PHYSICAL MODEL TEST OF GULLY POT EFFICIENCY

Construction of the experimental set up and study of the performance of a scale 1:1 transparent gully pot for its sediment trapping efficiency

In cooperation with:

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ABSTRACT

Urban flood prevention is an intensifying prerequisite of urban inhabitation due to a multiplicity of threats to population health and property. One of the components of urbanisation that can fail to fulfil its function and cause urban flooding is gully pot clogging. Frequently this is the result of an insufficient or inappropriate cleaning frequency of gully pots; and although formulas to resolve this have been proposed, they do not take in consideration some factors that influence gully pot efficiency. Therefore, the aim of this study was to test such features through the experimental set up and study of the performance of a scale 1:1 transparent gully pot for its sediment trapping function.

In this thesis, diverse parameters affecting gully pot efficiency, such as discharge, sediment size and depth are analysed, discussed and demonstrated. The sediment deposition over time in the gully pot can be divided in three stages: linear build up – constant deposition, parabolic build up – decreasing deposition and zero build up – no further increase of mass, change in geometry of the deposited solids and risk of clogging. The results show that the most influencing parameter in gully pot efficiency is the flow pattern, which is influenced by diverse factors, namely gully pot geometry, flow velocity, discharge and inlet direction. The outcome of these experiments, combined with further research about the sediment concentration in runoff water, can be used to predict sediment build up in the gully pot. Overall, although this research is not conclusive, it presents thought provoking considerations whilst indicating avenues for future research.

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LIST OF SYMBOLS

Symbol	Unit	Property
A	$[m^2]$	Area of free water flow
A_c	$[m^2]$	Catchment area
c	[g/L]	Sediment concentration
C	[-]	Runoff coefficient
D	[cm]	Depth of the gully pot
d	$[\mu\mathrm{m}]$	Size of the sand particles
d_{50}	$[\mu\mathrm{m}]$	Median size of the sand particles
ϵ	[%]	Gully pot efficiency
Eff	[%]	Recorded efficiency
g	$[\mathrm{m}/s^2]$	Gravitational acceleration
I	$[\mathrm{l/s.ha}]$	Intensity
ρ_s	$[\mathrm{kg}/m^3]$	Density of the sand particles
ρ_w	$[\mathrm{kg}/m^3]$	Density of the water
S_s	$[\mathrm{g}/s]$	Sand supply
Q	$[m^3/s]$	Discharge
T	[year]	Return period
ΔV	$[m^3]$	Volume difference
V_D	$[m^3]$	Volume of the pot with a certain depth “D”
ν	$[m^2/s]$	Kinematic viscosity
w_s	$[m/s]$	Settling velocity

1. INTRODUCTION

1.1. BACKGROUND

Urban flooding is an increasing problem in cities, causing both tangible and intangible damage to property and potential health risks to inhabitants (Post et al., 2017). Phenomena like urbanization and climate change will only increase this problem, identifying the need for more research and investment in sewer systems to improve urban flood prevention.

In the past urban drainage has been considered a vital natural resource, a convenient cleansing mechanism and an efficient waste transport medium (Burian & Edwards, 2002). Furthermore, Butler and Davies (2000) noted that the most valuable benefit of an effective urban drainage system is safeguarding public health.

Traditionally two types of urban drainage sewer systems are adopted: combined and separate systems. Combined systems convey both dry-weather flow (wastewater) and storm-water runoff, while separate systems convey these two flows via two separate pipeline systems. However, which of these is the best solution in terms of cost-benefit analysis remains a controversial subject (Mannina & Viviani, 2009).

Both systems make use of gully pots, which link impervious areas with the drainage system. Therefore, as stated by Bolognesi (2008), gully pots are a fundamental part of the sewer system. In this they serve two functions. Firstly, they serve as a connection point between street runoff water and the sewer system itself. Secondly, retaining the solids inflowing into the sewage system, they prevent possible reductions of the hydraulic capacity of the system and/or clogging.

These solids are captured in the sand trap of the gully pot. This sand trap silts over time and finally gets clogged causing street flooding. Gully pots require to be cleaned regularly to avoid these problems.

With the advent of industrialisation and the increasing urban density, the problems caused by inflowing solids into the storm sewer system via gully pots became acute (Halliday, 1999).

Thus, recognising this augmenting problem, this research examines the build up of the experimental set up and studies the performance of a transparent gully pot for its sediment trapping function to improve urban flood prevention.

1.2. PROBLEM STATEMENT

In the Netherlands most municipalities clean their gully pots in residential areas annually, and two to four times a year in intensively used, commercial locations, e.g. markets (Ten Veldhuis & Clemens, 2011). Hence, as the cleaning frequency is not generally based on the physical parameters influencing solid deposition in gully pots, redundant cleanings and late cleanings of gully pots are often applied. Thus, accurate predictions of the silting level are needed for a sustainable urban sewer system. Two factors are required to estimate this, namely the inflow of solids and the capturing efficiency of those solids over time. The second factor is addressed in this research.

The efficiency of capturing inflowing solids in gully pots was tested by means of a physical lab model. This physical lab model was used to study the silting rate in the gully pot, for different types of sediment, flow intensities and gully pots depths.

Gully pot efficiency has been previously tested by Butler & Karunaratne (1995) and Boogard et al. (2014). They investigated the initial capturing efficiency of a gully pot. However, it is very likely that the efficiency decreases when the sediment layer thickens. Therefore, in this research the silting process was measured over time. This process was studied in a transparent, scale 1:1 gully pot.

1.3. GOAL AND OBJECTIVES

The goal of this thesis is to study the trapping efficiency of gully pots as well as visualizing the flow patterns within Dutch gully pots. Therefore, the main research question is:

What physical parameters influence the sediment trapping efficiency of gully pots?

Consequently, the following the research objectives are:

- To determine the inflowing and deposing solids.
- To determine the main influencing parameters in respect to gully pot efficiency.

Therefore, the research sub-questions are:

- What is the influence of solid characteristics on gully pot efficiency?
- What is the influence of the discharge on gully pot efficiency?
- What is the influence of the geometry on gully pot efficiency?
- How do different rainfall events affect gully pot efficiency?
- Is there any other parameter that influences the efficiency of the gully pot?
- What is the main flow pattern in a gully pot?

1.4. OUTLINE

Chapter 1 contains a general introduction to gully pots and their functioning. Chapter 2 presents a brief overview of the relevant related theory. Chapter 3 includes an extensive explanation of the materials and method applied to conduct this research. Chapter 4 presents the results of the tests and Chapter 5, the conclusions and recommendations. Finally, Chapter 6 presents the bibliography.

2. THEORETICAL FRAMEWORK

2.1. GULLY POTS

According to Bolognesi (2008), roadside gully pots are the link between surface runoff and the drainage system. Therefore, they are a relevant component of it. Additionally, Bolognesi (2008) outlines their main functions to be the protection of downstream drainage to treatment plants and the receival of waters from excessive sediment loads.

Moreover, Post et al. (2016) described them as essential assets designed to relieve the downstream system by trapping solids and attached pollutants suspended in runoff.

In terms of mass, sediment is the most important potential pollutant conveyed with storm runoff. Therefore, it is beneficial to trap it in gully pots. However, the continuous inflow of solids unavoidably leads to gradual silting and possibly to clogging (Bolognesi, 2008). For this reason, gully pots have to be cleaned to avoid street flooding.

2.1.1. Dutch gully pots

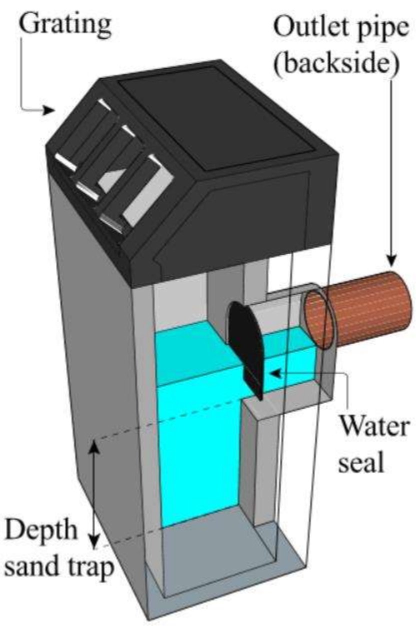

Figure 1: Example of Dutch gully pot (Post, Pothof, Dirksen, Langeveld, & Clemens, 2016)

Dutch gully pots are unique in their form. Being smaller than pots in most other countries, there are more pots per unit length of street. Additionally, many of them have side inlets, which is a less common feature in other countries.

Regarding the separation distance, gully pots can be found every fifteen to twenty meters in the Dutch streets, with a designed connected catchment area in order of 200 m^2 (RIONED Foundation, 2004).

In terms of maintenance, most municipalities clean the gully pots about once a year. Nevertheless, there are vulnerable locations, such as markets, where they are cleaned between two to four times per year (ten Veldhuis & Clemens, 2011). Next to that, cleaning actions are performed after complaints of citizens.

2.2. POTENTIAL FUNCTIONAL ISSUES OF GULLY POTS

Delectic et al. (2000) state that certain pollutants, such as heavy metals and nutrients, usually attach to the smallest organic particles and that this is the reason why gully pots should retain the suspended solids while allowing water to run through. However, a continuous inflow of solids to a device designed to trap them leads unavoidably to gradual silting (Bolognesi, 2008). This then may lead to clogging which increases the probability of urban flooding problems during rainstorms (Silvagni & Volpi, 2002). Moreover, the silting level in gully pots may not only increase, but in extreme conditions decrease due to re-suspension of the sediment (Butler & Karunaratne, 1995). This means that during these storm events extra pollutants can enter the sewer system.

In addition, Post et al. (2016) show that the capturing efficiency drops to zero after a few months. After that period all inflowing solids are transported to the main sewer. This causes to deposits in the main pipes and therefore hydraulic losses resulting in an increase of the risk on flooding (van Bijnen et al., 2017).

Both patterns are unfavourable. In the case of gradual silting, streets will flood due to a clogged gully pot outlet. In the second case of an efficiency drop, all solids will flow to the main sewer, where they can settle. Therefore, in both cases the gully pots require to be regularly emptied.

The question remains what the best moment in time is to do so. This depends on the strength of the efficiency drop and the costs of both cleaning gully pots and main sewers.

Silting levels in gully pots could be estimated if a model for the characteristics of solids delivered to the sewer system was combined with a model of the efficiency of a gully pot (Bolognesi, 2008). Clearly, such a complete model would be very useful to municipalities. Unfortunately, the individual parts of this model are still not sufficiently developed for this purpose.

2.3. SOLID CHARACTERISTICS

2.3.1. Sediment sources

To understand the sedimentation within gully pots, it is important to have an overview of the origin and natural characteristics of the potential inflowing sediments. The nature of solids (origin, sizes and pollutant loads) has been researched extensively in recent decades. For example, as shown in Table 1, Ashley and Hvitved-Jacobsen (2002) studied the main sources of storm sewer sediment and identified that inflowing sediment originate from several sources, including: atmospheric deposition, wash-off from the surfaces within the catchment, sewer pipes themselves and construction sites. From empirical data it was shown that the characteristics of these sediments are highly area-specific.

Source	Particle characteristics	Description
Winter de-icing	Particle size range approximately from 0.05 to 20 mm.	Sand or grit used for winter de-icing might be flushed into storm sewers.
Catchment surface	Wide size range, primary inorganic.	Include grit from road abrasion, particulates from vehicles, construction materials, particles from erosion of roofing material, etc…
Runoff from impervious areas	Typical solids < 250 µm entering sewer carried by runoff.	These solids may be up to 40% by mass of the total storm sewer sediment load.
Soil erosion	Typical solids < 1 mm.	Due to leaks or pipe/ manhole/gully failures.
Wind-blown from sand/soil/litter	Large organics possible, inorganics < 5 mm.	Entry via catch basins/ inlets, size reduced when discharged into storm sewer due to the sediment capture ability in catch basins/inlets

Table 1: Sources of storm sewer sediment (Ashley & Hvitved-Jacobsen, 2002)

Table 1 shows that the inflowing solids in gully pots range from nanometre-sized colloidal organic material to millimetre-sized gravels.

2.3.2. Sediment distribution

The type of sediment inflowing into the gully pots depends on a variety of factors, such as the type of soil in the area, type of street, meteorological conditions and frequency of street cleaning.

Figure 2 shows the different sediment size distributions, alongside the sand trap growth, collected from storm water runoff in different areas, years and researches.

Boogaard et al. (2014). compared the particle size distribution in gully pots with research performed in other countries. As can be seen, half of the deposited mass consists of particles smaller than 70 µm. This means that the particles are predominantly fine (60% of the particles ≤ 100 µm) (Boogaard et al, 2014).

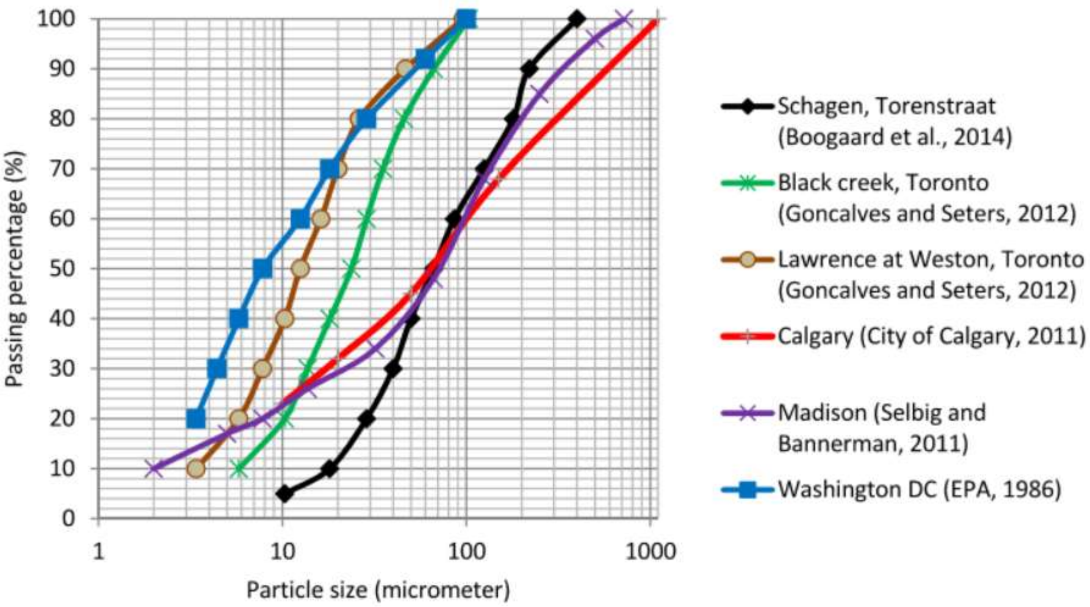

Figure 2: Particle size distributions of sediment in gully pots in different studies. (Yangbo, 2016)

A different way to study the sediment deposits is by using d_{50} values. d_{50} is the particle diameter representing the 50% cumulative percentile value (50% of the mass in the sediment sample are finer than the d_{50} grain size) (HORIBA Instruments, 2017).

According to Table 2, the minimum value of d_{50} found by Yangbo (2016) in storm water systems is 350 µm. The maximum value is set to be 1 mm. It is also notable that the size of sediment is bigger in sewer inlets when compared to the storm sewer pipes. This is due to the trapping capacity of gully pots.

Sample locations	Nation	Weather	d_{50} (µm)	Source
Storm sewer inlet	US	Wet	550	Sansalones et al., 1998
Storm sewer inlet	GER	Dry	1000	Grottker, 1990
Storm sewer	JAP	Dry	350	Shimatani et al., 1989
Storm sewer	KUW	Dry	400	Almerdeij et al., 2010

Table 2: The median size, d50, of deposit sediment found in storm sewer systems (Yangbo, 2016)

2.4. PROCESSES OCCURRING IN THE GULLY POTS

Gully pots are not only designed to transport water from impervious areas to the sewer systems, but they are also meant to capture inflowing solids. These solids can undergo a few processes. Solids can settle in the gully pot, they can undergo biochemical processes in the pot, they can be resuspended after they have settled and finally leave the pot via the exit pipe. These processes will be described in more detail in the following sections.

2.4.1. Sedimentation

Sedimentation is the predominant process occurring in a gully pot. According to Xanthopoulos and Augustin (1992), gully pots are designed to trap a part of the sediments entrained in storm water.

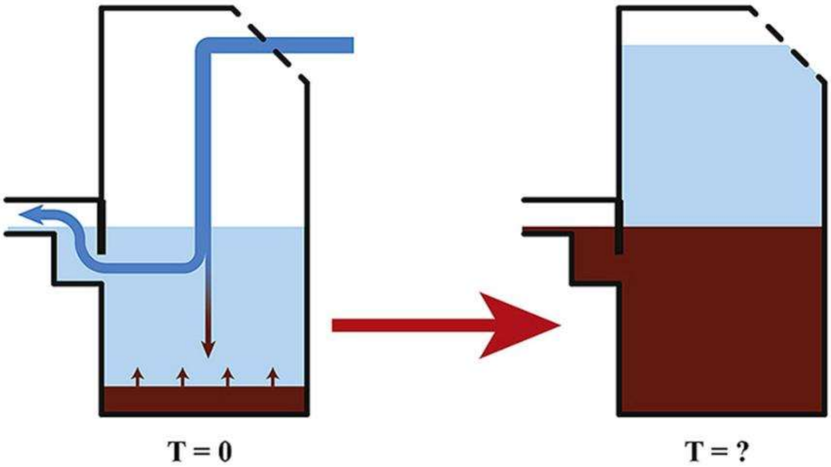

Figure 3: Sedimentation in gully pots. (Post, Pothof, Dirksen, Langeveld, & Clemens, 2016)

The sediment layer in the gully pot is mainly formed by settleable solids sized between 250 and 500 µm. This range complies with the grain diameter of 350 µm which is the basis for the design of sediment-free sewer systems (Xanthopoulos & Augustin, 1992).

Gully pots are designed to trap these settleable solids to prevent settling in the main sewer. Smaller particles have less chance to settle and can therefore be ignored in the design process of a gully pot. However, especially over time and when the filling rate of the sediment bed increases, research has shown that not all settleable solids are captured in the gully pot.

2.4.2. Resuspension of sediment

During the inflowing process of the water in the gully pot, part of the already deposited sediment is resuspended. This is caused by the turbulence that the water creates when impacting the sand trap. This erosion was seen to be limited to a short period of time (20-40s) at the beginning of constant inflow followed by a rapid inverse exponential reduction (Butler & Karunaratne, 1995). Where the flow rate does not correlate, the peak erosion was proved to be a function of particle size and bed depth.

Also, as stated by Butler and Karunaratne (1995), two different mechanisms, related to sediment resuspension, occur in the gully pots:

Mechanism 1: Consider a sediment bed surface, consisting of particulate material, over which water has passed for sufficient time, so all the particles are arranged to form resistance to the horizontal velocity component near the bed. This is the concept of a graded bed.

Mechanism 2: When the sediment bed surface is disturbed it will become ungraded to some extent. In this situation some particles will protrude from the surface, being more susceptible to erosion.

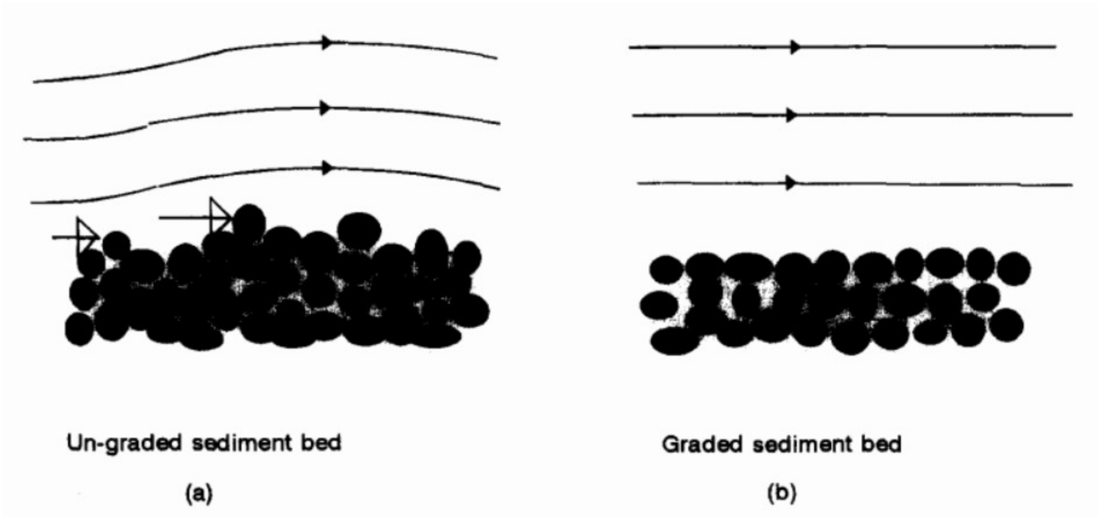

Figure 4: Representation of graded and un-graded sediment beds (Butler & Karunaratne, 1995).

The degree of settlement will depend on size and specific gravity.

The Figure 5 illustrates the importance of the two mechanisms.

- At time A, the water was fist discharged until two minutes before time B, which caused a suspended solids peak in the effluent flow.
- At time B flow was re-started without disturbing the bed, only mechanism 2 applies.
- At time C, the sediment bed surface was artificially disturbed while the water was flowing. In this case only mechanism 1 applies.
- At time D the water flow was re-started after being stopped for two minutes. Both mechanism 1 and 2 apply in this situation

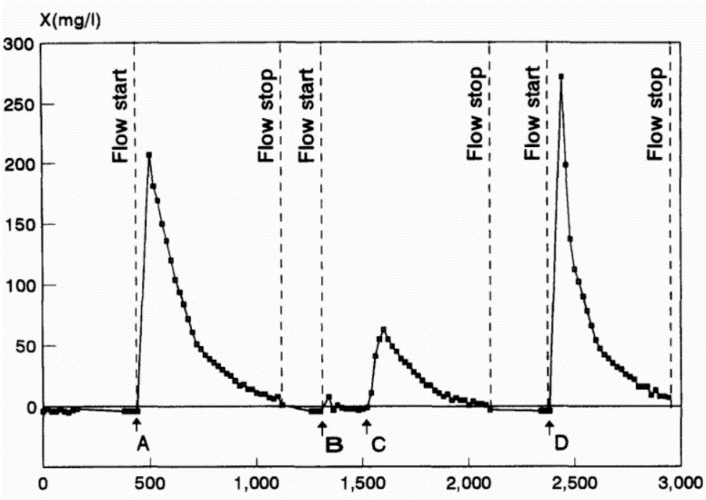

Figure 5: Effects of disturbing of bed and re-start of flow on erosion. (Butler & Karunaratne, 1995)

Observing the peak concentrations at each instant, it is highest at D, and A shows a comparable magnitude. At B the peak is very low compared to D and C implying that mechanism 1 is the most influential (Butler & Karunaratne, 1995).

2.5. TRAPPING EFFICIENCY OF GULLY POTS

Laboratory studies of the capturing efficiency of gully pots report that gully pots can remove medium to coarse sands very efficiently (65% to 90%) over a wide range of flow rates. However, a negative capture efficiency can appear when the sand trap is filled over 40 to 50% of its total depth, which is mainly caused by scouring (Tang et al., 2016). Butler and Karunaratne (1995) studied the trapping efficency of gully pots, and they found that virtually all particles > 246 µm are trapped compared with under 30% for solids < 43 µm.

Results from single-size quartz sand particles show that, for a given pot size, retention is influenced primarily by influent flow rate and particle diameter and to a lesser extent, retained sediment bed height (Butler & Karunaratne, 1995). Bolognesi (2008) agreed that trapping efficiency of gully pots was not significantly affected by the sediment bed height. Additionally, he stated that the amount of solids supplied for each run rather than the outlet type had significant influence on the performance of the gully pots.

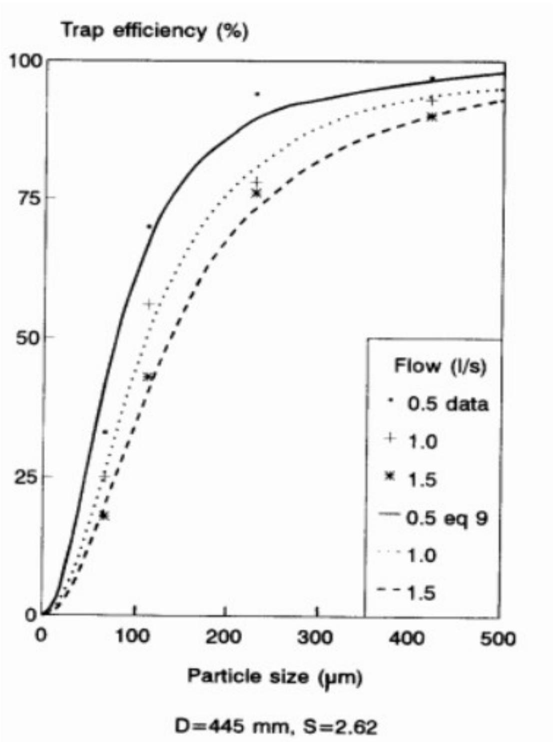

Figure 6: Measured and modelled gully pot trapping efficiency. (Butler & Karunaratne, 1995)

Tests conducted using samples of mono-granular sand have confirmed that the efficiency of gully pots is inversely proportional to flow rate and directly proportional to the particle size and specific gravity (Bolognesi, 2008).

Although Butler and Karunaratne (1995), and Bolognesi (2008) did not consider the sediment bed height as one of the main factors, Post (2016) claims that the retaining efficiency decreases as sediment bed levels increase. The depth of the sediment layer, elapsed time since cleaning and the road type were identified as the main properties without regard of progressive accumulation from stabilising sediment bed levels (Post et al., 2016).

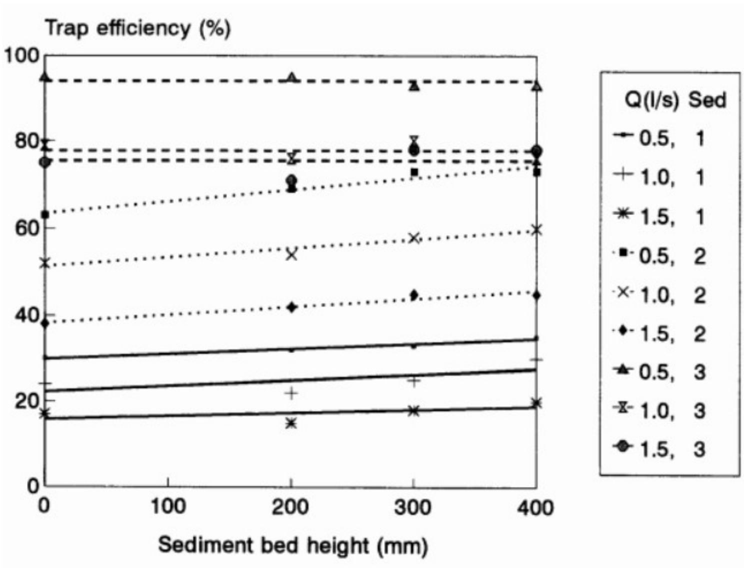

Figure 7: Influence of sediment bed height on solids trap efficiency (Butler & Karunaratne, 1995).

Formulas have been proposed for retention efficiency. However, as their basis is rather limited, their application is questionable in differing circumstances, such as the shape of the gully pot and the flow rate into the gully pot.

Lager et al. (1977) found that the retention efficiency is directly proportional to the diameter of particles and that the discharge is inversely proportional to the retention. Butler and Karunaratne (1995) proposed the following equation for the efficiency:

$$\epsilon = \frac{w_s}{w_s + \frac{Q}{A}} \tag{1}$$

In which d is the particle diameter, ρ_w is the density of water, ρ_s is the density of the solid and ν is the kinematic viscosity. Stokes' law relates to laminar flow, but it can be used by multiplying with a correction factor α *(0.6)* to incorporate the effect of turbulence. This term is set to 0.6 by Butler and Karunaratne (1995).

$$w_s = \frac{gd^2\left(\frac{\rho_s - \rho_w}{\rho_w}\right)}{18\nu} \tag{2}$$

Bolognesi et al. (2008) found agreement between their data and the formula proposed by Butler and Karunaratne (1995) for a different geometry, but based on their measurements they proposed a different value for α, namely:

$$\alpha = 0.8574\ \mathrm{e}^{(-1.7602\cdot d)} \tag{3}$$

3. METHODOLOGY

This chapter contains a description of the materials and measuring devices necessary to build this lab model; and amongst other features a description of the experimental set-up, protocol and data processing.

3.1. REQUIREMENTS OF THE EXPERIMENTAL SET-UP

3.1.1. Functional requirements

- The water must be able to flow into (and out) the gully pot, mixed with sediment that will be provided by the sediment feeder.
- The model must be able to be tested for diverse pot depths, flow rates, sediment sizes and sediment concentrations.
- The water must be able to flow into the pump without carrying any sediment.
- The measurements must be collected on one computer for synchronising reasons.

3.1.2. Technical requirements

- The pump must have enough pumping capacity to deliver a flow of at least 2.0 L/s and deliver water free of sand.
- The sediment feeder must be able to supply sand for the desired sediment concentration. For this, the screw which will rotate and supply the sediment must be calibrated properly.
- The holes of the shower head should have an appropriate diameter to deliver the desired pressure to avoid sedimentation in the gully.
- The connected computer must be capable of processing all the information received from the measurement devices.
- The second bottom within the gully pot must be adjustable to test different gully pot depths.
- The valve must be easily adjustable to supply the desired discharge rate.

3.2. MATERIALS

3.2.1. Experimental setup

A lab model, based on the one from Butler and Karunaratne (1995) and Boogaard et al. (2015) , was built in a basement in the Deltares' hydraulic lab to describe the influence of different parameters in the gully pot's sediment trapping efficiency.

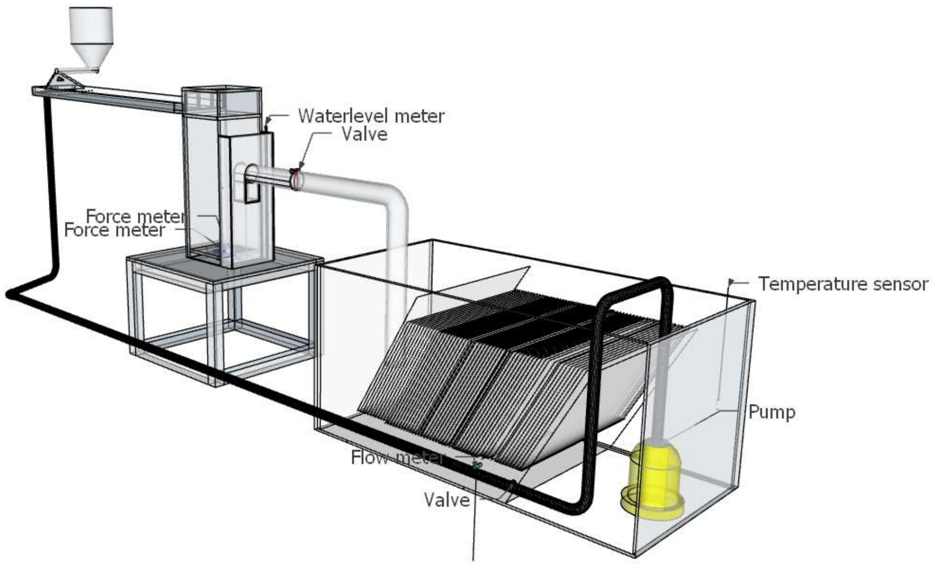

Figure 8: 3D model of the experimental set-up.

The main parts of these setup were:

Pump: For the water to reach the gully pot, the use of a pump was necessary. The upper and lower limits of the discharge are based on design parameters.
The pump used was Einhell GE-DP 7330 LL ECO Vuilwaterpomp, with 730W power.

Gully pot: A transparent gully pot was required to study the water flow and the accretion of the solids. Since gully pots in the Netherlands have different depths, a deep gully pot with an adjustable bottom was used. It was built out of PMMA (acrylate) for this research.

Sediment feeder: Although some researchers claim that the sediment concentration does not have an influence upon gully pot efficiency, it was also tested. Additionally, it was necessary to know the exact sediment supply over time to be able to calculate the trapping efficiency over that duration. The sediment was fed in a controlled rate. This required an automatic sediment feeder. The sediment feeder used was a funnel shaped tank connected to a valve at the bottom that supplies the sediment.

Settling tank: Two settling tanks were used for the settling of the solids that were flushed through the gully pot. Lamella separators were used to trap the solids and avoid their inflow into the pump. The trapped solids were dried afterwards and re-used. The two settling tanks were connected with a third tank, which contained the pump.

The following figure describes the cycle followed by the water during the experiments.

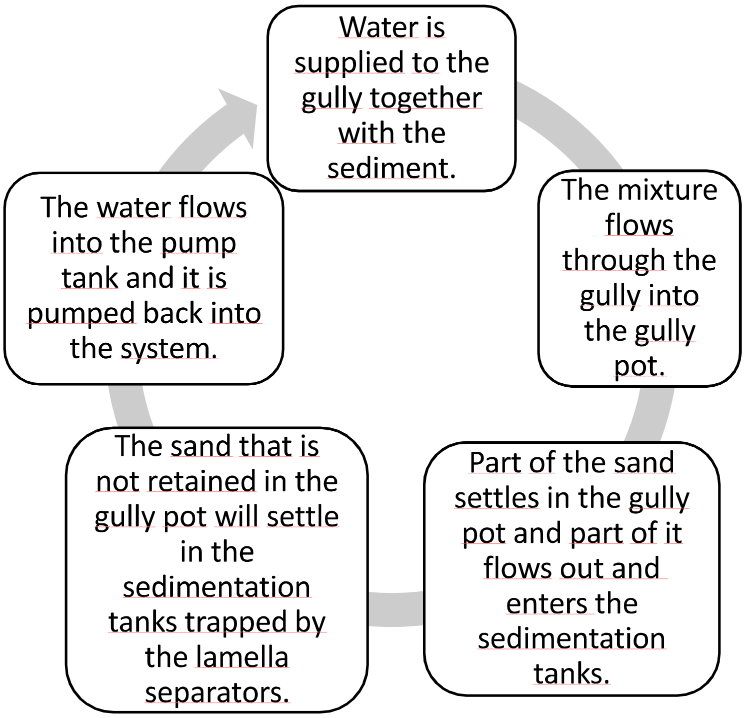

Figure 9: Experimental cycle

To set up the lab model, it is necessary to purchase several items. They were classified according to the role they have within the model. These were the solids/sediment, the parts needed to build the model and finally the measurement instruments.

3.2.2. Measurement instruments

Flow meter: The discharge supplied to the pump was measured by a magnetic flow meter. The range of the flow meter was linked to the experiments to obtain significant data.

The flow meter provided by Deltares was a magnetic flowmeter designed by Fischer and Porter, model D10d. Its maximum measuring range is 3.5L/s

Figure 10: Flow meter

Figure 11: Weighing platform with two force meters

Weighing device: Two force meters was used to measure weight of the sedimented solids and water above the sediment.

The water level continuously changes, and these fluctuations were filtered out. It was possible to do this by measuring the water levels with a frequency higher that these fluctuations. The weighing device used was a Scaime AVX30 C3 CH 15e TR, provided by Deltares.

Water level meter: The water level was measured in the same way as the build-up of the sediment. Again, the frequency of these measurements was higher than the water level fluctuations.

The water level meter provided by Deltares was an MTS, Temposonic G-series. It was placed in a tank connected to the main pot to prevent distortion in the flow of the gully pot itself.

Figure 12: Water level meter

Figure 13: Thermometer

Thermometer: It was important to take in account the temperature of the water since it has a direct influence on the viscosity of the water and, consequently, the sedimentation rate. Although the experiment was located in a basement with a stable temperature, the water's temperature will change due to the friction in the pump and pipes. To ascertain the temperature fluctuations a thermometer PT100-RS was used. This thermometer was provided by Deltares.

3.2.3. Solids

The main sediment tested was sand. The sand used for the tests was of different sizes. The following table describes the characteristics of the diverse types of sands used for the experiment.

Sediment type	Size range (μm)	d_{50} (μm)	Picture
Sand 200 μm	100-300	200	
Sand 400 μm	200-600	400	
Sand 1000 μm	800-1500	1000	

Table 3: Solids' characteristics

3.3. BUILD UP AND CALIBRATION

The different measurement instruments had to be calibrated properly to obtain reliable data from the different tests. The calibration form of the flow meter, water level meter, thermometer, and weighing device can be found in Appendixes C, D, E, and F, respectively.

3.3.1. Sediment Feeder

One of the most important features of the physical model test was the sediment feeder.

The sediment feeder consists of a funnel shaped tank (with a capacity of 100 litres), an electrical motor, a 3D printed screw, a 3D printed conveyer pipe to couple the tank and the screw, and an Arduino (open source microcontroller) which regulates the sand supply.

Diverse motors were used to provide both high and low supply rates. This was necessary to ascertain similar concentrations at different discharges. Next to that there are two upper limits of this concentration. The first one is the carrying capacity of water in the gully. The second one is the minimum concentration at which particles start to interact and start to influence the sediment deposition.

The Arduino was used to control the rotational speed of the screw. To avoid a clogged screw, diverse screws were used to supply particles with different sizes. The rotational speed of the screw determines the sediment supply rate. This screw must be calibrated for the different parameters, such as different sediment sizes, different rotational speeds and filling rate of the sediment tank.

Therefore, a correlation between the rotational speed and the sediment supply was recorded. This graph was used to select the desired sediment supply for each test.

However, it was found that the shape of this graph changes for small movements of the sedimentation tank. These were not possible to avoid, because the screw had to be uncoupled when the sand needed to be replaced.

Therefore, later it was decided not to identify the entire curve, but to just identify the rotational speed required for the upcoming test.

Figure 14: Valve for sand supply

3.3.2. Weighing device

To measure the weight of the sediment in the gully pot, two force meters were used. The force meters used are rectangular steel devices, that, when supported at one of the ends, can measure the bending moment that occurs in the opposite end after a force is applied. This bending moment is then used to calculate the force applied and, therefore, the weight of the sand retained.

To make use of these force meters, it was necessary to design a platform where the sand would settle. This platform consisted of a square steel plate, a cross-shaped plate and two small connection plates.

A 3D sketch of the weighing platform was provided, and a definitive design had to be performed in AutoCAD. After adjusting the preliminary design, and fitting all elements symmetrically in the platform, it was ordered from "Metaalwinkel".

The separation between the gully pot's walls and the weighing platform had to be sufficiently small for the sand not to pass through but sufficiently big to weigh the sand and not transfer the weight to the gully pot's walls. Carefully placed tape was used for this purpose.

To install the weighing platform, a sucking pad was needed to carefully introduce it through the top opening of the gully pot.

The force meters were submerged in the water. The area below the force meter and above the force meter were connected via a side channel. Therefore, there was no pressure difference between the water above and below the weighing devices, which meant that the weighing devices did not measure the weight of the water.

3.3.3. Sedimentation tanks

The experimental setup was a closed system. This means that the water introduced to the gully pot was reused. Therefore, it was essential to let the sediment that was not settled in the gully pot to settle in the sedimentation tanks. Two sedimentation tanks were used to limit the flow velocity and to make sure that the sand could settle. Each sedimentation tank was linked with two hoses to a third tank. This third tank contains a pump to circulate the flow.

Figure 15: Sedimentation tanks with wooden supports to achieve the desired filling rates of the tanks.

These sedimentation tanks acted as lamella clarifiers.

The lamella clarifiers are u-sectioned sheets that cover a large area to reduce the flow velocity.

This principle can be divided in three steps:

1) The water enters the tanks through the T-junction pipes and flows downward through the chamber, entering the plates through openings in the bottom

2) As the water flows upwards, the solids settle on the inclined, parallel plastic plates and slide into the bottom of the unit.

3) The clarified water leaves the plate through the outlet and is transported through the hoses to the water tank, ready to be re-circulated into the system

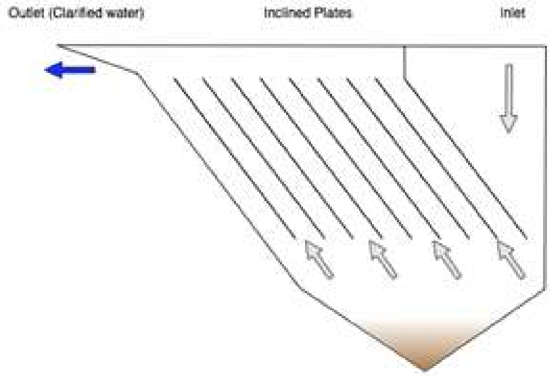

Figure 16: Schematization of the principle functioning in the sedimentation tanks.

3.4. EXPERIMENTAL PROTOCOL

In order to carry out a test, there are diverse steps that have to be followed. These steps will ensure the correct functioning of the experimental set-up as well as the reliability of the results.

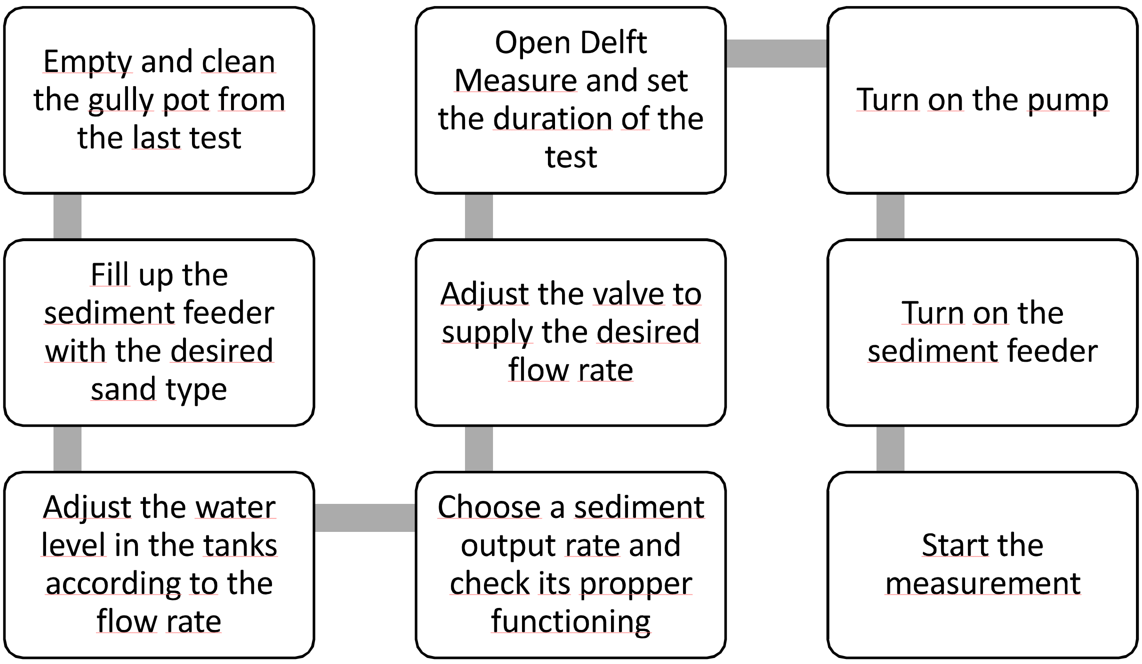

Figure 17: Experimental protocol.

3.5. EXPERIMENT AND DATA PROCESSING

3.5.1. Comparison to the proposed formula

Although the formula proposed by Butler & Karanuratne (1995) was also agreed by Bolognesi (2008), a comparison between efficiency calculated with the formula and the tests' results was conducted to check its reliability and further analyse the parameters that it does not include.

3.5.2. Stages of sediment deposition over time

To understand the different processes that occur in the gully pot, it was necessary to analyse the build up of sand deposition over time. The mass retained by the pot was compared with the mass supplied, enabling the build up patterns to be analysed and the different stages of sediment deposition identified.

3.5.3. Re-using of the sand

Before proceeding with the tests, a sediment size distribution graph needed to be produced to determine if the sieve curve of the sand settled in the gully pot after a test is the same as before being used.

3.5.4. Parameter analysis

The variable parameters in this experiment that might influence the silting rate were the flow intensity, particle size and gully pot depth, among others. In total four different parameters were studied.

Concentration

Several studies claim that the sediment concentration in the inflowing water does not influence the trapping efficiency of gully pots. However, it was worthwhile to check if this statement is true by running tests with different sediment concentrations. The supply rate of the sediment was provided by altering the rotational speed of the valve of the sediment feeder. During the calibration phase, a relation between the rotational speed of the sediment feeder and the supply rate was recorded.

Diverse concentrations were used to discover if the findings of previous studies were correct and the inflowing concentration has no influence in the trapping efficiency. High concentrations were favourable from a practical point of view, because this shortens the duration of the test.

Flow (4 options)

The flow in the system should mimic the rainfall. According to Rijkswaterstaat (1988) the design of a drainage system in an urban area must be based on a maximum rainfall of 167 L/s.ha, which is equal to an average intensity of 60 mm/h. The catchment area connected to the gully pot is designed to be in the order of 200 m^2. This leads to a discharge of 3,3 L/s.

The discharge was regulated by a valve that was controlled by means of a flow meter. Discharges of 0.5,1,1.5 and 2 L/s were tested to study the correlation between the different flow rates and the sediment deposition within the gully pot. Although the maximum discharge was calculated to be 3.3 L/s, the experimental set-up's maximum discharge was 2L/s.

Particle size (3 options)

It was fundamental to test different particle sizes to study their interaction with the flow and ascertain whether they washed away or settled in the gully pot. Samples of field gully pots were taken to couple the size of the particles with their density.
Three different particle sizes were used to obtain a broad view of their interaction with the flow. These were particles with a diameter of 200 µm, 400 µm and 1000 µm.

Gully pot depth (3 options)

Earlier EPA research (Lager, *et al.* 1977) found that an optimal catch basin design should have the following dimensions: if the outlet pipe is D in diameter, its bottom should be located about 2.5D below the street level and 4D from the bottom of the catch basin sump. The overall height of the catch basin should therefore be 6.5D, with a diameter of 4D.

However, in reality, the dimensions of gully pots differ from this design rule. Therefore, three different gully pot depths were tested. These are 38 cm, 27 cm and 16 cm. Two different second bottoms were used to change the pot depth. Once all the tests at one base were performed, suction pads were used to change it to a new bottom depth.

3.5.5. Rainfall analysis

After obtaining the results of the parameter analysis, the efficiencies relative to the tested discharges were used to analyse three different design rainfall events. These are: T= 0,25 year, T= 0.5 year and T= 1 year.
Additionally, a simulation of T= 0.5 year was carried out with a full gully pot in order to analyse the re-suspension and the sand deposition during a realistic rainfall event.

3.5.6. Data processing

Data was processed using Matlab ®, a program that allows matrix manipulation and plotting functions and data, among others. Graphs were generated to represent and analyse the obtained results.

4. RESULTS AND DISCUSSION

4.1. COMPARISON TO THE PROPOSED FORMULA

To compare the diverse recorded efficiencies, it is needed to first calculate it according to the formula proposed by Butler & Karunaratne (1995). This equation incorporates the discharge *(Q)*, the cross section of the gully pot *(A)*, and the settling velocity (w_s).

$$\epsilon = \frac{w_s}{w_s + \frac{Q}{A}} \, .100 \qquad (1)$$

The settling velocity in laminar condition can be calculated with Stokes's law. This equation is defined as following:

$$w_s = \frac{gd^2\left(\frac{\rho_s - \rho_w}{\rho_w}\right)}{18\nu} \qquad (2)$$

In which g is the gravitation acceleration, ρ_s is the density of the sand particles, d is the diameter of the sand particles, ρ_w is the density of fluid, and ν is the kinematic viscosity of fluid. Stokes' law is applicable in laminar conditions. However, most often the flow is turbulent during lab experiments with gully pots. Therefore, Butler & Karunaratne (1995), proposed to include a correction factor for the settling velocity. The equation is as following:

$$w_s = \alpha \frac{gd^2\left(\frac{\rho_s - \rho_w}{\rho_w}\right)}{18\nu} \qquad (4)$$

In which α is the correction factor, which was set at 0.6.

Figure 18 shows the comparison of test with Q= 1L/s, d= 400 µm and D= 38 cm with the equation proposed by Butler.

It is noticeable that, after around 20.000 seconds, the efficiency starts dropping. This is due to the reduction of the volume in the gully pot caused by increase of sediment trapped, sediment resuspension and reduction of holding time.

By comparing the calculated value of $\epsilon = 82.5\%$, with the recorded value of Eff= 84% at the peak, it is concluded that the formula is reliable for the first 20.000 seconds in this specific graph. The decrease of efficiency is analysed in the following chapter.

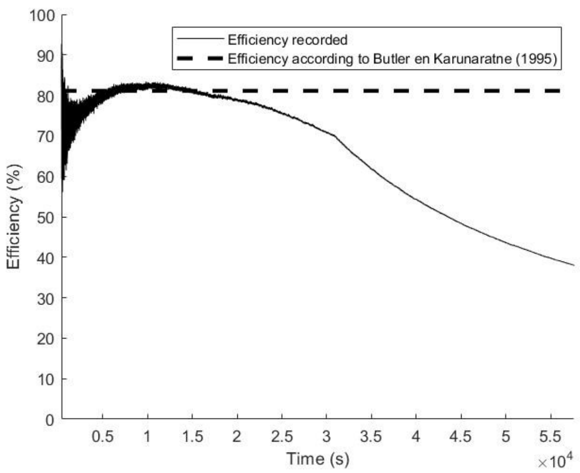

Figure 18: Comparison of the efficiency recorded with the efficiency proposed in the formula by Butler en Karunaratne (1995)

4.2. STAGES OF SEDIMENT DEPOSITION OVER TIME

A comparison between the amount of mass retained within the gully and the mass supplied over the period the time is shown in Figure 19. The mass supply stays constant while the rate at which the mass deposits slowly reduces with time and eventually reaches zero.

Furthermore, Figure 20 suggest that sediment transport can be separated in three stages

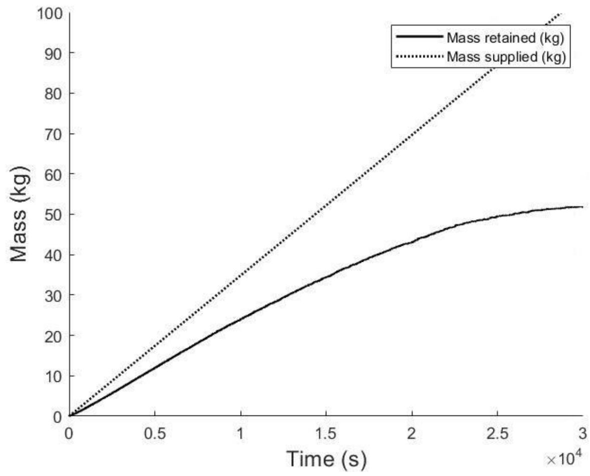

Figure 19: Comparison of the mass supplied and the mass retained in relation to the time

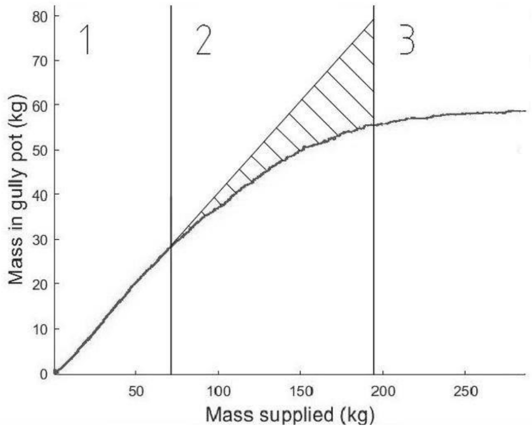

Figure 20: Comparison of mass supplied with mass retained in the gully pot.

4.2.1. Linear build up

During the first stage, the relation between mass supplied and mass retained is linear, meaning that the sediment is building up in the gully pot at a constant rate and high separation efficiencies are realised.

This stage corresponds to the formula proposed by Butler & Karunaratne, 1995. During this stage, the slope of the line can be explained with the discharge and sediment size.

4.2.2. Parabolic build up

As the mass in the gully pot reaches a certain percentage of around 60% to 70%, which may vary depending on inflow, sediment size and depth of the pot, the efficiency starts reducing.

The hatched area in Figure 20 represents the loss of sand due to the influence of the increase of filling percentage in the gully pot. The filling percentage is an important factor in gully pot efficiency because as it increases, the volume of water in the gully pot reduces and, therefore, the velocity of the flow increases and so does the erosion. Another parameter that plays a role in the decrease of the efficiency is the sediment re-suspension.

Resuspension is the phenomenon in which the sand that was settled in the gully pot gets disturbed by the impinging jet and gets suspended in the water. After this occurs, part of the sand will settle again and a certain amount of it will be transported to the sewage system.

To give an advice in the gully pot cleaning frequency, it is fundamental to find out at which filling percentage (of the pot) the efficiency starts decreasing.

4.2.3. Zero build up and risk of clogging

As the gully pot nears the maximum filling, the efficiency decreases to zero. Although the amount of sand in the gully pot does not increase at this stage, the constant inflow of water and sand affects the geometry of the deposited solids.

Additionally, in a real street, there are vibrations of the pavement caused by cars and pedestrians, which can cause the less settled sand particles to collapse into the outlet and clog it.

Figure 21: Stages of sand trap growth: stage 1 (left), stage 2 (middle) and stage 3 (right).

4.3. RE-USING OF THE SAND

Before the realisations of the main tests, it was important to determine whether the sand that settled in the gully pot could be re-used in order to optimise the resources.

Although it was expected that the smallest particles would not settle, the sizes and distribution appeared to be very similar before and after the experiment.

Before using the sand, the median diameter was $d_{50} = 438.89$. For the sand settled in the pot, the median diameter is $d_{50} = 449.18$.

Therefore, it was concluded that the sand could be re-used at least once.

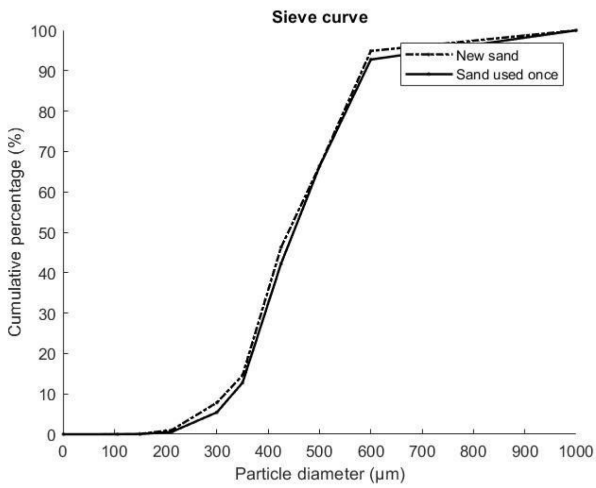

Figure 22: Sieve curve of new and used sand.

4.4. PARAMETERS STUDIED

4.4.1. Concentration

It is known from different researches that the concentration of sediment in the runoff water is not a parameter that has a great influence in the gully pot efficiency. However, the concentration does influence the time it takes for a gully pot to get full. Therefore, the first experiments to be carried out were concentration tests.

A way to compare the influence of the concentration in the gully pot efficiency is by comparing the supplied and retained amounts of sand of different tests. This means that speed of build up over time will differ, because the total amount of sediment supplied is different. Therefore, it is better to compare the accumulated mass versus the supplied mass of the sand. If the efficiency is indeed similar, the two graphs lie on top of each other.

Figure 23 shows the trapped sediment of two different tests with a discharge of 1.5 L/s, sediment size 400 µm, depth of 38 cm and concentrations of 4.82 g/L and 2.63 g/L respectively.

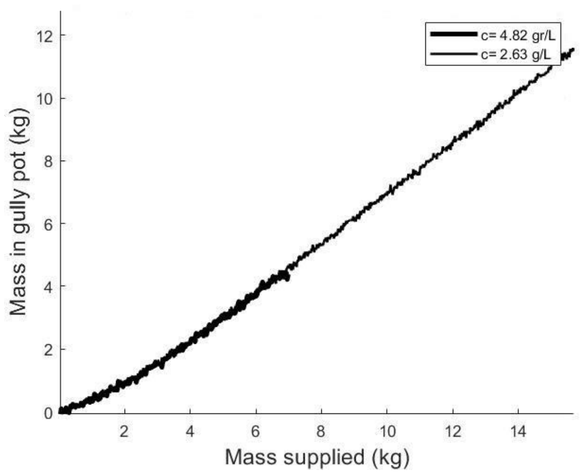

Figure 23: Comparison of the mass trapped relative to the mass supplied, for two different concentrations.

After analysing the amount of trapped sediment for the two tests, two lines lying on top of each other emerged, identifying that the influence of the concentration is insignificant.

With these comparisons there is an agreement with the previous tests that claimed that the sediment concentration has a negligible influence in the gully pot's trapping efficiency.

4.4.2. Discharge

The discharge is an important parameter in the existing efficiency equation. Therefore, this section studies the influence of this parameter on the capturing efficiency.

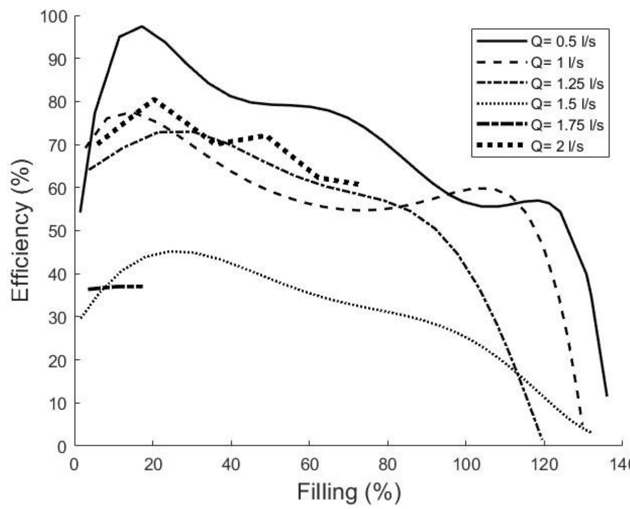

Figure 24: Efficiency for different inflows in relation with the filling percentage of the gully pot.

The recorded efficiency of the gully pot is defined as:

$$\mathrm{Eff} = 100\,.\frac{Mt}{Ms} \quad (5)$$

In which M_t is the mass trapped and M_s is the mass supplied.

Figure 23 shows this efficiency compared to the filling percentage of the sand trap. The dimensions of the sand are: 35 by 35 cm in the horizontal plane and 38 cm in height. This has been taken as a 100% filling of the gully pot. Although it would be ideal to correlate the 100% filling to the moment when it clogs, it is not realistic since the geometry and discharge determine the maximum filling of the pot.

As it can be seen in the Figure 23, the maximum filling percentage the gully pot can be filled before clogging is around 140%. Although the figure only shows the tests with d= 400 µm, and D= 38cm, it has been confirmed by comparing it with different tests.

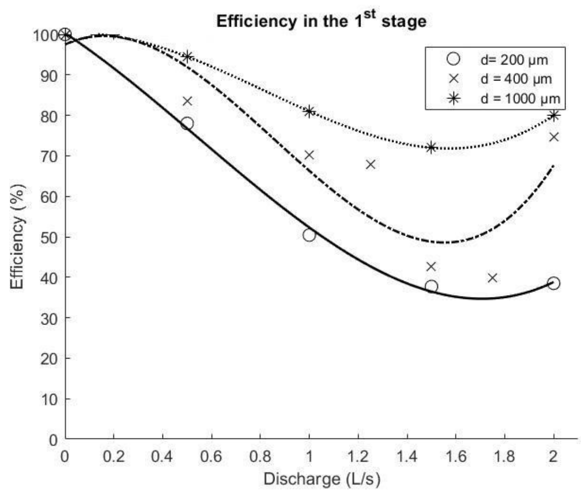

Figure 25: Trapping efficiency of the pot for three sizes of sand particles in relation with the discharge

For the discharges of 0.5 - 1.5 L/s, the experiment confirms that the trapping efficiency is inversely proportional to the discharge. The higher the discharge, the shorter the water stays in the gully pot.

However, at a discharge of 2.0 L/s the efficiency increases. At this discharge the flow pattern was seen to have changed drastically. It was observed that the impinging jet was very close to the outlet of the gully pot, causing the flow in the gully pot to follow a more circular motion. Additionally, most of the bubbles caused by the impinging jet flow directly to the outlet. These results suggest that the influence of the flowed pattern could influence the efficiency stronger than just simply via the value of the discharge.

Figure 25 shows the two possible main streams corresponding to the two aforementioned flow patterns

As can be seen in the Figure 26, a particle of sand travels a longer route in the second type of flow pattern (at the right of the image) in order to leave the gully pot, which increases the holding time of the particles, facilitating them to settle.

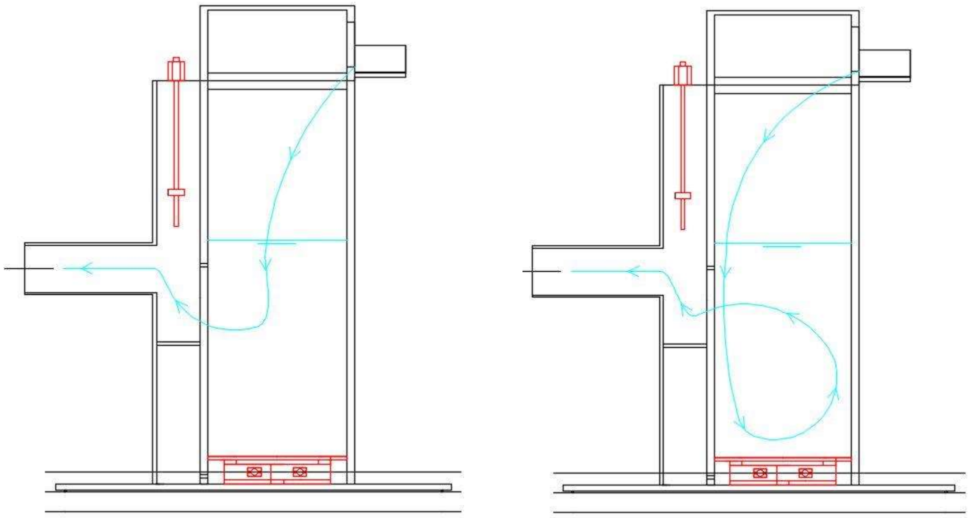

Figure 26: Main flow patterns in the gully pot.

Although in this experimental set-up the tipping point between the two flow patterns happened at higher discharges than 1.5 L/s, there might be an influence of the location where the jet hit the water. This depends on the flow velocity and pot geometry. Therefore, further research should be conducted into the relation between the flow velocity and the discharge in order to determine at which discharge the flow pattern changes.

Another phenomenon that depends on the flow pattern, discharge, and partly on sediment size, is the angle at which sand settles relative to the outlet. The geometry of the deposited solids has a great influence in the risk of clogging, as previously explained in the third stage of sediment deposition over time.

During the sedimentation process in the gully pot, not all the sand settles in the sand trap, but a small percentage of sand also accumulates in the syphon under the outlet pipe.

In Figure 27 it is visible that, at a low discharge (left), there is barely any sand under the exit pipe, but at higher discharges (right) , sand accumulates in the syphon under the exit pipe. The solids accumulated in the syphon are constantly resuspended and filled by inflowing sediment. The build-up rate in the syphon is closely related to the efficiency.

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Figure 27: Different geometries of the deposited solids for Q= 0.5 L/s (left) and Q= 1.5 L/s (right)

4.4.3. Sediment size

The results of the sediment size tests show a clear influence of the sediment size in the trapping efficiency of gully pots, which is directly proportional. The heavier the particles, the faster they will settle in the bottom of the pot.

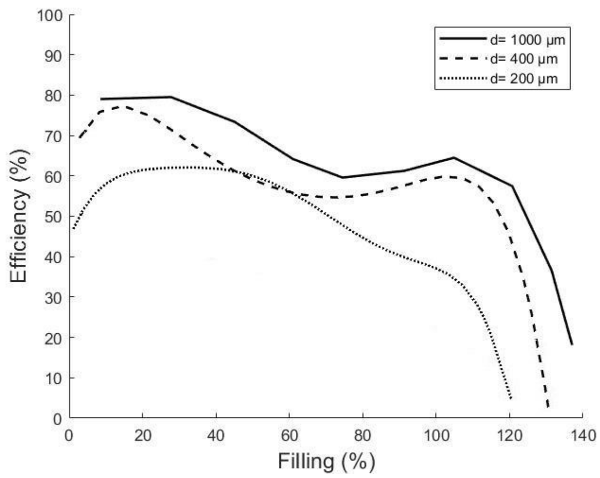

Figure 28: Efficiency for different sediment sizes in relation with the filling percentage of the gully pot.

When comparing three different sediment sizes, it is visible that the difference that they represent is evident. For the sand with a diameter of 1000 μm, a maximum efficiency of Eff= 90% happens, while it is Eff= 75% for 400 μm and Eff= 60% for 200 μm.

Thus, a Figure representing a correlation between sediment size and trapping efficiency for different discharges can be drawn,

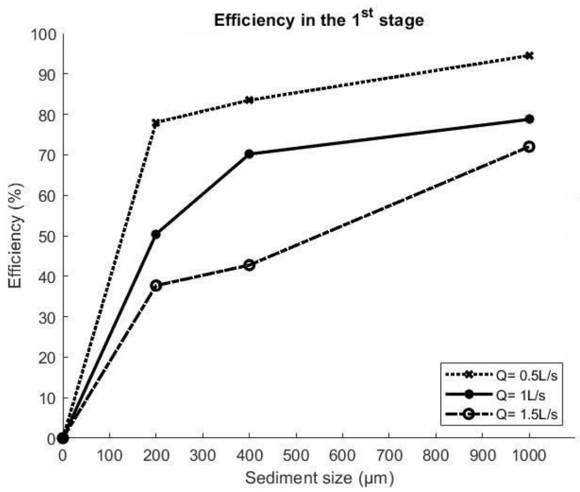

Figure 29: Trapping efficiency of the pot for three discharges in relation with the sediment size

The three lines represent the relation between trapping efficiency of gully pots and sediment size, tested at different discharges

The slope between 200 μm and 400 μm is steeper at 1 L/s than at 0.5 L/s and 1.5 L/s. This is because both 0.5 and 1.5 L/s are relatively small and big discharges, and the size of the sediment does not influence as much as the discharge does.

4.4.4. Gully pot depth

The depth of the gully pot produces a change in the flow pattern. Therefore, the efficiency will vary.

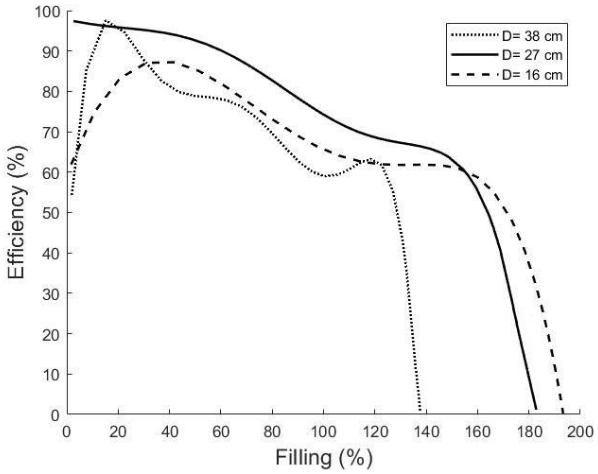

Figure 30: Efficiency for different pot depths in relation with the filling percentage of the gully pot.

The different depths have an influence in the maximum filling percentage in the gully pot. While a regular pot (D= 38 cm) has a maximum filling before clogging of about 140%, a smaller pot, of D= 16 cm, gets full to its 190%.

Although the top level that the deposited solids reaches is roughly the same level as D= 16 cm, the percentages relative to the total are different.

Since the 100% is set to be at the level of the outlet, the amount of sand over it represents a bigger part to the smaller pot, and therefore the final filling percentage is bigger.

It is evident that, although the efficiencies are very similar, there is a small difference between them. This is due to the change of depth of the gully pot.

Although the depth could be mistaken by the filling percentage, the fact is that the two of them act very differently. To explain how both parameters act, the efficiency with D= 38 cm and D= 16 cm can be compared:

First, the volume relative to the 100% filling rate is calculated for each pot.

$$V_{38} = D \, . \, A = 0.04655 \, m^3$$
$$V_{16} = D \, . \, A = 0.0196 \, m^3 \quad (6)$$

where V_{38}= volume of the sand trap when D= 0.38 m (m^3)
V_{16}= volume of the sand trap when D= 0.16 m (m^3)
D= depth (m)
A = cross-sectional area of the gully pot (m^2)

By subtracting V_{16} from V_{38}, the volume representing the difference can be obtained.

$$\Delta V = V_{38} - V_{16} = 0.02695 \, m^3 \quad (7)$$

In which ΔV is the volume difference (m^3)

To compare the depth with the filling percentage, this volume is associated with the percentage of filling that the volume represents for the most conventional pot (D= 38 cm).

$$\text{Eff} = 100 \cdot \frac{0.02695}{0.04655} = 56.9\% \quad (5)$$

The efficiency of a pot of D= 38 cm filled at 56.9% has a value of Eff= 78.43%, while the efficiency of an empty pot of D= 16 cm is Eff= 85.5%.

The difference in efficiencies happens because the sand trap mostly grows in an angle respect to the outlet and, therefore, there is an increase of the surface area of the top of the deposited solids.

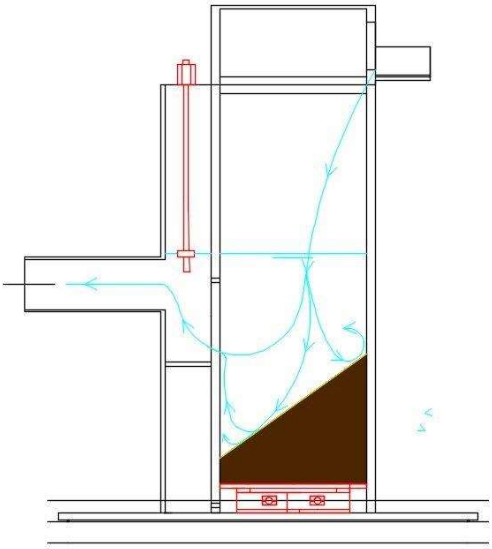

Figure 31: Comparison of the flow patterns with a pot of D= 38 cm filled at 56.9% and an empty pot of D= 16 cm.

After comparing the different tests, Figure 32 was produced to show the relation between the efficiency and the depth of the gully pot for different discharges and d= 400 µm.

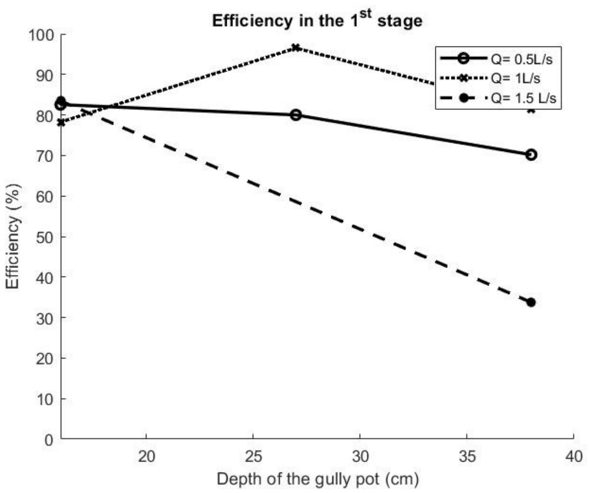

Figure 32: Trapping efficiency of the pot for three discharges in relation with the gully pot depth.

In the graph it is visible that at Q= 0.5 L/s and Q= 1.5 L/s, the efficiency is directly proportional to the depth, while at Q= 1 L/s it is inversely proportional. The depth of the gully pot proved to affect the efficiency inconsistently. More tests should be carried out with different sand types in order to determine a pattern.

4.5. EFFICIENCY DURING RAINFALL EVENTS

Previous experiments have been conducted at a constant discharge. However, in reality, storm events differ in intensity over time.

This could change the settling and resuspension behaviour. For the examination of this behaviour, three different storm events were analysed. These storm events are so-called 'design storm events' created by "RIONED" for testing drainage systems.

The created storm events had different return periods. For this analyses storms with a return period of T=0.25 year, T= 0.5 year and T= 1 year were analysed.

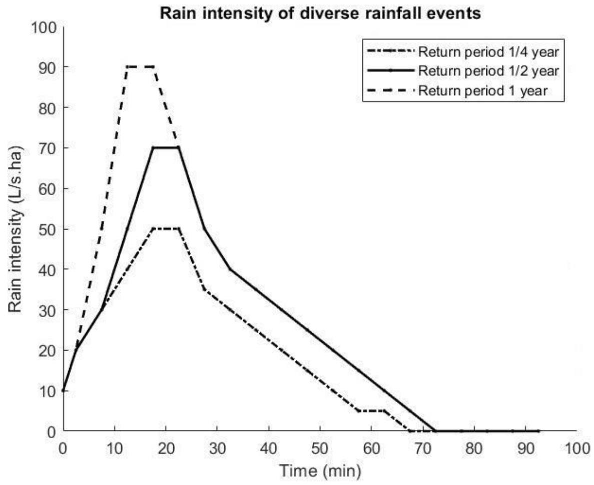

Figure 33 Rainfall intensity of events with different return period.

A return period is an estimation of the likelihood of an event, in this case, a rainfall event.

In a rainfall event, the discharge is not constant, but it has a peak discharge.

The different discharges that inflow the gully pot in each rainfall event can be calculated by using the rational method. The recorded intensities, provided by "RIONED", can be related to the designed catchment area of 200 m^2 (Rijkwaterstaat, 1988).

$$Q = C \times I \times A \qquad (8)$$

This equation incorporates the discharge *(Q, in m^3/s)* , the run-off coefficient *(C, -),* rain intensity *(I, in l/s.ha*) and the cross section of the gully pot (*A, in m^2*).

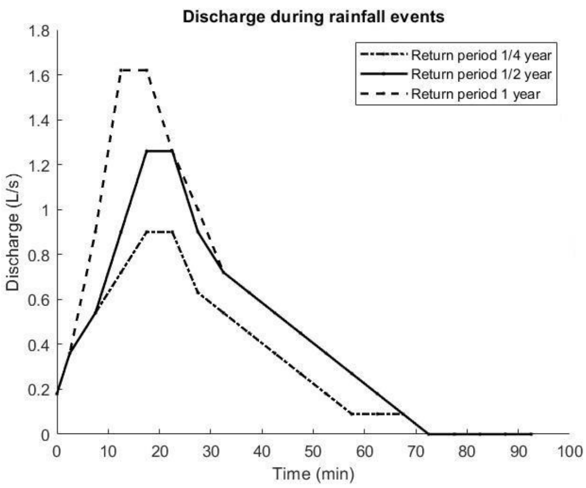

Figure 34: Discharge into the gully pot of the different proposed rainfall events

As it can be seen in the Figure 34, as the return period increases, so does the peak discharge of the rainfall event.

By interpolating the discharges in Figure 34 to the efficiency in Figure 25, it is possible to produce a graph that represents the efficiency of the gully pot for the different return periods.

By using these graphs, and a certain concentration, it is possible to predict how much sediment will settle in the gully pot. According to Xanthopoulos & Augustin (1992) the grain diameter of 350 μm is the basis for the design of sediment-free sewer systems.

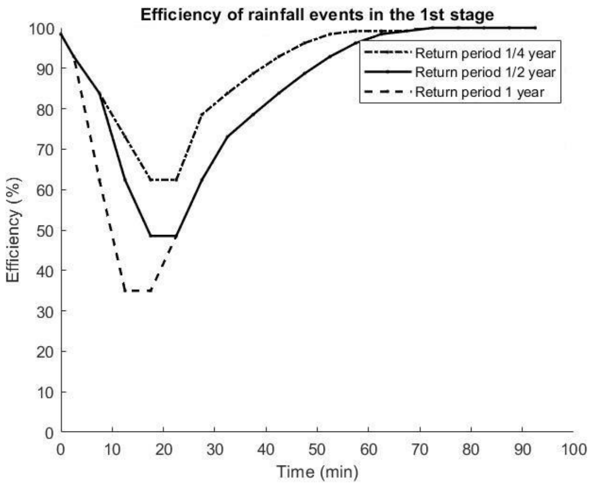

Figure 35: Gully pot efficiency for the different proposed rainfall events

However, this does not incorporate the induced resuspension by the changing discharge.

One of the rainfall events (T=0.5 year) was recreated in the lab. The experiment was performed with a 100% filling of the sand trap, in order to see how a full gully pot reacts to a realistic rainfall simulation.

Figure 36 shows the mass balance of T= 0.5 year.

As is noticeable in the Figure 36, the decrease of mass happens until the maximum discharge is reached. At the moment of the peak discharge, almost 1 kg of sand has been resuspended and transported into the sewage system. After reaching the peak discharge, the effect of re-suspension stops and, therefore, the sediment starts building in the gully pot.

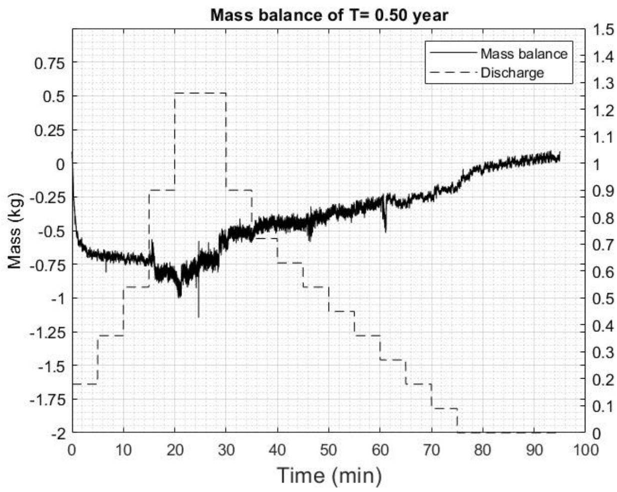

Figure 36: Mass balance of the simulation of T= 0.5 year

At this simulation, the initial and final amount of sand is roughly the same. At a rainfall of, for example T= 1 year, with the same concentration as the simulated test, the amount of sand re-suspended would be higher, and therefore the mass balance would be negative.

5. Conclusions and Recommendations

5.1. Conclusions

After a total of twenty-seven tests, with six different discharges, three sediment types and three pot depths, it was concluded that the most influential parameter in gully pot efficiency is the flow pattern.

The formula proposed by Butler & Karunaratne (1995), defines the efficiency as a variable of settling velocity of the particles, discharge and cross-sectional area of the gully pot. This formula only applies for the first stage of gully pot efficiency, but it neglects the progressive decrease of efficiency in the gully pot, caused by the reduction of the volume of water and therefore the retaining time of the particles (stage 2).

When the gully pot is entirely filled, although the efficiency is zero, a change of the geometry of the deposited solids happens. This alteration in the geometry combined with the vibrations caused by cars and pedestrians in the street can cause the deposited solids to collapse into the syphon. When this does occur, the exit of the gully pot is likely to clog and result in urban flooding.

Concerning the parameter analysis, the results of the tests show a similarity with the previous researches. As for the concentration, the tests showed that this parameter has a small influence on the gully pot efficiency. The effect of the concentration lies in the duration of the tests. In respect to the discharge, the tests confirm that its relation with the efficiency is inversely proportional. Nevertheless, the observed change in flow pattern and its affect to the efficiency shows that it is a parameter which should be more researched about.

The flow pattern is mainly influenced by gully pot geometry, velocity at the inlet, discharge and inlet direction. When the flow pattern changes, so does the holding time, which is a factor that heavily influences gully pot efficiency.

Regarding the sediment size, the tests confirm previous researches: the efficiency is directly proportional to the particle size. The combination between the discharge and sediment size heavily influences gully pot efficiency. In respect to the depth, the tests show that the efficiency at a certain gully pot depth is different from its associated filling percentage.

The inflowing discharges during different rainfall events were calculated by means of the rational method. The calculated discharges were used to represent the trapping efficiency of the gully pot during the different rainfall events.

Cleaning of the gully pot:

To propose an optimum filling percentage at which the sediment should be removed from the pot to avoid urban flooding, an analysis of the efficiency decrease patterns was carried out. It is important to find a balance between keeping gully pot efficiency at an acceptable percentage and a reduced risk of clogging.

In lab results, the greatest drop in efficiency happened at a range of 100% to 130%, depending on the discharge. Even though clogging does not happen until 140% filling of the pot, this is in lab conditions and at a constant inflow. In real conditions, it is reasonable to assume that a conventional gully pot, with a depth of 38 cm, filled at more than 100% of its capacity is subject to clogging. Although lab results show that a storm event would not clog the pot at 100% filling, perhaps other larger solids could cause gully pot clogging.

After comparing the drop of efficiency in the different graphs and recognising efficiency decrease patterns, it is recommended to empty the gully pots when the sand trap is filled at 80% of its capacity. Although at 80% filling, the efficiency is lower than at the first stage of sediment deposition, it has not reached its biggest drop yet. The balance between efficiency and reduced risk of clogging is optimum at 80% filling of the gully pot.

5.2. RECOMMENDATION

The tests' results suggest that the flow pattern in the gully pot is a parameter that heavily influences the efficiency. This is due to the variation in holding time of the particles. More research should be done about the parameters that most influence the flow pattern, namely gully pot geometry, velocity at the inlet and inlet direction.

To check the hypotheses on the influence of the flow pattern, it should be better visualised. This can be done with a technique called particle image velocimetry (PIV). The use of PIV measurements could then be used to determine the optimum angle at which the water should enter the gully pot for a maximal gully pot efficiency.

Field measurements should be performed to determine the real tipping point between the two different flow patterns. For this purpose, it is necessary to study the relation between the discharge inflowing into the gully pot and the velocity of the water at the inlet. These field measurements should also record the average concentration of sediment in different street types.

Another important variable that influences the flow pattern is the inlet direction relative to the outlet pipe. Tests could be performed by rotating the inlet 90 and 180 degrees, for side and back inflow tests respectively. These tests would be used to determine the most efficient flow pattern relative to the inlet direction.

In respect to the proposed formula for gully pot efficiency, it is concluded that does not include some parameters that affect the efficiency, such as the filling percentage of the gully pot and the holding time. The progressive decrease of efficiency should be studied more in depth in order to propose a formula that takes into account the diverse factors that influence it.

With knowledge in the average sediment concentration in different types of streets, combined with the adjusted efficiency tables for the new relation between discharge and inflow velocity, the progressive sediment deposition could be predicted.

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APPENDIX A: EXPERIMENTAL MATRIX

	Q (L/s)	d (µm)	D (cm)	S_s (g/s)	C (g/L)
Concentration 1	1	400	38	0.7832	0.7832
Concentration 2	1	400	38	2.4952	2.4952
Discharge & Depth 1	0.5	400	38	1.75	3.5
Discharge & Depth 2	1	400	38	2.3	2.3
Discharge & Depth 3	0.5	400	27	1.04	2.08
Discharge & Depth 4	1	400	27	1.95	1.95
Discharge & Depth 5	0.5	400	16	1.11	2.22
Discharge & Depth 6	1	400	16	1.22	1.22
Discharge & Depth 7	1.5	400	16	1.17	0.78
Discharge & Depth 8	1.5	400	38	3.852	2.568
Discharge & Depth 9	2	400	38	5.27	2.653
Discharge & Depth 10	1.25	400	38	3.47	2.776
Discharge & Depth 11	1.75	400	38	5.06	2.8914
Sediment Size 1	0.5	200	38	0.94	1.88
Sediment Size 2	1	200	38	1.48	1.48
Sediment Size 3	1.5	200	38	6.37	4.24
Sediment Size 4	2	200	38	8.28	4.14
Sediment Size 5	0.5	400	38	1.75	3.5
Sediment Size 6	1	400	38	2.3	2.3
Sediment Size 7	1.5	400	38	3.852	2.586
Sediment Size 8	2	400	38	5.27	2.653
Sediment Size 9	0.5	1000	38	1.2	2.4
Sediment Size 10	1	1000	38	1.78	1.78
Sediment Size 11	1.5	1000	38	4.14	2.76
Sediment Size 12	2	1000	38	4.31	2.155
Rainfall T= 0.25 years	Variable	400	16 (filled 100%)	1.05	Variable
Rainfall T= 0.5 years	Variable	400	16 (filled 100%)	1.198	Variable

Additionally, diverse calibration experiments were carried out before the main tests.

APPENDIX B: MEASURING INSTRUMENTS

Measurement	Measuring instruments			Calibration
	Sensor		Amplifier	
Type	Type	Reach	Type	
Temperature (gr.C.)	PT100	100 gr.C.	RS	12.5 gr/V+2
Force (N)	Scaime AVX30	300N	KWS 3020b	30N/V
Flow (l/s)	F&P-D10d	3,5 l/s		0.875l/V+1
Water level (mm)	Temposonic	250mm		12,5mm/V-10

APPENDIX C: CALIBRATION OF THE DISCHARGE METER

Type: F&P – D10d 1465D

Calculate discharge from flow velocity: 40l/s at 1m/s

This means 1m/s 40l/m / 60 sec: 0.666 l/s nij 1m
This means 10m/s 0.666 l/s x10= 6.666 l/s

Simulate the discharge meter with the calibrator and insert a range of 3.5 l/s
The calibrator must be 4.5/6.666= 5.25 m/s
The calibrator should display 5.000 volt
If not, then change the convertor with the switch

Adjust with the switch to 3.5 l/s= 522 sd.
Check the following steps with the calibrator:

Settings calibrator (m/s)	U_{out} (V)
0	1.004
1.3125	2.007
2.6250	3.003
3.9375	4.002
5.250	5.000

APPENDIX D: CALIBRATION OF THE WATER LEVEL METER

Type: GHM0250MD601V3
MTS Temposonic G-series

The used devices can be converted to SI units.

Power 24Vdc	TTi EX354T
Voltmeter	Agilent 34401A

Calibration:	[(Uuit + 50N) + (|Uuit| - 50N)] : 2 = 10 V ± 5 mV	
Conversion:	12.5mm/V	(-10V…+10V ≡ -125mm…+125mm)
Range:	250mm	

Calibration:

Distance (mm)	Output voltage (Volt)
0	-10.020
25	-8.017
50	-6.010
75	-4.007
100	-2.004
125	0
150	2.004
175	4.009
200	6.013
225	8.019
250	10.021

APPENDIX E: CALIBRATION OF THE THERMOMETER

Type: PT100-RS

1. Check on damage and dust. If necessary clean the device with a degreaser (concentration 6%)

2. Check the imput voltage. Turn on the power supply and keep it running for 10 minutes for it to properly warm up. Measure according to the following table:

	Requirement: +12V -24V[1]
Power	+15 V

3. Calibration: The range is 2-10 Volt = 0-100 ºC.

The requirement for this calibration check:

Check at three temperatures (0,20 and 50 ºC). Check that the values will deviate less than 0,05 ºC

Imputed temp (ºC)	U_{out} (V)	Measured temp (ºC)	Deviation temp (ºC)
0.326	2.026	0.325	0.001
10.291	2.821	10.263	0.028
20.081	3.606	20.075	0.006
30.184	4.415	30.187	0.003
40.190	5.217	40.212	0.022
50.226	6.018	50.225	0.001

APPENDIX F: CALIBRATION OF THE FORCE METER

Type: Scaime AVX30 C3 CH 15e TR

Range: 300N
Insulation resistance relative to outside $> 10^4\ M\Omega$
Insulation resistance relative to protection $> 10^4\ M\Omega$

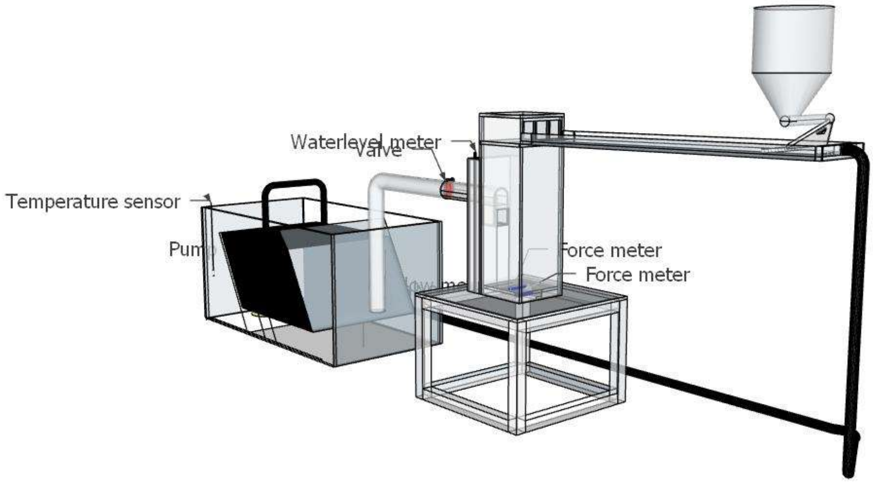
0 Point: -69 U_{strain}

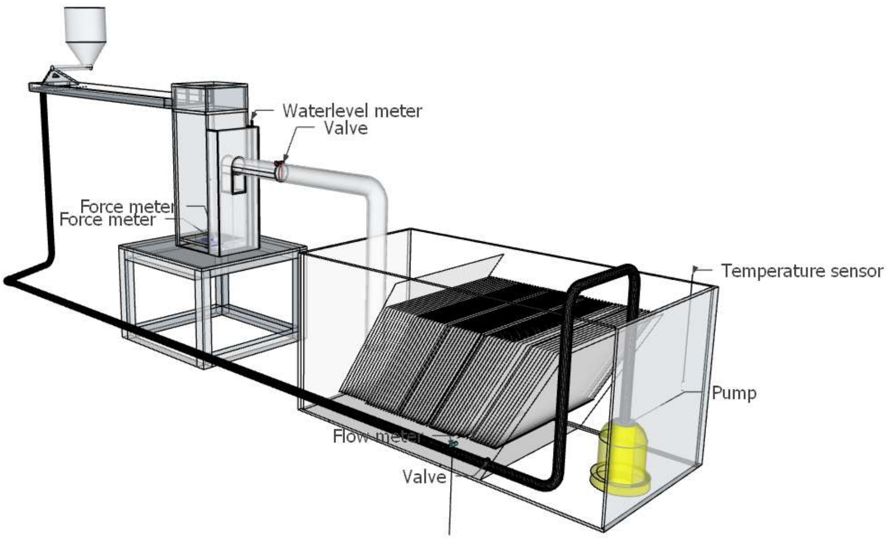
Calibration: Calibrate up to 300N

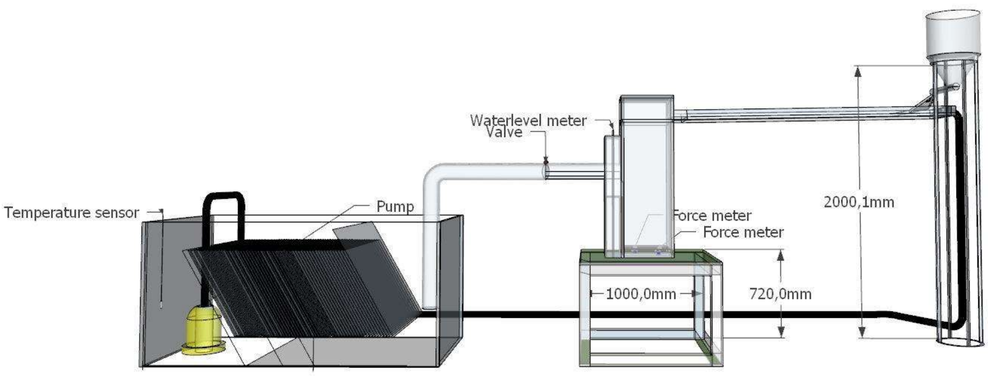
N	+(v)	-(v)
0	0	0
10	0.334	-0.034
20	0.668	-0.667
30	1.001	-1.001
40	1.335	-1.335
50	1.669	-1.669
60	2.003	-2.002
70	2.336	-2.336
80	2.670	-2.668
90	3.004	-3.004
100	3.338	-3.338
120	4.005	-4.005
140	4.672	-4.673
160	5.338	-5.341
180	6.004	-6.009
200	6.671	-6.677
220	7.337	-7.336
240	8.003	-8.004
260	8.668	-8.677
280	9.333	-9.349
300	10.000	-10.012

KWS-settings U_b: 5 Volt Sensitivity.: 1mV/V Range: 10mV/V bij 1 V_{ub}
Calibration number (at a range of 10mV/V) at 1 V_{ub}: 4.886 Volt.

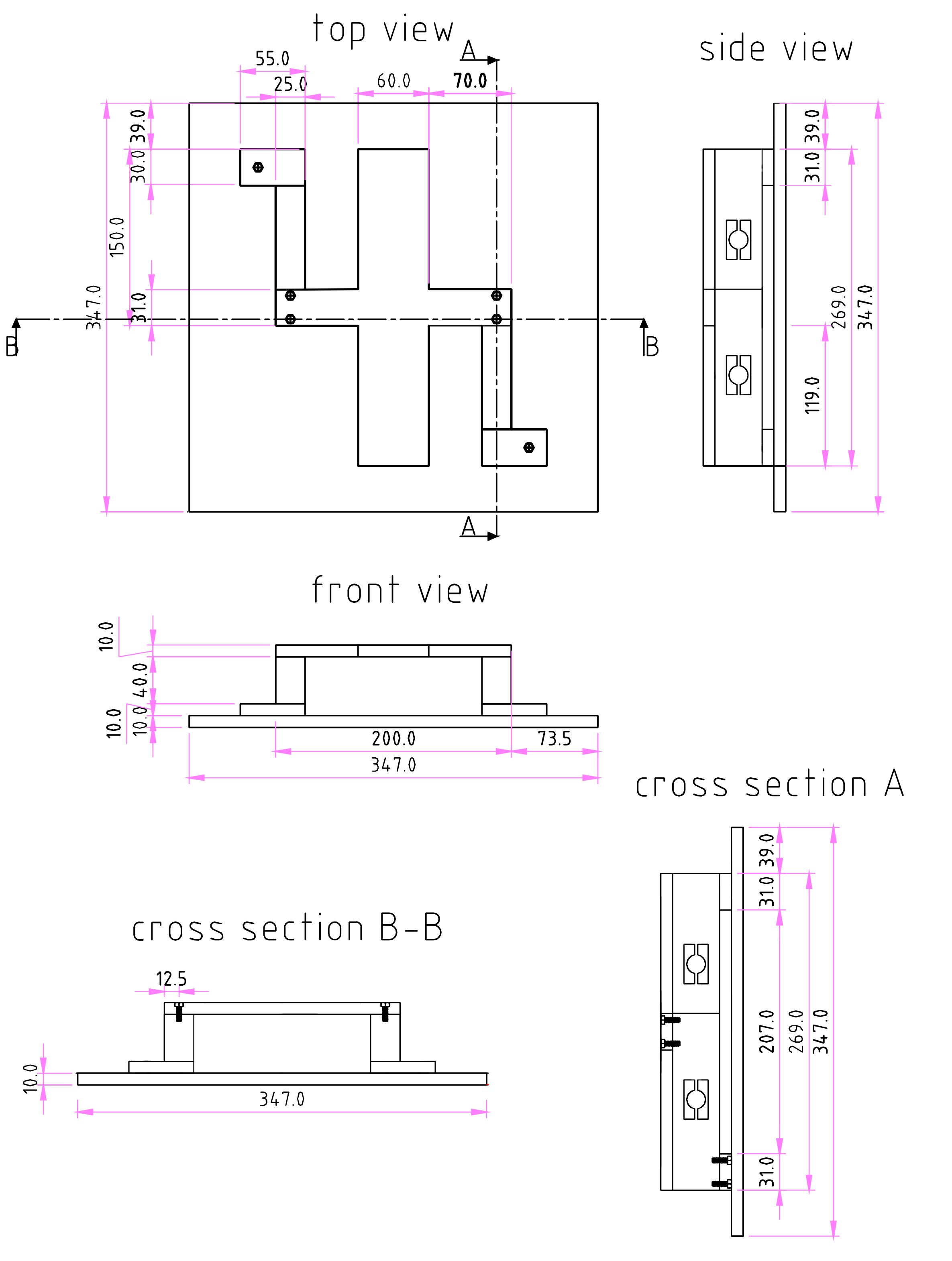
APPENDIX G: 3D DRAWINGS







APPENDIX H: TECHNICAL DRAWINGS



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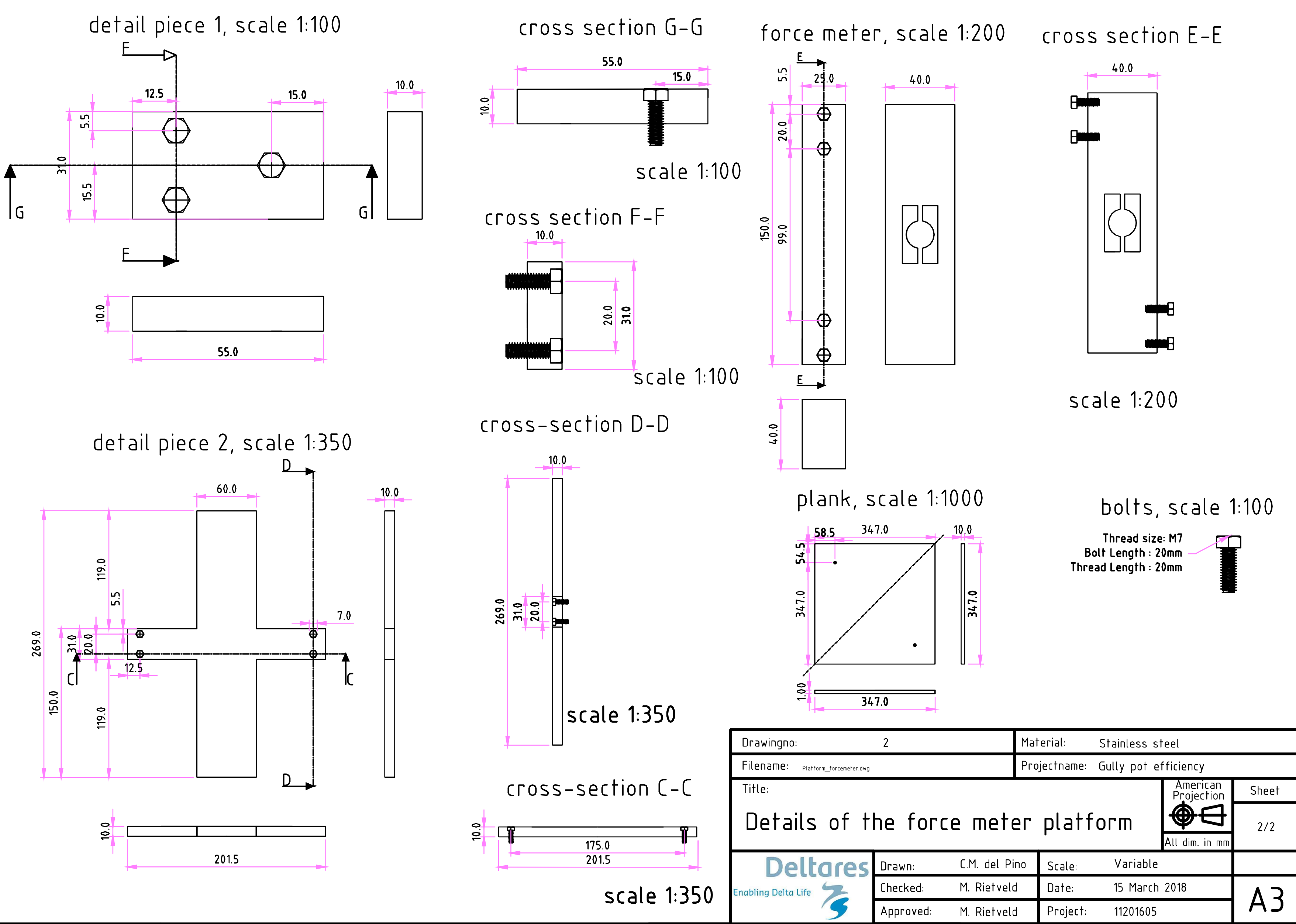
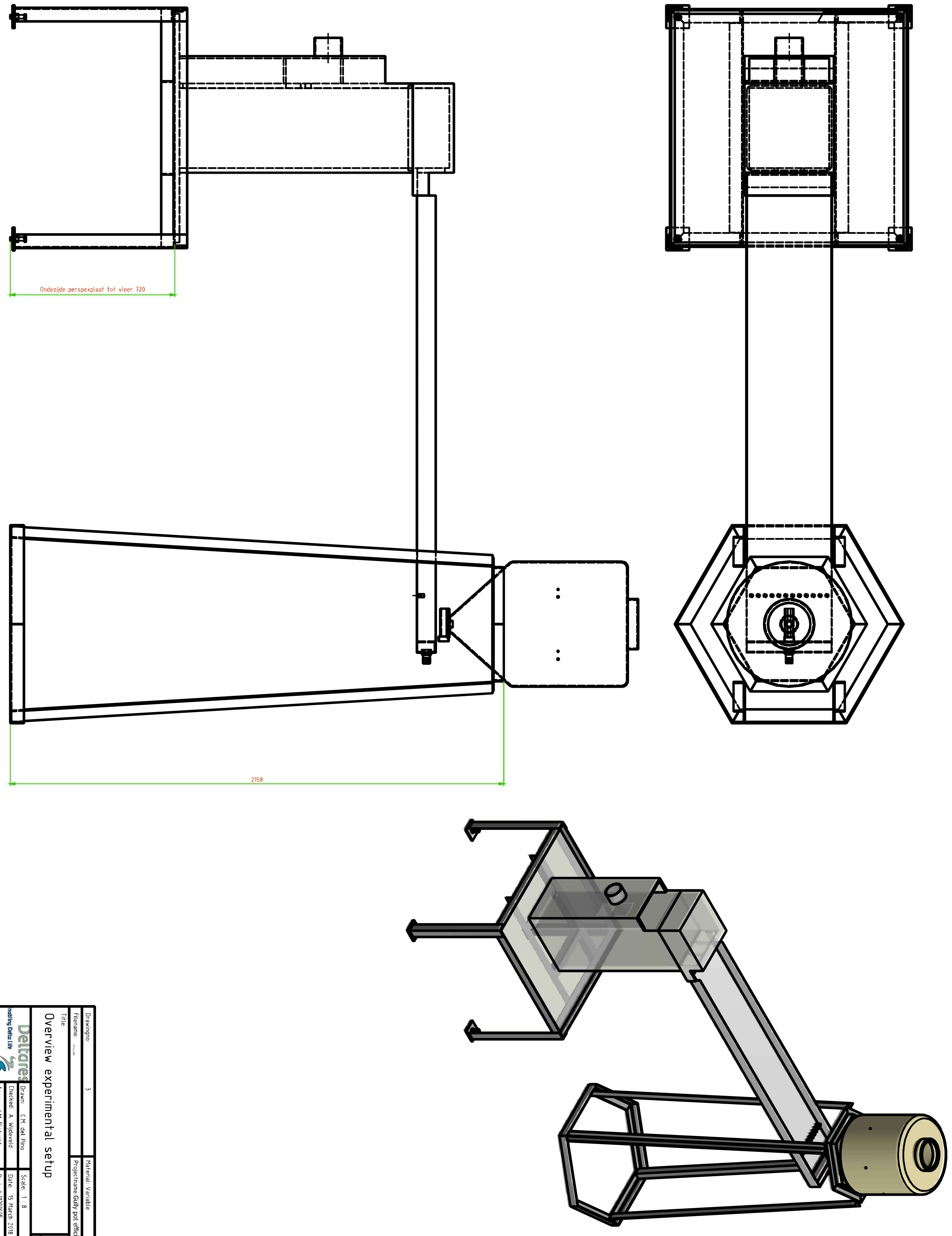
Title: Force meter platform		American Projection / All dim. in mm	Sheet 1 / 2
Deltares Enabling Delta Life	Drawn: C.M. del Pino	Scale: 1:500	
	Checked: M. Rietveld	Date: 15 March 2018	A4
	Approved: M. Rieveld	Project: 11201605	



Drawingno: 2		Material: Stainless steel	
Filename: Platform_forcemeter.dwg		Projectname: Gully pot efficiency	
Title: Details of the force meter platform		American Projection All dim. in mm	Sheet 2/2
Deltares Enabling Delta Life	Drawn: C.M. del Pino	Scale: Variable	
	Checked: M. Rietveld	Date: 15 March 2018	A3
	Approved: M. Rietveld	Project: 11201605	



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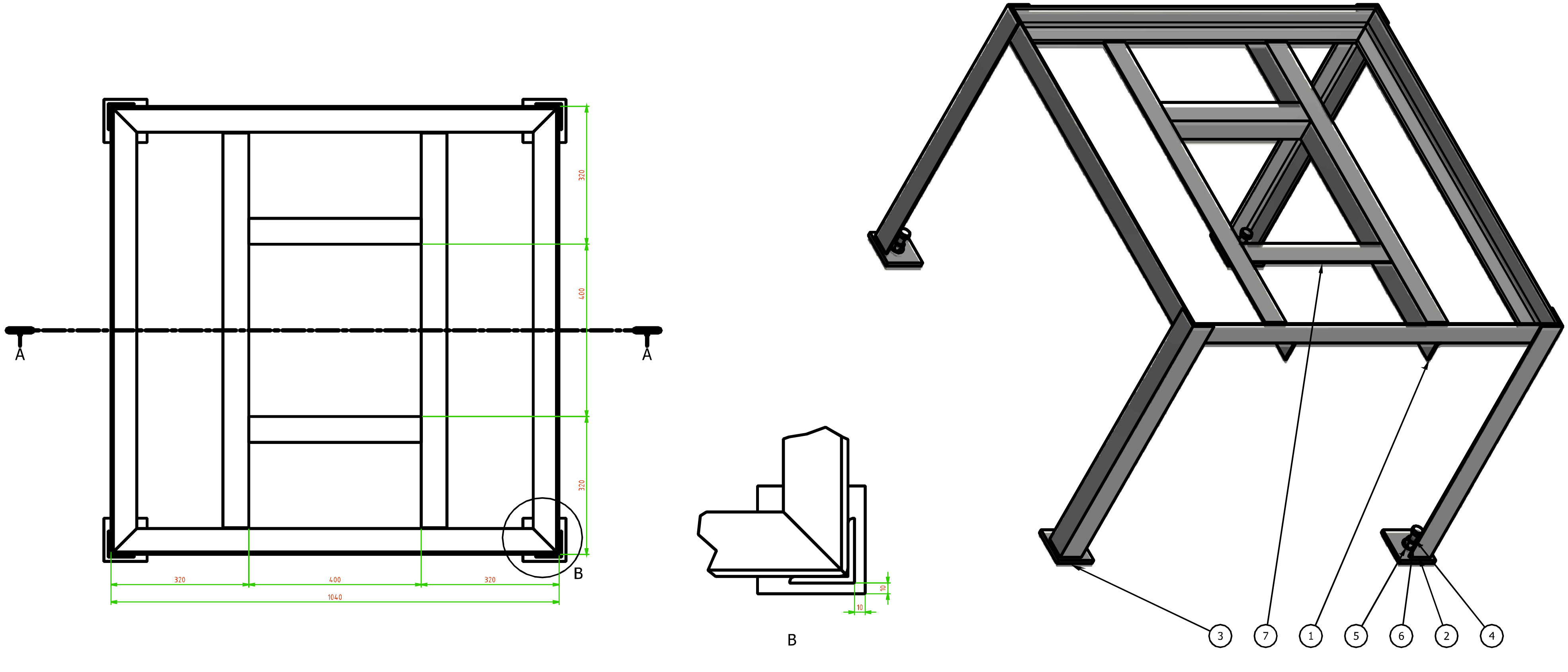
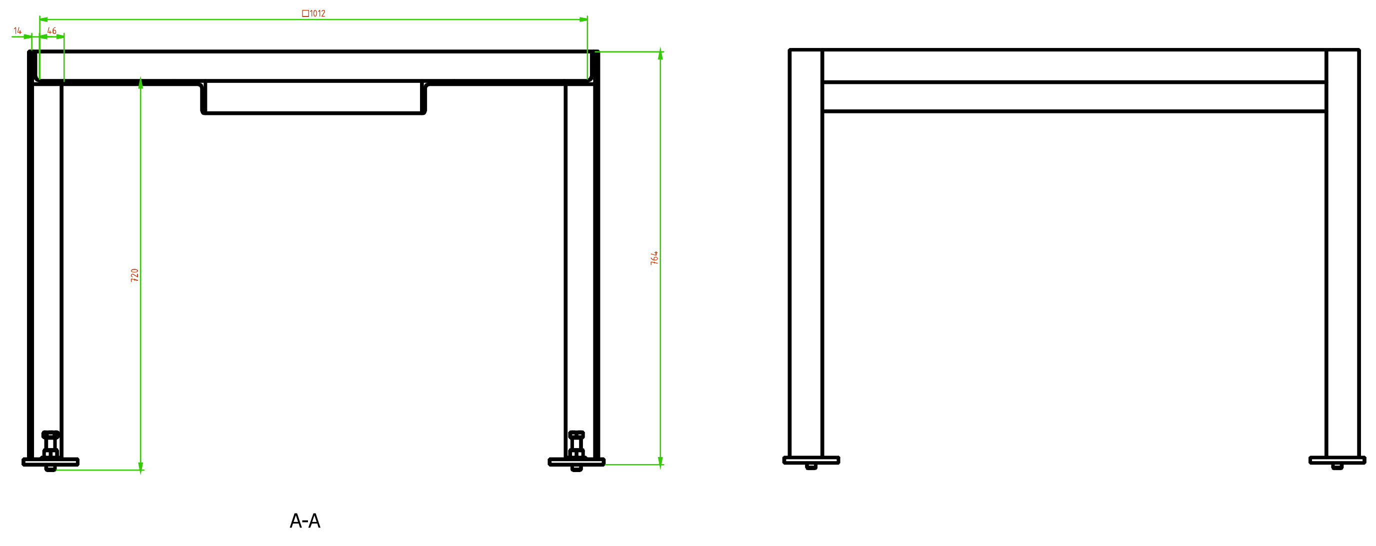
Filename:	Projectname: Gully pot efficiency
Title: Overview experimental setup	American Projection; All dim. in mm
Drawn: C.M. del Pino	Scale: 1 : 8
Checked: A. Wijdeveld	Date: 15 March 2018
Approved: M. Rietveld	Project: 11201605
Deltares — Enabling Delta Life	Sheet 1 / 1 — A1

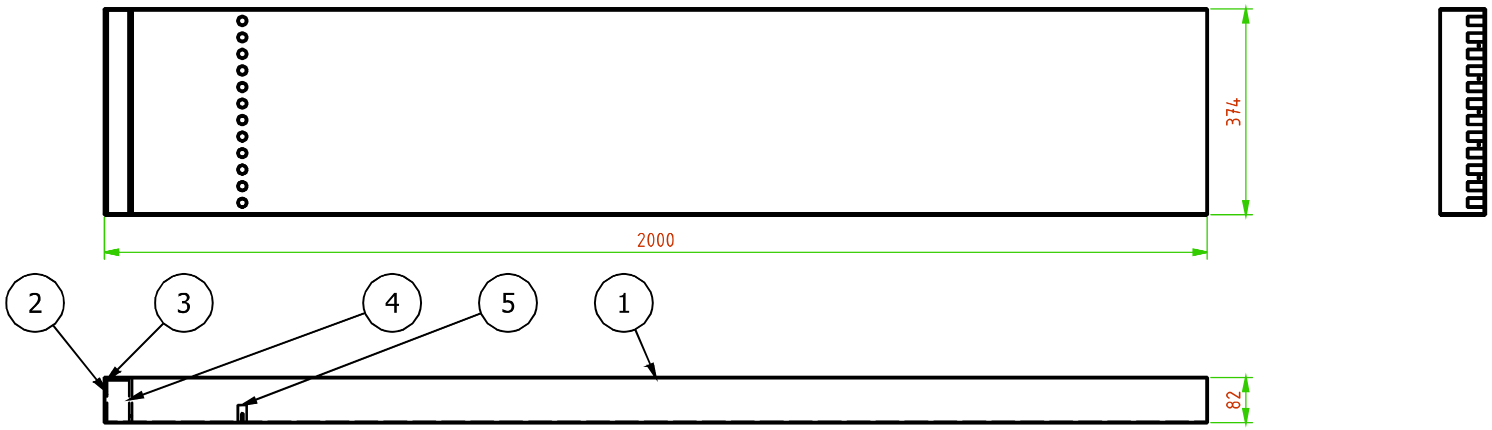


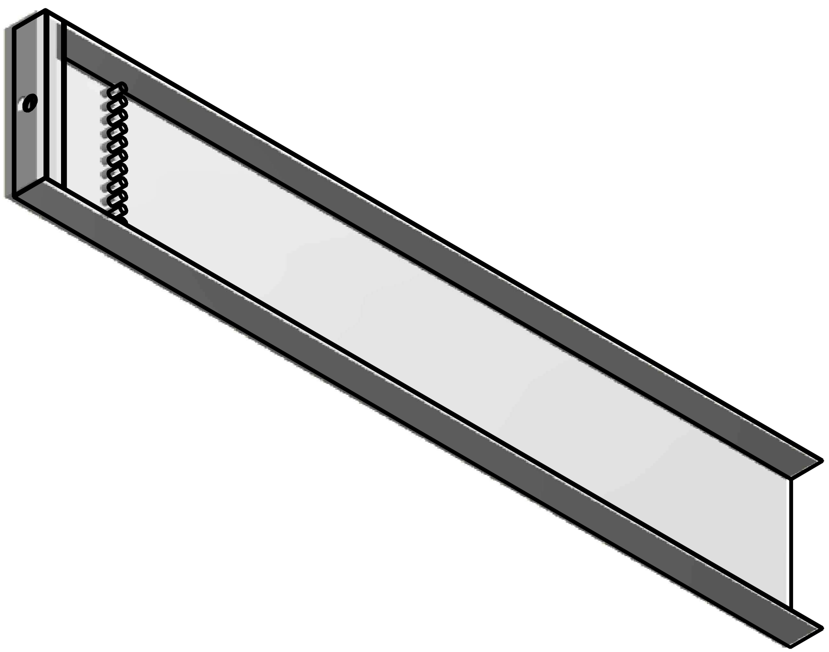


Weight +/- 57kg

PARTS LIST		
ITEM	QTY	PART NUMBER
1	6240 mm	L60x60x6-1040
2	3016 mm	L60x60x6-754
3	4	Groundplate_M16
4	4	Stud bolt M16 x 60
5	4	Ring 18mm
6	4	Nut M16
7	800 mm	L60x60x6-400

Drawingno: 4		Material: Stainless steel	
Filename:		Projectname: Gully pot efficiency	
Title: Table		American Projection, All dim. in mm	Sheet 1 / 1
Deltares Enabling Delta Life	Drawn: C.M. del Pino	Scale: 1 : 5	A1
	Checked: A. Wijdeveld	Date: 15 March 2018	
	Approved: M. Rietveld	Project: 11201605	





PARTS LIST

ITEM	QTY	PART NUMBER
1	1	Aluminium gully
2	1	PVC plate with hole 1
3	1	PVC Lid
4	1	PVC Outflow plate
5	12	PVC Pilars

Drawingno: 5
Material:
Filename: Setup_3.dwg
Projectname: Gully pot efficiency

Title:
Gully

American Projection
All dim. in mm
Sheet 1 / 1

Deltares
Enabling Delta Life

Drawn: C.M. del Pino
Checked: A. Wijdeveld
Approved: M. Rietveld
Scale: 1 : 10
Date: 15 March 2018
Project: 11201605
A3