates into the ground and the chance that the wastewater makes contact with groundwater. Some systems release their effluent (end product) into the ground on purpose, while for some systems this action will be due to leakage or bad assembly (not fully filtered yet).

In Table 4.5 the scoring for the MCA is shown, while in Table 4.6 the legend for the scoring of the MCA is shown. The scoring is performed based on the explanations of the different treatment options and the accompanying literature review which was necessary to determine the various options. The sources used for this comparison are cited alongside the treatment options.

Table 4.5: Comparison of wastewater treatment systems

System	**Land avail.**	**Energy demand**	**Install. costs**	**O&M costs**	**Effl. quality**	**Reliab./ robust.**	**Risk to groundw.**
Septic Tank	+	+ +	+	+	-	+ +	-
Constructed Wetland	-	+ +	+ -	+ -	+	+ -	+ -
Composting Chamber	+	+ -	-	+	+ -	-	+ -
Anaerobic Baffled Reactor	-	+ +	-	+	+ -	+	+ -
Anaerobic Filter	-	+ +	-	+ -	+ -	+ -	+ -
Biogas Reactor	+ -	+ +	- -	+ -	-	+ -	+ -
Wastewater Lagoons	- -	+ +	+	+	+ -	+	-
Aerobic Treatment Unit	+	- -	-	-	+	-	+

Table 4.6: Scoring scale used in the multi-criteria analysis (MCA).

Score	Meaning
+ +	Very favourable
+	Favourable
+ -	Intermediate
-	Unfavourable
- -	Very unfavourable

Using Excel, the MCA is carried out and calculations are made using the tables above. In Appendix E the weighting of the scores and the full tables used for the MCA are shown. After fully executing the MCA the following results are found:

The septic tank and the constructed wetland are the two most optimal options for Swaen according to the MCA and the weighting of the criteria. The septic tank alone is a very basic treatment option and does not provide adequately treated effluent on its own. That is why the decision has been made to use the septic tank as a treatment option, but also add the constructed wetland to combine the two wastewater treatment solutions. This way, the benefits of both options can be combined into a single system and the effluent will be treated on a more sufficient level. The MCA compares the treatment options individually, but since only applying the septic tank is not an option for the future, this combination of solutions has been proposed. Combining the two most optimal alternatives according to the MCA is in that case the most preferable option for Swaen.

4.2.3 Layout of wastewater solutions

To get an idea of how large the constructed wetlands need to be, a calculation will be performed based on the required removal of BOD_5 from the wastewater. The required area will be calculated using the

Table 4.7: Rating of wastewater treatment solutions

Solutions	Land avail.	Energy demand	Install. costs	O&M costs	Effluent quality	Reliab./ robust.	Risk to groundw.	Rating
Septic Tank	4	5	4	4	2	5	2	347.0
Constructed Wetland	2	5	3	3	4	3	3	326.4
Anaerobic Baffled Reactor	2	5	2	4	3	4	3	319.8
Wastewater Lagoons	1	5	4	4	3	4	2	318.7
Composting Chamber	4	3	2	4	3	2	3	298.9
Anaerobic Filter	2	5	2	3	3	3	3	291.8
Aerobic Treatment Unit	4	1	2	2	4	1	4	276.6
Biogas Reactor	3	5	1	3	2	3	3	269.1

average wastewater flow in Swaen instead of the peak flow, including all the relevant factors. This is because peak flows are partly stored in the septic tanks and therefore do not have to pass through the constructed wetlands immediately after entering the system. It is assumed that the wastewater flows through the wetlands at the average wastewater flow rate.

The formula used to determine the required wetland area based on BOD_5 removal is given below [70]:

$$A_s = (L)(W) = \frac{Q\left[\ln\left(C_0/C_e\right)\right]}{K_T dn} \tag{4.12}$$

Where:

- L = length of bed (m);
- W = width of bed (m);
- n = effective porosity of the media (Table 4.8), expressed as a decimal;
- d = average depth of liquid in the bed (m);
- Q = average flow through the bed (m^3/d);
- C_0 = influent BOD_5 concentration (mg/L);
- C_e = effluent BOD_5 concentration (mg/L);
- K_T = temperature-dependent first-order rate constant (d^{-1}).

Table 4.8: Typical media characteristics for SF wetlands [70]

Type	Porosity, n (%)
Coarse Sand	32
Gravelly Sand	35
Fine Gravel	38
Medium Gravel	40
Coarse Rock	45

Note: The porosity is used to determine the actual flow velocity in the void spaces and to determine the size of the subsurface-flow (SF) bed. Porosity is equal to void volume divided by total volume and is expressed as a percentage.

The formula used to calculate the temperature-dependent first-order rate constant is given as follows [70]:

$$K_T = K_{20}(\theta)^{(T-20)} \tag{4.13}$$

Where:

- K_T = rate constant at temperature T (d^{-1});
- T = average temperature (°C);
- K_{20} = rate constant at 20 °C (d^{-1});
- θ = temperature coefficient.

In Table 4.9 the design parameters for the required wetland area are explained and exhibited.

Table 4.9: Design parameters for constructed wetland sizing

Parameter	Value	Unit	Justification
n	0.39	–	Average porosity of fine gravel (0.38) and medium gravel (0.40), based on Table 4.8.
d	0.50	m	Assumed constant water depth in the constructed wetland.
Q	17.27	m^3/day	Average wastewater flow rate.
C_0	184	mg/L	Influent BOD_5 concentration, based on De Silva De Freitas' septic tank influent tests [71].
C_e	50	mg/L	Target effluent BOD_5 concentration, based on the irrigation standards presented in Table 4.2.
K_{20}	1.104	d^{-1}	Rate constant at a reference temperature of 20 °C [70].
θ	1.06	–	Temperature correction factor used to calculate the temperature-dependent rate constant [70].
T	30	°C	Assumed average temperature in Curaçao over a full day.

Using the formula's 4.12 and 4.13 and the gathered information about the parameters, the required area for the constructed wetlands can be determined. In the following calculations this process is shown:

$$K_T = 1.104 \cdot (1.06)^{(30-20)} = 1.977 \tag{4.14}$$

$$A_s = \frac{17.27 \cdot \ln\left(\frac{184}{50}\right)}{1.977 \cdot 0.5 \cdot 0.39} = 58.37\ m^2 \tag{4.15}$$

The required area of the constructed wetlands is 58.37 m^2 , which could be executed in a lot of different configurations regarding the length and width of the constructed wetlands. For Swaen, 3 different variants using septic tanks in combination with constructed wetlands are developed. For all three different variants a different design consideration has been made.

Variant 1: Individual septic tanks with shared constructed wetlands (individual septic tanks and wetlands shared by some residents).

Variant 2: Individual septic tanks with one big communal constructed wetland.

Variant 3: Neighbourhood-scale septic pretreatment with one big communal constructed wetland.

In Figure 4.4 the base map of Swaen is visible where the various wastewater solution will be implemented on. On this map the roads, buildings and spatial arrangement of the area are shown. For every variant an example area layout is made to show how the different treatment solutions could be implemented. These layouts could be changed according to the wishes of the residents and future project developers, but they give a good idea of the spatial layout and the required wastewater constructions of the Swaen region. The maps presented are therefore indicative and not definitive, they just provide a general impression of how the proposed system could be designed.



Figure 4.4: Base map of Swaen for wastewater solutions

Variant 1: In this variant, each household has its own septic tank for primary wastewater treatment. The effluent from several septic tanks is collected and transported to a communal constructed wetland for further treatment. Multiple smaller wetlands are constructed throughout the Swaen area, each serving a group of households. This approach allows for flexible implementation and reduces the need for a single large treatment site, but requires multiple wetlands and regular maintenance of the individual

septic tanks. (See Table 4.10) An overview of a possible wastewater system using these characteristics is displayed in Figure 4.5 and Figure 4.6.

Table 4.10: Advantages and disadvantages of Variant 1

Advantages
Area of the wetland units is relatively small.
Only short and simple pipes are required to set up the system.
Localised failures of the system do not affect the whole neighbourhood, just a small part.
Easily adaptable to terrain and flexible implementation.
Disadvantages
Many septic tanks, which all have to be maintained and emptied periodically.
Multiple wetlands, which all have to be maintained.
Treatment efficiency may vary between the different systems in Swaen.
Land has to be available for the wetlands throughout the whole of Swaen.



Figure 4.5: Variant 1, layout of wastewater facilities example



Figure 4.6: Variant 1, layout of sewer pipes example

Variant 2: In this variant, each household has its own septic tank for primary wastewater treatment. The effluent from all septic tanks is collected through a shared pipe network and conveyed to one large communal constructed wetland for further treatment. This configuration concentrates secondary treatment at a single location, potentially simplifying wetland maintenance and monitoring. However, it requires a large area for the constructed wetland and a big collection network connecting the individual septic tanks to the central treatment location. (See Table 4.11) An overview of a possible wastewater system using these characteristics is displayed in Figure 4.7 and Figure 4.8.

Table 4.11: Advantages and disadvantages of Variant 2

Advantages
The same efficiency and quality for all secondary treatment.
Only one wetland has to be maintained instead of multiple.
Effluent out of the septic tanks is already filtered of solids, which reduces the filth in the transport pipes.
Disadvantages
Many septic tanks, which all have to be maintained and emptied periodically.
Large land requirement at one location in Swaen.
Increased complexity in pipe network and higher chance of blockages.
Differences in elevation and flow between houses can complicate the collection network.
In the case of a wetland failure, the whole system is down for maintenance.



Figure 4.7: Variant 2, layout of wastewater facilities example



Figure 4.8: Variant 2, layout of sewer pipes example

Variant 3: In this variant, wastewater from multiple households is collected through a shared sewer network and conveyed to a communal septic pretreatment unit. The pretreated wastewater then flows to one large constructed wetland for further treatment. Compared with the first two variants, this approach eliminates the need for individual household septic tanks and centralises both pretreatment and secondary treatment in the area. Although this may simplify maintenance and operation, it requires a more complex collection network and entails coordinated management of the shared treatment facilities. (See Table 4.12) An overview of a possible wastewater system using these characteristics is displayed in Figure 4.9 and Figure 4.10.

Table 4.12: Advantages and disadvantages of Variant 3

Advantages
Reduced number of individual septic tanks requiring inspection, maintenance, and desludging.
Concentrated maintenance possible due to centralized collection and treatment in the Swaen area.
The overall treatment process is easily manageable and the quality of effluent will be the same for the whole region.
Efficient land usage, everything is concentrated in one place.
Disadvantages
Wastewater from all houses must be transported to the shared pretreatment facility, potentially increasing excavation and pipe installation costs in rocky ground.
A single failure in the shared facilities will affect the whole neighbourhood.
Greater hydraulic complexity due to the whole neighbourhood being connected in one network.
Large treatment site required due to centralization in the area.



Figure 4.9: Variant 3, layout of wastewater facilities example

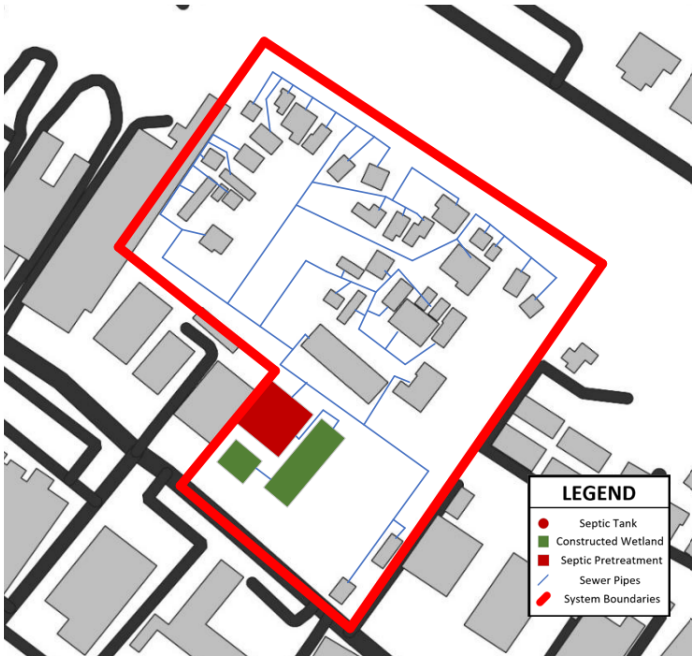

Figure 4.10: Variant 3, layout of sewer pipes example

The effluent of the constructed wetlands is for now assumed to be of high enough quality to be irrigated into the ground. This will have to be tested in a further development stage of the Swaen region. Irrigation will be the main purpose of the effluent and in all three variants the treated wastewater will be used for irrigation.

The three variants offer different approaches to combining septic treatment with constructed wetlands in Swaen. After comparing their advantages and disadvantages, Variant 3 was selected for further development because it provides the most integrated approach to wastewater collection, treatment, and maintenance.

A key consideration for this choice is the amount of primary and secondary treatment facilities in Swaen. In variants 1 and 2 every household has its own septic tank, resulting in a large amount of tanks required for the neighbourhood. In variant 1 there are even multiple constructed wetlands required. Variant 3 avoids this by collecting wastewater from every household in the area and directing it to a shared septic pretreatment facility in combination with a large wetland. This allows the collection and treatment of the wastewater to be centralized in a single location within Swaen and reduces the amount of facilities that require maintenance. Furthermore, concentrating the treatment facilities reduces the need to distribute wetlands across the neighbourhood, making more efficient use of the available land.

However, variant 3 also presents challenges in terms of wastewater management. Connecting the houses to a shared sewer network increases the complexity of the system, resulting in increased maintenance costs. Adding on to this, a shared collection system may also increase the construction costs due to the rocky ground conditions in Swaen.

Despite these challenges, variant 3 provides a suitable basis for further development of the wastewater system. The next design stage will therefore focus on developing a more detailed variant. In this design the location, dimensions and practical feasibility of a system is determined to show what the possibilities are in Swaen.

4.2.4 Conceptual design of a wastewater system

Main design assumptions

This part of the report will provide preliminary engineering dimensions and a technically substantiated layout for a wastewater system which could be implemented in Swaen, rather than striving for a final detailed construction design. Based on the comparison of the three proposed variants, it has been decided to follow through with the designs concepts made for variant 3. The proposed wastewater system consists of the following five components:

1. **Household connections:** Each residence is connected to the communal wastewater collection network.
2. **Gravity sewer network:** Wastewater is transported from the households towards the central treatment location. It is assumed that for a gravity sewer there is sufficient gradient of the pipes due to the hillside in Swaen.
3. **Communal septic pretreatment:** The collected wastewater enters a shared septic treatment unit, where the solids in the wastewater are settled and floating materials are separated from the wastewater.
4. **Constructed wetland:** The pretreated wastewater flows into a subsurface-flow constructed wetland, where further removal of organic pollutants takes place through biological processes.
5. **Effluent collection and reuse:** The treated effluent is collected and used for irrigation, depending on the effluent quality.

The hydraulic design of the wastewater facilities will be based on the peak design flow for the Swaen region, which was determined to be 87.25 m^3/day . However, the constructed wetland is dimensioned using the average wastewater flow rather than the peak flow. This is due to the storage capacity of the septic installations, which allow the flow through the wetland to be equal to the average domestic wastewater flow of 17.27 m^3/day.

For this conceptual design, a gravity-based sewer network is proposed as the preferred collection method. This choice is based on the topographical characteristics of Swaen. The area generally slopes downwards towards one end, due to the area being built against the side of a hill, creating opportunities to transport wastewater naturally towards one side of the area without needing continuous pumping. The proposed pipe network should follow the existing or planned roads as much as possible, this will allow easier maintenance and installation when the network is built. However, the actual feasibility of gravity transport depends on the elevation of the individual connections, the final treatment location and the natural available gradients. The elevations must therefore be verified using a detailed topographical survey before the final sewer alignment is established.

The required pipe diameters of the system are determined based on the expected wastewater flow, the amount of connected households and the flow velocities. With the following formula the pipe diameters for the system will be estimated:

$$D = \sqrt{\frac{4Q}{\pi V}} \tag{4.16}$$

Where:

- D = pipe diameter;
- Q = flow rate;
- V = flow velocity.

This formula is obtained by combining the formula for flow rate [72] and the circular area of a pipe, after which the formula is rearranged for D. The flow velocity is determined to ensure that the wastewater is transported through the systems without any accumulations in the pipe network. In literature is found that with a velocity of at least 0.6 m/s [73] the pipe-cleaning velocity is often reached, thus a flow velocity of 0.6 m/s will be assumed. Since Swaen is such a small community, with a small amount of people living there, the calculated pipe diameters resulted in extremely small values. Therefore it is concluded that small pipes with a diameter of 150 mm, since this is the lowest allowable diameter for gravity sewer systems [73], will be utilized for the whole pipe network in Swaen. This diameter is sufficient for the household connections, secondary collection pipes, main collection pipes and the inlet for the septic facility.

The wastewater collection system will be designed with continuous downward gradients towards the septic tank facility so that gravity will be the driving force for the wastewater. The pipe slopes should also be sufficient to prevent accumulation of solid particles in the pipes. The minimum design slope is found to be 0.40 m/100m for the smallest allowable sewer pipes [74].

Another asset of the sewer system in Swaen are the manholes of the pipe network. Manholes are required for inspection, cleaning and maintenance [75]. Manholes should be applied at every main pipe intersection and optionally at the end of every pipe line. For the conceptual design, a maximum spacing of approximately 50 metres between manholes is proposed. This relatively short spacing provides sufficient access for inspection and maintenance while keeping the number of structures manageable. The manholes should be designed with particular care in order to prevent rainwater from entering the

wastewater system. Especially due to the reported surface water accumulation in Swaen during heavy rainfall.

The proposed wastewater collection system is designed to solely operate with the help of gravity. Based on the available elevation data of Swaen (Figure 4.2), the general downward slope appears to be favourable for transporting wastewater towards a central collection point. Therefore, a pumping station is not deemed necessary and is not included as a standard component of the preliminary design. In reality, exact elevation differences should be determined in detail to judge if pumping is deemed necessary between different pump intersections.

The treatment facilities in Swaen will consist of three parts, namely the septic pretreatment facility, the constructed wetland and the effluent collection system. The septic pretreatment facility should consist of multiple tanks connected in series, each with multiple compartments. This way the water sedimentation will be sufficient for the constructed wetland. The communal constructed wetland will be a subsurface-flow wetland, in which wastewater passes through a porous filter bed containing gravel and vegetation. By utilizing a subsurface variant, nasty smells will be mostly prevented and pest control is easier to handle. The human public health and safety will therefore be accounted for. The wetland should be constructed using a suitable impermeable lining to prevent untreated or partially treated wastewater from infiltrating directly into the underlying soil. The final stage of the treatment consists of the collection of the effluent. The treated effluent will be collected in a suitable storage facility or directly conveyed to the designated irrigation areas, depending on the irrigation demand and operational requirements. The final storage capacity and distribution network are not determined in this conceptual design.

Spatial layout and technical specifications

The proposed network and treatment facilities should be integrated into the spatial development of the Swaen area. The main sewer lines should follow the road network as much as possible, with smaller household connections connecting individual properties to the main collection pipes.

The preferred arrangement of the network is to collect wastewater from the different residential sections and gradually combine the wastewater flows into one main sewer leading towards the communal treatment facilities. The septic pretreatment unit and the constructed wetland should be close to each other to minimize the length of the connecting pipes and simplify the process. The proposed location of the treatment facilities should have sufficient space and should be selected with consideration of the surrounding residential buildings, accessibility and potential nuisance. That is why the location should be close to the road on the bottom end of the area.

The proposed layout is presented in Figure 4.11. It provides an indicative representation of how wastewater solutions could be implemented within Swaen. The exact sewer alignment and treatment location could change depending on the final urban development plan, land availability or detailed elevation measurements.

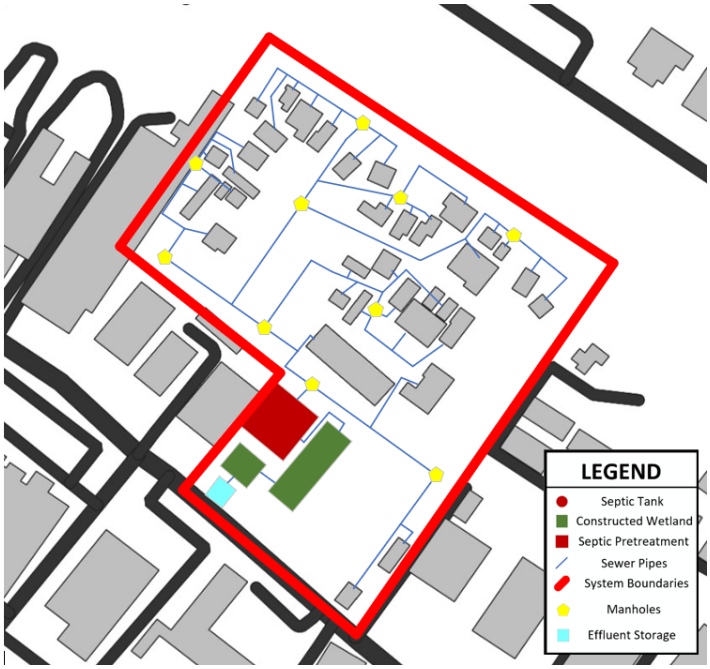

Figure 4.11: Proposed conceptual sewer plan for Swaen

In Table 4.13 the main design components and parameters are shown for the proposed wastewater solutions in Swaen.

Table 4.13: Design components and parameters of the proposed design

Component	**Proposed Design**
System type	Decentralized neighbourhood-scale
Collection method	Gravity sewer network
Design population	∼149 residents
Average wastewater flow	17.27 m^3/day
Peak wastewater flow	87.25 m^3/day
Pipe diameters	150 mm
Minimum pipe slope	0.40 m/100 m
Minimum pipe flow velocity	$>$ 0.6 m/s
Manhole spacing	50 m
Pumping requirements	Not anticipated
Primary treatment	Communal septic pretreatment facility
Secondary treatment	Subsurface-flow constructed wetland
Required wetland area	58.37 m^2
Target BOD_5 effluent	$<$ 50 mg/L
Final effluent destination	Irrigation usage

5 Constructed Wetland

As mentioned in Section 1.1.2, the majority of Curaçao is not connected to a centralized sewerage system [9]. Due to the rocky soils, combined with differences in elevation, installing these systems is expensive. This motivates the effort into investigating the use of a constructed wetland (CW). CWs offer a low-energy, nature-based way to improve water quality [76]. Different types exist but this report considers a *horizontal subsurface flow (HSF) constructed wetland*, since this is the type that was built at the UoC.

5.1 Constructed wetland design and performance

Wetlands in nature are complex systems that have many different parts: water, substrate, plants, litter, larvae and microorganisms all come together to make up this ecosystem [76]. As such, they have many different mechanisms for improving water quality. The idea of a constructed wetland is to simulate these conditions to achieve a natural system which can improve the quality of human wastewater. A constructed wetland generally consists of a basin where wastewater influent is allowed to flow at a slow pace, often with hydraulic retention times between 4 and 15 days [77]. In an HSF constructed wetland, the water in the basin flows through a substrate, often gravel, below the surface. In the substrate, wetland plants are growing. As the water flows through, four main mechanisms of pollution removal take place: sedimentation, filtration, microbial degradation, and plant uptake [78]. Sedimentation and filtration are mechanical processes and are caused by the water slowing down, and particles sticking to the substrate or sinking to the bottom. Microbial degradation is caused by many different types of microorganisms that develop on the roots of the wetland plants, forming a biofilm, and removing pollutants through a range of different chemical reactions. Lastly, the plants also take their nutrients from the water, filtering pollution in the process. The plants grow their roots down to maximize surface area and nutrient and water uptake. This type of system has the potential to achieve significant reduction in pollutants for household and other types of wastewater [79]. A general overview of the considered system is shown in Figure 5.1.

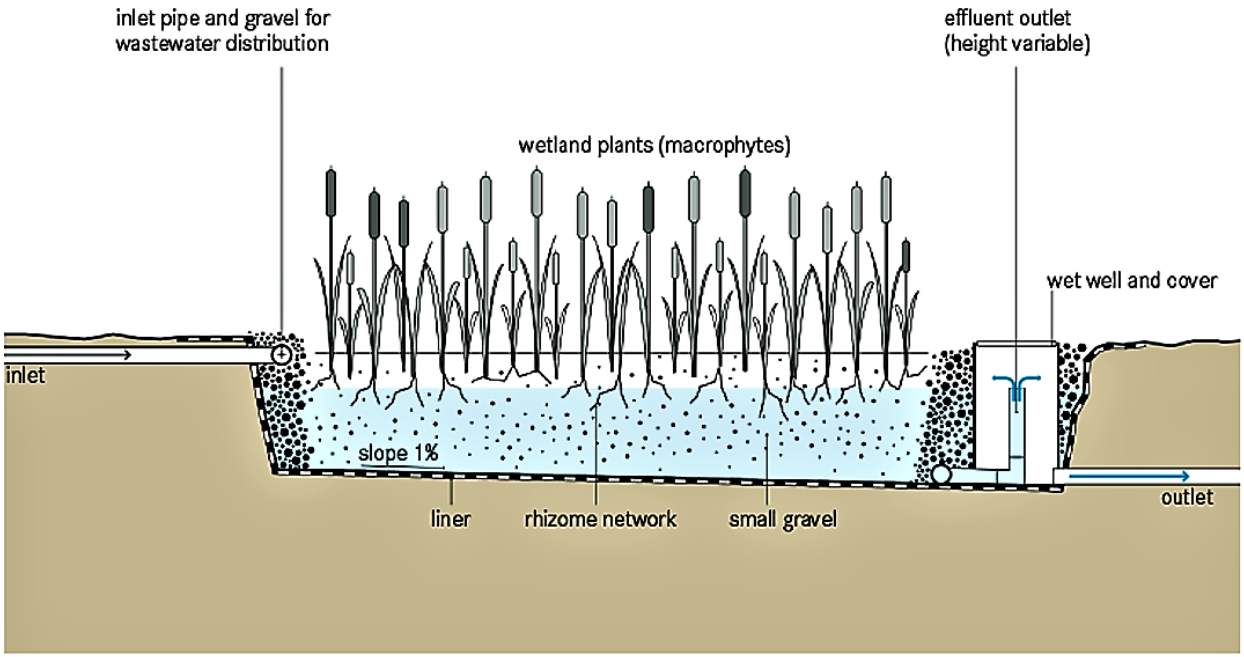

Figure 5.1: General overview of a horizontal subsurface flow constructed wetland [80]

The effectiveness of CW systems is the subject of many studies. A meta study, utilizing a review of 78 studies, found that median removal efficiencies differ over different pollutant types [81]. Removal reaches about 90 % for suspended solids and often exceeds 75 % for heavy metals. However, removal of nitrogen and phosphorus is generally inconsistent and depends strongly on design and local conditions [81].

Most constructed wetland research has been carried out in temperate climates in the United States, China and Australia, and validation in arid and semi-arid regions is lacking [81]. Temperature also affects performance: higher temperatures were found to increase phosphorus outflow concentrations [82]. It is therefore uncertain whether the removal efficiencies reported in the literature apply under Curaçao's arid climate. This motivates testing the constructed wetland at the UoC, to quantify how well it removes pollutants under local conditions and to inform local authorities about a potential localized solution for the problems in Curaçao.

5.2 Specifications of UoC Constructed Wetland

As was specified, the constructed wetland at the UoC is an HSF constructed wetland, set up in a similar way to the schematic in Figure 5.1. The CW was built 8 years before the project group arrived on site. The original intention for it was to filter the water from two main facilities of the campus of the UoC: the student canteen (or *mensa*) and the student housing facilities. Wastewater from these buildings is collected in an unfinished septic tank on the southern edge of the campus. The plan was to connect the septic tank to the CW, which is why the CW is built right next to the septic tank. It was constructed as part of a graduation project of one of the students at the UoC. The construction was carried out in accordance with the technical drawings in Figure 5.2, which were made by the student.

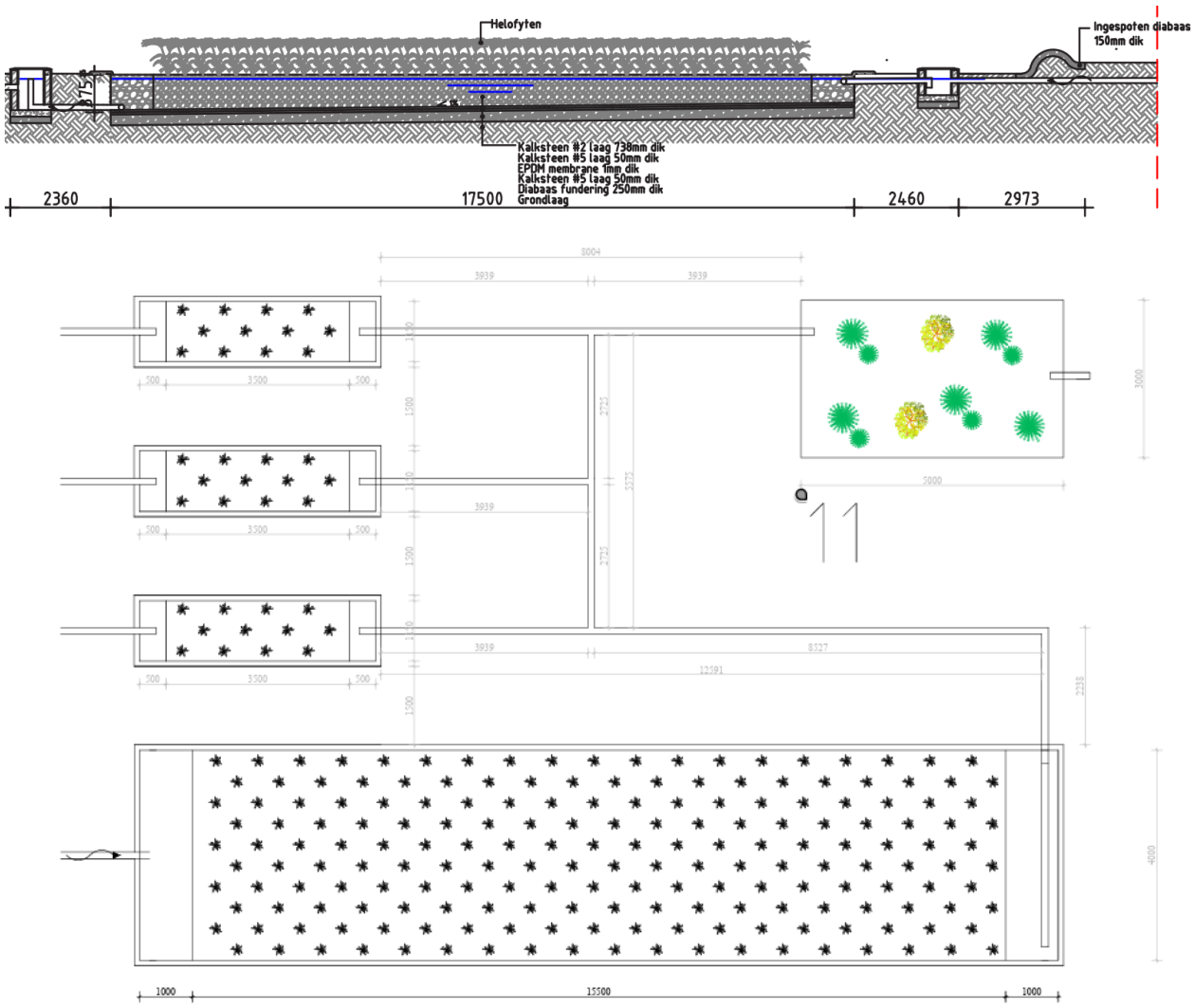

Figure 5.2: Technical drawings of the original design of the CW system at UoC. The upper figure shows a section view of the larger CW, which is also shown in the top view (bottom figure) (source: provided by the UoC).

The technical drawings in Figure 5.2 show the configuration as it had been built before this project started. The configuration features one big, and three smaller CWs that could be used for testing different growth types. All CWs connect to the same last basin, which is an open-air basin with a spillway that was originally intended to be used for a final treatment step involving UV radiation from the sun. The effluent that flows over the spillway is allowed to infiltrate into the ground, thereby replenishing the groundwater. This, combined with a groundwater pump in a different location on campus, was intended to work as a closed loop for the water. The groundwater could in turn be used for the irrigation of plants. The project was unfortunately left unfinished.

5.3 Final Construction Experimental Setup

In order to test the effectiveness of the CW system on the campus of the UoC, two aspects of the system had to be finished:

1. The water from the septic tank was not connected to the CW. This connection had to be designed and put into place.
2. No plants were present in the system. An effective selection of wetland plants had to be made and planted.

In the next sections, the process of tackling these two challenges is described.

5.3.1 Connecting the Septic Tank

A pump was found on the site of the septic tank, which was pumping water through a fire hose. The fire hose was found to lead to a green patch where banana trees were growing. A little further away, there was another green patch with banana trees, to which the water was sometimes redirected using a pvc pipe from the first green patch. The origin of this system is unknown but it was being used by the campus gardener to care for the banana trees. To supply the CW with water, the existing pump and fire hose were used. A green hose was connected using hose clamps, which redirected the water towards the CW system. Right before the CW, the hose was split into three directions using two splitters. This connection system is shown in Figure 5.3. After becoming aware that the campus gardener was caring for the banana trees, a system was devised to continue watering these plants while still getting the water from the septic tank for testing the CWs. The system consisted of a second pump and hose that takes the water from the final treatment basin back around to where the trees are growing. The system made for returning the water to the banana trees is shown in Figure 5.4



(a) Septic tank basin with partially submerged pump and fire hose



(b) Connection of the fire hose to the green hose



(c) Three-way split right before the constructed wetland basins

Figure 5.3: Pictures of the inflow system from the septic tank (left) to the split at the CWs (right)(pictures taken by authors)



(a) Pump used to pump water from the final treatment basin



(b) System used to split water between the two banana patches



(c) Outlet at the first banana tree

Figure 5.4: Pictures showing the system used for running water back to the banana trees (pictures taken by authors)

5.3.2 Choice of Wetland Plants and Setup

The next step was to choose and acquire the wetland plants. The choice was made to fill the three smaller CWs with one type of plant each, to be able to compare effectiveness between them. The optimal plant density of CWs is dependent on many conditions. Design guides specify 2-4 plants as being standard practice [83], [84] but higher densities have been shown to be effective as well [85]. A higher density of 5-6 plants was chosen for this project. CWs are place-dependent systems, often working best when using native, local plants[76], [83]. A list of local plants with a potential for filtration was supplied by CARMABI, which was used as a starting point for choosing which plants to use (list available in appendix F). Some of the plants on the list are known to be effective in wetland settings but most are not wetland plants by nature. For this reason, availability became the most important criterion in choosing the plants. None of the plants on the list are sold commercially, since they are naturally occurring plants in Curaçao and often are viewed by the people as weeds. The list was shown at local plant nurseries and also taken to CARMABI's own plant nursery in the Christoffelpark National Park in the west, to inquire about the availability of these plants. From these trips, two plants were identified which could be used for the project: *Ruellia Simplex* [1] from Vivian's Nursery and *Gundlachia Corymbosa* from CARMABI. A third option presented itself when the project group was alerted to a location where lots of reeds could be seen growing naturally in Willemstad. This reed type, identified to be *Typha Domingensis*, was chosen as the last candidate for the constructed wetland at the UoC. The reeds were extracted from their original location by gently pulling them out of the soil and were taken to the campus using a borrowed pickup truck. The following steps were taken to get the plants established into the saturated zone of the constructed wetlands:

1. The plants were taken to the site of the CW on the UoC campus.
2. The CW beds were emptied of gravel until water was found, which was at around 30 cm below ground.
3. Planting then proceeded one by one, starting with digging a hole into the saturated gravel.
4. The plant was lowered into place with the roots now being submerged in the water.
5. The plant was then locked into place by putting some of the gravel back.
6. These steps were taken for all plants in the CW bed.

[1] Not the same as the local variant *Ruallia Tuberosa* from the list (which was not sold), but closely related

7. Gravel was put back into the CW to cover any water at the surface, taking care not to damage the plants.

It was at this stage that the discovery was made that one of the CW beds was not holding water, leading to the conclusion that there was a leak in the rubber layer separating the basin from the outside soil. Since there was limited time, the project was continued with two CWs, testing two different plants. It was decided to use the none native species *Ruellia Simplex*, which had been tested in CW systems before [86], [87], and *Typha Domingensis*, which is a well known wetland macrophyte that has been studied extensively for CWs [88], [89]. Both these plants have been shown to have filtering capacity in a constructed wetland setting, while the third option *Gundlachia Corymbosa* is not associated with wetland terrain and CW usage, leading to this decision being made. In Figure 5.5, the two finished constructed wetlands can be seen, as well as a picture of the final treatment basin.



(a) Constructed wetland with *Typha Domingensis* growing inside



(b) Constructed wetland with *Ruellia Simplex* growing inside



(c) Final treatment basin

Figure 5.5: Figures showing the three filtration basins (pictures taken by authors)

5.3.3 Final setup characteristics

Now that the water had been redirected into the system and plants were put into the the beds of the CWs, the system had been finished. However, before a significant filtering capacity can be reached with a CW, the plants need time to become established in the new conditions, usually taking upwards of 1-3 months [76]. Due to time constraints on this project, the plants were left to settle and grow over the course of only 25 days in the case of *Typha* and 18 days for the *Ruellia*. A schematic visualization of the final test setup can be seen in Figure 5.6

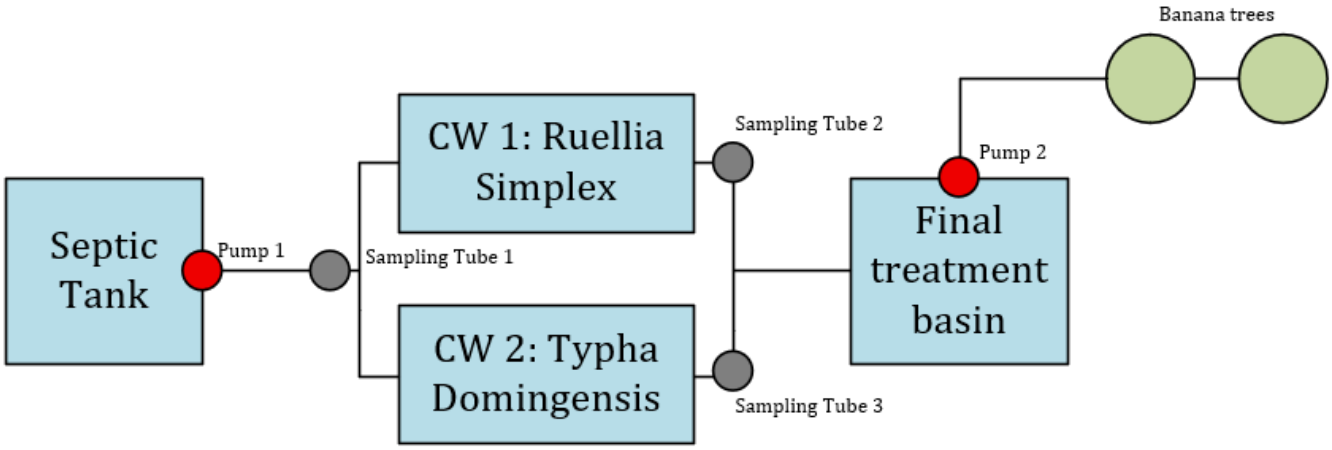

Figure 5.6: Schematic of final test setup, using two constructed wetlands

5.4 Sampling and Test Plan

The parameters that could be tested in the local laboratories are shown in Table 5.2. All tests were done at the facilities of *Klein Hofje*, except for the *E. Coli* and *Enterococci* tests, which were done at the *ADC* facility. The machine for testing BOD_5 was unfortunately not working and these tests had to be dropped from the plan.

Table 5.1: A list of wastewater quality parameters that were tested in the lab

Parameter	**Unit**
COD	mg/l
N-tot.	mg /l
E. Coli (freshwater)	CFU/100 ml
Enterococci (salt water)	CFU/100 ml
Oil / Grease	mg/l
pH	-
Electrical Conductivity	μS/cm
Chloride	mg /l
Temperature	°C
SO_4	mg/l

Sampling was done by lowering the sampling container shown in Figure 5.7 into the sampling tubes of the CW systems, and then transferring the contents into sample collection containers of the type shown in Figure 5.8. These were taken to the lab within the hour for testing.



Figure 5.7: Sampling device



Figure 5.8: Sample containers

Samples were taken from the raw influent from the septic tank and from both constructed wetlands. By comparing different parameters before and after passing through the CW system, the filtering capacity of the system can be shown, as well as compared between the two plants. All samples were taken once, and all tests were carried out once.

5.5 Lab Results

The results of the lab tests are presented in Table 5.2.

Table 5.2: Results of the wastewater quality lab tests

Parameter	Unit	Septic Influent	Ruellia	Typha
COD	mg/l	351	183	148
N-tot	mg /l	>40	>40	>40
E. Coli (freshwater)	CFU/100 ml	>8,000,000	5,500,000	1,400,000
Enterococci (salt water)	CFU/100 ml	200,000	100,000	<10,000
Oil / Grease	mg/l	10	4.5	14
pH	–	6.86	7.13	7.12
Conductivity	μS/cm	1140	1165	1169
Chloride	mg /l	99	98	100
Total Suspended Solids	mg/l	65.2	0.0	0.0
Temperature	°C	28.5	28.5	29.3
SO_4	mg/l	36.8	15.8	8.29

The water quality indicators in the influent and effluent of the system are compared. A clear reduction in COD is noted. Both CWs showcase a significant reduction in *E. Coli* and *Enterococci*. The exact reduction is not known, since the number of CFU for the influent is not known exactly, due to only being able to measure up to 800m,000 CFU/100ml. While grease and oil reduces in the *Ruellia* CW, an increase is observed in the *Typha* CW. A slight increase in pH is observed in both CWs. Total suspended

solids are reduced to zero. Lastly, sulfate levels show a dramatic decrease in both CWs, with the biggest decrease observed with *Typha*. Temperature, conductivity and chloride show no significant changes.

Table 5.3: Results of the wastewater quality lab tests compared with a combined standard for irrigation, based mainly on the Curaçao standard

Parameter	Unit	Combined Standard for Irrigation	Ruellia Constructed Wetland	Typha Constructed Wetland
COD	mg/l	125	183	148
N-tot	mg /l	28	>40	>40
E. Coli (freshwater)	CFU/100 ml	126	5,500,000	1,400,000
Enterococci (salt water)	CFU/100 ml	35	100,000	<10,000
Oil / Grease	mg/l	10	4.5	14
pH	–	6–8	7.13	7.12
Conductivity	μS/cm	2250	1165	1169
Chloride	mg /l	250	98	100
Total Suspended Solids	mg/l	50	0.0	0.0
Temperature	°C	32	28.5	29.3
SO_4	mg/l	400	15.8	8.29

In Table 5.3, the resulting water quality indicators for the effluent of the CW system are compared to the standard for irrigation water. The standard is made up of the Curaçao standards for irrigation water as seen in Table 4.2, with some additions:

1. *E. Coli* and *Enterococci*: the maximum values of 126 and 35, respectively, are taken from the UN recommendations [53]; also specified in Table 4.2.
2. Oil/Grease and Temperature: For oil/grease and temperature, the Curaçao standard for surface water is used (also from Table 4.2), with respectively 10 mg/l and 32 °C.
3. Sulfate: Here, the sulfate standard for irrigation water is given that is used by a United States consulting company called *EarthWorks*, which gives a maximum value of 400 mg/l [90].

A summary of the results is given Table 5.4. Here, the six main changes are given as reduction percentage. The parameters that showed little change are not shown.

Table 5.4: Reduction percentages of the six water quality indicators showing significant change in CW effluent compared to influent (positive numbers indicate a reduction)

Plant Type	COD	E. Coli	Enterococci	Oil/Grease	TSS	Sulfate
Ruellia CW	48%	> 31%	50%	55%	100%	57%
Typha CW	58%	> 82.5%	>95%	- 40%	100%	77%

A few important remarks:

1. A potential reduction in total nitrogen was not observed because the test measures up to 40 mg/l only.
2. Phosphorous, fecal coli and BOD_5 were not measured.
3. The exact reduction in *E. Coli* and *Enterococci* is not known, since the value for the influent is unknown. The percentages in Table 5.4 therefore represent a minimum reduction percentage.

6 Conclusion

This chapter synthesizes the primary findings of the study to directly answer the main research question. To systematically address this overarching objective, the conclusions are structured around the core contextual and technical domains investigated in this research. The subsequent sections detail the final outcomes for each supporting subquestion. Afterwards, the main research question is answered.

6.1 Rainwater management

This section answers the core rainwater management subquestion:

> *What decentralized retention measures can be selected and spatially integrated to effectively mitigate local street flooding and reduce total downstream outflow?*

Based on the hydrodynamic evaluation detailed in section 3.9, the optimal mitigation strategy integrates decentralized household storage tanks with a centralized retention area at the western edge of the Swaen as shown in figure 3.8. Specifically, capturing 114 m^3 of runoff at the parcel level via rain barrels, combined with a 290 m^3 area-wide storage basin (Storage 1), provides the most efficient balance between hydraulic performance and spatial footprint.

This spatial integration effectively mitigates local street flooding by reducing the inundation volume across the Swaen area from 215 m^3 to 144 m^3. Furthermore, this strategy successfully alleviates stress on the broader infrastructure by reducing total downstream outflow from the baseline of 1898 m^3 to 1551 m^3.

6.2 Wastewater management

The assessment of the current wastewater situation in Swaen shows the need for an improvement on the wastewater system of the region. Currently, the neighbourhood is not connected to a central sewerage network, and wastewater is mainly managed by collecting it in self-made cesspits and septic tanks. Considering the costs, effort and the knowledge gap associated with a centralized sewerage solution, a decentralized wastewater treatment solution is considered a suitable approach for Swaen.

The specific wastewater research question addressed in this study is:

> *How can an effective wastewater management system be developed for the Swaen area, considering the local conditions and existing infrastructure limitations?*

Three proposed wastewater collection and treatment alternatives were developed and compared against each other. Out of these solutions, a neighbourhood-scale septic treatment facility followed by one large communal constructed wetland was selected as the best choice. This variant centralizes wastewater

collection and treatment in the Swaen area, reducing the need of individual facilities at the residences.

The conceptual design for the wastewater management in Swaen consists of household connections from every residence to a shared gravity sewer network (Figure 6.1). This network transports the wastewater to the communal septic pretreatment unit and constructed wetland. The required wetland area for Swaen is calculated to be 58.37 m^2, based on the average wastewater flow of 17.27 m^3/day. The treated effluent is intended for irrigation purposes, provided that the required water quality is reached. In Table 6.1 the final characteristics of the system are shown.

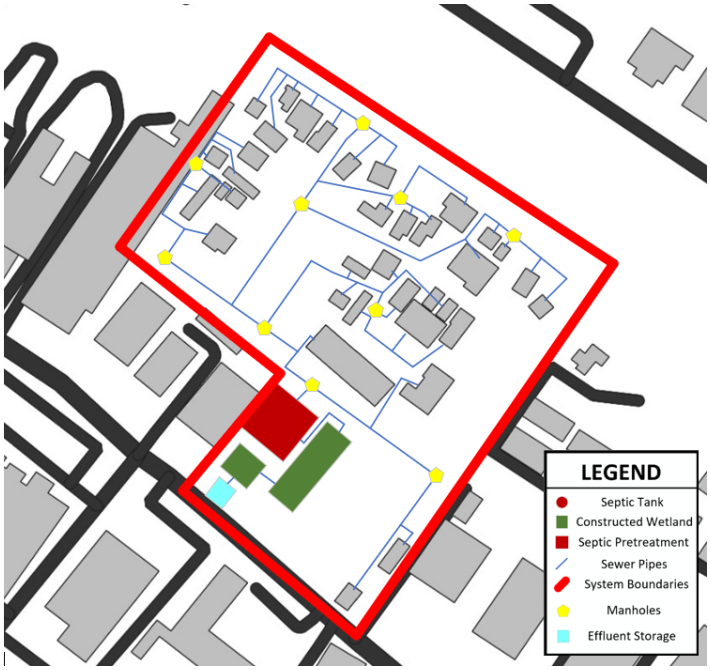

Figure 6.1: Proposed conceptual sewer plan for Swaen

Table 6.1: Design components and parameters of the proposed design

Component	Proposed Design
System type	Decentralized neighbourhood-scale
Collection method	Gravity sewer network
Design population	∼149 residents
Average wastewater flow	17.27 m^3/day
Peak wastewater flow	87.25 m^3/day
Pipe diameters	150 mm
Minimum pipe slope	0.40 m/100 m
Minimum pipe flow velocity	> 0.6 m/s
Manhole spacing	50 m
Pumping requirements	Not anticipated
Primary treatment	Communal septic pretreatment facility
Secondary treatment	Subsurface-flow constructed wetland
Required wetland area	58.37 m^2
Target BOD_5 effluent	< 50 mg/L
Final effluent destination	Irrigation usage

Although this conceptual design provides a promising basis for improving the wastewater management in Swaen, several aspects require further investigation before implementation. This includes the feasibility of gravity transport, the final sewer alignment, the construction costs of the network, and the availability of land in Swaen in the future. In addition, the quality of the effluent should be extensively verified in order to ensure that it meets the applicable irrigation standards (specified in Section 5.5). Therefore, the proposed system should be considered as a conceptual design that requires further technical development.

6.3 Constructed wetland

A constructed wetland, being an example of a decentralized solution, can offer some advantages over more traditional centralized systems, as mentioned in Chapter 1. As part of this research, a horizontal subsurface flow constructed wetland at the University of Curaçao was finalized and first results were obtained of its capacity to improve wastewater. With these results, the following research question is answered:

> *What is the effectiveness of a constructed wetland system on the island of Curaçao for the purpose of treating household wastewater to reach irrigation level quality?*

The standards for irrigation water in Curaçao have been established in Section 5.5, shown in Table 5.3 together with the results of the tests. This table enables comparison between the standards and the effluent of the constructed wetland. It can be seen from the table that the water effluent from both constructed wetlands is not yet up to the combined standard for irrigation water that is used as reference.

To get the water up to irrigation standards, some further changes are necessary:

1. *COD*: further reduction in COD of 16% (*Ruellia*) and 6% (*Typha*) of the total.
2. *N-tot*: A reduction in nitrogen of at least 30% of the total.
3. *E. Coli*: A reduction of at least 99.984% is necessary, meaning a further reduction of at least 68.98% for *Ruellia* and at least 17.48% for *Typha*.
4. *Enterococci*: A total reduction of at least 99.996% is necessary, meaning a further reduction of 50% for *Ruellia* and up to 4.996% for *Typha*.
5. *Oil/grease*: In the case of *Typha*, the increase in oil/grease needs to be eliminated.

The parameters of phosphorous and fecal coli need to be investigated further. The remaining parameters are sufficient for irrigation water: pH, conductivity, chloride, total suspended solids, temperature and sulfate. The total suspended solids are the only parameter that suffices due to the filtering of the constructed wetland. The rest is already within the norm.

6.4 Integrated solution

This section combines the findings of the previous sections to answer the main research question:

> *How can a spatial and technical water management plan be designed for the Swaen area to integrate and improve rainwater management and wastewater treatment?*

This research shows that a water management plan for Swaen can be designed as a combination of two decentralized systems that are technically separated, but spatially connected.

Technical separation. It is desirable to keep the rainwater and wastewater systems technically separated. Rainwater is captured at the source in household storage tanks and in a central storage area at the western edge of Swaen. Wastewater is collected in a closed gravity sewer and treated in a communal septic pretreatment unit and constructed wetland. This separation prevents rainwater from overloading the wastewater system during heavy rainfall, and prevents untreated wastewater from being spread through the neighbourhood during floods. Since the wetland is an open construction, rainwater will enter the wastewater system in that way, but this is unpreventable. Apart from this, these water flows can be kept separate. The separation addresses one of the main problems identified for Curaçao: sewer overflows and the spreading of pollution to terrestrial and marine environments during the wet season.

Spatial integration. Both systems require space in a small neighbourhood. The central storage area, the septic pretreatment unit, the constructed wetland and the sewer route have to be placed within the limited open spaces of Swaen. Both systems also follow the natural slope of the area: rainwater flows towards the storage area and wastewater flows by gravity towards the treatment facility, so that no pumping is expected to be needed. In the final design, the locations of these facilities should be aligned with each other and with the future development plans of the Swaen project, so that the available space is used efficiently.

Within this plan, the rainwater measures are ready for further detailing. The wastewater system is still

conceptual: the sewer alignment, the required wetland area and the effluent quality must be verified before implementation. The first test results of the constructed wetland at the University of Curaçao show that this technology can significantly improve the quality of household wastewater under local conditions, but that additional treatment or a longer settling period of the plants is needed to reach irrigation standards.

In conclusion, a decentralized approach that combines source control of rainwater with neighbourhood-scale collection and nature-based treatment of wastewater provides a suitable, affordable and adaptable basis for improving water management in Swaen. Because many neighbourhoods in Willemstad face similar problems, this approach can also serve as an example for other areas of Curaçao, provided that it is adapted to the local conditions.

7 Discussion

This chapter evaluates the methodological assumptions, data limitations, and technical constraints encountered during the research and design phases of this project. The discussion points are presented in descending order of significance, meaning that the most critical limitations and uncertainties are addressed first. Each section assesses how these underlying uncertainties influence the validity of the proposed mitigation measures and final system designs.

7.1 Rainwater management

This modeling pipeline integrates a government LiDAR Digital Elevation Model with a custom QGIS land-use classification into a HEC-RAS model. Manning roughness coefficients and field-tested infiltration rates are incorporated to simulate water movement. Because the objective is to compare and assess various mitigation measures, flow volumes under 50 cubic meters (total over the simulation period) are considered negligible for this study. A profile line analysis measuring inflow, outflow, inundation storage, and infiltration across the Swaen catchment revealed a computational mass balance error below this threshold. For a catchment of this scale, this low residual demonstrates strong model computational stability and ensures the volume accounting is highly reliable for evaluating mitigation effectiveness.

Regarding model calibration and verification, the baseline model has not been calibrated using historical data. Rainfall events of a sufficient scale did not occur during the fieldwork period in Curaçao to allow for on-site routing observation. Consequently, the model values may contain unknown systemic biases. Furthermore, a formal sensitivity analysis was not conducted, meaning the exact impact of potential variations in the derived infiltration rates or roughness parameters on peak water surface elevations remains unquantified.

Infiltration mechanics present a notable limitation that results in a conservative assessment of surface flooding. While infiltration is represented using the Constant Deficit option in HEC-RAS, simulations indicated that overland runoff occasionally remained pooled on unsaturated soil after several hours. This reflects a known computational constraint where the 2D solver struggles to apply infiltration to moving surface water as efficiently as it processes direct precipitation. Consequently, the model inherently underestimates total infiltration and overestimates surface runoff.

To address topography and major barriers, walls and flow routes were cross-referenced manually through site visits, Google Earth, and Google Maps. This process required adding several missing walls to the DEM and removing a vehicle from a road cell. Although these specific DEM errors were corrected and primary flow paths were verified, minor flow-path inaccuracies may still persist within the model due to the chosen mesh resolution and baseline geometry schematization. Additionally, stormwater drainage systems were intentionally excluded from the model because they can be unreliable and fall outside the testing scope. Such infrastructure was largely absent within the Swaen area itself, with only a single stormwater drain located near the eastern inflow.

Regarding spatial data, the shallow, grid-like inundation patterns visible in the higher northern region of the subsequent depth maps are a direct reflection of interpolation artifacts present in the raw source LiDAR DEM. These patterns represent artificial terrain stepping rather than actual hydrodynamic anomalies. However, they represent an acceptable spatial compromise as they do not significantly impact the macro-routing of surface water or the overall volume accounting within the primary catchment.

Additional limitations include the assumption that the study area can be adequately divided into four main land-use types, and that the derived Manning and infiltration parameters are uniformly representative across each category. Furthermore, a rigid-bed assumption is applied, meaning the DEM is assumed to remain unchanged during a flood event, whereas actual flooding can cause erosion and alter morphology.

Despite these limitations, the model performs adequately to assess the scale of rainwater issues in Swaen and evaluate the effectiveness of potential mitigation solutions.

7.2 Wastewater management

For the wastewater management in Swaen, a connection to the centralized sewerage system still remains as a potentially viable option. Openbare Werken indicated that such a connection should be possible in the case that this is deemed necessary. However, insufficient information regarding connection points, costs, and the capacity of existing infrastructure was available. The rocky subsurface of Willemstad and the potential need for pumping further complicate the situation. Therefore, a centralized solution could not be reliably compared with the decentralized alternatives within this research. Further investigation is deemed necessary before excluding this option in future considerations.

The conceptual wastewater design is based on the current situation and available information about Swaen. However, future development plans for the region are not yet known. Changes in housing, road layouts and land availability could greatly affect the required system capacity or the proposed layout. The presented sewer alignment and facility locations are therefore indicative and should be reassessed when future development plans are available.

In this report, a MCA was used to determine what decentralized treatment options were the most optimal for Swaen. The MCA provided a structured comparison between the alternatives, but its results heavily depend on the stated criteria and the assigned weights. The selection of the preferred variant could therefore be considered a reasoned preference, rather than a definitive conclusion. In another research with different criteria, weights and objectives, this choice could be different.

The conceptual design relies on assumptions regarding population, wastewater production and topography. The population data for Swaen is not fully verifiable, thus the calculated results for the wastewater flows should be considered estimates. In addition, the elevation map of the Swaen area is used to check the feasibility of a gravity sewer. This map lacks accuracy, meaning that for a actual implementation the elevation data should be measured exactly.

The proposed decentralized approach could also be relevant in similar neighbourhoods with the same sort of wastewater problems. However, the design cannot be directly applied elsewhere without considering local population density, topography, soil conditions, groundwater vulnerability, land availability and

maintenance capacity. Further pilot projects and monitoring in other neighbourhoods would help establish the wider applicability of this approach. A scale-up of the conceptual design falls within the possibilities of the project. In that case there should be more research conducted in how the scaling would be applied in reality.

7.3 Constructed wetland

As part of this project, the constructed wetland at the UoC, which was built by a student 8 years prior, was finished by connecting it to the septic tank and planting the wetland plants necessary for filtration to take place. Due to time constraints, comprehensive performance testing of the system was not possible. Preliminary results were gotten by testing samples from the influent and effluent of the system. These first results give an indication of performance, by showing clear differences in some pollutant concentrations between effluent and influent. However, multiple points of discussion were identified during the research. These are mentioned here.

Firstly, as was established in Chapter 5, to fully assess the filtration capacity of a constructed wetland, the wetland plants have to be left to grow and stabilize in their new habitat. This is a process that takes from 1-3 months usually but can take longer as well. For this study, the CWs were tested with plants that had been planted 25 and 18 days before taking the samples. This likely leads to an underestimation of the eventual filtration capacity of the CWs. This needs to be taken into account when looking at the results.

Secondly, also specified in Chapter 5, the hydraulic retention time (HRT) of the water in a well-designed constructed wetland is usually 4-15 days. It is a challenge to guarantee this time in the system for every water particle that enters. This is because, between the inlet and outlet, the flow is not evenly distributed, and the water will form pathways through the system with higher and lower velocities. This leads to a difference in HRT between different water particles. There is no simple way to get rid of this problem completely. The easiest way to handle this problem is by controlling the flow rate in and out of the system, which together with the dimensions of the CW will give the theoretical HRT of the system. Afterwards, multiple different HRTs can be tested to find the balance between filtration and efficiency. However, in this project the setup was too rudimentary to be able to control flow rate. The pump in the septic tank sometimes turned off by itself and had to be turned on manually. Because a constant flow rate could not be guaranteed with this system setup, the flow rate was not measured, meaning that the theoretical HRT of the system at the time of sampling is unknown. This means that the results of this study are lacking an important piece of information to compare it with other systems.

Thirdly, the results of this study offer only a partial conclusion on the filtration capacity of the system, because multiple water quality indicators could not be measured, or measured accurately enough. In Table 7.1, this lack of information is summed up. Any conclusions drawn from this research can only tell something about the parameters that have been tested (accurately).

Table 7.1: Parameters for which results are not accurate or missing entirely

Parameter	**Limitation**
Nitrogen	Test not accurate enough
E. Coli	Test not accurate enough
Phosphorous	Not measured
BOD_5	Not measured
Fecal Coli	Not measured

The fourth, and last, point of discussion is the lack of repeated testing. Due to time constraints on the project, the team was not able to measure the performance at multiple points in time. This means that results are limited to only one snapshot of the performance of the system. With more time, one could think of tracking performance over the time of year or even the time of day. Furthermore, repeated testing would also mean taking multiple samples or doing tests multiple times on the same sample to remove the effect of inaccuracies and spatial dependence of pollutants as much as possible. This would greatly improve the reliability of the results. In any case, the current results do show a significant change between in- and effluent of the system, leading to the conclusion that, while the exact effectiveness of the system is yet to be determined, some clear reductions take place which can be attributed to the constructed wetland.

8 Recommendations

8.1 Rainwater management

On-Site Hydrological Observation
Future research should prioritize conducting on-site observations within the Swaen catchment during or immediately following a significant storm event. Capturing empirical data of the physical catchment response will allow researchers to accurately verify primary flow paths and confirm the exact locations of active localized depressions, ensuring the model's spatial routing aligns with real-world hydrodynamics.

Parameter Sensitivity Analysis
A formal sensitivity analysis should be conducted on the primary input variables. Systematically varying the derived Manning roughness coefficients and infiltration parameters will quantify their exact influence on peak water surface elevations, ensuring that the safety margins for sizing proposed mitigation measures are mathematically justified.

8.2 Wastewater management

Further Investigation Centralized Sewer Connection
Before definitely proceeding with the decentralized solution, the feasibility of connecting Swaen to the existing central sewer network should be investigated further in consultation with Openbare Werken. This should be an in depth investigation where all the opportunities and disadvantages will be compared with each other in order to determine the final judgement on the system type for Swaen. This should include identifying potential connection points, checking the capacity and condition of the existing infrastructure, and determining whether gravity transport is possible or pumping is required. A comparison of the estimated construction and operational costs would further help establish whether a centralised connection is a viable alternative.

Detailed Measurements And Verification Of Parameters
If the decentralized solution is pursued, a detailed measurement study will have to be conducted in order to verify the elevations of household connections and pipeline routes. This is necessary to confirm the application of a gravity sewer and to get to the final pipe alignment design. Adding on to this, the current situation in Swaen should be investigated thoroughly. This way the population number, wastewater production and wastewater facilities in the area can all be confirmed and used for further research. The dimensions of the sewer network, septic pretreatment facility and the constructed wetland should then be reassessed using this data as well.

8.3 Constructed wetland

Letting the plants grow to full capacity
It is expected that the plants will not be at full capacity for another month or two. Waiting this time

and then testing again will likely yield better results, as the plants have gotten time to fully settle into the system.

Controlling the flow rate and HRT
A system would need to put into place that can control the flow rate of the water running into the constructed wetland. Ideally, this would either guarantee a certain flow rate, so that the theoretical hydraulic retention time of the system could be calculated. Not only can this give more meaning to the results, it also opens the door for testing with different HRTs and trying to optimize the value of the HRT for this particular system.

Testing remaining parameters
Most importantly, it would be good to investigate the capacity for phosphorous and nitrogen removal of the system, as well as BOD_5 reduction. Finally, testing the bacterial content in a more accurate way could give insight into the actual filtration capacity of the system in this regard. With all these additional results, the picture of filtration capacity and efficiency is completed, and the results can be compared to the standards for irrigation to see whether they suffice.

Fixing the third basin and further plant testing
Fixing the third CW basin would open up new possibilities for testing with different configurations of the already tested plants, or for testing completely new plants, such as *Gundlachia Corymbosa* which was dropped from the test plan. Fixing it would likely mean removing all of the gravel in the basin, and then removing and replacing the rubber lining that is supposed to keep water in. Also, the system could be checked for other potential causes of the problem when the gravle is removed.

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A IDF-Curves of Curaçao

This appendix presents the Intensity-Duration-Frequency (IDF) curves for Curaçao, which serve as the meteorological basis for the design storms applied in the 2D hydrodynamic modeling of the Swaen catchment. The graph defines the relationship between rainfall duration (ranging from 15 to 120 minutes) and maximum intensity (mm/h) across return periods of 2, 5, 10, and 25 years. These regional curves were utilized to extract the specific rainfall parameters for the simulation, including the 92 mm/hr intensity derived for the critical 10-year, 30-minute design storm.[91]

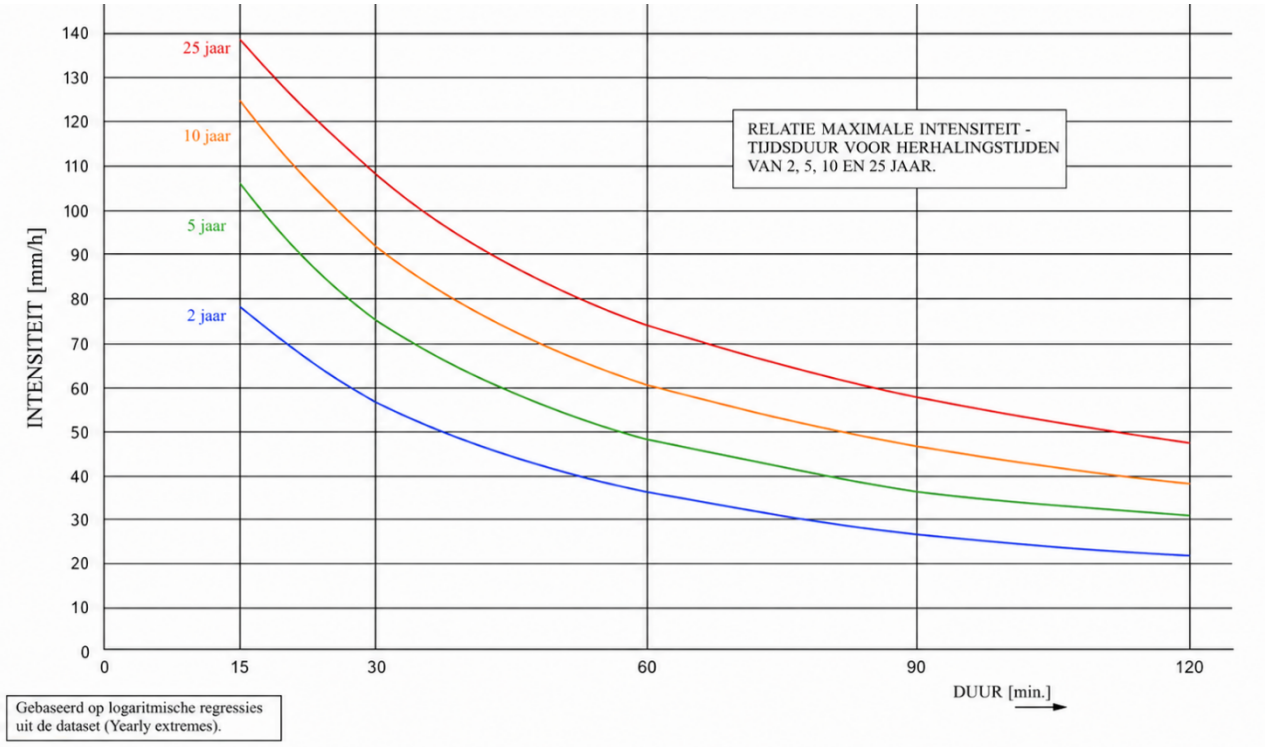

Figure A.1: IDF-Curves of Curaçao

B Hydrodynamic Model Configuration and Mass Balance Analysis

This appendix details the underlying computational parameters, equation sets, and numerical tolerances used in the HEC-RAS 2D hydrodynamic model for the Swaen rainwater management project. While the main report focuses on baseline hydrology and physical mitigation strategies, the configuration settings provided here govern the mathematical routing of surface water across the computational grid. Documenting these specific tolerances and stability logs demonstrates the numerical stability of the model, verifies mass conservation during rapid precipitation events, and ensures the technical reproducibility of the simulations.

Simulation Time Steps and Output Configuration

A 1-second computation interval was selected to maintain numerical stability across the highly refined 1×1 meter grid, governed by the Courant-Friedrichs-Lewy (CFL) condition. The numerical stability of the model depends on the Courant number (C), defined as:

$$C = \frac{V \Delta t}{\Delta x}$$

where V is the flow velocity, Δt is the computation time step, and Δx is the computational cell size. To prevent mathematical instability or volume loss, the boundary condition for the Courant number should ideally remain $C \leq 1.0$. Assuming localized overland runoff velocities approaching 1 m/s, a grid size of $\Delta x = 1$ m necessitates a time step of $\Delta t = 1$ s to satisfy this stability threshold.

The Mapping and Hydrograph output was set to 1 minute to ensure the rapid runoff peaks of convective rain events are accurately captured without generating excessively large HDF files. The Detailed Output was set to 1 hour to reduce unnecessary hard drive load.

Governing Equations and Tolerances

Surface water routing was calculated using the 2D Diffusion Wave equation set. This approach is highly efficient and mathematically stable for rain-on-grid simulations where gravity and bottom friction dominate over inertial forces. HEC-RAS formulates the Diffusion Wave approximation by substituting the simplified momentum equation (assuming the friction slope equals the water surface gradient) into the mass conservation continuity equation:

$$\frac{\partial H}{\partial t} - \nabla \cdot \left[\frac{R^{2/3} h}{n |\nabla H|^{1/2}} \nabla H \right] + q = 0$$

where H is the water surface elevation, t is time, R is the hydraulic radius, h is the water depth, n is Manning's roughness coefficient, and q represents source/sink terms.

The implicit weighting factor (θ) was set to 1.0 for both the warm-up and the main simulation. A value of 1.0 provides a fully implicit backward-difference scheme, which maximizes stability when handling

the highly non-linear wetting and drying fronts inherent to precipitation-driven modeling. To balance accurate mass conservation with computational speed, both the water surface and storage area calculation tolerances were defined as 0.006 meters. The maximum abort tolerance was set to 30.0 meters with 20 iterations allowed per time step.

Model Stability Logs and Mass Balance Analysis

As summarized in the main report, the simulation maintained robust computational stability, achieving an excellent global cumulative mass balance error of only 0.04358% across the entire model domain. For the specific Swaen sub-area, localized volume accounting recorded a minor volume continuity error of 50.6146 m^3, equating to a 2.12994% percentage error.

While global mass balance errors below 1% indicate high overall model integrity, localized sub-area errors in 2D rain-on-grid applications can marginally increase due to shallow overland flow over complex terrain, rapid wetting and drying transitions, or sub-grid boundary interactions. The 2.12994% localized error remains well within the standard acceptable tolerance (typically $< 5\%$) for high-resolution 2D surface water schematization.

Furthermore, a review of the detailed HEC-RAS computational output logs confirmed that the simulation rarely hit the maximum of 20 iterations per time step. Maximum cell velocities and water surface elevation changes remained within realistic physical bounds, confirming that the minor continuity error is a mathematical artifact of the localized control volume rather than an indication of hydrodynamic instability.

C HEC-RAS runs

First, QGIS layers (fig B1 to B5) are exported to HEC-RAS through shape files. These shape files are then imported into HEC-RAS to create a table based on land use. Next, LIDAR data is imported into HEC-RAS, and adjustments are made to the LIDAR data using the same shape files to choose which areas to use for storage. This involves adjusting the LIDAR data by setting the data points inside the storage areas to -10. After making a run, the volume of the storage areas is determined for both the total Swaen area and individual storage areas. Finally, the outflow is measured through profile lines at the boundaries, and the infiltration volume is calculated using the average infiltration over the Swaen area.



Figure C.1: Baseline QGIS layers



Figure C.2: Locations of different storage areas



Figure C.3: Location of Storage2



Figure C.4: QGIS layers with houses in Swaen and houses not in Swaen



Figure C.5: Storage 1 and Household tanks, considered the best mitigation strategy



Figure C.6: QGIS layers Permeable Roads

Table C.1: Comprehensive comparison of baseline, individual storages, permeable roads, and combination strategies.

Metric	Baseline	Household Tanks	Storage 1	Storage 2	Storage 3	Storage 4	Perm. Roads (small)	Perm. Roads (large)	Storage 1 + tanks	Stor. 1 + small stor. 2 + tanks	Stor. 1 + large stor. 2 + tanks	Stor. 1, 3, 4 + tanks
Inflow (m^3)	1552.02	1556.82	1521.72	1614.42	1610.76	1615.20	1552.56	1550.82	1526.16	1598.46	1600.62	1604.40
Outflow (m^3)	1897.80	2025.54	1611.18	1788.30	1293.36	1391.52	1677.17	1265.81	1551.60	1615.14	1451.04	635.64
Storage / Stored Volume (m^3)	–	114.22	311.00	186.00	674.00	578.00	446.00	860.00	404.22	435.22	601.22	1424.22
Infiltration Volume (m^3)	212.93	327.04	210.74	206.47	209.97	210.00	200.51	200.51	324.33	320.05	320.05	320.77
Volume Error (m^3)	50.61	52.38	39.12	40.55	39.75	42.99	46.71	51.33	22.59	23.85	37.31	17.90
Error Percentage (%)	2.13%	2.20%	1.67%	1.73%	1.76%	1.76%	1.97%	2.16%	0.93%	0.98%	1.54%	1.54%

D Explanation wastewater contaminants

This appendix gives a short explanation for the contaminants present in domestic wastewater. In Table D.1 the contaminants in the wastewater are named and briefly described.

Table D.1: Main wastewater parameters explained, based on von Sperling [92].

Parameter	Name	Description
BOD_5	Biochemical Oxygen Demand	Measures the amount of dissolved oxygen consumed by microorganisms during the biological degradation of organic matter over five days. It indicates the biodegradable organic pollution in wastewater.
COD	Chemical Oxygen Demand	Measures the oxygen equivalent required to chemically oxidise organic and other oxidisable substances in wastewater. It indicates the total oxidisable pollution.
N-total	Total Nitrogen	Represents the total nitrogen content in wastewater, including organic nitrogen, ammonia, nitrite and nitrate. Excessive concentrations can contribute to eutrophication.
P-total	Total Phosphorus	Represents the total phosphorus content, including organic and inorganic phosphorus compounds. Excessive concentrations can promote algal growth and eutrophication.
Faecal Coli	Faecal Coliforms	A group of bacteria originating primarily from the intestinal tract of humans and animals. Their presence indicates faecal contamination and the potential presence of pathogenic microorganisms.
E. coli	Escherichia coli	A specific group of faecal bacteria commonly used as an indicator of faecal contamination. Its presence indicates a potential risk of pathogenic microorganisms.
Enterococci	Intestinal Enterococci	Bacteria naturally occurring in the intestinal tract of humans and animals. They are used as indicators of faecal contamination, particularly in marine waters.
Oil / Grease	Oil and Grease	Refers to fats, oils and grease present in wastewater. High concentrations can cause blockages in sewer systems and interfere with wastewater treatment processes.
pH	Potential of Hydrogen	Indicates the acidity or alkalinity of wastewater. It influences biological treatment processes and the activity of microorganisms.
Electrical Conductivity	Electrical Conductivity	Measures the ability of water to conduct an electrical current, mainly determined by the concentration of dissolved ions. It provides an indication of wastewater salinity.

Parameter	Name	Description
Chloride	Chloride Concentration	Represents the concentration of dissolved chloride ions in wastewater. High concentrations can indicate increased salinity and negatively affect irrigation suitability.
Suspended Solids	Total Suspended Solids	Represents the organic and inorganic particles suspended in wastewater. High concentrations increase turbidity and can contribute to sediment accumulation in receiving waters.
Temp. Max.	Maximum Temperature	Indicates the maximum temperature of wastewater. Temperature influences microbial activity, biological treatment efficiency and the solubility of gases.
SO_4	Sulphate	Represents the concentration of dissolved sulphate ions in wastewater. Under anaerobic conditions, sulphate can be converted into hydrogen sulphide, causing unpleasant odours and infrastructure corrosion.

E Excel used for MCA

This appendix presents the Excel sheets used for the calculations made in the MCA.

Solutions	Land Availability	Energy Demand	Installation Costs	O&M Costs	Effluent Water Quality	Reliability /robustness	Risk to groundwater	Rating
Septic Tank	4	5	4	4	2	5	2	347,016
Constructed Wetland	2	5	3	3	4	3	3	326,368
Anaerobic Baffled Reactor	2	5	2	4	3	4	3	319,835
Wastewater lagoons	1	5	4	4	3	4	2	318,729
Composting Chamber	4	3	2	4	3	2	3	298,892
Anaerobic Filter	2	5	2	3	3	3	3	291,834
Aerobic Treatment Unit	4	1	2	2	4	1	4	276,618
Biogas Reactor	3	5	1	3	2	3	3	269,117

Solutions	Land Availability	Energy Demand	Installation Costs	O&M Costs	Effluent Water Quality	Reliability /robustness	Risk to groundwater	
weight	11,82	8,73	13,81	14,44	20,72	13,56	16,92	

Score	Meaning	Value
+ +	Very favourable	5
+	Favourable	4
+ -	Intermediate	3
-	Unfavourable	2
- -	Very unfavourable	1

Figure E.1: Excel sheet 1

	Maurits	Joaquin	Luka	Tim	Anthonie
Land availability	2	0,8	2	0,8	2
Energy Demand	1	0,6	1	0,5	3
Installation cost	3	0,6	4	0,7	2
O&M costs	3	0,8	3	0,7	3
Effluent water quality	4	1	5	0,9	5
Reliability / robustness	2	0,8	2	0,8	4
Risk to groundwater	2	1	4	1	4
	17	5,6	21	5,4	23

	Maurits	Joaquin	Luka	Tim	Anthonie	RESULT
Land availability	11,76	14,29	9,52	14,81	8,70	11,82
Energy Demand	5,88	10,71	4,76	9,26	13,04	8,73
Installation cost	17,65	10,71	19,05	12,96	8,70	13,81
O&M costs	17,65	14,29	14,29	12,96	13,04	14,44
Effluent water quality	23,53	17,86	23,81	16,67	21,74	20,72
Reliability / robustness	11,76	14,29	9,52	14,81	17,39	13,56
Risk to groundwater	11,76	17,86	19,05	18,52	17,39	16,92

Figure E.2: Excel sheet 2

F List of Local Plants with a Filtering Capacity

Table F.1: List of local Curaçao plants with a potential filtering function, as provided by CARMABI

Category	**Scientific Name**
Herbs / Forbs	*Ammannia latifolia*
Herbs / Forbs	*Amaranthus dubius*
Herbs / Forbs	*Echinodorus berteroi*
Herbs / Forbs	*Stachytarpheta jamaicensis*
Herbs / Forbs	*Phyla nodiflora*
Herbs / Forbs	*Egletes prostata*
Herbs / Forbs	*Stemodia maritima*
Herbs / Forbs	*Ocimum* ssp.
Herbs / Forbs	*Ruellia tuberosa*
Herbs / Forbs	*Typha domingensis*
Shrub	*Sesbania bispinosa*
Shrub	*Pluchea odorata*
Saline Environment	*Sesuvium portulacastrum*
Saline Environment	*Batis maritima*
Saline Environment	*Sophora tomentosa*
Saline Environment	*Suriana maritima*
Saline Environment	*Tournefortia gnaphalodes*
Saline Environment	*Gundlachia corymbosa*
Grasses	*Sorghum halepense*
Sedges (Cyperaceae)	*Cyperus ligularis*
Sedges (Cyperaceae)	*Eleocharis mutata*
Sedges (Cyperaceae)	*Fimbristylis mutata* & *F. ferruginea*
Sedges (Cyperaceae)	*Lipocarpha micrantha*