DTU Civil Engineering
Department of Civil Engineering

Micro scale analysis of open urban waterscapes in early design stages

Development and use of water management and open urban waterscapes (OUW) solutions in urban spaces on a micro scale. Demonstration of design and analysis tools on a case study in collaboration with a design studio, DTU BYG and DTU MILJØ.

Bachelor thesis

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Abstract

As a result of global warming and urbanization, more frequent and larger rainfalls impacts the globe and especially the cities suffer the consequences. Therefore, an increasing need for water management in urban environments has emerged. Open urban waterscapes (OUW) help manage water and is a crucial help to many unwanted rainfalls. It is important to implement these in the early design stages, as they require space and often is costly to implement later in the process. There are many hydrology solutions that can manage water and implement OUW, but this thesis seeks to analyze particle simulation method on a micro scale, in order to implement OUW early in the design phase. The particle simulations are completed in Blender 2.8, which is iteratively and experimentally fitted throughout the thesis to simulate rainfalls as accurate as possible. Those fit rely upon Manning's formula, OUW Potential Tool V.1.5, related studies and literature. Occasionally, some test are completed in order to confirm the results. Alternative methods are discussed along with uncertainties of the particle simulation method. Last the fitted particle simulation method is applied on a case study ”Milan Citylife” from Bjarke Ingels Group, which is an ongoing project in the design phase and a final proposal of specific OUW are made.

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Katrine Sandstrøm, Architect / Landscape Architect, Bjarke Ingels Group. Contact person. Supplied with case study material.

Contents

1 Introduction

The need for water management is rising as climate change is becoming a significant global factor creating more frequent and larger rainfalls. As urbanisation at the same time is increasing, focus on water management in an urban context is highly relevant, not least during the early design stages. If architects and engineers too late realize the problem it might lead to the need of costly secondary solutions.

One solution to help managing rainwater is by using the open urban waterscapes (OUW) technique. OUW includes a number of actions that in total enables to store, delay, evaporate, or infiltrate rainwater with the intention to minimize water overflow into unwanted places.

Managing rainwater in an urban context and applying OUW requires a suitable method to be formed. As technology advances and more complex software is developed such techniques are becoming a powerful help. Blender[1] is an example of a software that can handle a huge number of ”particles” in a scale that might simulate rain. Rainwater simulations like that might then determine the catchment and identify how accumulation of rainwater is supposed to be on a specific spot described mainly by volume and time lapse. Information like this is highly valuable right from the early design phases.

Throughout this paper the Blender software is the basis for analysis refinement made in order to match real world parameters as close as possible through experimental and iterative methods. Finally, the whole OUW concept is applied onto a case study, ”Milan Citylife”[2], from the design studio ”BIG”[3].

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[1] ”Blender is a free and open-source 3D computer graphics software toolset used for creating animated films, visual effects, art, 3D printed models, motion graphics, interactive 3D applications, virtual reality and computer games.” [1]

[2] Milan Citylife, an ongoing architecture project in Milan, Italy, run by Bjarke Ingels Group

[3] BIG, Bjarke Ingels Group, International design studio, Copenhagen, Denmark

1.1 Abbreviations

Area	A
Design studio Bjarke Ingels Group	BIG
Flow rate	Q
Friction coefficient	FC
Gauckler-Manning	GM / n
Hydraulic conductivity	HC
Hydraulic radius	R
Height	H
Length	L
Manning’s formula	MF
Open urban waterscapes	OUW
Storm Water Management Model	SWMM
Slope	S
Velocity	V
W	Width

2 Theory

Water management in an urban context is complex as many components and parameters are involved. All factors are important in order to understand the many processes involved in a rainfall situation, like the accumulation and distribution of water as well as the drainage when emptying water pools. The following section seeks to explain the major processes involved.

2.1 Open urban waterscapes

As urbanization is evolving and cities are expanding more impermeable surfaces are constructed, like roads, squares, and buildings. This creates a problem by water accumulation in unwanted locations and might cause major damages on different parts of the whole infrastructure. Usually, this water handling is taken care of by the sewer systems but as cities expand and at the same time the global climate changes create more frequent and more extensive rainfalls the problem needs to be addressed.

Open urban waterscapes (OUW) is a technique developed to address this issue. OUW is used to help managing local rainwater in an urban context as the key is to slow down the accumulation of rainwater, to save time for the water to infiltrate into the ground or evaporate into the air. Some of the elements addressed here are gabions, rain gardens, green roofs, gutters, and reservoirs. There are many advantages using such elements compared to the traditional sewer system. In the sewer the rainwater is mixed with the sewage water which enlarge the volume of water to be rinsed and thereby wasting power for rinsing and loosing costly energy. Furthermore, sometimes the sewage water during heavy rainfalls leaks and contaminates the environment, like lakes, ponds, or sea. The OUW elements are supposed to reduce the water overflow, enhance the water quality and even be an supposedly attractive element in the landscape of the city architecture. Because of the slow infiltration into the ground the OUW is supposed to work as an extended filtration system and slow down the accumulation of water. Rainwater typically do not contaminate the environment but in an urban context you might see a *'first flush'*[4] event, cleaning the roads from dirt created by cars and garbage. [2]

2.1.1 Categories of rainfall

OUW might work differently depending on the amount of rainwater so when discussing this issue some sort of categorization of rainfall events is essential. One system is to categorize rainfalls into 3 domains based on the statistical occurrence seen from Danish standards [2]. First, there is the "*everyday-domain*" which represent 75% of the yearly rainfall and the statistical occurrence is 0.2 yearly which corresponds to about 20 mm of rainfall, shown in fig. 2.1. These are frequent but light rainfalls.
Next is the "*design-domain*" which has a statistical occurrence of an episode every 10 years and corresponds to about 70 mm of rainfall. These are critical rainfalls which the sewer systems are just designed to handle and this represents this size of rainfall analyzed in this thesis.
Finally is the "*extreme-domain*" which only include 1% of the yearly amount of rain while statistically such type occurs only every 100th year and corresponds to about 110 mm of rainfall. These are extreme scenarios which are almost impossible to manage in an urban context. [2]

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[4] The first flush after a period of no rain, where the rainwater rinses the dirty surfaces from contamination of cars, garbage, etc. and thereby become dirty

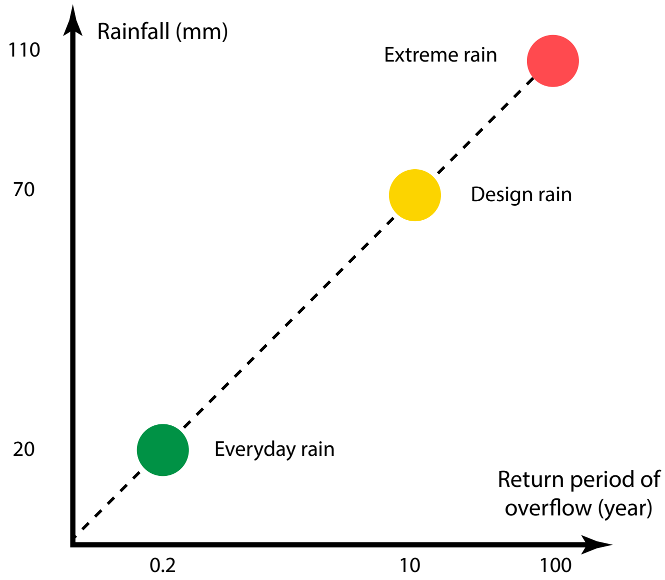

Figure 2.1: Rain domains and their frequency of overflow [years (logarithmic scale)] (x-axis) and the amount of water in the rain domains [mm] (y-axis)

It may seem attractive to use the OUW elements to replace the sewer systems as rainwater drainage would create a natural circuit of the water. This will, though, require much space which is a limited feature in an urban environment so a long-lasting solution has to involve systems where rainwater is directed to other locations. [2]

2.1.2 Rainwater balance

The rainwater balance deals with analysing the entrance and the exit of the water. Depending on the scenario, water will enter by direct precipitation of rain or by inflow from the catchments while the water leaves by evaporating, by infiltrating, or simply by running off. Water evaporation depends on parameters like air temperature, wind, humidity, and the presence of plants. Infiltration of water depends mainly on the surface and ground. Different materials have different hydraulic conductivities (HC) and can differ from $0.1[m/s]$ (e.g. large sand grains) to less than $10^{-9}[m/s]$ (e.g. clay), showed in the table 2.1. Water run-off depends on the slope of the surface running off from and from the surface material. The precipitation of rain depends on the intensity and the time while the water inflow depends on the flow rate and the time lapse. These principles of the OUW are illustrated in fig. 2.2. [2]

2.2 Infiltration and evaporation

Water constantly is forced by gravity meaning it will always flow downwards until it meets the sea, an ocean, a lake or a valley, where it will accumulate if the in-flow is larger than the out-flow. If the water runs off the site or into the sewer system it is referred to as ”run-off”. Often it is desired to delay this run-off to counteract flooding meaning that water will have more time to infiltrate or evaporate. Delaying water is done with elements like gutters, reservoirs, or rain gardens that have high HC or high roughness.

Water will always evaporate in some rate depending on the temperature, the humidity, and the surface area. Evaporation rates are often calculated as if the water was still since in that situation it is easier to calculate the surface area. Many evaporation rates were

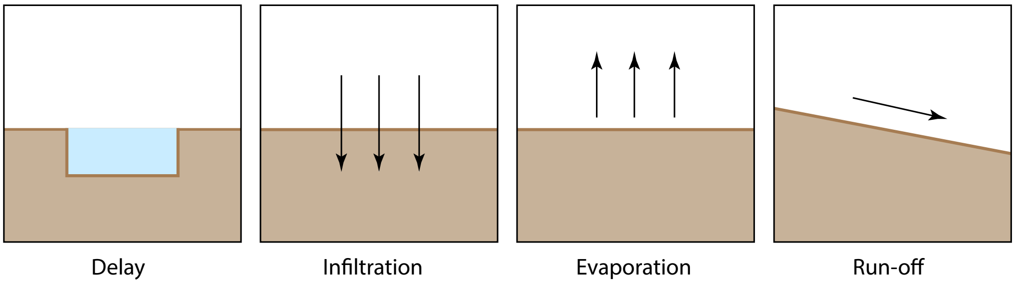

Figure 2.2: Principles of OUW [Backhaus, A.]

assumed at some average values as it is mainly the weather situation that influences the rate and the often quickly changing weather situation makes it difficult to take such details into account in a precise manner.

Water is almost always infiltrating the surface depending on the surface material; the infiltration especially is high if the surface has pores.

2.2.1 Hydraulic Conductivity

The HC might be difficult to calculate since it vary depending on the many factors, including the material of the soil. [3] The HC therefore has to be determined on the specific site analysed since it might vary a lot, even on short distances.

There are more ways of determining the HC. 1) An experimental approach, e.g. applying Darcy's Law,[5] if it is possible to measure the HC on site by creating a tube well and measuring the fluid flow. 2) A second way is to collect samples from the soil and measure the flow of fluid in a laboratory, also by using Darcy's Law. Such measurements most often display the most precise and reliable methods. 3) A third way is, though less recommended as it often is less accurate, an empirical approach where the HC is calculated using the data of the soil, like pore size and texture. This method is easier to perform and might be used if there isn't experimental data available. Table 2.1 gives a rough estimate of different types of soil and how much the HC varies according to that.

Description	**Hydraulic conductivity (HC) [m/s]**
Gravel	1E-3 - 0.1
Sand	1E-5 - 1E-2
Silt	1E-0 - 1E-5
Clay	<E1-9
Boulder clay	1E-10 - 1E-6

Table 2.1: Rough range of hydraulic conductivites of different soil types (Ref: Lerer, S. M.)

2.2.2 Open urban waterscapes properties

OUW in an urban context might be an efficient way to get rid of rainwater. Different OUW elements have different properties and each of them display both positive and negative features. In this paper from the various OUW elements with similar properties is selected

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[5] Darcy's Law describes "flow of a fluid through a porous medium" [4] by Henry Darcy

three elements that are explained in more detail: rain gardens, gabions, and permeable surfaces.

Rain gardens

Rain gardens have a small reservoir with plants that are connected to a catchment area (Fig 2.3). Rain gardens have more advantages; they can store huge amounts of rain volumes, are relatively cheap to construct, have a visible overrun that makes the rainwater visible which can be an attractive element in urban areas. The downside is they take up much place which is a limited resource in an urban environment. [5]

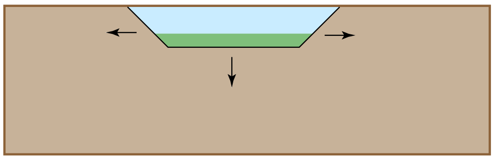


Figure 2.3: Rain garden illustration

Gabions

A gabion consists of a cavity beneath the surface where water accumulates into 'tanks' of either plastic or stones connected to a catchment area (Fig. 2.4). Plastic ones have a higher cavity percentage (95%) compared to stone cavities with a cavity percentage of only about 30%. Gabions are not visible in the urban environment which can be convenient. Though, gabions are more costly since they need to be maintained, they are less aesthetic since the water is not visible and they need a well for overflow. Also, gabions do not utilize evaporation well since they are located underground. The gabions, though, utilize infiltration well since water can infiltrate from the walls. [5]

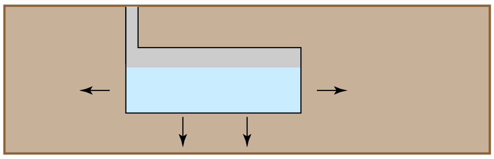


Figure 2.4: Gabion illustration

Permeable surfaces

Permeable surfaces are often grass or other materials with a high HC (Fig. 2.5). This solution is probably the most simple one since it only requires a specific surface; it doesn't take up space, it makes the rainwater visible and it utilizes evaporation well because of its usually large surface. The permeable surfaces might become very wet during rainfalls making this solution less usable in handling major rainfalls. [5]

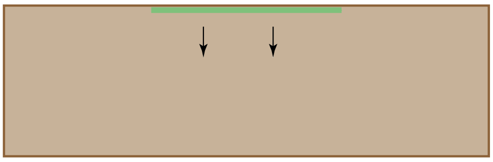


Figure 2.5: Permeable surface illustration

2.3 Types of hydrology methods

Generally, there are three types of water management and OUW methods; empirical method, statistical method and the particle simulation method.

The *empirical method* rely on empirical data, that are deducted from observations and often in the form of formulas or patterns from an experimental work, this is e.g. Manning's formula, that describes velocity or flow of water, or e.g. Darcy's law that describes flow of fluid through a porous medium.

The *statistical method* includes collection of big data-sets. Often statistical analysis have modified the data to a more narrow context. One example is OUW Potential Tool V.1.5, that rely on many simulations performed in SWMM (Storm Water Management Model). Many models often include this statistical method within the model.

The last method is the *particle simulation method*. This method is different from the two others as it simulates rainwater directly on the terrain. The simulations can be modified to copy real scenarios and calculate the water accumulation on the terrain which makes this method unique. This was done by Sung W. who created a script for calculating the water flow on terrain. Basically, it takes a point (rain-particle) on a surface of the terrain and the point will determine the steepest direction. The point then moves to that direction x-length. This can interatively be done to create paths for each point and thereby visualize the water flow. This concept is shown in fig. 2.6. [6]

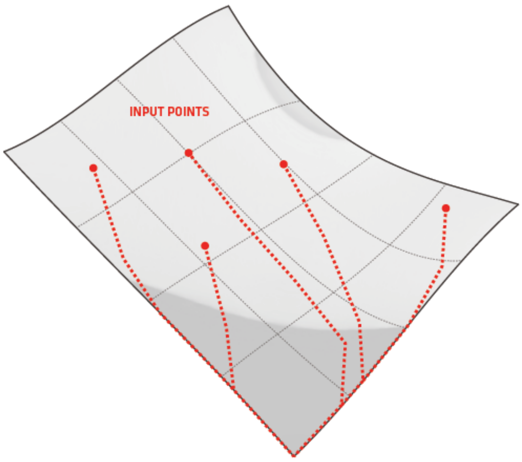
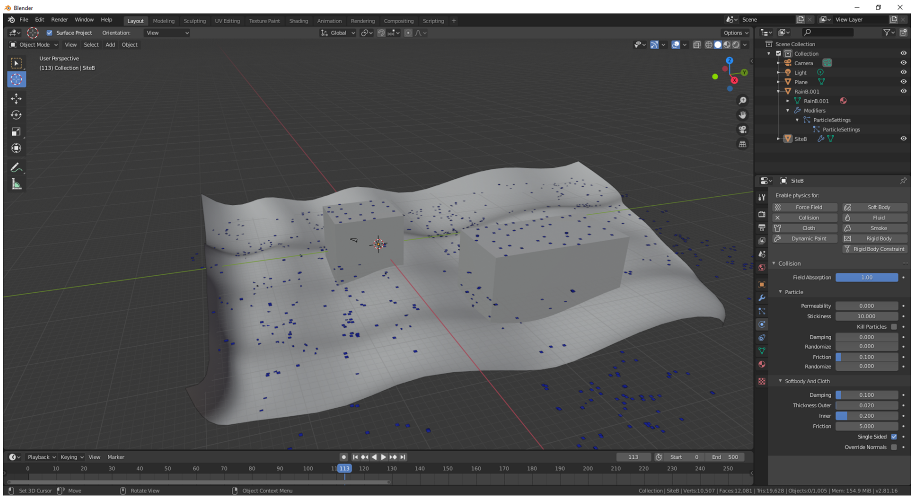


Figure 2.6: Particle simulation script visualized

2.3.1 Blender 2.8

In order to develop a water management and OUW solution in urban spaces and on a micro-scale, Blender 2.8 is introduced. This solution is complex but performs very well in a micro-scale view in urban spaces.

Blender 2.8 is a "open-source 3D computer graphics software tool-set" [1] mostly used for "animated films, visual effects, art, 3D printed models, motion graphics, interactive 3D applications, and computer games." [1] but the software also has a particle simulation included that is adjustable to simulate specific scenarios, including rain water. It has so far not been used to simulate scientific rainfall events, that might foresee unexpected events. The simulation consists of a surface that the particles emit from. This could be any surface, usually the emitter is chosen to be a rectangle for simplicity. The particles have many settings but in general the number, the size and the lifetime of particles are the most important ones. E.g. when a 10 year rain scenario is setup, (equal to 70 mm shown in fig. 2.1) the total area of the site has to be multiplied with the depth of rainfall which is 70mm. Then the total volume of the rain is known. When assuming the particles are 5 cm in radius (standard setting) the volume will equal 0.5 liter per particle. Then the total amounts of particles can be calculated by dividing the total volume of rain by the volume of one particle. An illustration of the Blender interface is shown in fig. 2.7. Last, the collision elements have to be set. Those include many settings as well but the main one is the friction coefficient (FC) which determines how much friction is seen between the particles and the surface. When those parameters are set the simulation can be performed.



Collision

Field Absorption 1.00

Particle

Permeability 0.000
Stickiness 10.000
Kill Particles ☐
Damping 0.000
Randomize 0.000
Friction 0.100
Randomize 0.000

Softbody And Cloth

Damping 0.100
Thickness Outer 0.020
Inner 0.200
Friction 5.000
Single Sided ☑
Override Normals ☐

Faces:12,081 | Tris:19,628 | Objects:0/1,005 | Mem: 154.9 MiB | v2.81.16

Figure 2.7: Screenshot of Blender-simulation. Settings on the right and timeline in the buttom

The primary function for the use of this software is for analyzing the capability of solving the water flow and for the accumulation from catchments. Next, the volumes can be handled in a statistical approach by including data from the past using information like evaporation and infiltration, shown in the next section.

2.3.2 "OUW Potential Tool V.1.5"

One particular tool for water management and OUW solution analysis in urban spaces is *OUW Potential Tool V.1.5*, created by Sara Maria Lerer" Postdoc from DTU Environment. This is a spreadsheet able to calculate the amount of rain on an arbitrary site in a way that can be handled. The program's output is a rainwater balance including a visualization of the rainwater balance, e.g. infiltration, evaporation, runoff, all seen both before and after applying OUW, based on data-sets generated from SWIMM (which is another urban water management software). Also, the program estimates the return period of overflow meaning how long time is needed to handle a rainfall on a specific location. This is a highly usable software that especially excel in the early design stages while but having some limitations in later stages which will be addressed later on.

2.4 Manning's formula

The Manning's formula (MF) is the main support of the studies carried out in the thesis. Therefore, a thorough explanation is addressed in this chapter and why it is a reliable source to depend on.

In 1889 an Irish engineer, Robert Manning, proposed an empiric formula, named the MF. It was based upon a French engineer, Philippe Gauckler, who was the first to come up with the core of the formula, why it is also known as the Gauckler–Manning formula. The MF is one of the most widely used formula to analyze open channel flows in pipes and channels. It comes in various forms, in eq. (2.1) is shown the average mean flow rate (Q) in SI-units and illustrated in fig. 2.8. [7]

$$Q = VA = \frac{1}{n} A R^{\frac{2}{3}} \sqrt{S} \tag{2.1}$$

It describes the relation between:

- Q (average cross-sectional flow rate)
- V (average cross-sectional velocity)
- A (cross-sectional area of flow)
- R (hydraulic radius)
- S (slope of channel)
- n (Gauckler–Manning coefficient (GM))

These parameters have been modified based on seven formulas from 34 experiments on artificial channels and later the relations within MF was refined by five investigators and more than 170 experiments. Since then, the formula is widely accepted and it has been widely used to analyze flows of water in pipes and channels. In 1899 it was said to be *”one of the best formulas of the day”*. [8]

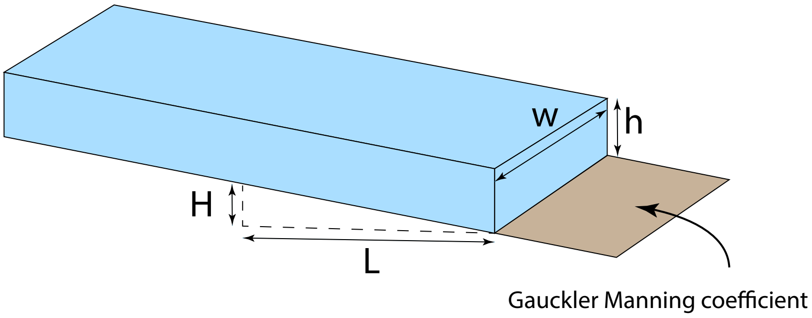


Figure 2.8: Manning’s formula illustrated

A is the area of wetted perimeter in the cross-section. This depends on the water level which can vary over time.

R is the hydraulic radius, which is defined as the ratio between the area of the cross-section and the wetted perimeter, P (length of the wetted surface of the cross-section).

S is the slope of the channel defined by vertical drop divided by horizontal length.

n is the Gauckler-Manning coefficient, which is an unitless empiric number that expresses the roughness of the channel.

Most of these parameters are self explanatory but some are more complex and have been discussed by a number of scientist. The hydraulic radius is one of them.

2.4.1 Hydraulic Radius

The hydraulic radius (R) is defined as the ratio between the area of the cross-section and the wetted perimeter, P. This implies, that it relies on the geometry of the cross-section and on the water level which is perpendicular to the water surface.

	Rectangular cross-section
Flow area	$w * h$
Hydraulic radius	$w * h/(w + 2 * h)$

2.4.2 Gauckler-Manning coefficient

The Gauckler-Manning (GM) coefficient **(note: in eq. (2.1) GM is also referred to as 'n', in this thesis, it will be referred to as GM)** is depended on the channel surface roughness. This number vary from 0.01 to 0.15, where 0.01 is a surface with almost no friction while 0.15 is a situation in which the channel bed consists of multiple trees and weed which slow down the water stream. An overview of the different GM coefficients is listed table 2.2 below.

Description	**Gauckler-Manning coefficient (GM)**
Plastic	0.009
Concrete	0.010
Cement	0.010
Clay	0.011
Unfinished concrete	0.014
Brick	0.015
Gravel	0.020
Earth	0.025
Flood plain (light brush)	0.050
Flood plain (trees)	0.150

Table 2.2: Table of Gauckler-Manning coefficients of different material types

For the results of MF to be reliable the flow has to be uniform. The classification of a uniform flow rely on the depth of water while the cross-section, the GM coefficient, and slope have to remain unchanged. If these criterion are fulfilled uniform flow will be expected after 60 meters. [9]

2.5 Catchment

A catchment is often an overlooked parameter. Many hydrology analysis only analyze it's concerning land, which is a common fault. The landscape is curved which leads water to accumulate from the catchment areas as water always will run downwards. Imagine living in a valley between mountains and only analyzing the water that lands on your own site. This will obviously be a huge mistake but also smaller slopes will contribute to increase water volumes. The question therefore arises; *how far shall the catchment analysis stretch?* This thesis analyze hydrology on a micro-scale in an urban context. But, in a context like this there are many regulations of water management which is often taken care of by the sewer, making it difficult to calculate the catchment. As well this study focuses on the micro-scale and not the macro-scale, even though it is an import factor to consider.

2.5.1 SCALGO

Another water management and OUW solution is SCALGO. This is an online browser tool using a topographic map that allows for many different kind of tools to coordinate. It excel in big scale as it is able to calculate catchment of larger areas which *OUW Potential Tool V.1.5* doesn't. It has the possibility to change terrain and to analyze how the water flows upon these changes. Unfortunately, SCALGO is not open source and the program was not able to be implemented in the final water management and OUW solution why it was left out. That being said, it is a powerful tool to use as it gives a good overview of the total catchment of a site, illustrated by an example of some Copenhagen catchments in fig. 2.9 below.

Figure 2.9: Catchment area of Copenhagen from SCALGO

3 Method

The aim of this study is to present a method to develop and to use unique water management tools, including OUW solutions for use in specific locations in the urban setting. With this purpose a number of phases need to be followed.

First of all, some basic information regarding the local weather should be available. How is the schedule regarding rainfalls, is it an area with local flooding, and similar questions. Usually such data are available from local weather institutes. Secondly, the area itself but also the surroundings need to be analysed. How is the ground (sandy or rocky?), which nearby buildings need to be taken into account, which areas are available for creating OUW-solutions, etc. Thirdly, the proposed changes within the specific area should be known; do you want to construct a new building, a parking lot, a park or other recreating areas, or something else? See to that the architects and the engineers work together in close teams when targeting issues like this.

When such basic information is available the time has come to consider different OUW-initiatives. Some of these require lots of space, others need the underground to be used, etc. Also the analysis tools need to be selected as many systems today are available, like ”MIKE URBAN”[6], ”SWMM” [7], ”SCALGO” [8], ”HEC-HMS” [9] which all are hydrology software plus a number of Excel programs [10] at different fields. When one (or more) solutions have been suggested it is important to look into the literature to see if similar settings have been tried elsewhere and how that worked out.

Finally, a decision is made to take into a testing and starting an optimization process to fit the model along with the requirements in more detail. This part of the process is the main focus in this thesis as an iterative and experimental method in which the refinement during the process step by step will depend on the results found. In this paper the developed model was tested on a case study, ”Milan Citylife”, a building in the planning phase managed by Bjarke Ingels Group (BIG).

3.1 Model fitting

The model fitting is based on a foundation from the Blender-model and is divided into 3 segments, as shown in the fig. 3.1. The goal is to find the relationship between the real-world parameters as the slope (S), the surface roughness (GM), the hydraulic conductivity (HC), combined with the Blender tool-settings, like the friction coefficient (FC) and the permeability (P). These segments represent the parameters that this thesis focus upon. As demonstrated in slope study and roughness study two parameters (blue and green) are based upon MF while the last one (yellow) is based on infiltration in the infiltration study.

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[6] ”MIKE URBAN is the urban water modelling software of choice when important parameters for model selection are stability, workflow, openness, flexibility, GIS integration and physical soundness” [10]

[7] ”Storm Water Management Model (SWMM) is a dynamic rainfall–runoff–subsurface runoff simulation model used for single-event to long-term (continuous) simulation of the surface/subsurface hydrology quantity and quality from primarily urban/suburban areas” [11]

[8] ”The national flood risk platform for working with climate adaptation, urban planning, emergency management and administration of watercourses” [12]

[9] ”The Hydrologic Modeling System (HEC-HMS) is designed to simulate the complete hydrologic processes of dendritic watershed systems” [13]

[10] ”OUW Potential Tool V.1.5” by Sara Maria Lerer

”Slope study”: The blue marking on the left is the first model fit with 6 simulations to be completed. The parameters to be analyzed is the slope (S=0.1,0.2 and 0.3) while the will be hold constant at GM=0.1 resembling concrete surface. What varies is the slope that are analysed using three values: S=0.1; S=0.2; S=0.3. Both the velocity (V) and the flow rate (Q) will be measured.

”Roughness study” The green is the next model to fit, where 6 other simulations will be performed. The parameter to be analyzed is the GM, which describe the roughness of the surface. The simulations consist of 3 slopes (S=0.1,0.2 and 0.3) with GM=0.02 (gravel surface) and GM=0.03 (grass surface).

”Infiltration study” The yellow is the last model to be fitted focusing on the infiltration that varies depending on the permeability of the surface. This setup is different as it consists of a flat 1x1 m square, where 9 simulations will be completed with the surface permeability (P) varying between 0.1-0.9. HC will be measured as the result.

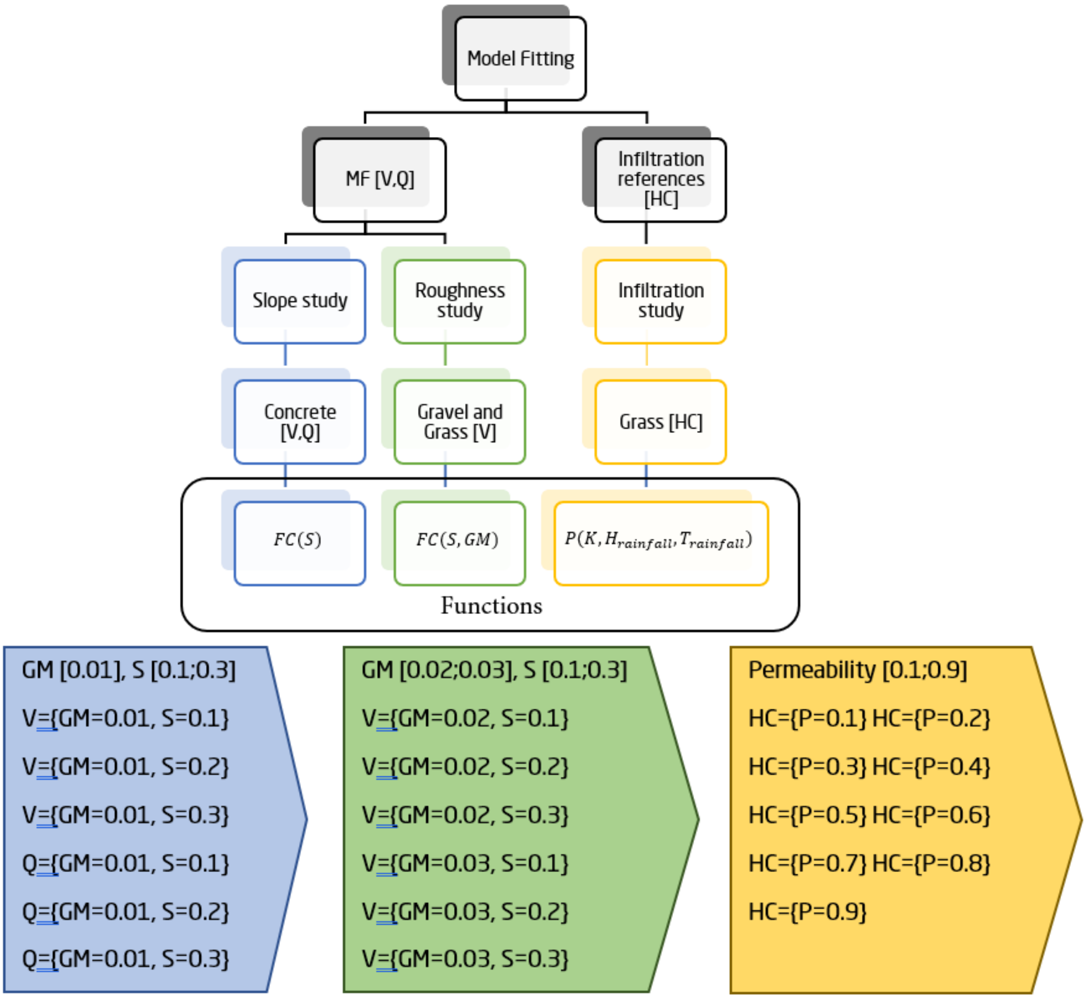

Figure 3.1: Flowchart of an overview of the model fitting including simulations and categories

3.2 Manning's Formula

For the simulations to be valid a mathematical model was applied in order to analyze and fit the results from the testing with the calculated Blender-model. For this purpose Manning's Formula (MF) was applied with the objective to create more precise, realistic and thereby more valuable data.

The main parameters to be adjusted by MF were the slope and the GM coefficient. Both of these parameters were adjusted into three different values creating in total 3x3 = 9 fluid velocities. Every one of these nine velocities were simulated and fitted to the MF values. 3 flow rate simulations were also a part of the fit, creating 12 total simulations.

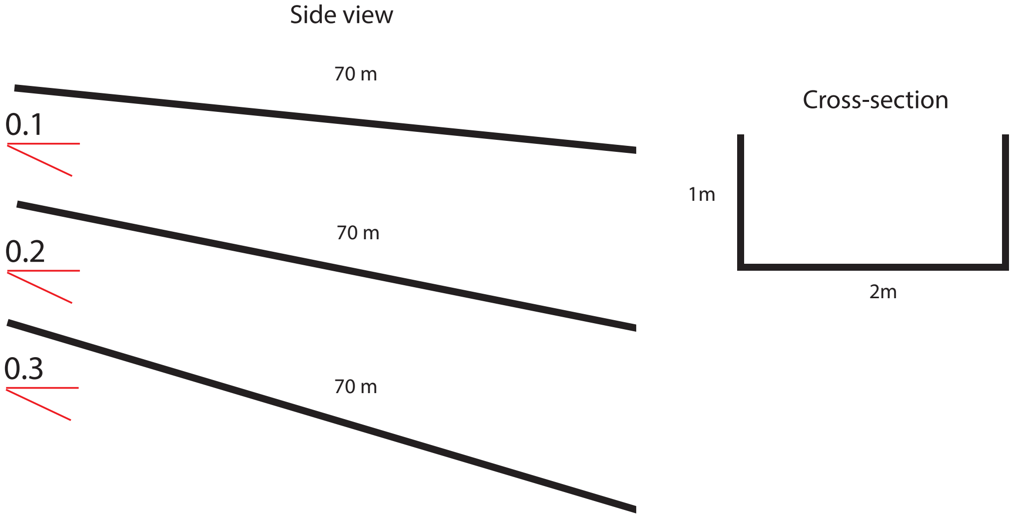

Figure 3.2: Testing setup including 3 channels of slopes; 0.1, 0.2 and 0.3 (left) and cross-section of the channel (right)

MF determined the velocity and the flow rate of water eq. (2.1), in a steady-state[11] situation regarding velocity and flow rate.

The main variable having an impact on the flow rate and velocity in Blender is the friction coefficient (FC) describing the friction of the surface of the water channel; higher friction results in slower velocity of the water flow while lower friction results in higher velocity of the water flow. On this basis, the objective is to find the right FC to match the MF results.

3.2.1 Least square regression analysis

In order to find the right FC many variables have to be taking into account; to sort this out a regression analysis needs to be performed.

The 'least square regression' is a common analysis tool that works by fitting the observed values with a function that determines which fitting is the best from the least sum of squared residuals (the difference between an observed value, and the fitted value provided by a model), also illustrated in fig. 3.3 as the red squares, since error is the square root of the area. [15]

---

[11] The definition of a steady-state is an unchanging condition, system or physical process that remains in balance. [14]

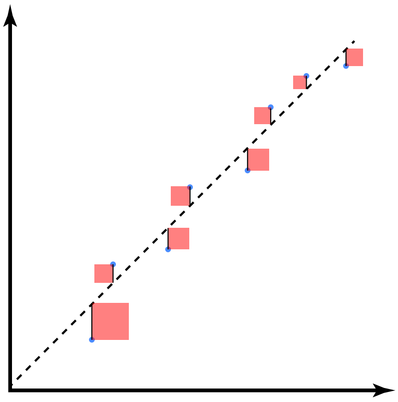

Figure 3.3: Least square regression visualized, where the square errors are represented in red

3.3 Infiltration and evaporation

Infiltration rates depend on the surface material, as different materials let different amounts of water penetrate the surface, named hydraulic conductivity (HC) [m/s]. Only a single parameter is needed to be taken into account here is the permeability (P) ranging between 0-1 where 0 is impermeable and 1 is fully permeable. The objective is to find the right P that matches the given HC.

Evaporation also aught to be taken into account as another way of removing a part of the water. Evaporation rates will be modelled using ”OUW Potential Tool V.1.5” and weather data based on huge weather-data sets, although the evaporation rate usually are rather stable.

3.4 Method summary

To gain a better overview of the overall methodology a flowchart is created.

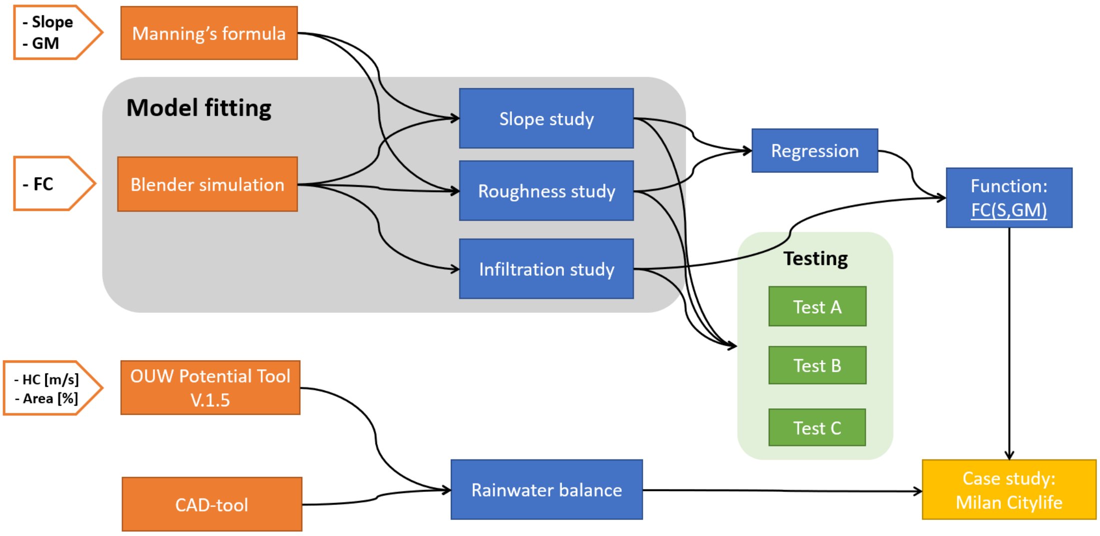

Figure 3.4: Flowchart of overall process

The flowchart in fig. 3.4 shows the complete process. The tools are coloured orange; the simulations and data processing are coloured blue; the tests are green; while the final case study is coloured yellow. First, the model fitting uses Blender and MF to /*complete the three studies; the slope, the roughness, and the infiltration studies. Three tests are conducted to confirm the results. The slope and the roughness study both results in a regressed state where a function is created. The OUW Potential Tool V.1.5 is used to calculate the rainwater balance together with a CAD-tool that calculates the volumes and the areas by geometric mathematics. The function from the regression and the rainwater finds the right FC for the given case study and the rainwater balance is found for the proposed OUW at the site of the case study.

4 Results

The overall model fitting will be achieved from two groups. The first group is dealing with velocity and flow rate of the water including variables of the MF which are the slope of the channel (S) and the Gauckler-Manning coefficient (GM) . The main variable to adjust these variables in Blender is the FC that describes the friction of the surface from [0-1]. The other group is dealing with infiltration and evaporation where the main variables are the hydraulic conductivity (HC) and the evaporation rate which both are adjusted with permeability (P) in Blender ranging from [0-1] where 0 is fully impermeable while 1 is fully permeable.

4.1 Velocity and flow rate

Three test setups are made i order to closely examine the behaviour of the rainwater simulation. The setups are identical to the MF conditions as to be as comparable as possible between each other. The only change from each of the setups is the slope gradient which respectively are 0.1, 0.2 and 0.3. The remaining variables are set to a standard that will be unchanged in order to examine the significance of the slope variable only. This study is named ”Slope Study”.

4.1.1 Slope Study of smooth surface

In this study the GM coefficient is set to 0.01 which is equivalent to a smooth surface (like concrete) with almost no friction. Later, this coefficient will change in order to examine the significance of GM, in the topic: ”Roughness Study”. The hydraulic radius (R) is find for a rectangular cross-section, measuring 1 m high and 2 m wide, calculated to an area of the cross-section of $2m^2$ and $R = 0.0476$. Below the flow rates for the setup are calculated by eq. (2.1) to compare with the simulations results.

$$Q = VA = \frac{1}{n_{concrete}} AR^{\frac{2}{3}}_{rectangle}\sqrt{S} \tag{4.1}$$

$$R_{rectangle} = \frac{b*h}{b+2*h} = \frac{2*0.05}{2+2*0.05} = 0.0476 \tag{4.2}$$

$$Q_{slope:0.1} = \frac{1}{0.01}(2*0.05)*0.0476^{\frac{2}{3}}*\sqrt{0.1} = 0.42\frac{m^3}{s} \tag{4.3}$$

$$Q_{slope:0.2} = \frac{1}{0.01}(2*0.05)*0.0476^{\frac{2}{3}}*\sqrt{0.2} = 0.59\frac{m^3}{s} \tag{4.4}$$

$$Q_{slope:0.3} = \frac{1}{0.01}(2*0.05)*0.0476^{\frac{2}{3}}*\sqrt{0.3} = 0.72\frac{m^3}{s} \tag{4.5}$$

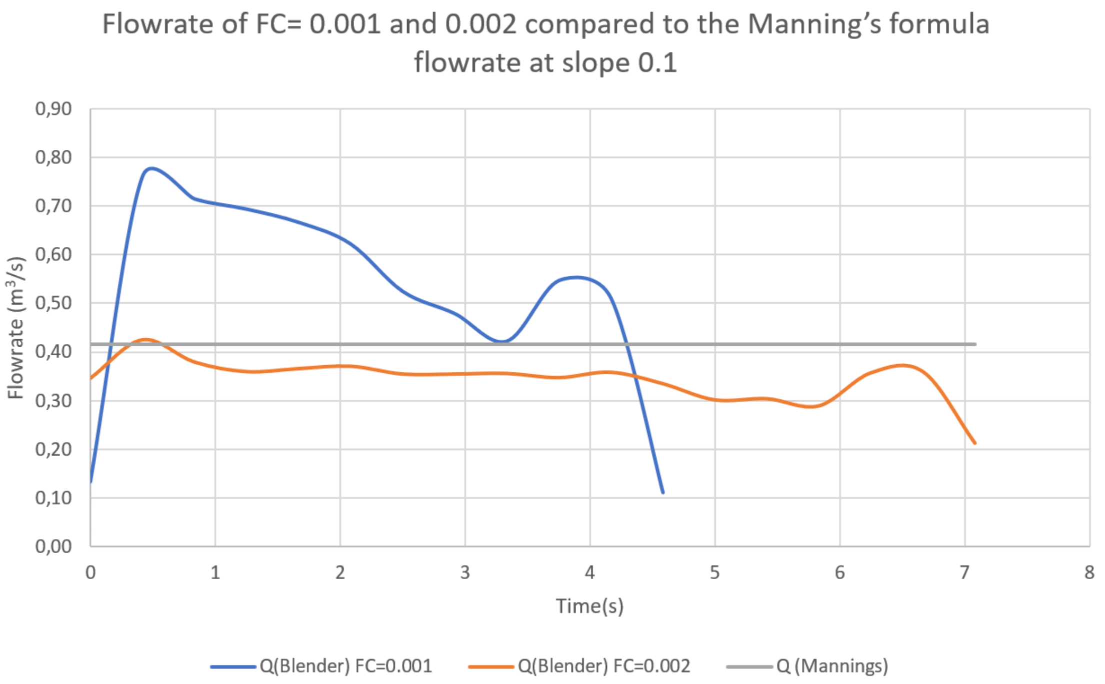

Figure 4.1: Flowrate of FC= 0.002 and 0.001 compared to the Manning's flowrate at S=0.1

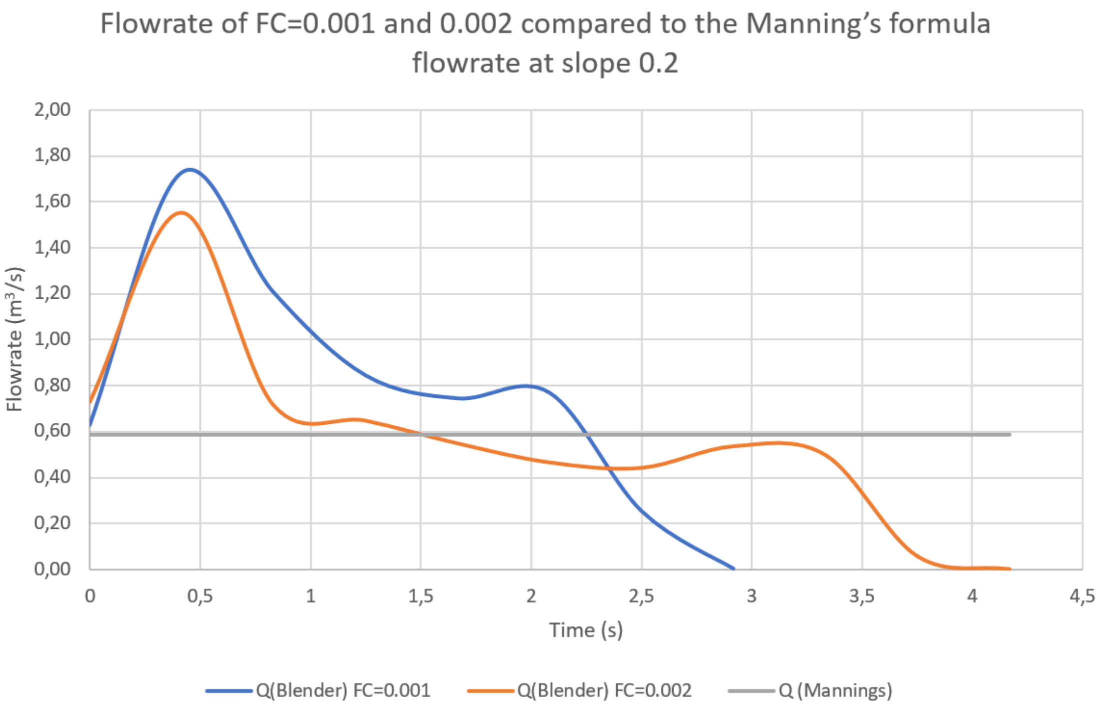

Figure 4.2: Flowrate of FC= 0.002 and 0.001 compared to the Manning's flowrate at S=0.2

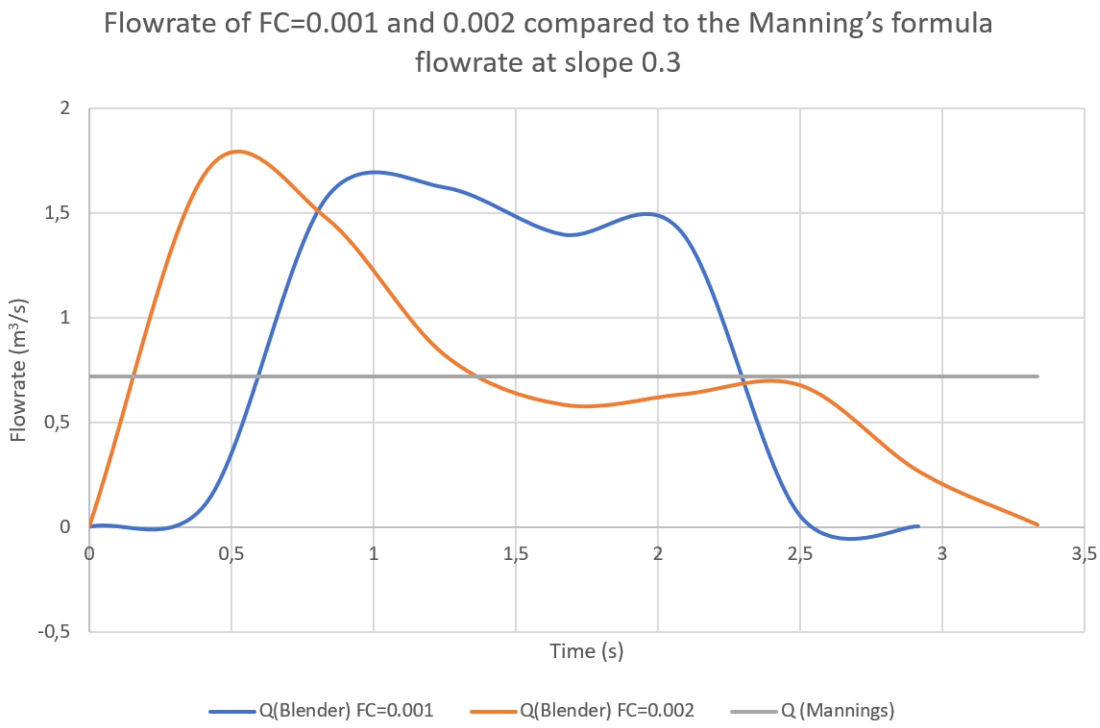

Figure 4.3: Flowrate of FC= 0.002 and 0.001 compared to the Manning's flowrate at S=0.3

Clearly, the MF only shows a static flow rate, as calculated above, whereas Blender shows the simulated flow rate. The peak of the Blender simulation in the beginning shows the flush of the water as it produces a wave when the particles collide with the surface. Later, the curves seem to stabilize into a steady-state condition before producing a final wave at the end. This is clearer seen by the slope at 0.3 as the water here moves faster. Finally, it seems like the FC for all of the three simulations are closest to 0.002. An illustration of the particles are shown in fig. 4.4 and fig. 4.5.

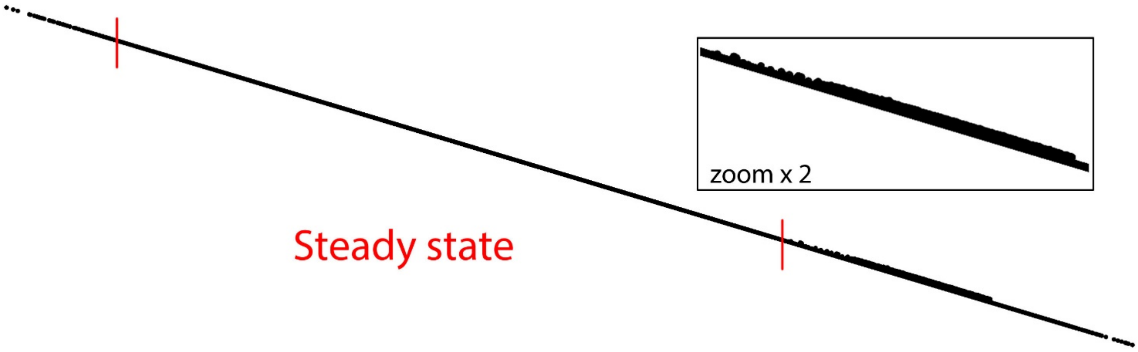

Figure 4.4: Steady state condition illustrated of a sideview in Blender

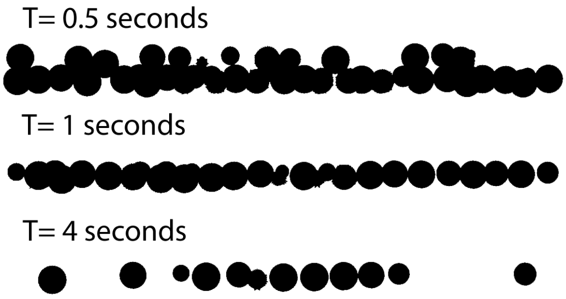

Figure 4.5: Cross-section of different time; 0.5, 1 and 4 seconds

The zoom (x2) shows the first wave which leads to the particles laying on top of each other after around 0.5 seconds, thereby increasing the water level. This causes a higher flow rate as well which is not taken into account in the MF calculations.

Next, the velocity is analyzed to see if it shows the same as for the flow rate results. Now, only one particle is simulated as only the velocity is measured. This will introduce a few smaller uncertainties but it will minimize the computational processing significantly giving power to more simulations. The test setups are identical from before now that the velocity is measured. Below are the velocities calculated by the MF.

$$V = \frac{1}{n_{concrete}} R_{rectangle}^{\frac{2}{3}} \sqrt{S} \tag{4.6}$$

$$V_{slope:0.1} = \frac{1}{0.01} * 0.0476^{\frac{2}{3}} * \sqrt{0.1} = 4.2 \frac{m}{s} \tag{4.7}$$

$$V_{slope:0.2} = \frac{1}{0.01} * 0.0476^{\frac{2}{3}} * \sqrt{0.2} = 5.9 \frac{m}{s} \tag{4.8}$$

$$V_{slope:0.3} = \frac{1}{0.01} * 0.0476^{\frac{2}{3}} * \sqrt{0.3} = 7.2 \frac{m}{s} \tag{4.9}$$

The fig. 4.6 shows that the higher slopes e.g. S=0.3 are overshooting the MF by quite a lot from 7.2 m/s to 10.9 m/s and the S=0.2 is overshooting by about 1 m/s where S=0.1 is undershooting by just 0.5 m/s. This indicates that there isn't a linear static FC for all slopes and might imply that the FC should be raised depending on the slope or suggesting that there might be a certain boundary for slopes.

To create a better fit a table is constructed. The percent difference between the velocity of the Blender simulation and the MF is calculated. The difference will be used to find a new FC for the particular simulation as calculated below using the eq. (4.10).

$$FC_{Fitted} = 0.002 * 1 - \%_{difference} \tag{4.10}$$

$$FC_{Fitted} = 0.002 * (1 - (-0.51)) = 0.0030 \tag{4.11}$$

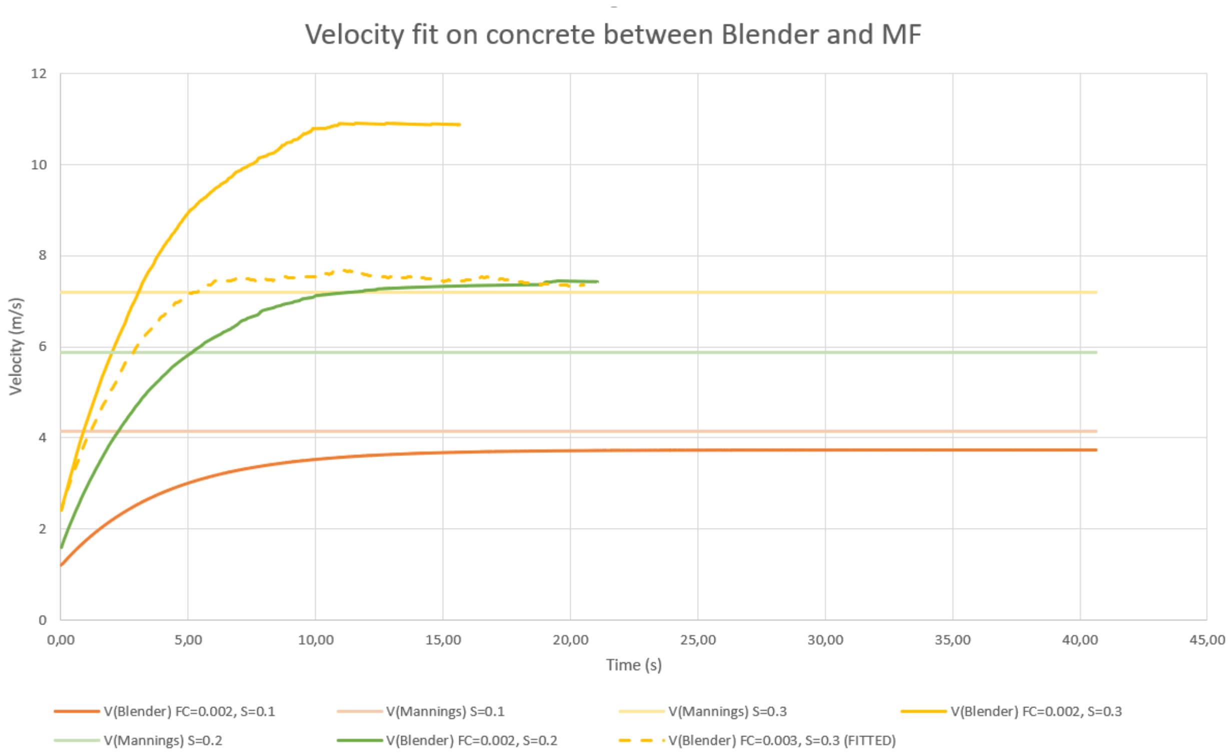

Figure 4.6: Velocity of rain from S=0.1, 0.2 and 0.3 on concrete

Slope	Velocity [m/s] MF	Velocity [m/s] Blender	Difference [%]	FC Before	FC After	Friction Fitted
0.1	4.15	3.89	6	0.002	0.0019	0.002
0.2	5.88	7.43	-24	0.002	0.0024	0.002
0.3	7.20	10.89	-51	0.002	0.0030	0.003
0.3 (Fitted)	7.20	7.49	-4			

Table 4.1: Table GM=0.01

Due to the limit of the Blender settings the FC cannot be adjusted more precisely than with three significant digits. This adds again some uncertainty since the slopes 0.1 and 0.2 will not be changed since the FC after this is closer to it's original of 0.002. On theother hand, the slope of 0.3 will be changed to a FC of 0.003 instead of 0.002. This new and updated FC is simulated again, now showed in fig. 4.6 that it fits the MF of 0.3 much closer. The percentage difference of before and after was lowered from 51% to 4%.

According to the table table 4.1 it shows the FC for the three test setups. If you want to find a FC for a specific slope, a linear interpolation can be made.

$$FC_{concrete} = 0.0055 * S + 0.0013, \quad 0.3 \leq S \leq 0.1 \tag{4.12}$$

The eq. (4.12) shows that for an arbitrary slope the FC can be found. The formula is based upon on three points within a boundary of slope 0.1 to 0.3. For this reason some uncertainty of the function might be seen outside the boundary. Though, the R-squared (a statistic measure of the relation between variables) is 0.9975, meaning the relationship between the variables, FC and slope is strong.

Summary of Slope study

The slope study shows that the FC=0.002 is a pretty good estimate around a slope 0.1 while if the slope becomes steeper the FC has to be higher. The slope study also shows a linear correlation between the FC and the slope of the channel. By simple linear regression a function of S can be made to find the FC of an arbitrary slope within S=0.1 - 0.3 for concrete surface (GM=0.01).

4.1.2 Roughness study of Gravel and Grass

Rainwater in an urban context can run over many surfaces before draining or evaporating. Taking a look at the MF, the GM coefficient is therefore an important parameter to consider. Water running on wood, plastic, gravel or grass can have a major impact on the velocity of the fluid. The goal is now to find a method to convert the GM coefficients from table 2.2 to FC in Blender. Simulating other surfaces with different GM coefficients is therefore relevant but first a grass surface is tested.

Grass surface

A similar setup as described above is constructed but now with a changed surface to grass that has a different GM. As there is no starting point the assumption of the FC will be 0.006. Because the GM coefficient is 0.01 for concrete and the FC was estimated to be closest to 0.002 a guess for a grass surface might be 0.006 as the GM coefficient is about 0.03 if is follows a linear correlation.

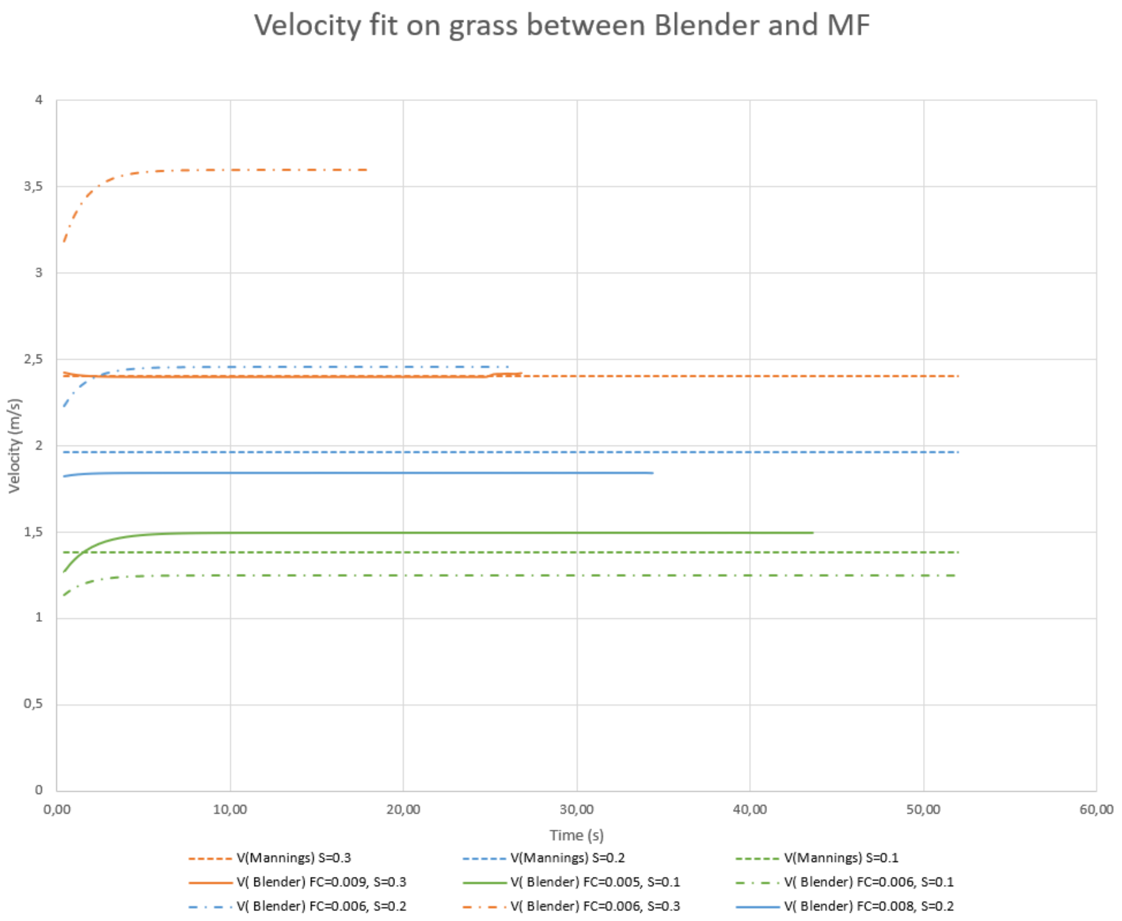

Figure 4.7: Velocity of fluid on grass including MF (dotted line), Blender simulation for FC of 0.006 (semi-dotted line) and fitted FC (full line) from eq. (4.10).

Taking a look at fig. 4.7 the estimated FC at 0.006 is partly close. It matches the velocity for a slope at 0.1 with only a 10% difference from MF. Moving to velocities for slopes 0.2 and 0.3 in both cases an overshooting is seen by 25% and 50% from MF. A similar pattern shows up as described above. The steeper the slopes are the higher the deviation is from the MF.

To counteract this behaviour table 4.2 is constructed to equalize the deviation. The 'fitting' equation from earlier eq. (4.10) is reconstructed by adding the GM difference.

$$FC_{Fitted} = 0.002 * \frac{GM_{material}}{GM_{concrete}} * (1 - \%_{difference}) \tag{4.13}$$

$$FC_{Fitted,S=0.1} = 0.002 * \frac{0.03}{0.01} * (1 - 0.1) = 0.006 \tag{4.14}$$

Slope	Velocity [m/s] MF	Velocity [m/s] Blender	Difference [%]	FC Before	FC After	FC fitted
0.1	1.38	1.24	10	0.006	0.0054	0.005
0.2	1.96	2.45	-25	0.006	0.0075	0.008
0.3	2.40	3.60	-50	0.006	0.009	0.009

Table 4.2: Table GM=0.03

The estimated FC at 0.006 is changed according to table 4.2 to respectively (0.1,0.2,0.3) 0.005, 0.008 and 0.009. Simulations are performed again with new fitted FCs and the results are plotted in fig. 4.7

Interestingly, the fitted FC all match MF far better than before the fit. The deviation in percent changed from 10%, 25% and 50% to 8%, 8% and 0%.

Gravel surface

In between the GM coefficient of concrete (0.01) and grass (0.03) is gravel (0.02). To improve the model the gravel surface will be conducted as well. The method is similar as before. The eq. (4.13) is used as it showed out to work as good starting point but, as to expect from previous simulations, a linear correlation between the slope and velocity should be present.

Slope	Velocity [m/s] MF	Velocity [m/s] Blender	Difference [%]	FC Before	FC After	FC Fitted
0.1	2.08	1.87	10	0.004	0.0036	0.004
0.2	2.94	3.68	-25	0.004	0.005	0.005
0.3	3.60	5.40	-50	0.004	0.006	0.006

Table 4.3: Table GM=0.02

Table 4.3 again proofs the linear correlation between the slope and the velocity with a deviation percent being the exact same as slope 0.3; 10%, 25% and 50%. Again the FC is equalized with the fitted values.

4.1.3 Conversion of GM coefficient and slope to FC

From the data generated for the three different slopes (0.1, 0.2 and 0.3) and the three surfaces of concrete, gravel and grass, 9 points in total are available for interpolation. Signs of the relations between the variables can be developed through interpolation and to have a better picture the GM coefficients and the FC's have been graphed of the 3 slopes in fig. 4.8. Exponential regression is also applied to each of the graph as to have the best fit.

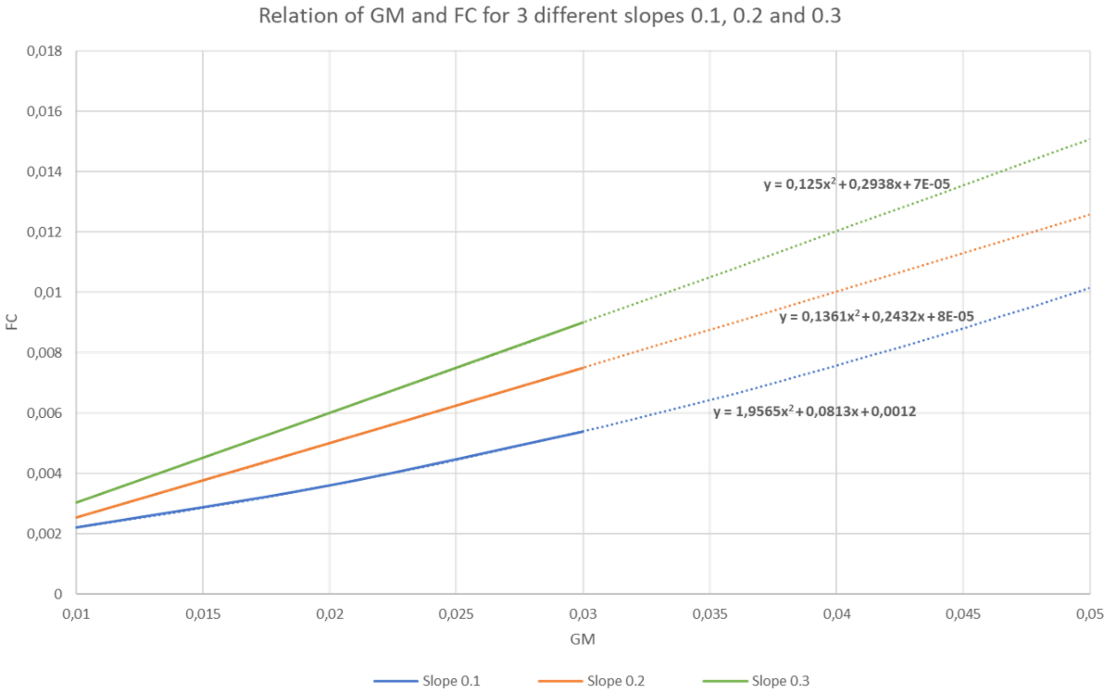

Figure 4.8: GM coefficient of FC from Blender settings for 3 different slopes.

$$FC_{S=0.1}(n) = 1.966 * n^2 + 0.081 * n + 0.0012, \quad 0.01 \leq n \leq 0.03$$

$$FC_{S=0.2}(n) = 0.136 * n^2 + 0.243 * n + 0.0001, \quad 0.01 \leq n \leq 0.03$$

$$FC_{S=0.3}(n) = 0.125 * n^2 + 0.2938 * n + 0.0001, \quad 0.01 \leq n \leq 0.03$$

For any given GM coefficient a FC can be found for the three slopes within the boundary using the formula above from the exponential regression.

Summary of roughness study

The roughness study shows that exponential regression is the best fit between the two variables FC and GM. The GM coefficient is only measured within the boundary of 0.01 to 0.03 and should therefore not be trusted outside of this boundary.

If the slope is not equal to one of the three slopes, 0.1, 0.2 or 0.3 a function of both the slope and the GM coefficient can be developed through another regression analysis.

Least square regression analysis

Least square regression analysis is a regression analysis that calculates the solutions for systems with more than one variable; in this case 2 unknown variables are present. It finds the solutions by fitting the observed values, which is our 9 points, to the fit with the least sum of squared residuals. This means that the residual (deviation of the observed points to the fitted points) squared will be the smallest possible for the given solution.

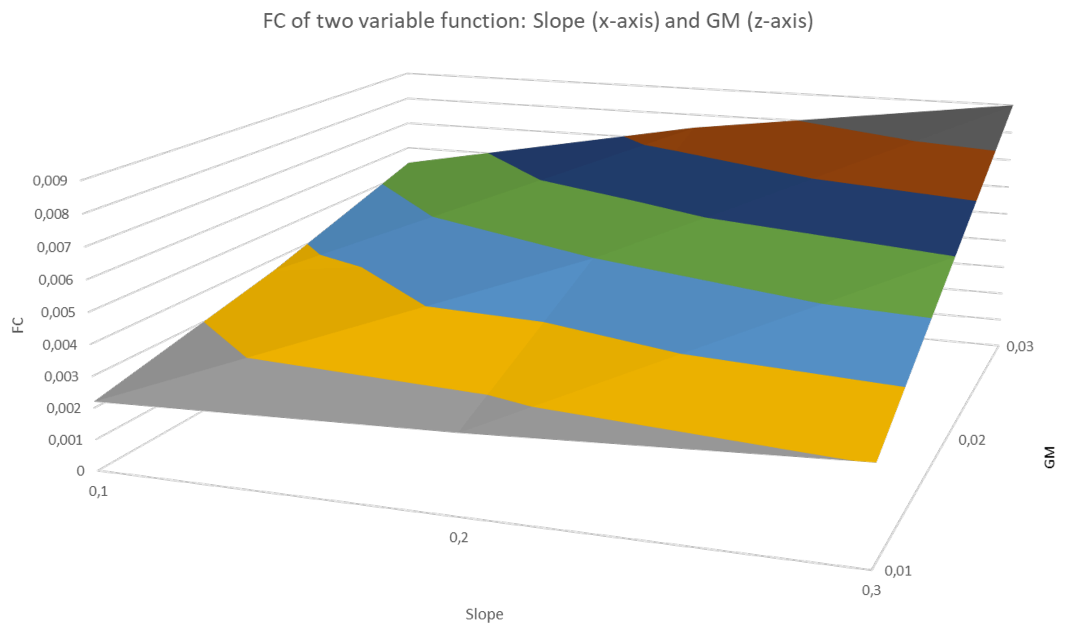

Figure 4.9: Results of Least square regression analysis, displaying the 2 variable function of GM and slope.

$$
\begin{aligned}
FC(n,S) &= 90.50 * S^2 * n^2 - 45.35 * n^2 * S - 5.57 * S^2 * n + 5.585 * n^2 + 0.055 * S^2 \\
&+3.29 * S * n + 0.192 * n - 0.028 * S + 0.003, \qquad 0.01 \leq n \leq 0.03, 0.3 \leq S \leq 0.1
\end{aligned}
\tag{4.15}
$$

For any given GM coefficient and any given slope (within the boundary) a FC can now be found.

To make sure our results are feasible another test will be conducted in order to confirm.

4.1.4 Model testing

Eq. 4.15 will be tested on different models in order to analyze if the model is fitted correctly and how it performs on more complicated channels where the slope changes and the surface material changes.

Test A

The first test (Test A) is on slope change. The test channel consists of 150 meters of 0.1 slope, then the slope changes to 0.3 for 10 meters and then the slope changes to 0.1 for 100 meters, which is illustrated in fig. 4.10.

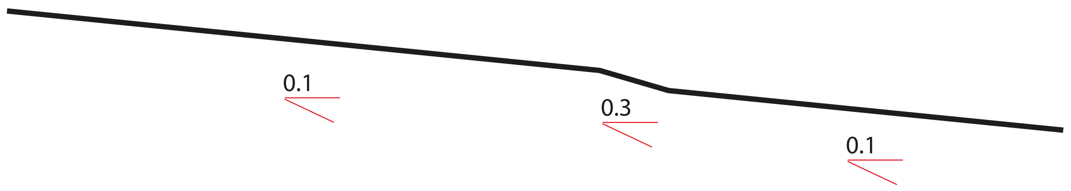

Figure 4.10: Sideview of Test A

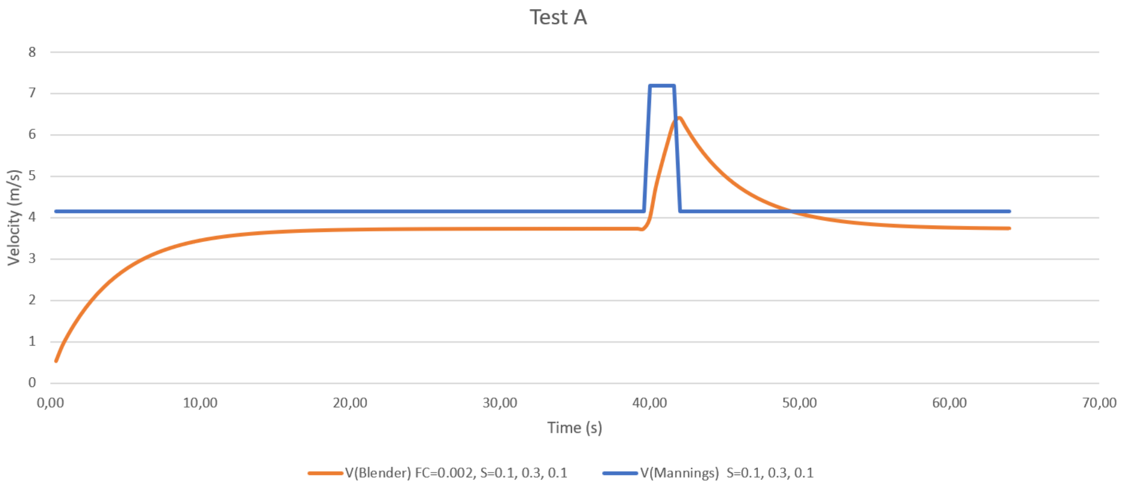

Figure 4.11: Velocity of Test A

Fig. 4.11 shows how the velocity of the fluid accelerates until it reaches it's maximum velocity at about 3.8 m/s. It doesn't reach the velocity of the MF (4.2 m/s) but that is due to the limitation of the FC. This is displayed in fig. 4.6 that the closest FC is 0.002 and if it were to be 0.001 it would be further from the MF velocity. Next, the velocity accelerates quickly to about 6.4 m/s, whereas the MF velocity reaches 7.2 m/s. In graph fig. 4.6 it is showed that the slope 0.3 at friction 0.003 is slightly higher (7.4 m/s) than the MF velocity at 7.2 m/s while in the test it only reaches 6.4 m/s. The reason for this might be the short distance calculated since the slope at 0.1 requires almost 80 meters to reach maximum velocity, where as the 0.3 slope only needs 10 meters. At the end, the velocity of the fluid returns to the original velocity which demonstrates consistency of the model predictions.

Test B

Test B includes changing surface material and slope. From previous test experiences the channel is made longer in order to reach maximum velocity. First part measures 150 m with a concrete surface and a slope 0.1, followed by 75 meter grass surface and the same slope. After this, the slope changes to 0.2 and the surface returns to concrete. Finally, the slope is changed to 0.3 and the material to gravel, illustrated in fig. 4.12.

Figure 4.12: Sideview of Test B

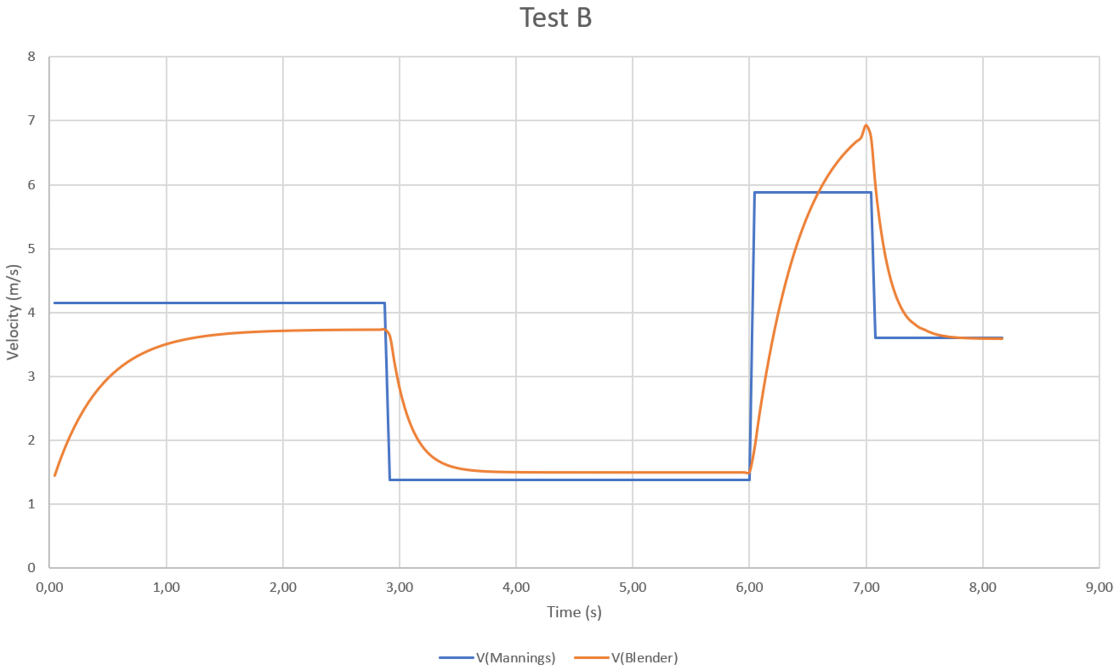

Figure 4.13: Velocity of Test B

Fig. 4.13 shows again that the S=0.1 slope after a few seconds stabilizes at 3.8 m/s and when the liquid meets the grass it quickly decelerates to about 1.5 m/s close to MF at 1.4 m/s. Next, the surface material changes to concrete and the slope changes to S=0.2, making the liquid accelerate to 6.7 m/s, which is slightly different to MF at only 5.9 m/s. Again this can be explained by the limitation of the FC and it is shown in the fig. 4.7 that the slope 0.2 velocities are further apart. Lastly, the slope changes to 0.3 and the surface material to gravel in which GM is just between concrete and grass. Here the fluid velocity matches the MF velocity almost perfect, where MF is 3.6 m/s and the fluid from the simulation at 3.58 m/s.

In overall, the two tests showed good approximation of the MF but due to some setting issues of the FC in Blender not all combinations of slopes and surface materials are 100% accurate.

4.2 Infiltration and evaporation

The infiltration and evaporation of rainwater can be divided into two parts; the present rainfall and the post-rainfall. When calculating infiltration a few factors need to be addressed. Catchment area, permeable surface area, impermeable surface area and the HC of the soil. When calculating the evaporation it is mostly the temperature, humidity and surface area that influence the evaporation of the water. To find these evaporation rates ”OUW Potential Tool V.1.5” will be used.

4.2.1 OUW Potential Tool V.1.5

The calculations of OUW can be created in different ways. One way is ”OUW Potential Tool V.1.5” by ”Sara Maria Lerer”. She has developed a spreadsheet to calculate the rainwater balance and the return period of overflow. It includes calculations of infiltration, evaporation, delayed runoff and immediate runoff, while it contains some waterscape elements to modify these parameters. The calculation is based off SWIMM-data simulations, and some assumption of data. The only input needed is the HC of the soil, impermeable surface area and area of the waterscape elements. The general concept of the tool is based on a table generated from the SWIMM-data simulations. These simulation have created a correlation between the percentage area of the permeable area over the impermeable area and the HC. Tables for infiltration and evaporation for instance a rain garden are shown in table 4.4 and table 4.5. There are tables for each OUW as the values differ from each, just the rain garden example is shown. This method is a quite simplified way of estimating the impact of the rainfall events as the results are highly depending on the terrain.

HC [m/s] | A/A [%]	100	50	30	20	15	10	5
E-08	0	1	1	2	3	4	9
E-07	4	9	13	22	31	43	67
E-06	27	48	62	76	81	83	78
E-05	60	78	84	87	87	85	78

Table 4.4: Infiltration [%] of rain garden OUW on a yearly basis from *OUW Potential Tool V.1.5*

HC [m/s] | A/A [%]	100	50	30	20	15	10	5
E-08	8	9	10	11	13	15	23
E-07	8	9	10	11	13	15	23
E-06	8	9	10	11	13	15	22
E-05	8	9	9	11	12	15	22

Table 4.5: Evaporation [%] of rain garden OUW on a yearly basis from *OUW Potential Tool V.1.5*

Table 4.4 show that the infiltration rises when the HC increase and the percentage of permeable area increase. The HC increase makes good sense, as the higher HC the higher the infiltration. The permeable area contribute to more surface area to infiltrate (if the terrain permits) and therefore increasing the infiltration.

Table 4.5 show that the HC have almost no influence on the evaporation, while the evaporation is a bit higher, for higher percentages of permeable area. This could be explained, by the permeable area is making the water flow slower and allow for more time to evaporate. Also, permeable surfaces like grass has more surface area than e.g. concrete, which contribute to more evaporation.

4.2.2 Infiltration study

Present rainfall

Calculating the infiltration of rainwater in Blender is different. The rainwater particles in Blender can be set to pass the surface it collides of a percentage ”permeability”. E.g. if the permeability is set to 0.1, 10% of the rainwater particles will pass the surface it collides with. This setting is tricky, because permeability (% particle passing) does not convert from HC (m/s) as used in in infiltration calculations. Another issue is that after the first collision between the particle and the surface it does not pass at all. This means that the process shall be divided into two parts as earlier addressed.
A proof of concept will be demonstrated, in order to show the process.
First the ”present rainfall” will be simulated on a 1x1 m surface where a rainfall of 5 mm will be simulated. The permeability will range between 0.1 to 0.9. Where the infiltration is calculated within the simulation.

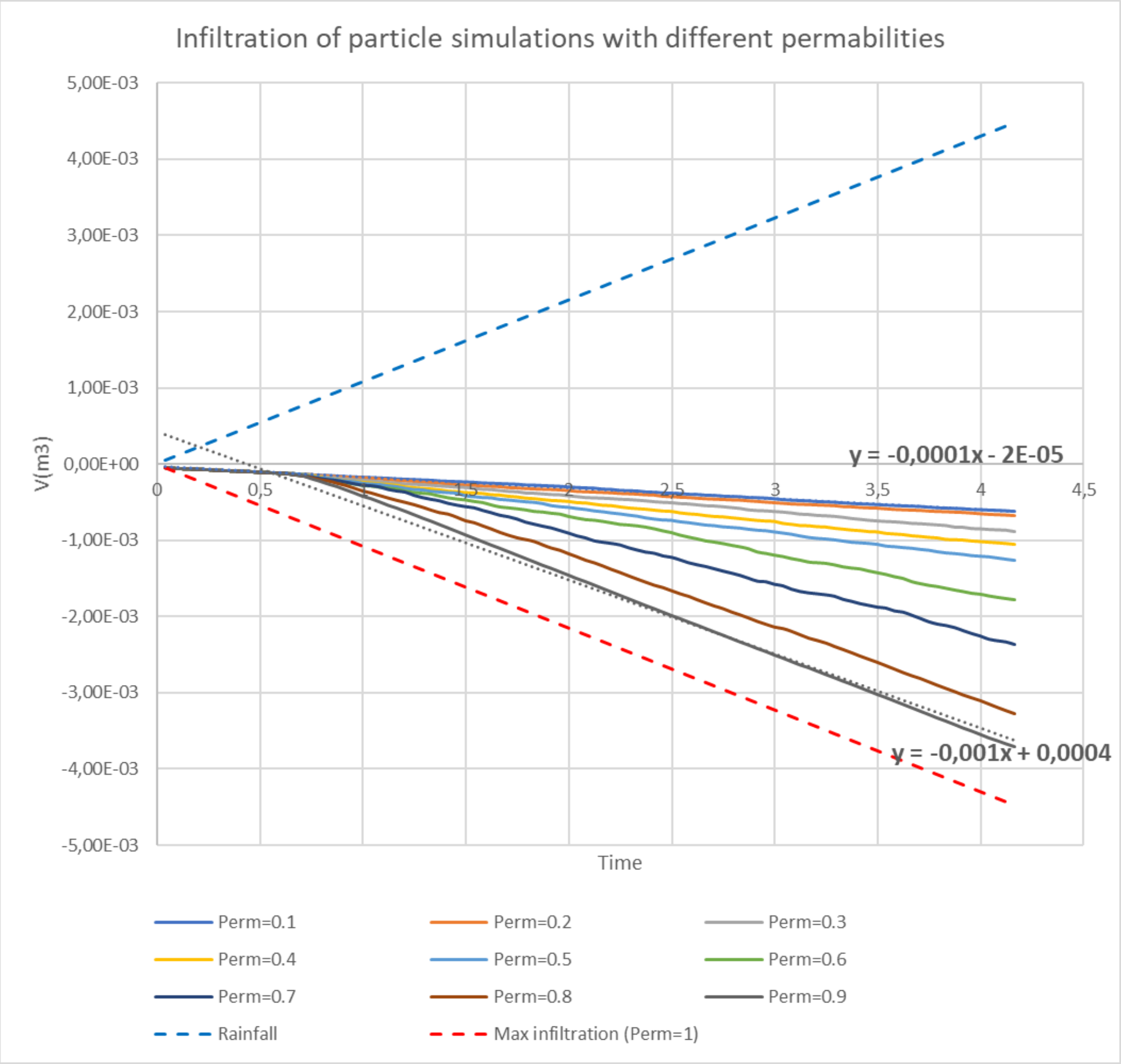

Figure 4.14: Illustration of particle simulations of permeabilities ranging between 0.1 to 0.9. Blue show the rainfall and red show the infiltration if all rain infiltrated directly.

From the fig. 4.14 it show that the permeability of the surface correlates between the infiltration well, as expected. For the first second it does not show infiltration, because the particles are mid air. The simulation is 5 mm rain over 100 frames or about 4 seconds.

The HC spans from 0.0001 to 0.001 m/s. This is expected since the rain falling at a rate of is $\frac{5[mm]}{100[frames]} = \frac{[5mm]}{(100/24)[s]} = 0.012[m/s]$. If the permeability is set to 0.1 the infiltration of that surface would be $0.012[m/s] * 0.1 = 0.00012[m/s]$ as well as the permeability of 0.9 which would be $0.012[m/s] * 0.9 = 0.0011[m/s]$.

Another method which is easier and more basic can be used instead. Let's say there is constant rain for 10 minutes and the the rain is 10 mm (for simplicity) this transfer to $10[mm]/10[min] = 10/1000[m]/10 * 60[s] = 1/60000[m/s] = 1.67 * 10^{-5}[m/s]$

And let's say the HC (note: in the equations HC is also referred to as K) is $K = 10^{-5}[m/s]$ then the remaining is only $1.67 * 10^{-5}[m/s] - 1 * 10^{-5}[m/s] = 0.67 * 10^{-5}[m/s]$

The permeability of the surface with the HC of $K = 10^{-5}[m/s]$ should therefore be: $P = 1 - (1 * 10^{-5}[m/s]/1.67 * 10^{-5}[m/s]) = 0.40$

A formula for calculating the final permeability including the HC and the evaporation can therefore be described as:

$$Permeability = 1 - (\frac{K + E}{\frac{\frac{rainfall[mm]}{1000}}{period[min]*60}}) \tag{4.16}$$

The *Present-rainfall* depends on the intensity of the rainfall and as the permeability value in Blender rounds off to 3 significant digits the minimum intensity is 0.001 m/s. Also, the method doesn't support the post-rainfall, which can be an issue under heavier rainfalls, where there will accumulate big volumes in the post-rainfall which can outweigh the present-rainfall process. The infiltration in the post-rainfall process have to be calculated another way.

Post-rainfall

After the rainwater has accumulated into small lakes the post-rainfall process can be calculated. This process is more simple, as the volume of water, the permeable and the impermeable area of the site, is found using Grasshopper[12]. These values can be used in the tables from "*OUW Potential Tool V.1.5*" to find the relevant infiltration and evaporation percentages on a yearly basis. The percentages show how much of the excess water that will either evaporate or infiltrate. When the infiltration rate (HC) is known, the evaporation rate can be estimated from table 4.5. When these factors are known the expected time of drainage left can be estimated. If the intensity of the rainfall is high it might be an option to neglect the "present-rainfall". Because if the time of rainfall is very short or the rainfall is heavy the post-rainfall it might outweigh the present-rainfall evaporation and infiltration. Also if the impermeable area is much bigger than the permeable, a lot of the water will accumulate and the time it takes for infiltration and evaporation will rise, making the post-rainfall process longer, due to little surface area and a lot of volume.

Summary of Infiltration study

The infiltration study showed that if, in the present-rainfall phase, the intensity of the rainfall are known (rainfall (mm) and period (s)) the permeability can be roughly estimated, only if the HC is relatively high and the intensity of the rain is low, this is due to limited settings in Blender, therefore making it an unstable method. The post-rainfall phase is more stable, as it is also more simple to calculate using CAD tools and OUW Potential Tool V.1.5. This allow for calculating the estimated time of water drainage and the water balance for evaporation and infiltration on a yearly basis.

4.2.3 Combining studies to final test

Final Test C

Now all the subresults including model fitting of slope, GM coefficient and permeability can be combined to a test, to illustrate how these results can be used to design with rain simulations.

The idea of this test is letting water flow down a channel filling up 3 containers on the way. When the first container is full the water will run off to the next and so on. In the middle container a gabion which will infiltrate some of the rainwater and depending on the size of the rainfall and the duration run off to the last, visualized in fig. 4.15.

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[12] "Grasshopper is a visual programming language and environment that runs with a 3D computer-aided design application." Version: 1.0.0004, 2009 McNeel & Associates

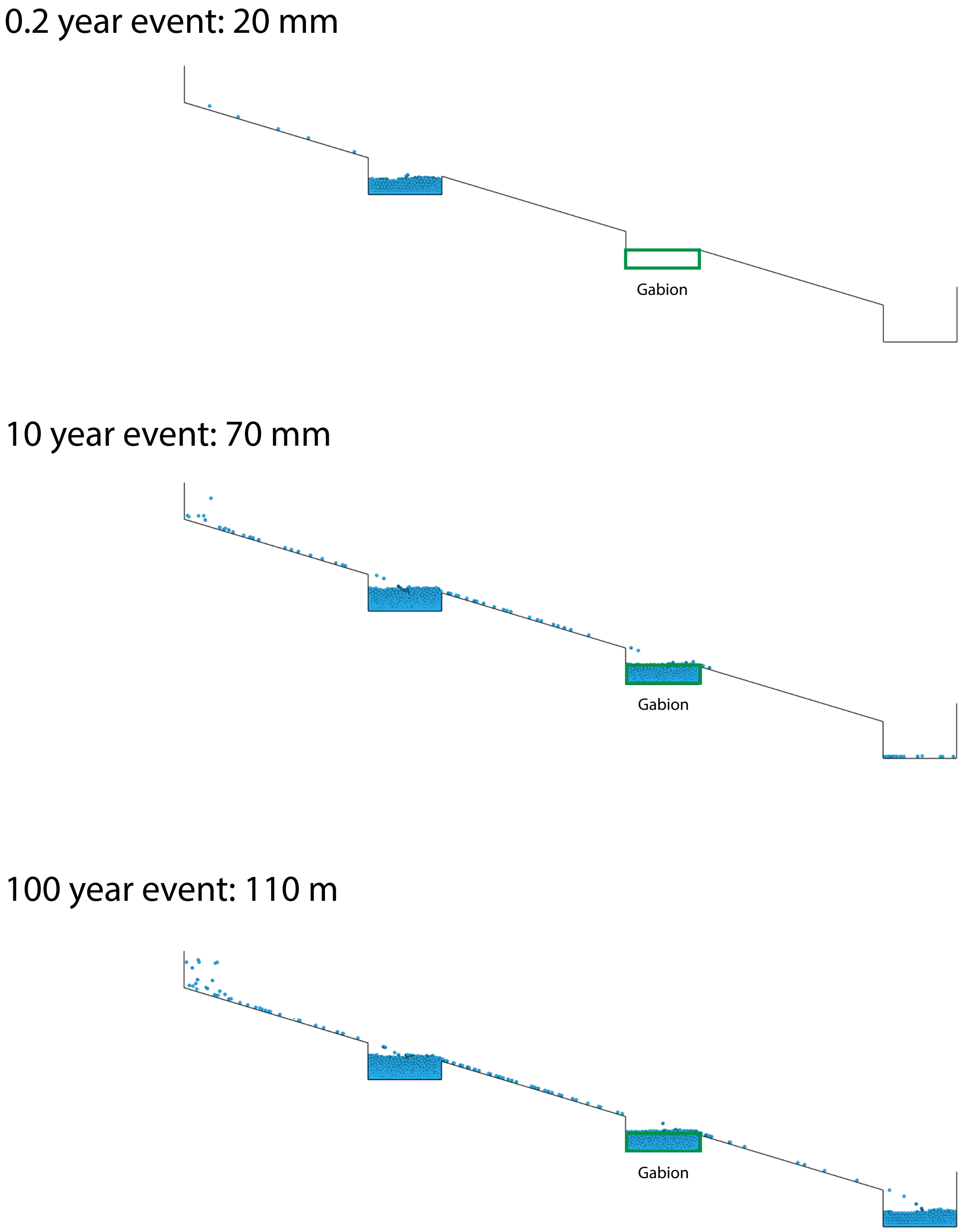


Figure 4.15: Test C: Testing overflow for three reservoirs, while the middle one has a gabion. The test simulate the 3 raindomains: Everydayrain (20mm), Designrain (70mm) and Extremerain (110mm). The catchment is 50 m^2 impermeable surface.

Test C show that for a 0.2 year rain of 20 mm and a 50 m^2 impermeable catchment area it will only fill up the first reservoir. This could be calculated as well, as the volume of the 0.2 year rain is $0.02m * 50m^2 = 1m^3$ and the first reservoir is $2m * 1m * 0.5m = 1m^3$. The 10 year rain of 70 mm does overflow the first reservoir and fills up the next. Interestingly, it only overflow a tiny amount of the second reservoir, which means the gabion added infiltrate water. This is positive, since the 10 year rain is the one that should be designed after. The evaporation is neclected since the time period is only 5 min. The total volume is $0.07m * 50m^2 = 3.5m^3$ and the two reservoirs is $2m^3$ which leaves a $1.5m^3$ that have infiltrated the soil or evaporated to the air.

The HC of the gabion is calculated.

$$A_{Gabion} = 2m * 1m + 2m * 0.5m + 2m * 0.5m * 2m = 5m^2 \tag{4.17}$$

$$HC_{Gabion} = \frac{1.5m^3}{5m^2 * (5 * 60s)} = 0.001\frac{m}{s} \tag{4.18}$$

The HC is rather high for a soil, but if the soil was sandy it could be realistic. The 100 year rain of 110 mm fills up the last reservoir half way. The total volume is now $0.11m * 50m^2 = 5.5m^3$ and the reservoir consist of $V_{reservoirs} = 1m^3 + 1m^3 + 0.5m^3 = 2.5m^3$ minus our total volume it leads to an infiltration volume of $5.5m^3 - 2.5m^3 = 3m^3$. This is double the amount of the 10 year rain. Reasons for this could be two things. First, the rain intensity is higher in the 100 year rain meaning it fills up the first reservoir up faster having more time to infiltrate the gabion. The other is the fact that the permeability in Blender infiltrate a percent of the particle that collide with the surface, meaning that if the intensity of rain particles is higher it also infiltrate more particles.

These type of scenarios are the one that make the Blender-method unique. It allow to make micro scale test, as other software aren't capable of. These test have potential to design with water and create channels that are completely customized. Now, the Blender-method is ready to be applied onto the case study of Milan Citylife.

4.3 Case study: Milan Citylife

In order to start the simulation a few parameters need to be found, including: HC, evaporation rate, average slope, GM-value for the surface.

The slope is find using a CAD-tool creating an average of about 0.1. The GM value is set to 0.01, as most of the surfaces are glass-like and smooth, except a few surfaces like the grass surfaces, which will be set to 0.03.

Last the HC on the site has to be found. Luckily a study of the HC have already been done in Milan. In Milan an aquifier is placed that supply water to the majority of the city. The aquifier can be separated into 4 parts. The first 3 is the upper confined aquifiers and one phreatic aquifier. Our interest is in the top aquifier as this is closest to the ground (0-47 m). The measured HC in this aquifier was $5.51 * 10^-5m/s$. [16]

Following the formula of permeability eq. (4.16), the permeability of the impermeable surfaces are found. The raindomain is set to a design rain of 70mm:

$$Permeability = 1 - (\frac{K + E}{\frac{\frac{rainfall[mm]}{1000}}{period[min]*60}})$$

$$Permeability = 1 - (\frac{5.51 * 10^{-5}[m/s]}{\frac{\frac{70[mm]}{1000}}{5[min]*60s}}) = 0.23$$

The permeable surfaces have to be set to a permeability of 0.23.

Similar, the FC is found for both the concrete surfaces and the permeable surfaces from the equation of slope and GM eq. (4.15).

$$FC(n, S) = 90.50 * S^2 * n^2 - 45.35 * n^2 * S - 5.57 * S^2 * n + 5.585 * n^2 + 0.055 * S^2$$
$$+3.29 * S * n + 0.192 * n - 0.028 * S + 0.003, \qquad 0.01 \leq n \leq 0.03, 0.3 \leq S \leq 0.1$$

$$FC(0.01, 0.1) = 0.002$$
$$FC(0.03, 0.1) = 0.005$$

The FC will therefore be set to 0.002 on the impermeable surfaces and 0.005 on the permeable surfaces as well as an permeability of 0.23. Now the simulation can be run.

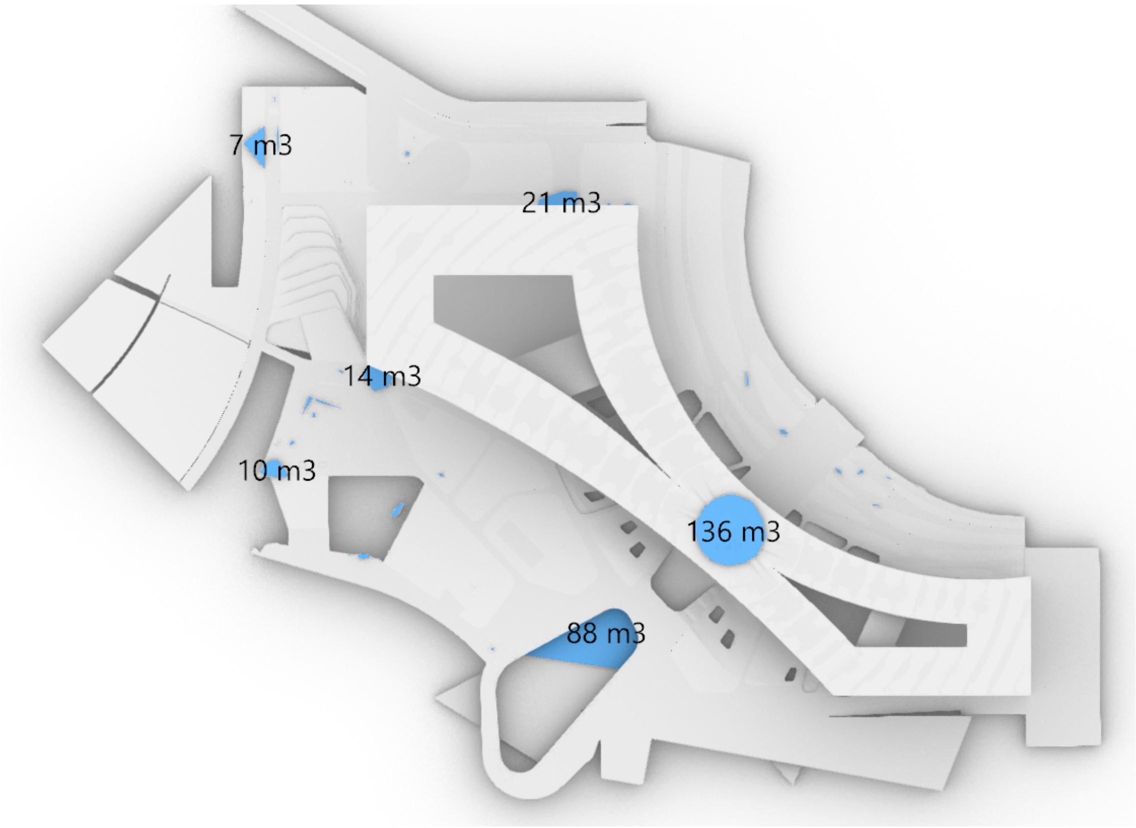


Figure 4.16: Rainsimulation of 10 year rain with concrete surfaces

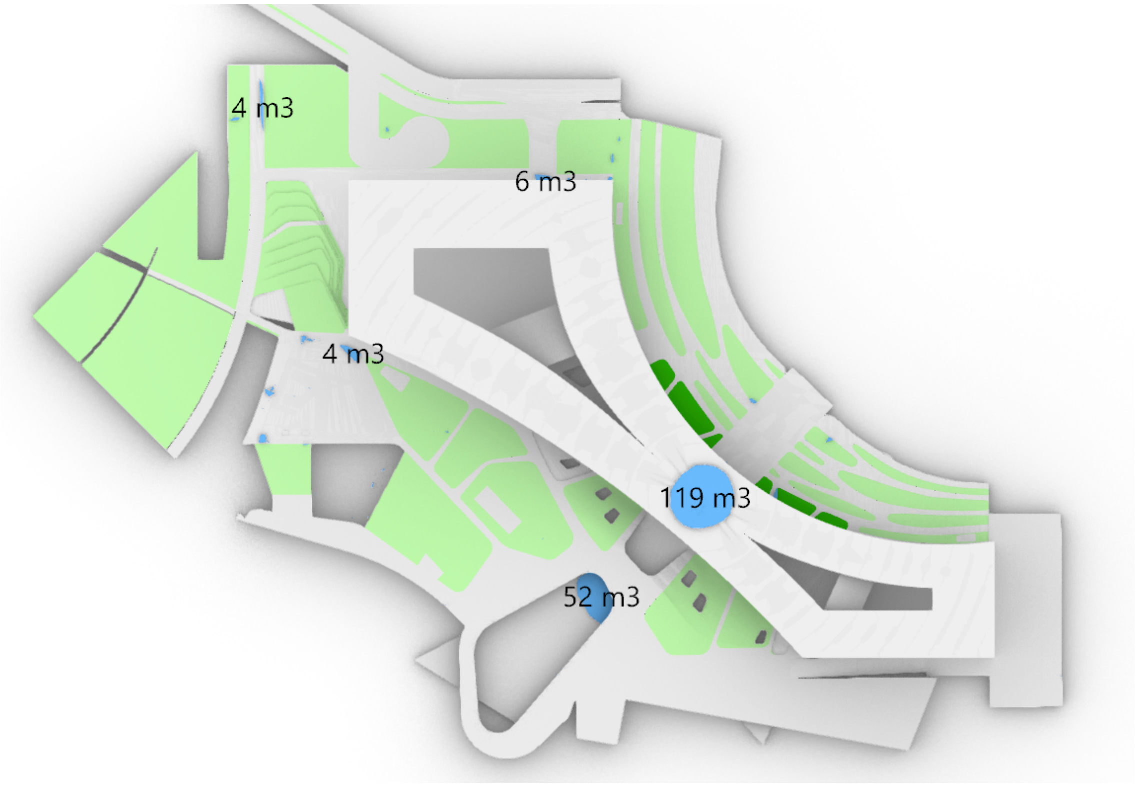


Figure 4.17: Rain simulation of 10 year rain with concrete and grass surfaces

The rainwater balance of evaporation and infiltration can be found using the *OUW Potential Tool V.1.5*. First the proportions of the permeable and impermeable areas are found.

$$\frac{Area_{impermeable}}{Area_{permeable}} = \frac{51712m^2}{17582m^2} = 2.94$$

Using the tables from *OUW Potential Tool V.1.5* table 4.5 and table 4.4 the rainwater balance can be found, also using the HC.

Now the rainwater balance can be found depending on the OUW. A proposal of OUW have been made to improve the performance of the water management.

The OUW A (rain garden) is 400 m^2 and a depth of about 0.3 m the pool is able to store the rain from the roof (120 m^3), which can be led through gutters. The rainwater balance of evaporation and infiltration can be found of the rain gardens from table 4.5 and table 4.4. Because the tables maximum goes to 1E-05 the HC have to be rounded. Also the proportion of the area are rounded to 5. The results of *OUW Potential Tool V.1.5* are for infiltration 78% and for evaporation 22% for rain garden on a yearly basis. The OUW B (gabion) measures 80 m^2 and a depth of 0.8 m. All of the water will be estimated to be infiltration as the water will stay underground. The cavity of the gabion is able to store the 58 m^3 rainwater. The OUW C (reservoir) is similar to Test C, where the water will fill up one reservoir and flow to the next. These reservoir are 700 m^2 and 0.1 m deep. Letting both of the pools 8 m^3 and 12 m^3 store in the reservoirs. There are endless opportunities of placing the OUW. As long as the volumes and the locations are known, then the OUW are easy to design. This proposal should be able to handle a design rain of 70 mm. Close up from the simulation together with the OUW are shown in fig. 4.18 and fig. 4.19.

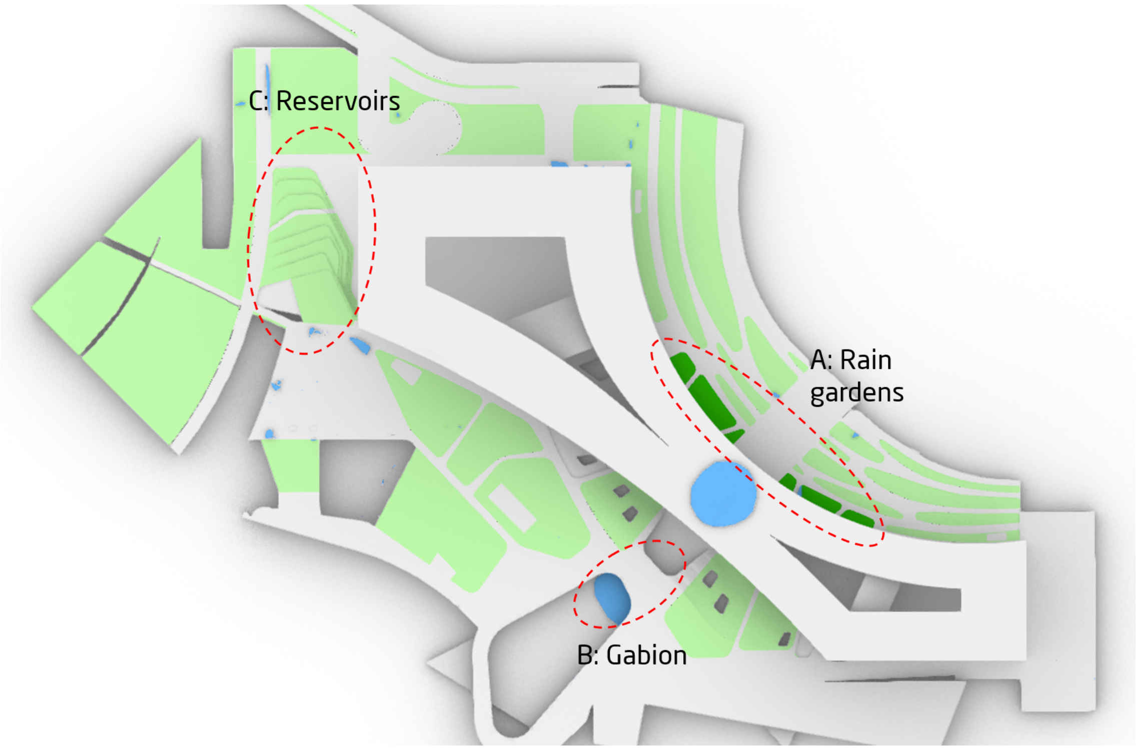
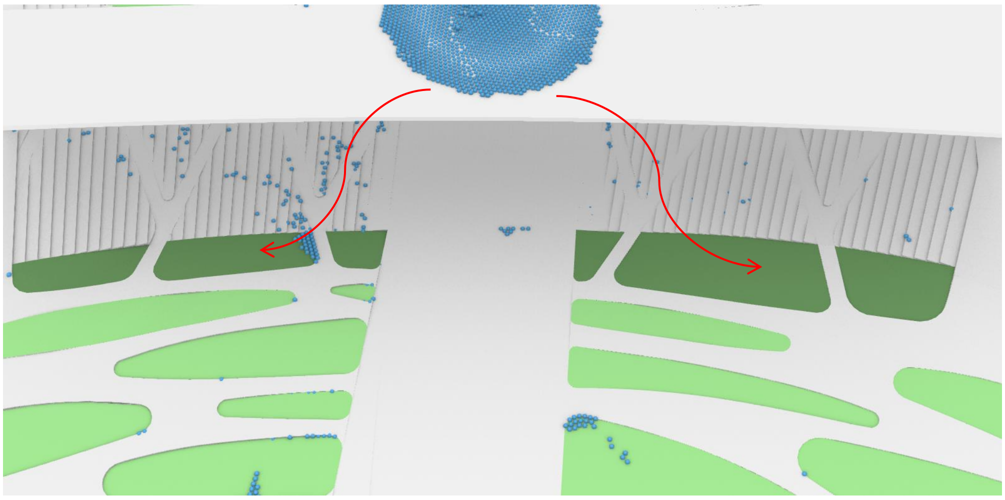
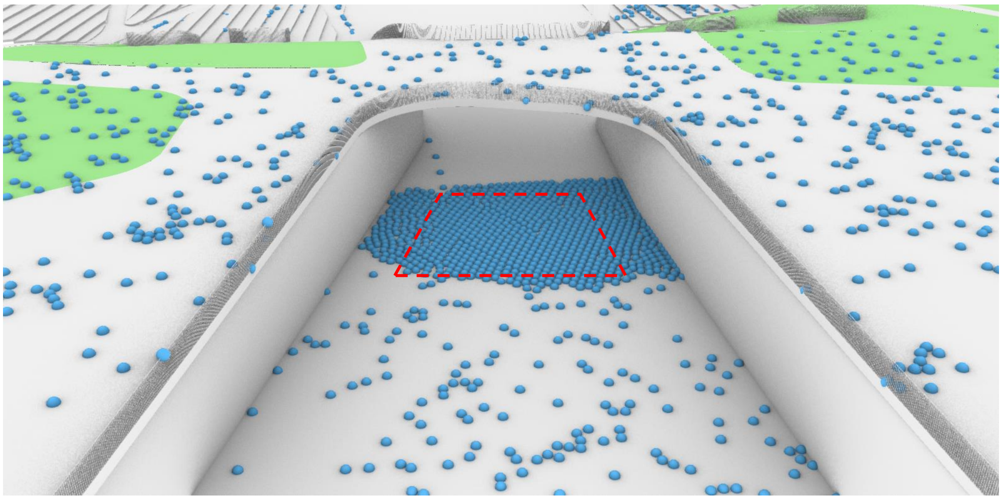


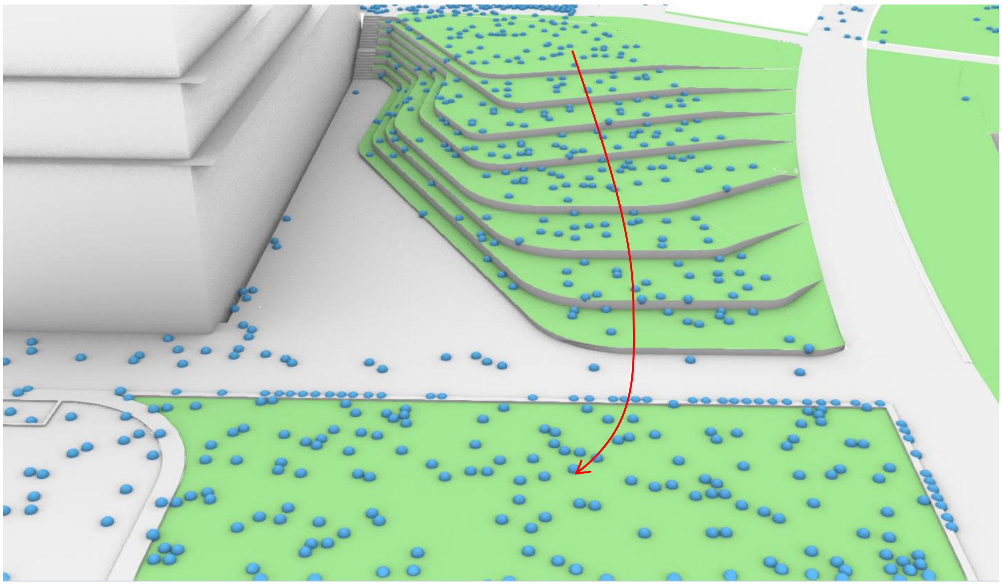
Figure 4.18: OUW Proposals



OUW A: Rain gardens (dark green)



OUW B: Gabion (underground)



OUW C: Reservoir

Figure 4.19: OUW Proposals

5 Discussion

The goal of this work was to analyse on a micro scale the effects of different urban waterscapes in early design stages. To analyse waterscapes, water management and OUW solutions were used, developed, and tested. The final proposal as a solution was applied on a case study, the ”Milan Citylife”, in collaboration with the design studio BIG.

5.1 Use of water management and OUW solutions

The study used a number of water management tools and OUW solutions, like the ”OUW Potential Tool V.1.5” and ”SCALGO”; both presenting various advantages as well as disadvantages.

5.1.1 SCALGO

SCALGO was demonstrated to have advantages regarding macro scale water management. It displayed a wide selection of tools of which especially the catchment illustrator was useful, see fig. 2.9. It allowed to analyse the greater picture of the terrain gaining a better impression of the water flow. On the other hand, working on a micro scale, unfortunately SCALGO did not perform as well mainly since the topographic map was not detailed enough for proper calculations. Also, SCALGO was not presented as an open-source program which therefore blocked additional tools to be implemented along with it. In conclusion, SCALGO was seen as a good starting point before simulation of the rainfall as it allowed the user to gain an overview of the water flow and magnitude.

5.1.2 OUW Potential Tool V.1.5

The *”OUW Potential Tool V.1.5”* showed to be especially useful for analyzing rather flat landscapes where the water doesn’t accumulate too fast. A major advantage was that this program was based upon a database with multiple simulations from the acknowledged software ”SWIMM” that also operates in an urban environment. Another advantage was that the program only required three inputs when changing settings making it fast to provide an overview of the water balance or a return period for overflow on the given site. On this basis the program was especially useful in the early design stages even if it only was able to hold data for a single type of OUW at a time. The results were powerful to keep hold of the total water balance and how the water was distributed. Knowing this was a ideal knowledge to have when planning the design, like having the goal to maximize the infiltration of the water. In addition, the return period was also important to know as it gave a rough idea of how much water the site was able to handle and how often the site will be flooded.

But when is ”OUW Potential Tool V.1.5” preferred compared to Blender or the opposite?

Both tools excel in different fields. The simplicity using the ”OUW Potential Tool V.1.5” is an advantage as it only require an input regarding the permeability of the surface area. On the contrary, it cannot take the topographic map into account which easily might be problematic since the water can end up in a single pool of only a small part of the total area, making the calculations unreliable. This problem is illustrated in the following example.

Imagine a surface of a square bent on the diagonal, illustrated in fig. 5.1. When it rains the water will split into two pools. If one of these pools has a OUW the water will be managed only on that side. If the other side has an impermeable surface, like concrete, the water can’t infiltrate the surface and only evaporation would reduce the water level.

This scenario would not be visible when using the ”OUW Potential Tool V.1.5” as this software does not take terrain into account. So, when the scenario was just a little complex it resulted in inaccurate calculations. Blender, on the other hand, is able to handle a set-up like this as is would manage to split the rainwater into two equal parts using a particle simulation a real rain. It should, though, be mentioned that also the Blender particle simulation tool has some assumptions involved resulting in a number of uncertainties when considering the presented results.

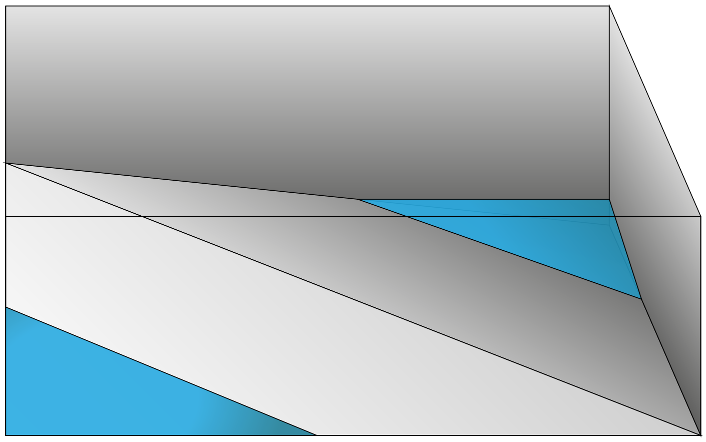


Figure 5.1: Setup catchment scenario

5.2 Development of water management and OUW solutions

In the initial phase of developing water management and OUW solutions for a specific location the Blender model according to the above mentioned advantages and disadvantages is a convenient choice for a programming tool. The impact from using the Blender tool in the following will be discussed in more detail.

First of all, it has to be mentioned that Blender simulates rainwater as particles. On a micro-scale the particles are solid and not a liquid as rainwater is in real-life. The size of the particles in this simulation is set to 0.05 meter in diameter which is vast bigger than average raindrops that normally are 0.5-4 mm in diameter. Naturally, this is a detail to be taken into account when evaluating the results.

The process of development began by FC being estimated to 0.002 from the flow rate analysis fig. 4.1, fig. 4.2 and fig. 4.3. The period of the simulation for this initial analysis was only 20 seconds which was hardly enough for reaching steady-state period. In MF the water level was set to a certain level and if the simulation in Blender differs from this, the results are not comparable. The height (water level) was set to 0.05 m, which was the same as the diameter of the particles. This means that the particles had to lay closer as to replicate a pool of fluid with a level of 0.05 m, illustrated in fig. 4.5. This figure says that T=1 is roughly the right estimate, while both T=0.5 and T=4 don’t reach the target. This might explain the variation seen in the flow rate analysis.

The next simulations fig. 4.6, showed that the velocity of the water flow was too high for larger slopes than 0.1. Therefore, FC=0.002 was not applicable on all slopes. This simulation was done with only one particle due to limited computer capacity. This adds another uncertainty as one particle has less momentum than a group of particles, which might reduce the velocity of the particle compared to simulation with more particles interfering with each other. In table 4.3 and table 4.2 demonstrates that the FC has a limited accuracy so the fitted FC has to be rounded and the FC's might not be accurate as expected. This, on the other hand, at the same time reduces the importance of the amount of particles simulated.

Another factor is the cross-section of the simulations regarding the slope study and the roughness study. Both studies simulate using a channel with a rectangular cross-section. The geometry of this influences the hydraulic radius which is a parameter in the MF formula. Accordingly, the hydraulic radius for a rectangle is defined as: $R_h = \frac{b*h}{b+2*h}$ while if the cross-section had been a triangular shape the hydraulic radius would be defined as: $R_h = \frac{m*h}{2*\sqrt{1+m^2}}$. But, since the height of the water level was rather low (0.05m) the difference between a cross-section of a rectangle and an open surface is not significantly different.

Taking a look at the three exponential regressions of the nine simulations in fig. 4.8 the slope 0.3 and 0.2 both look linear and as the functions have rather small exponential coefficients (0.125 and 0.136 , respectively) while slope 0.1 has a slightly bend curve. These trends might mean that for higher and lower slopes the correlation between FC and GM is somewhat different compared to the middle part.

The infiltration simulations in fig. 4.14 are difficult to measure precisely as many parameters have to be taken into account when programming Blender. Examples of such parameters are the rain intensity, the post-rainfall phase, etc.

Evaporation rates in general are low in Denmark $10^{-8} m/s$ [17] as the air temperature is rather low most of the year and the weather in general is not very sunny. The evaporation rate is too low for Blender to calculate because the permeability (note: evaporation and infiltration are both managed by the permeability in Blender) is out of the boundary of the Blender, but may differ in other climate.

Both the calculation of infiltration and the evaporation are manageable to calculate during the post-rainfall period as both the evaporation rate and the infiltration rate are subtracted from the volumes primarily generated by Blender. These calculations can be made in a program like Grasshopper. The total period for the evaporation and for the infiltration can then be found and this method is a more stable as it avoids a number of uncertainties and limitations seen in the Blender calculations.

This study lacks some more detailed considerations regarding the infiltration, like the saturation level of the soil at certain points. Permeable surfaces infiltrate water while the infiltration will decrease when the soil becomes saturated with water. Such saturation levels depend on multiple factors and considering these would have improved our method.

5.3 Discussion summary

This study demonstrated that by using modern technology it is possible to make calculations of rainwater movements in an urban setting and to take into account a variety of possible interventions, like a number of OUW. As cities worldwide are heavily expanding and since at the same time global climate changes result in more intense and more frequent rainfalls creating preventions to avoid damage on local infrastructure are becoming more and more essential. Predicting rainfalls and other weather forecasts requires huge computer power as to handle an enormous amount of date. Also, it is essential that software programs suitable for such calculations are developed and available. Software programs for this purpose are developed these years and most of them are open-source making them suitable for further development. This paper used a number of such programs and the advantages and disadvantages of them in certain situations are evaluated and discussed.

5.4 Future Perspectives

Naturally, the model could be improved in many ways. Limited computer power was a basic limitation analyzing these issues. With more computer power available more simulations could have improved our analysis and allowed forming of a more reliable model. Additional simulations might include a larger spectrum of slopes, GM coefficients and longer time intervals plus more factors could have been taken into account, like the hydraulic radius, factors such as wind, particle size, saturation level of the soil.

Finally, also more OUW-settings might have been analyzed. For this purpose Blender has many "add-ons" which are programs running within the program itself. These add-ons often have specific tasks to address. Two of these are Mantaflow[13] and FLIP-fluids.[14] Those programs aim at simulating a realistic water fluid and both programs could potentially be usable for simulations of extreme-rainfalls where the water volumes are huge and accumulates into large pools, illustrated in fig. 5.2 and fig. 5.3.

Figure 5.2: Flip Fluid add-on to Blender visualization

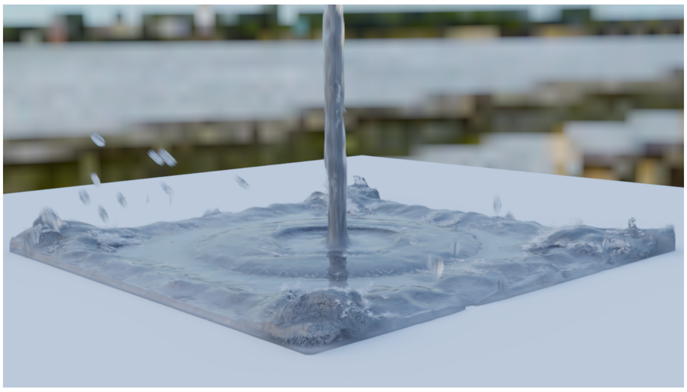


Figure 5.3: Mantaflow add-on to Blender visualization

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[13] "Mantaflow is an open-source framework targeted at fluid simulation research in Computer Graphics and Machine Learning.

[14] "The FLIP Fluids add-on is a tool that helps you set up, run, and render liquid simulation effects. Our custom built fluid engine is based around the popular FLIP simulation technique that is also found in other professional tools"

Another option is the use of *"Graph Networks"*[15] [18] which is a branch of neural networks. The idea is to learn a program to simulate based of data from many other approved simulations. The more data generally the more reliable the simulations are. Fig. 5.4 demonstrates an example of different material simulated. In the upper bar you see the initial setup (T=0); in the middle bar is shown the prediction from the trained model while in the lower bar the real situation is displayed. It is seen that the predicted simulations from the trained model is very close to reality. *"h"* shows a complex model and even here the predicted simulation is almost perfect close to reality.

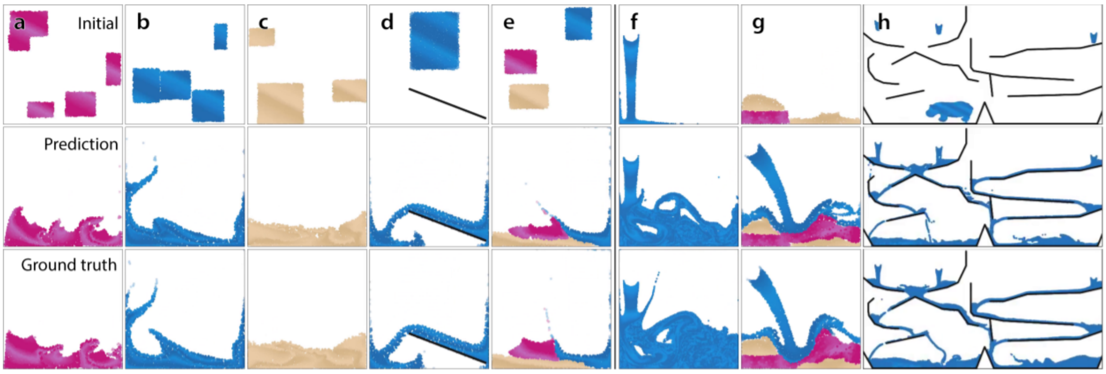

Figure 5.4: Results of the Graph Networks model training

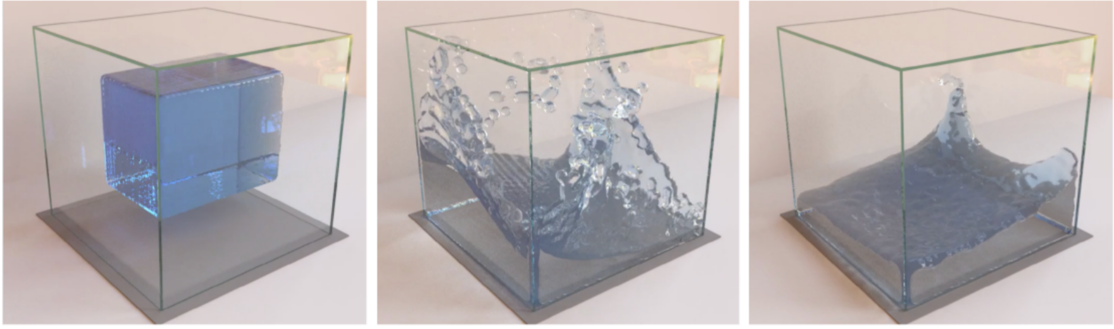

Figure 5.5: Rendered results of the Graph Networks model training

This area of research definitely is very important as to better forecast and prevent damages from heavy rainfalls within the urban environment. It is good to see that both institutions, like technical universities, and private companies, like urban design studios, enter into this field of research. The results from this work are highly important and the interventions developed from this knowledge might have a tremendous impact for the future urban planning.

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[15] "Graph neural networks (GNNs) are connectionist models that capture the dependence of graphs via messages passing between the nodes of graphs"

6 Conclusion

The thesis demonstrate thorough analysis of open urban waterscapes. The analysis is based upon development and use of water management and OUW solutions in urban spaces on a micro scale. *SCALGO* and *OUW Potential Tool V.1.5* are the main solution used and evaluated. The main outcome was that *SCALGO* is great in the beginning to gain a overview of the site on a macro scale, as it has a detailed map that show catchment of the terrain. *OUW Potential Tool V.1.5* is great for gaining a quick overview with limited knowledge of the site, it show meaningful results as rainwater balance and period of overflow. The solution developed is based upon the particle simulator in Blender. Throughout the thesis this solution is fitted and improved through 3 studies: slope, roughness and infiltration study. The slope study showed that FC=0.002 is good estimate for slopes close to 0.1, but if the slope increase the FC must equally increase, which revealed a linear correlation between these two parameters. The roughness study on the other hand showed exponential correlation between the FC and the GM, but with some uncertainty outside the boundary of slope 0.1 to 0.3. Last, the infiltration study showed that, if the rainfall period and magnitude is known a permeability can roughly be estimated, including some uncertainties and boundaries. Considering those, another method was used including *OUW Potential Tool V.1.5* and CAD tools. This allow for calculating the estimated time of water drainage and the water balance for evaporation and infiltration on a yearly basis, which showed out to be a more stable method. Finally, the developed solution for water management and OUW was practised on the case study,*"Milan Citylife"*. A 10 year rain was simulated, and based on these result, a proposal of OUW was made, in order for the site to handle the rain. In the end some future prospects of the practised method was discussed. Including, add-ons to the Blender software, which already have hopeful results. These add-ons are *"FLIP-fluids"* and *"Mantaflow"* which are very realistic. The main issue is the computer power needed as these simulations a very computational demanding.

Bibliography

[1] *Blender*. URL: https://www.blender.org/.

[2] Sara Maria Lerer, Hjalte Jomo, and Danielsen Sørup. “LOKAL AFLEDNING AF REGNVAND, Byens hverdagsregn”. In: (2016).

[3] Antje Backhaus and Marina Bergen Jensen. “Lokal afledning af regnvand - LAR”. In: *Grønt miljø* 3 (2010), pp. 30–35. URL: http://www.teknologisk.dk/lokal-afledning-af-regnvand-lar/28273.

[4] Reza Masoodi et al. *Numerical simulation of LCM mold-filling during the manufacture of natural fiber composites*. 2012, pp. 363–378.

[5] *ANVISNING FOR HÅNDTERING AF Forord*. 2012. ISBN: 8799123975.

[6] Component Oriented, Scripting In, and Grasshopper Vb. “Component Oriented Scripting in Grasshopper Vb”. In: (2011).

[7] Manning Robert. “MANNING Robert”. In: *Short History dictionary on Hydrology and Drainage* (1897).

[8] Ralph W. Powell. “History of Manning’s formula”. In: (1960).

[9] “Lab Notes : Classification of Open Channel Flows”. In: (2005).

[10] *MIKE URBAN*. URL: https://www.mikepoweredbydhi.com/products/mike-urban.

[11] L A Rossman. “STORM WATER MANAGEMENT MODEL USER’S MANUAL Version 5.1”. In: *National Risk Management Laboratory Office of Research and Development. United States Environmental Protection Agency, Cincinnati, Ohio.* September (2015), p. 352. URL: http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100N3J6.TXT.

[12] *SCALGO Live Flood Risk*. URL: https://scalgo.com/en-US/live-flood-risk.

[13] *HEC-HMS*. URL: https://www.hec.usace.army.mil/software/hec-hms/.

[14] Paul A Gagniuc. *Markov Chains: From Theory to Implementation and Experimentation. USA*. 2017, pp. 46–59.

[15] WILL KENTON. *Least Squares Method Definition*. 2020.

[16] Mattia De Caro et al. “A regional-scale conceptual and numerical groundwater flow model in fluvio-glacial sediments for the Milan Metropolitan area (Northern Italy)”. In: *Journal of Hydrology: Regional Studies* 29.July 2019 (2020), p. 100683. ISSN: 22145818. DOI: 10.1016/j.ejrh.2020.100683. URL: https://doi.org/10.1016/j.ejrh.2020.100683.

[17] Niels Thorup Bent Hasholt Bent Elbek. “Fordampning”. In: (2014). URL: https://denstoredanske.lex.dk/fordampning#:~:text=Den%20fordampning%2C%20som%20faktisk%20finder,vandmangel%20i%20dele%20af%20%C3%A5ret..

[18] Alvaro Sanchez-Gonzalez et al. “Learning to Simulate Complex Physics with Graph Networks”. In: (2020). URL: http://arxiv.org/abs/2002.09405.

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