Swale Filter Drain System: Inflow–discharge relation

Master thesis

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Swale Filter Drain System

Inflow – discharge relation

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Preface

This thesis is a product of a study during a period from February until November 2010. For this research I have studied the inflow – discharge relation of swale filter drain systems.

The process of this study was interesting and exciting. First of all it was decided that a field study had the priority. For this an appropriate location had to be found where the necessary measurement data could be collected. With special thanks to the municipality of Utrecht this location was found. Due to the further cooperation with Utrecht it was possible to produce the self designed discharge measurement devices and to use them to collect the necessary data. With special thanks to Kanters Staalbouw BV the discharge measurement devices were produced in a way they gave accurate data. For the calibration of the measurement devices the necessary location and tools were provided by Döhler Holland BV. During brainstorm sessions and discussions about the possibilities of these measurements people from Deltares, the TU Delft and the municipality of Utrecht helped a lot. I learned a lot about what is involved in carrying out measurements. It was surprising how well the fieldwork went. Especially because the chosen method was the cheapest one and definitely proved it was accurate enough for the purpose of this study. Secondly the modeling was instructive for me. The constraints of Hydrus 2D and how to deal with them to finally fulfill the purpose of the modeling was very interesting.

I would like to thank my supervisors as well. The discussions during the whole process and critical reading of the report by them helped a lot to get finally to this thesis.

My fellow students helped a lot as well. Especially the lunches, the coffee breaks and the cookie breaks were enlightening.

Finally many thanks goes to my family and friends. Especially my girlfriend Tessa and my parents Harrie and Tiny. They probably do not want to hear anything about swale filter drain systems for the coming decades. Due to the fact that I was either explaining or complaining about the subject the whole time.

I hope you will enjoy reading this thesis. Hopefully it is used in further research about the swale filter drain systems and in further design of it.

Delft, 26 November 2010

Erik Donkers

Summary

In urban water management for a long time it was the practice to discharge the storm water in a centralized manner. For instance the peak loads of the sewer systems and the wastewater treatment plants in times of heavy rainfall and the needs of water retention in urban areas nowadays ask for a decentralized discharge of the precipitation. The runoff is not discharged as fast as possible, but it is retained and (partly) discharged to the surrounding soil and the surface water. For this purpose among others there is made use of swale filter drain systems (SFDSs).

The principle of a SFDS is as follows: The precipitation in the urban area is transported to the SFDS by means of a storm water sewer system or a gully. The water ends up in a deepened grassplot and infiltrates into a soil improvement underneath the grass. Within the soil improvement a drain is installed which leads to the surface water or a storm water sewer system nearby. The water is partly infiltrated into the original surrounding soil and partly discharged by the drain.

SFDSs have both qualitative and quantitative features. The research described in this thesis focuses on the quantitative features. From this perspective the SFDS provides retention, infiltration and delayed discharge of the runoff through the drain. This research has focused on the quantitative relation between the inflow to the SFDS and the discharge through the drain.

The research question for this study is: 'What is the inflow – discharge relation of Swale Filter Drain Systems, with respect to the total discharge reduction, the discharge peak reduction and the peak delay?'.

The purpose of this research is to determine the characteristics that have effect to the inflow – discharge relation. How these characteristics affect the relation and if the knowledge about this is usable for predicting the relation in practice. For this purpose measurements are carried out and a model is used.

By monitoring a SFDS in Leidsche Rijn, a district of Utrecht, the actual working of the system in practice is examined. With these measurements the effect of different inflow characteristics is determined. The studied inflow characteristics are the intensity, the peak inflow, the duration of the inflow and the total volume of the inflow. Hydrus 2D is used to make a two dimensional numerical model of a SFDS. This model gives the opportunity to investigate the effect of the change of some characteristics of the SFDS and its surrounding on the inflow – discharge relation. The studied characteristics are the drainage depth, the groundwater level, the shape of the trench (the soil improvements below the grass) and the width of the trench.

The main findings of the effects of the characteristics to the inflow – discharge relation are presented here point by point. There are more outflow characteristics analyzed which can be found in the conclusions as well.

- No clear inflow – discharge relation is found. This is caused by the different initial conditions for the measured events. Furthermore the distribution of precipitation events differ. Therefore during the analyses a rough distinction is made between all the measurements and those with a shallow initial water level in the trench. A distinction between short duration and long duration events is made as well. The short events have a duration between 77 minutes and 385 minutes. The long events have a duration of around 1000 minutes.
- For all measured events the peak delay has a range between 10 minutes and 108 minutes. The peak reduction has a range between 40% and 100%. The total volume reduction is between -8% and 100%.

- The events with a shallow initial water level in the trench give some different values. The peak delay is between 10 minutes and 41 minutes. The peak reduction is between 40% and 89%. The total volume reduction values are between -8% and 89%.
- The difference between the start of the inflow and the start of the outflow is between 1 minute and 100 minutes for all measurements. For events with a shallow initial water level in the trench the values are between 1 minute and 28 minutes.
- There is found a minor effect for some studied characteristics in case the peak delay is the most important outflow characteristic. Only for short events there is an effect of the duration of the event and the total inflow volume of the event. This means that during the design period this may be taken into account. When a certain peak delay is found during modeling this peak delay is different with for instance another duration of the event. Although the effect is very small.
- The inflow characteristics have no or not much effect on the peak reduction. When a large peak reduction is purposed one may use a shallow drainage level. Furthermore it is recommended to use a t-shaped trench instead of a rectangular shaped trench. The groundwater level has a certain effect on the peak reduction as well. When the groundwater level is deeper the peak reduction is larger. This may be important for calculations during the year. The groundwater level may change during the year.
- When the total volume reduction has the priority during the design phase the intensity and the peak inflow of the event have an effect to it. A larger intensity and peak inflow causes a smaller total volume reduction. This means that when the design is modeled with a certain event the results are different when the design is modeled with an event with a larger intensity. This needs to be taken into account during the design phase to prevent for overestimation of the volume reduction by the system. The total inflow volume has a minor effect to the total volume reduction. During the design phase it still may be taken into account.

  In case a large total volume reduction is purposed a shallow drainage level may be used. The groundwater level has an effect as well. This means that the fluctuation of the groundwater level during the year needs to be taken into account. By enlarging the volume of the soil improvement the total volume reduction is increased as well.
- For all outflow characteristics it must be noted that the emptying time of an SFDS for the native soils with a small hydraulic conductivity is relatively large. Because of this it takes more time after a precipitation event to get back to the maximum storage capacity of the SFDS. Because of this simulations with a sequence of events may be used. This will simulate the designed SFDS with different initial conditions caused by the former events.

Samenvatting

In het stedelijk waterbeheer is het lang de gewoonte geweest het regenwater gecentraliseerd af te voeren. Door onder andere de piekbelasting van de riolering en de rioolwaterzuiveringsinstallaties bij hevige regenval en de behoefte aan waterretentie in de stad wordt tegenwoordig vaak gekozen voor een gedecentraliseerde verwerking van het regenwater. Dit vindt vaak plaats door middel van afkoppeling. Dit houdt in dat het regenwater niet meer zo snel mogelijk wordt afgevoerd, maar wordt vastgehouden en (gedeeltelijk) afgevoerd wordt naar zowel het grond- als het oppervlaktewater. Binnen dit afkoppelingsbeleid wordt onder andere gebruik gemaakt van wadi's (Water Afvoer door Drainage en Infiltratie). Het principe van een wadi in stedelijk gebied is als volgt: Het regenwater dat valt in de stad wordt door middel van gootjes en/of regenwaterriolering naar de wadi gevoerd. Het water komt terecht op een verdiept grasveld en infiltreert naar een grondverbetering die zich onder het gras bevindt. In deze grondverbetering is een drain geïnstalleerd die uitkomt op het oppervlaktewater of een regenwaterriool. Het water infiltreert gedeeltelijk naar de oorspronkelijke omringende grond en gedeeltelijk wordt het afgevoerd door de drain.

Wadi's hebben zowel een kwalitatieve als een kwantitatieve functie. Het in deze scriptie beschreven onderzoek richt zich op de kwantitatieve functie. Vanuit dit perspectief zorgt de wadi voor retentie, infiltratie en vertraagde afvoer door de drain van het regenwater. Dit onderzoek heeft zich gericht op de kwantitatieve relatie tussen het regenwater dat de wadi instroomt en het water dat wordt afgevoerd door de drain.

De onderzoeksvraag voor dit onderzoek is: 'Wat is de instroom – afvoer relatie van een wadi, met betrekking tot de totale afvoer reductie, de piek reductie en de piek vertraging?'

Het doel van dit onderzoek is om te bepalen welke karakteristieken invloed hebben op de instroom – afvoer relatie van wadi's. Hieruit volgt wat voor invloed deze karakteristieken hebben op de relatie en of deze kennis bruikbaar is om de relatie in de praktijk beter te kunnen voorspellen. Om dit doel te bereiken is veldwerk verricht en is er een model gemaakt.

Door middel van monitoring van een wadi in Leidsche Rijn, een wijk in Utrecht, is de werking van een wadi in de praktijk onderzocht. De invloed van verschillende instroom karakteristieken is onderzocht met de resultaten uit de metingen. De onderzochte instroom karakteristieken zijn de intensiteit, de piek instroom, de duur van de instroom en het totaal ingestroomde volume. Verder is gebruik gemaakt van een numeriek tweedimensionaal model in Hydrus. Met dit model is de invloed van een aantal fysieke kenmerken van de wadi op de instroom – afvoer relatie bestudeerd. De onderzochte karakteristieken zijn de drainage diepte, het grondwater niveau, de vorm van de grondverbetering onder het gras en de breedte van deze grondverbetering.

De belangrijkste bevindingen van de instroom karakteristieken worden hier opgesomd. Er zijn meer afvoer karakteristieken onderzocht. Deze zijn in de conclusies opgenomen.

- Er is geen duidelijke instroom – afvoer relatie gevonden. Dit wordt onder andere veroorzaakt door de verschillende initiële condities van de wadi bij aanvang van de verschillende neerslaggebeurtenissen. Ook de verdeling van de neerslaggebeurtenissen verschilt. Om deze redenen is een ruwe verdeling gemaakt tussen de gemeten neerslaggebeurtenissen met een ondiepe initiële waterstand in de wadi en deze met een diepere initiële waterstand in de wadi. Ook is er een scheiding gemaakt tussen korte gebeurtenissen (77 minuten tot 385 minuten) en lange gebeurtenissen (rond de 1000 minuten).

- Voor al de gemeten gebeurtenissen ligt de piek vertraging tussen de 10 minuten en de 108 minuten. De piek reductie ligt tussen de 40% en de 100%. De totale volume reductie ligt tussen de -8% en de 100%.
- De gebeurtenissen met een ondiep initieel waterniveau in de SFDS laten andere bereiken zien. De piek vertraging ligt tussen de 10 minuten en de 41 minuten. De piek reductie ligt tussen de 40% en de 89%. De totale volume reductie ligt tussen de -8% en de 89%.
- Het verschil tussen de start van de instroom en de start van de afvoer ligt tussen 1 minuut en 100 minuten voor al de metingen. Voor gebeurtenissen met een ondiepe initiële waterstand liggen de waarden tussen de 1 minuut en de 28 minuten.
- Er is een minimaal effect gevonden voor enkele karakteristieken op de relatie met betrekking tot de piek vertraging. Alleen wanneer gekeken wordt naar korte duur gebeurtenissen is er een effect van de duur en het totale instroom volume van de gebeurtenis waarneembaar. Dit betekend dat tijdens de ontwerpfase deze karakteristieken in de gaten gehouden moeten worden wanneer de piek vertraging een doel is van de te ontwerpen wadi.
- De instroom karakteristieken hebben geen of niet veel effect op de piek reductie. Wanneer een grote piek reductie wordt beoogd kan men deze verkrijgen door een ondiep drainage niveau te gebruiken. Verder is het aan te raden een T-vormige grondverbetering toe te passen in plaats van een vierkante. Het grondwaterniveau heeft ook een bepaalde invloed op de piek reductie. Als het grondwaterniveau dieper ligt is de piek reductie groter. Omdat dit niveau veranderd door het jaar heen is het belangrijk hier rekening mee te houden.
- Wanneer de totale volume reductie de prioriteit heeft moet rekening gehouden worden met het effect van verschillen in de intensiteit en de piek van de instroom. Een grotere intensiteit en piek instroom veroorzaken een kleinere totale volume reductie. Dit betekend dat wanneer het ontwerp is gemodelleerd met een bepaalde gebeurtenis als instroom de resultaten anders zullen zijn wanneer het model wordt doorgereken met een gebeurtenis met een andere intensiteit. Hiermee moet rekening gehouden worden tijdens de ontwerpfase om overschatting of onderschatting te voorkomen. Het totaal ingestroomde volume heeft een minimaal effect op de totale volume reductie.

  Een ondiepere drainagehoogte zorgt voor een grotere volume reductie. Het grondwaterniveau heeft hier ook effect op. Dit betekend dat ook hier rekening gehouden moet worden met de fluctuaties van het grondwaterniveau gedurende het jaar. Door de vergroting van het volume van de grondverbetering wordt de totale volume reductie ook vergroot.
- Voor al de afvoer karakteristieken moet opgemerkt worden dat de ledigingtijd de grondverbetering van de wadi afhangt van de grondsoort waarin deze is aangelegd. Bij grondsoorten met een slechte doorlatendheid duurt het relatief lang na een neerslaggebeurtenis voordat de maximale capaciteit weer beschikbaar is. Hierdoor is het aan te raden een reeks van neerslaggebeurtenissen te simuleren wanneer een wadi wordt doorgerekend in een model.

Content

1 Introduction

In the past urban water management focused on fast and efficient storm water drainage. The runoff is centralized collected. For water management in this way four drawbacks can be summed up (Boogaard, Bruins, & Wentink, 2006).

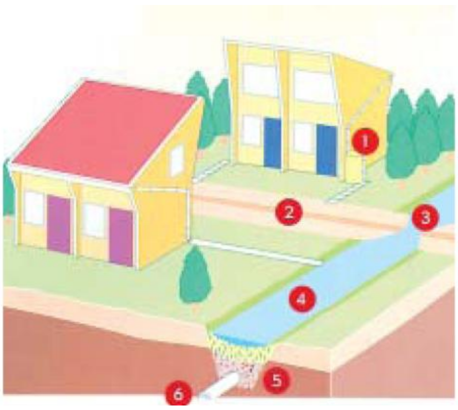
In the first place large peak discharges occur. The consequence is a fluctuation in surface water levels and an overload of water transported to the sewer system.

The latter causes the second drawback. When the sewer system is overloaded it is discharging a part of the runoff direct to the surface water. This water is polluted which means the water quality of the surface water is affected.

The third drawback is the probable water shortage caused by the decrease of infiltration and the increase of groundwater drainage. In the Netherlands regularly water is added to maintain water levels. Water levels that are too low may increase subsidence of the soil by oxidation in peat areas. A second problem of too low water levels is caused by rotting of old wooden pile foundations. Intensive draining probably has a disadvantage for the surroundings as well. For instance nature may develop less because of excessively low water levels.

The fourth difficulty is groundwater nuisance. In winter the water levels may rise. By that, water may enter cellars with leakages, houses get moist and gardens are marshy. The groundwater nuisance probably may be linked with the water shortage harms. More drainage to avoid groundwater nuisance in winter will cause more water shortage in summer.

Fortunately urban water management nowadays is more focused on approaching the pre-urban hydrologic situation within the city. For this purpose Sustainable Drainage Systems (SUDS) are used. These SUDS are aimed to retain and slowly convey the runoff in urban areas. More water is infiltrated and peak discharges are reduced. These decentralized systems may partly be the solution to the previously mentioned troubles. Examples of these SUDS are green roofs, permeable paving and Swale Filter Drain Systems (SFDS).



Increasingly the SFDSs are used in urban water management. An example is shown in figure 1.1. In this concept the runoff is captured in the swales. From there it infiltrates to the trench underneath the grass layer. The trench contains a soil improvement. From the trench water may infiltrate into the surrounding soil and it may be drained by the perforated pipe. The perforated pipe discharges the water to the surface water or a storm water drain. The main benefits of this system are filtration, retention, infiltration into the ground and delayed conveyance of the runoff. In this way a quantitative and qualitative improvement is achieved.

Figure 1.1 A Swale Filter Drain System (SFDS). (Boogaard, Bruins, & Wentink, 2006)

1 and 2	runoff to the SFDS.
3	discharge from an overloaded SFDS to the next SFDS.
4	swale with the runoff water gathered to infiltrate.
5	trench with coarse sand, gravel or a different coarse material.
6	tile drain.

Figure 1.2 shows a schematic view on a cross section of a SFDS in winter and in summer. In winter the groundwater level naturally is relatively high. Due to this the SFDS especially has a draining function. In summer the groundwater level naturally is relatively low. The SFDS in that case especially has an infiltrating function.

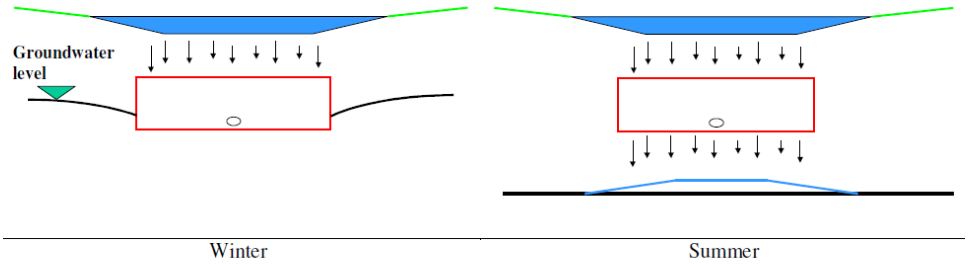


Figure 1.2 A schematic view on a cross section of a SFDS in winter and in summer. (Van de Ven, 2007)

1.1 Problem description

There are many processes affecting the quantitative efficiency of a SFDS. These processes include the inflow, infiltration, storage and outflow. In the design phase it is hard to predict the behavior of the system in practice.

The purpose of an SFDS is threefold. The first is peak reduction, the second is peak delay and the third is total discharge reduction. The lack of knowledge of the processes within the SFDS and what effects these processes have makes it difficult to predict the performance of an SFDS.

1.2 Purpose of the study

The purpose of this study is to determine an inflow – discharge relation for the Swale Filter Drain System. The characteristics that have effect to this relation will be determined for this purpose. This study will improve the knowledge about the quantitative processes within the SFDS, so that total discharge reduction, peak reduction and peak delay may be predicted more accurately. The main research question is:

What is the "inflow – discharge relation" of Swale Filter Drain Systems, with respect to the total discharge reduction, the discharge peak reduction and the peak delay?

The sub questions are:

- Which characteristics have effect on the inflow – discharge relation in Swale Filter Drain Systems?
- How do these characteristics have effect on the inflow – discharge relation?
- Is the knowledge about the affecting characteristics usable for predicting the inflow – discharge relation in practice?

1.2.1 Research approach

The following research approach is followed to find answers to the previous listed questions.

Measurements in the field are undertaken. For this purpose one SFDS is investigated. This SFDS is located in Utrecht. The measurements are analyzed to determine what the effect of different precipitation events is. An experiment is carried out to calibrate the model output data with measurement data. The measurement description and results may be found in chapter 4.

More scenario's may be simulated by modeling the investigated SFDS and calibrating the outcomes of the model with the measurement data of the experiment. The effect on the inflow – discharge relation of different properties of the SFDS may be investigated by means of this model. The model description and results are presented in chapter 5.

A discussion of the measurement results and model results is presented in chapter 6.

Conclusions are drawn from the results of the measurements and the model. These conclusions are reported in chapter 7.

Finally the recommendations are drawn from the results, discussion and conclusions. These are described in chapter 8.

2 Literature

As mentioned before the purpose of this study is to determine an inflow – discharge relation for the Swale Filter Drain System. As stated in the main research question the relation may be split into three discharge relations. These three relations are the peak reduction, the peak delay and the total volume reduction. In this chapter the relations known from literature are described. Finally the constraints of the findings in literature and how this research will add interesting aspects to literature is summed up.

2.1 Literature summary

Barber (2003) performed a study using laboratory experiments and computer modeling. The effects of storm size, storm distribution, constant rate application, initial conditions, media used in the trench and trench size are investigated in this study. It was shown that peak reductions were dependent on the media used in the trench, the input hydrograph distribution and the trench size.

The peak reduction is dependent on the storage characteristics of the media. Finer medias tend to retain water better causing larger percent peak reductions. The peak delay time is dependent on the effective hydraulic conductivity. Finer soils having a lower hydraulic conductivity produce a larger peak delay.

The peak reduction decreases exponentially with an increasing storm size until it is a certain minimum peak reduction. The peak delay decreases exponentially with an increase of the storm size till a certain minimum peak delay.

Barber uses three storms of the same size. The three storms that were used had a duration of 1, 3 and 6 hours. In general, the peak reduction decreased with an increasing storm duration. The impact of distribution on peak reduction and peak delay time was further tested by comparing results generated by the SCS Type I-A distribution to those from a modified distribution. The modified distribution is wider in the area of the peak. The impact of the input hydrograph shape may have the single largest effect on the efficiency of the SFDS to attenuate the peak flow. The peak delay time increases with an increasing storm duration.

As the applied peak duration increases, the moisture content in the transmission path approaches the steady-state water content for a given peak intensity. The steady-state water content along the liner is dependent on the storm intensity. Theoretically, if steady-state flow is reached before the peak input drops off, then no peak reduction will be observed. The peak delay time is relatively unaffected by the input storm distribution.

The effect of initial conditions only impacted the hydraulic performance during smaller storms. A higher initial water content causes a lower peak reduction. The effect of initial conditions only impacted the hydraulic performance during smaller storms. A higher initial water content causes a lower peak delay time.

To test the hydraulic behavior of the SFDS as a function of size, three different geometries were tested. A larger trench makes a substantially difference in the minimum values of the peak reduction. An increasing trench size causes an increasing peak reduction.

Abide (2006) performed a storm water quantity monitoring program in Canada. For this a continuous monitoring of rainfall and storm water quantity was conducted within three residential areas in the City of Nepean, Ontario, Canada. Two of these subdivisions (Heart's Desire and McFarlane-Pine Glen) had grass swale-perforated pipe systems while the third (Amberwood Phase I) had a conventional concrete pipe system. This research showed that the total seasonal discharge for the SFDS of Mc Farlane – Pine Glen is 37% of those for the conventional system. The total seasonal discharge for the SFDS of Heart's Desire is 7.7% of those for the conventional system.

Based on the latter mentioned research, Sabourin (2008) concluded that the peak flows from the outlet of the SFDSs were 14 to 53% of those of the conventional system.

To get insight in the working of the SFDS in Enschede the municipality decided to start a monitoring program. This program is executed from 1999 until 2005. A study published by Boogaard (2006) based on these six years of research in Enschede shows almost no discharge. The period from May 1999 until May 2002 was relatively wet. The measured precipitation in that period exceeded the historical average values. Despite of this wet period around 99% of the water was infiltrated into the native soil. This amount is determined by measuring if the drain was discharging. It was not measured what the quantity of the discharge was. It should be noted that the permeability of the study site is high and the groundwater tables are relatively low.

2.2 Constraints of literature and adding's by this research

Barber (2003) performed a study using laboratory experiments and computer modeling. A laboratory experiment is performed under well controlled circumstances. This is not the case in field experiments. The inflow characteristics in this research are not natural and there is no interaction with the surroundings. To investigate the working of the SFDS in practice measurement in the field are performed. Furthermore no research is done to the difference in the drainage level, the groundwater level in the surrounding, the native soil type and the shape of the trench. To investigate the effect of these characteristics on the inflow-discharge relation in this research a model is used.

In this chapter it is shown that there are some measurements performed in the field that are published in literature. These measurements were not performed to determine for instance the peak reduction and peak delay. Furthermore the inflow is not measured directly, but calculated from the precipitation measurements. In this research a direct inflow measurement and a direct outflow measurement is performed to improve this.

3 Theory

The SFDS is a system that is affected by certain processes that take place within the system. Furthermore the SFDS is constructed on many places with a different purpose. Some processes will and some won't have effect on specific aims of the SFDS. In this chapter it is presented what the affecting processes for the specific purposes are expected to be.

3.1 The purpose of the SFDS

The three main purposes as mentioned before are peak delay, peak reduction and volume reduction. How these characteristics are determined is explained in paragraph 4.3.5.

The peak delay will be affected by the initial condition of the SFDS. In case of a dry SFDS it takes more time before discharging of the water to the surface water starts than when the SFDS is saturated at the start of the precipitation event. There is more water needed to saturate the soil before the drain starts discharging. Furthermore the duration of the event and the total inflow during the event are expected to have effect on the peak delay. A longer duration and a larger inflow causes more saturation. It depends on the time the peak occurs if this will have any effect. When the peak happens early in the event the duration will have less effect than when the peak happens late in the event. The intensity of the inflow will cause an increasing or decreasing water level in the SFDS. When the intensity of the inflow is larger than the infiltration capacity of the SFDS to its surrounding the water level will increase. A smaller intensity of the inflow will cause a decrease of the water level. Therefore how long it takes to exceed the drainage level in the trench depends on the intensity. This affects the peak delay as well.

For the peak reduction the same processes and characteristics are expected to have effect. Therefore the initial condition, the duration, the total volume inflow and the intensity are characteristics that have effect on this aim. Furthermore the peak inflow have effect on the peak reduction as well. When two events have different inflow peak values and the same outflow peak values than there is a different peak reduction.

The volume reduction is affected by the infiltration capacity from the trench to the native soil. This infiltration is affected by the storage available underneath the drainage level and it is affected by the infiltration capacity from the trench to the native soil. Depending on this native soil infiltration capacity the inflow characteristics will have more or less effect. Especially the intensity is expected to be an affecting inflow characteristic.

3.2 Processes

Before the water is discharged from the SFDS or infiltrated to the native soil it has passed some phases. First the water is transported from the place the precipitation fell on to the SFDS. Thereafter the water is processed by the SFDS.

The amount of precipitation that is transported to the SFDS is affected by the amount of sealed area the precipitation is collected in. In case of a larger sealed area there will be transported more water to the SFDF. Furthermore the distribution of the precipitation and the weather conditions before the event have their effect on the amount of water that reaches the SFDS. This research will not go in detail into this subject.

Some precipitation will reach the SFDS the other part won't. This research focuses on the part that reaches the SFDS. The part that reaches the SFDS has a certain distribution, which has effect on the working of the system. The short inflow will be processed in a different way than the inflow with a longer duration. The water is spread in the swale where it is infiltrated to the trench. This infiltration to the trench is regulated by the infiltration capacity of the swale. In the system the available volume to store water is crucial for the working. This volume is dependent on the water level in the trench and the available pore volume of the soil type used for the soil improvement. Furthermore the native soil characteristics will affect the infiltration from the SFDS to the surrounding. The part of the inflow that is exceeding the amount of water that may be processed by the SFDS by infiltrating it to the surroundings and by storing it is discharged by the drain.

3.3 Scenario's

On basis of the mentioned processes four scenario's can be outlined. These scenarios are combinations of a different initial condition of the SFDS and the duration of the inflow event. The initial condition of the SFDS is divided in a dry initial condition and a wet initial condition. The duration of the inflow event is divided in short inflow events and long inflow events.

The combination with a dry initial condition and a short inflow event will cause little discharge through the drain or no discharge at all. This is caused by the large amount of storage availability. The volume reduction, peak delay and peak reduction therefore will be relatively large.

A dry initial condition in combination with a long inflow event will give the SFDS more time to reach saturation in large part of the trench. This causes more discharge through the drain in comparison with the first mentioned combination. Because of this a smaller volume reduction, peak delay and peak reduction will occur. It must be noted that especially for the peak delay and peak reduction the place of the peak during the event is affecting this theory. A peak at the beginning of the event will be processed by the SFDS the same way as the one of a short event. When the peak occurs at the end of the event the duration is more affecting.

When a short event happens and the initial condition of the SFDS is wet there is no volume to store the water in the trench or a small part of the volume is available. It depends on the degree of saturation if the mentioned effects of the first two scenario's may be applied here as well. For a saturated trench the least possible volume reduction, peak delay and peak reduction will take place. With this wet initial condition the characteristics of the surrounding soil will be more important. Especially the infiltration capacity of the native soil where the SFDS is situated.

Finally the combination of the long inflow event with the wet initial condition of the SFDS will behave like the latter mentioned combination. The least possible volume reduction, peak reduction and peak delay will take place.

4 Measurements

In a field study measurements are carried out to investigate the functioning of a SFDS. For the measurement location three sites were evaluated. These locations were situated in Enschede, Almelo and Utrecht. The major criteria for the study site is that there is expected to be outflow through the drain. The first two places have a low groundwater level. In the past even in wet seasons almost no discharge was observed from the drains (Been & Boogaard, 2007). In Utrecht the groundwater levels are somewhat higher, which means that there is more chance of measuring discharge from the drains. Therefore Utrecht was chosen. The municipality of Utrecht consented to do measurements in Leidsche Rijn. Leidsche Rijn is situated in the west of Utrecht. There are a lot of SFDSs situated in this residential area. The purpose of these systems is to reduce the peak outflow and to filter runoff from precipitation events. The location of these measurements is the SFDS at the Castellumknoop. This chapter gives a description of the study site, the performed measurements and the results.

4.1 Study site (Castellumknoop, Utrecht)

Figure 4.1 shows the location of the SFDS at the Castellumknoop (number 1). The right part of this figure shows the design of the site. The water is discharged into the SFDS by a sewer system that connects the surrounding roads shown in the right figure to the SFDS. The SFDS has an overflow and a drain to the surface water. The sealed surface draining towards the SFDS is approximately 2000 m^2. In figure 4.2 and figure 4.3 some pictures of the SFDS are shown.

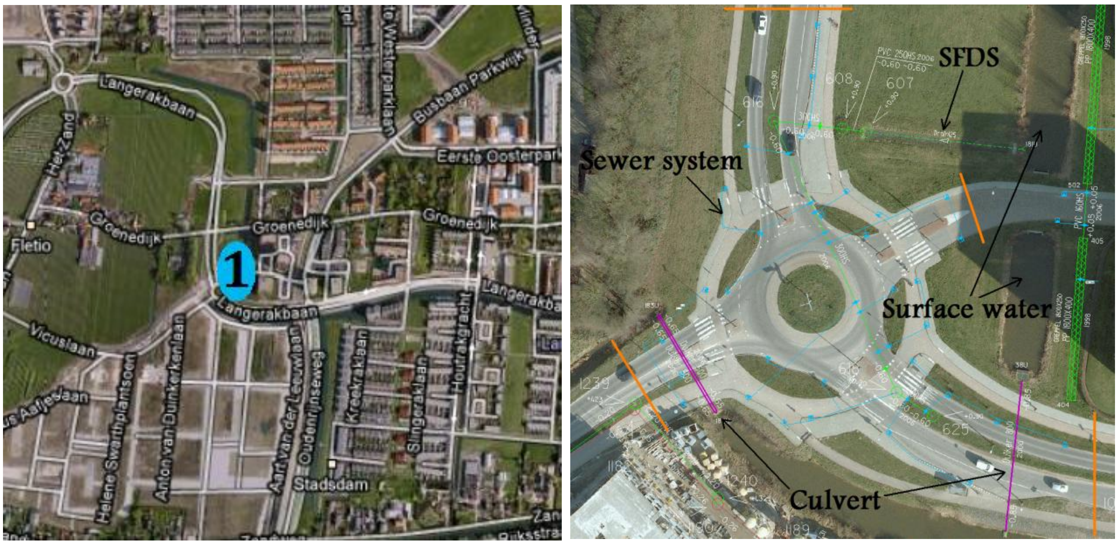


Figure 4.1 Left: Location SFDS. (google maps, 2010) Right: Design of the SFDS at location Castellumknoop. The purple lines are culverts. The blue lines denote the sewer system. The orange lines denote the boundaries of the sealed draining surface.

Figure 4.2 Construction SFDS at location Castellumknoop (June 2009). The left picture shows the drain in the excavated trench of the SFDS. The right picture shows the coarse sand with on top 'bomenzand' (bomenzand is a kind of soil with a high permeability in addition to good properties for grass to grow on).

Figure 4.3 SFDS at location Castellumknoop. 1 = Inflow. 2 = Outflow. (March 2010)

The information of the study site with respect to soil structure, groundwater levels, hydraulic conductivity and SFDS characteristics is extracted from the design document of the study site (Palsma & Rijsdijk, 2005).

Soil structure

In table 4.1 the soil description of the surrounding area is given. This soil description is made by using hand drilling.

Depth (m in respect to surface)	Layer description
Surface to -0.5	Variable extremely fine, clayey sand (locally humus) or sandy clay
-0.5 to -2.3	Extremely to moderate fine sand (clayey or silty)

Table 4.1 Soil structure. (Palsma & Rijsdijk, 2005)

Groundwater levels

The observed groundwater levels in 2005 were around NAP -0.2 m. The average surface level is at a height of NAP +0.8 m.

The surface water level is in the range of NAP +0.15 m and NAP +0.45 m.

The hydraulic head in the sand below the top layer has a seasonal variation between NAP -0.5 m and NAP +0.4 m. The mean hydraulic head is NAP -0.2 m.

Hydraulic conductivity

Before this research the municipality of Utrecht already determined the hydraulic conductivity of the native soil by making use of the falling head test. This test is performed at a depth of 0.5 to 1.0 m below surface. The calculated values are in the range of 0.09 m/day to 0.36 m/d.

SFDS characteristics

Figure 4.4 shows the schematic profile of the SFDS. In table 4.2 the designed and constructed characteristics of the SFDS are shown. Figure 4.4 shows the characteristics of the cross section of the SFDS.

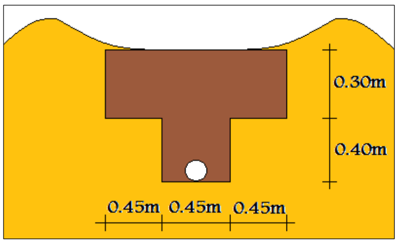


Figure 4.4 Schematic profile of the SFDS. Yellow: native soil. Brown: soil improvement.

SFDS	Characteristics
Level receiving discharge	+0.70 m NAP
Level outgoing discharge (swale overflow gully)	+0.75 m NAP
Level bottom	+0.65 m NAP
Bottom trench	-0.20 m NAP
Level drain	-0.20 m NAP
Drainage level	+0.35 m NAP
Side slope	1:3
Bottom width	2.5 m
Length	35 m
Top layer	0.20 m
Diameter drain	0.125 m

Table 4.2 SFDS characteristics.

4.2 Measurement setup

Some measurement devices are used to do the field study. In this paragraph the setup of these measurement devices and a short introduction of the measurement devices is given.

4.2.1 Discharge measurements

The discharge of the inflow from the sewer system and the outflow through the drain is measured. This is done by means of a device with a v-notch. Figure 4.5 shows the positions of the measurement devices. In this paragraph the inflow and outflow measurement devices are presented.

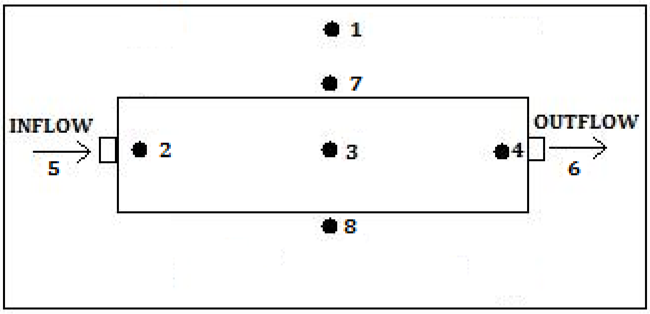


Figure 4.5 Positions of measurement devices. The numbers 5 and 6 show the positions of the discharge measurement devices.

4.2.1.1 General

In this section a general description will be given of the measurement devices that are used for the discharge measurements. Figure 4.6 shows the measurement device for the inflow measurements of the SFDS.

Figure 4.6 Discharge measurement device made by Staalbouw Kanters Oosterhout BV. Left picture: Measurement device with tire to make a waterproof connection to the inflow pipe. Right picture: Measurement device installed in the inflow construction.

Connection to drain

The discharge measurement device will be connected to the drain by means of a pipe. This pipe has a smaller diameter than the pipe it is installed to. A waterproof connection is needed. This will be realized by making use of a tire between the pipes. In figure 4.6 this is shown in the left picture.

Outflow

The outflow of the box takes place over a v-notch. This v-notch is calibrated. This means there is determined a relation between the discharge and the water level above the v-notch threshold. The relation is used to determine the discharge through the measurement device. A v-notch weir is shown in figure 4.7.

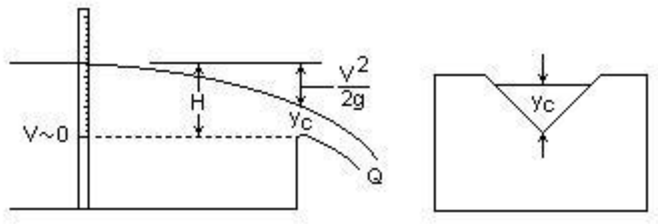


Figure 4.7 V-notch weir. (Open channel flow, 2007)

Water level measurements

For the measurements of the water level in the box pressure transmitters will be used. Two types of these measurement devices are investigated for this research. At first Divers from Schlumberger and secondly pressure transmitters from Keller. They both store the measured values in time steps that are determined by the user by programming them. Figure 4.8 shows a Schlumberger Diver and a Keller pressure transmitter. To be sure the water level will be measured every time step at the same place of the box the devices will be attached to the box.

Figure 4.8 Left: Diver. (Technet) Right: pressure transmitter Keller. (Keller, 2009)

Cover

A cover is used to fulfill three functions. At first it prevents for robbery of the pressure transmitter. Secondly animals may enter the box less easy. Thirdly the cover will protect the measurement from weather influences.

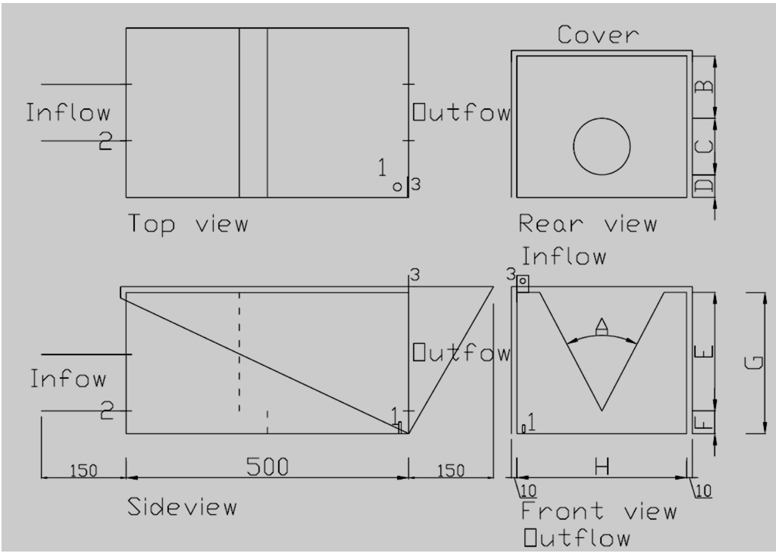


Figure 4.9 Discharge measurement device. Dimensions in mm.

Dimensions

Based on the maximum expected precipitation events and the known sealed area the maximum expected inflow discharge is determined. With the theoretical formula of the v-notch and some experiments it was tested which dimensions were appropriate to be able to measure the maximum expected inflow discharge. For the outflow discharge a relatively small discharge was expected. To be able to measure the outflow in an accurate way the angle of the v-notch is made smaller. This means that when the discharge increases with the same amount the water level measured in the outflow device increases more than the water level measured in the inflow device. Furthermore the maximum outflow discharge was estimated to be sure that the device was able to measure that as well.

In table 4.3 the dimensions of the discharge measurement devices is shown. The characters refer to the characters used in figure 4.9. At number one in this figure the pressure transmitter is attached to the device.

Character in drawing	Device inflow	Device outflow
A	30 ^{o}	10 ^{o}
B	45 mm	140 mm
C	200 mm	100 mm
D	55 mm	60 mm
E	260 mm	210 mm
F	40 mm	90 mm
G	300 mm	300 mm
H	300 mm	180 mm

Table 4.3 Dimensions of the discharge measurement device.

Calibration discharge measurement devices

The calibration of the discharge measurement devices was done with the Schlumberger Divers, the Keller pressure transmitters and a ruler. In figure 4.10 the inflow discharge measurement device is show with the different water level measurement devices.

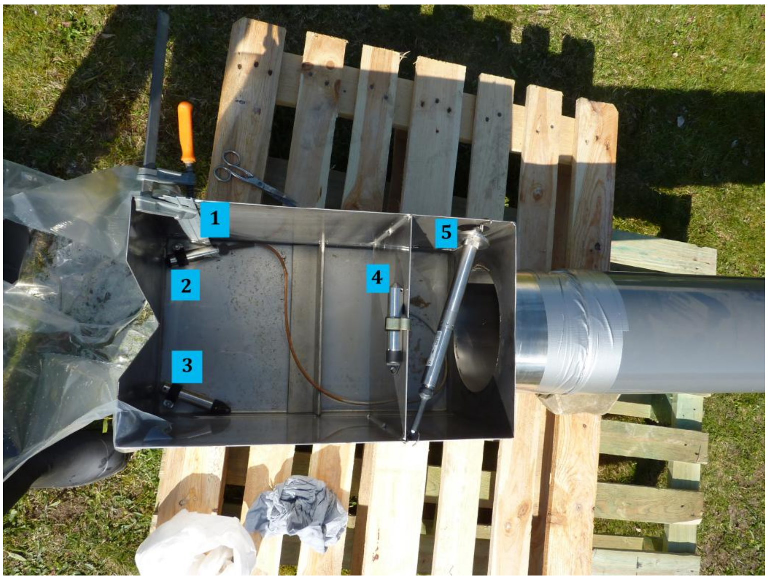


Figure 4.10 Discharge measurement device with water level measurement devices. 1. Ruler. 2. Keller water level measurement. 3. Schlumberger water level measurement. 4. Schlumberger Baro Diver. 5. Keller Baro pressure transmitter.

The calibration setup is shown in figure 4.13. For 16 different discharges in a range of 0 m^3/h to 7.2 m^3/h the water level in the discharge measurement devices is measured. For each discharge value during a stable situation of 5 minutes the water level was measured. Every second the water level was measured for the Schlumberger Divers and the Keller pressure transmitters. The mean value of this measurements was used as the water level associated to the regarding discharge. With the 16 points the Q-h relation is determined.

During the calibration the discharge is measured in two different ways. The first discharge measurement is done by means of a flow meter. The second discharge measurement is done by making use of a 10 liter bucket. This bucket is not checked for accuracy. Therefore the inaccuracy is hard to define. The time to fill the bucket is measured. In figure 4.11 the relation between the measured values is shown. For this test the criteria is that the measurement of the bucket lies within 10% of the measurement with the flow meter. The relation shows that the bucket gives a 1.147 times larger value than the flow meter. This deviation is mainly affected by the large discharges which is logical because it is less easy to measure large discharges with a bucket. With lower discharges there is less splashing and gushing than with a larger discharge. This makes the measurements of the low discharges more accurate than those of the large discharges. The deviation lies within 6% when the values above 5500 l/h are neglected. With this results it is shown that the flow meter is measuring the discharge accurate enough.

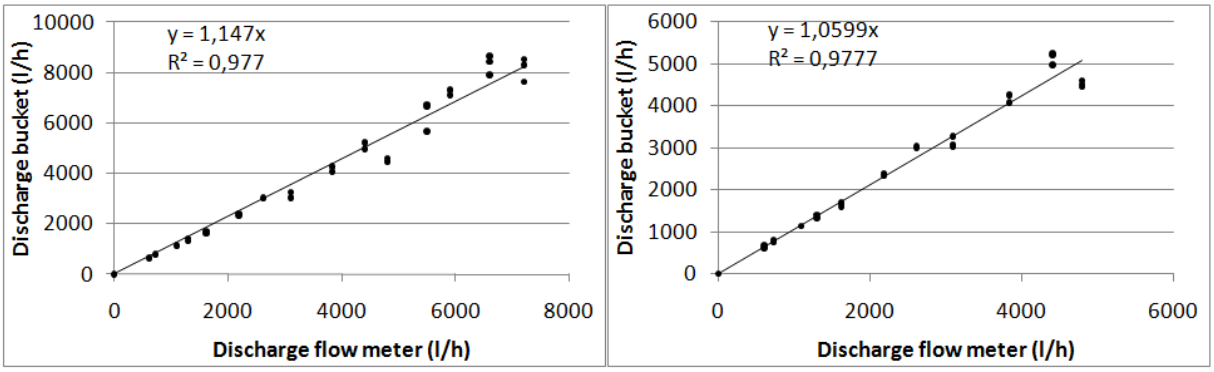


Figure 4.11 Relation between the discharge measured by a bucket and the discharge measured by the flow meter. The left graph shows the comparison of all the measured discharges. The right graph shows the comparison of the discharges less than 5500 l/h.

During the calibration there was a difference in performance between the Keller pressure transmitter and the Schlumberger Diver. For the discharge measurement devices it is important to use the most accurate water level measurement devices. The standard deviations of the measurements during the calibration are used to determine which device performs best. The maximum standard deviation of the Keller pressure transmitter was 1.37 mm and for the Schlumberger Diver 3.97 mm. This means that the 95% accuracy for the Keller pressure transmitter lies within 2.74 mm above and underneath the mean value. For the Schlumberger Diver this is 7.94 mm. On basis of this and the calibration there is a difference in measured inflow discharge of 4.3% for the Keller pressure transmitter and 12.3% for the Schlumberger Diver. For the measured outflow discharge this is 4.2% for the Keller pressure transmitter and 8.7% for the Schlumberger Diver. The normal distributions of the Keller pressure transmitter and the Schlumberger Diver are shown in figure 4.12. The distributions are given for the different discharges during the calibration. Each of the data sets of the calibrated discharges contains 300 data points.

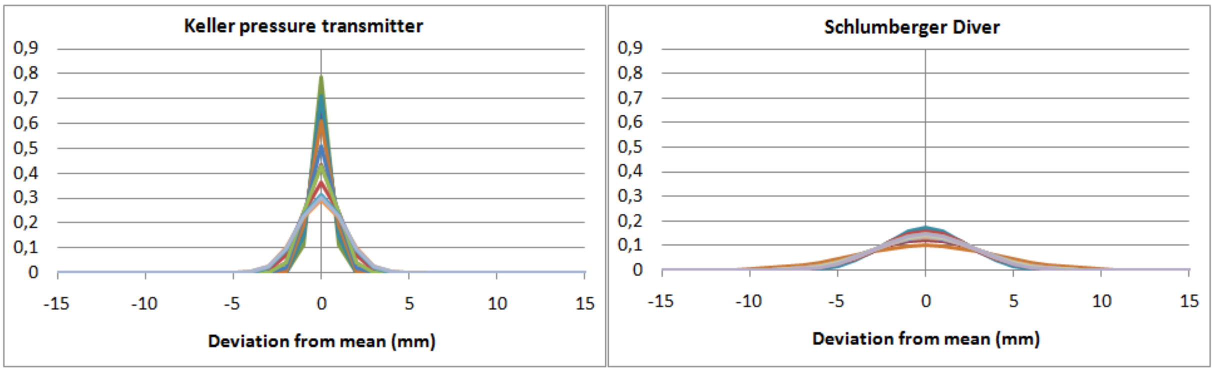


Figure 4.12 Normal distributions of the Keller pressure transmitter and the Schlumberger Diver. The normal distributions are given for the different discharges used during the calibration.

It is shown that the Keller pressure transmitters performed best during the calibration. They are used in the research for the measurements. The calibrated relations are given below.

Inflow discharge measurements: $Q_{in} = 0.5509 \cdot h^2$ (eq 1)

Outflow discharge measurements: $Q_{out} = 0.2402 \cdot h^2$ (eq 2)

where:

Q = discharge (l/h)

h = water level above threshold (mm)

Figure 4.13 Calibration setup at the area of Döhler Holland BV. A pump is pumping water from the pond to a flow meter. The water is transported from the flow meter to the first discharge measurement device by means of a pipe. In the measurement device the water level is measured. Over the v-notch the water is flowing to the second pipe. This pipe transports the water to the second measurement device. Here the water level is measured as well.

4.2.1.2 Discharge measurement devices in the field

In figure 4.14 an overview is given of the discharge measurement devices in the field. The Keller pressure transmitters will measure and store the water level every minute. This frequency is used to measure the peaks in the discharges. With this frequency the storage capacity of the logger is exceeded after 8 days. Therefore a higher frequency is not practical to use.

Figure 4.14 Overview of the discharge measurement devices in the field.

4.2.2 Infiltration capacity measurements

The infiltration capacity of the top layer is determined by an infiltrometer test. With this test at several places in the SFDS the infiltration capacity of the swale is determined. In figure 4.15 the infiltrometer test is shown.

Figure 4.15 Left and middle: Infiltrometer test in practice. Right: Schematic impression infiltrometer test. (Boogaard & Slagter, Meetplan monitoring wadi's Leidsche Rijn, 2007)

For this test first two rings with a diameter of 32 cm and 55 cm are pushed approximately 10 cm into the soil of the swale. Then water is added to the outer ring. After the outer ring is filled, the inner ring is filled. Every 5 minutes the water level is measured. The water level of the inner ring and outer ring is kept the same by adding water to the outer ring. In this way the pressure head for both is the same. Due to this the outer ring prevents for lateral flow. By dividing the water level difference by the time step the infiltration capacity is determined.

4.2.3 Water level

The hydraulic heads are measured by Divers in piezometers. In figure 4.16 and figure 4.17 the position of the piezometers is shown. The filters of the piezometers are situated at the bottom fifty cm of the piezometers. They have a length of 50 cm.

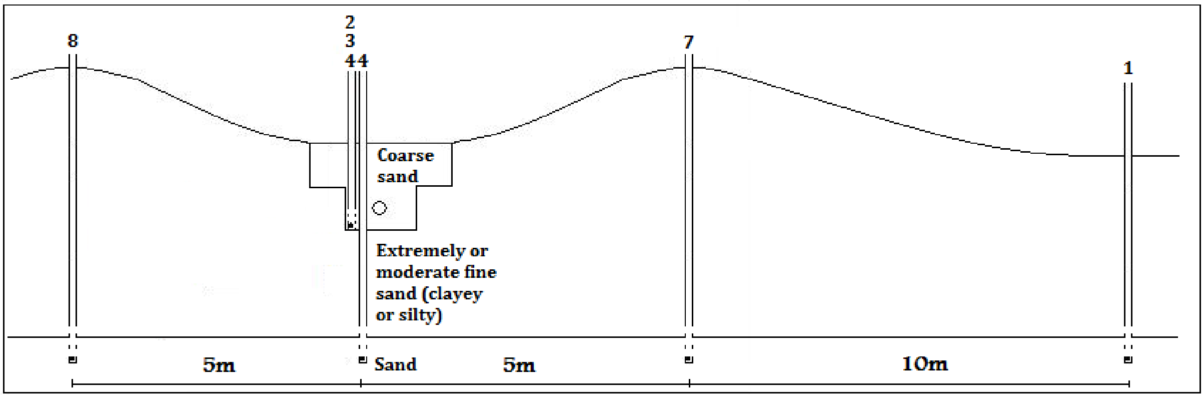


Figure 4.16 Piezometers in and around the SFDS. Piezometer 2 and 4 measure the hydraulic head in the trench. Piezometer 3 measures the hydraulic head just below the bottom of the trench (This is a piezometer that already was installed before this research began). Piezometer 1, 4, 7 and 8 measure the hydraulic head in the aquifer underneath the trench.

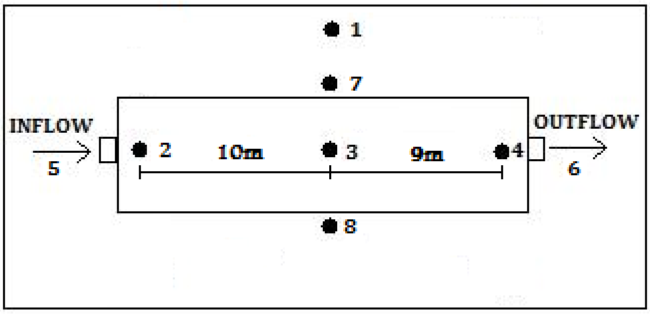


Figure 4.17 Positions of the measurement devices. The numbers correspond with the numbers in figure 4.16.

4.2.4 Precipitation

To verify the discharge data of the inflow with the actual rain events there is made use of precipitation data from the Koninklijk Nederlands Meteorologisch Instituut (KNMI). The KNMI has measurement stations all over the Netherlands. The precipitation data of the stations give the precipitation duration in hours, the total depth of precipitation in mm, the maximum measured hourly rainfall in mm and the time when the maximum rainfall did occur.

For this research the data from the measurement stations De Bilt and Cabauw are used. De Bilt is at a distance of 9 km to the west from the study site and Cabauw is at a distance of 15 km to the southeast from the study site. The surface of the sealed area of the study site is known by the municipality of Utrecht and is approximately 0.2 ha. Due to this the sealed area may be used to verify it with the precipitation measurements. To verify the sealed area of the study site the measured discharge is divided by the average total precipitation. This is done only for the measurements during long precipitation events. During these events there is not only a local event. Due to this the same precipitation event is measured within a large area. Therefore the measurement stations De Bilt and Cabauw measure the same precipitation event that happens at the study site.

The sealed area of the study site is known. By comparing this area by the area from the calculations of the measurements it is possible to verify whether the measurements are accurate.

4.3 Measurement results

The measurements as described above provided a lot of data which is processed and analyzed. In this paragraph the results are presented.

4.3.1 Discharge measurements

Before the discharge measurement devices were made and installed it is tested if there is any discharge from the drain when there is a certain inflow to the SFDS. To determine this a test was done at the 6th of April 2010. Approximately 1 m^3 of water was pumped into the SFDS in a period of 6 minutes. After three minutes pumping the drain started discharging water. This proved that it is possible to measure the discharge of the outflow at this study location.

Figure 4.18 Pumping water into the SFDS on the 6th of April 2010. This is done to check if it is possible to measure the discharge of the outflow.

4.3.2 Infiltration capacity

Infiltrometertest

In this section the results of the infiltrometertests are presented. The results are shown in table 4.4. The average infiltration capacity is 0.31 cm/min.

Castellumknoop	Test 1	Test 2
Date	6-4-2010	6-4-2010
Results (cm/min)	0.21	0.42
Weathercondition during test	dry	dry
Soil condition before test	wet	wet
Average result (cm/min)	0.31	

Table 4.4 Results of the infiltrometertests.

Completely saturated infiltration capacity

The discharge of the drain and the infiltration to the surrounding soil determine the capacity when the SFDS is completely saturated. During an experiment on the 11th of May 2010 water is pumped into the SFDS until it was totally filled. It was completely saturated when the lowering of the water level was measured each five minutes. The capacity for the completely saturated SFDS is 0.1 cm/min.

4.3.3 Hydraulic conductivity native soil

The hydraulic conductivity of the native soil was determined by the municipality before this research. This was done by a falling head test. This test was done 3 times at 3 different location. Therefore the hydraulic conductivity is determined 9 times. Values between 0.09 m/day and 0.36 m/day were found. For this measurements the hydraulic conductivity is determined as well.

This is done by analyzing the period where the start water level in the trench is the same as the end water level in the trench. In this period the water balance is zero without storage. This means that the inflow volume of that period is discharged by the drain and infiltrated to the native soil. The discharged volume by the drain is subtracted from the total inflow volume to get the infiltrated volume to the native soil. By taking into account the infiltrated volume, the time between the start and end of the period and the head difference between the trench and the aquifer underneath the SFDS the hydraulic conductivity is determined. For this Darcy's law is used and the hydraulic conductivity is assumed to be the saturated hydraulic conductivity. The values found with this method are in the range of 0.076 m/day to 0.135 m/day. These values are determined for six water balance periods longer than 1000 minutes. This is done to reduce the effect of short period processes. For the measurements in the trench the average of piezometer 2 and piezometer 3 is used. Piezometer 4 is not used because of the smaller measurable depth of 40 cm under the surface level. The head of the first aquifer that is used is the average of piezometer 4 deep, piezometer 7 and piezometer 8.

4.3.4 Precipitation verification

As stated before the inflow discharge measurement is verified by making use of precipitation data from the KNMI. The sealed area of the study site is calculated for 5 events. From this calculations the average sealed area is 0.18 ha with a range between 0.15 ha and 0.22 ha. The sealed area known by the municipality is 0.20 ha. This means that the discharge measured is the discharge one could expect taking into account the precipitation measurements and the known sealed area. In this way it is proved that the inflow discharge measurement device is generating reliable data.

4.3.5 Processing results discharge measurements

The data of the measurements is first converted from the water level measurements in the devices to the discharges. This is done with the Q-h relations from the calibration. A graph can be drawn that shows the discharges of the inflow and the outflow. This is shown for event 9 in figure 4.19. The measurements of this event took place on the 3rd of July 2010.

Single events are separated by periods with zero inflow. The splitting of two events is demonstrated in figure 4.19 and is denoted with number 1.

With this information the peak delay (eq 3) in *minutes,* the peak reduction (eq 4) in *l/h,* the volume reduction (eq 5) in *l* and the delayed volume (eq 6) in *l* may be determined.

$$t_{delay} = t_{Qout(max)} - t_{Qin(max)} \quad \text{(eq 3)}$$

$$Q_{reduction} = Q_{in(max)} - Q_{out(max)} \quad \text{(eq 4)}$$

$$V_{reduction} = \int Q_{in} - \int Q_{out} \quad \text{(eq 5)}$$

$$V_{delayed} = \int Q_{out} - \int Q_{in} \qquad \text{for} \qquad Q_{out} > Q_{in} \quad \text{(eq 6)}$$

Where:

t = time (min)

Q = discharge (l/h)

V = volume (l)

In figure 4.19 the peak delay in *minutes* is denoted by 'A' and the peak reduction in *l/h* is denoted by 'B'. The peak delay is converted from *l/h* to a percentage of the maximum inflow peak discharge.

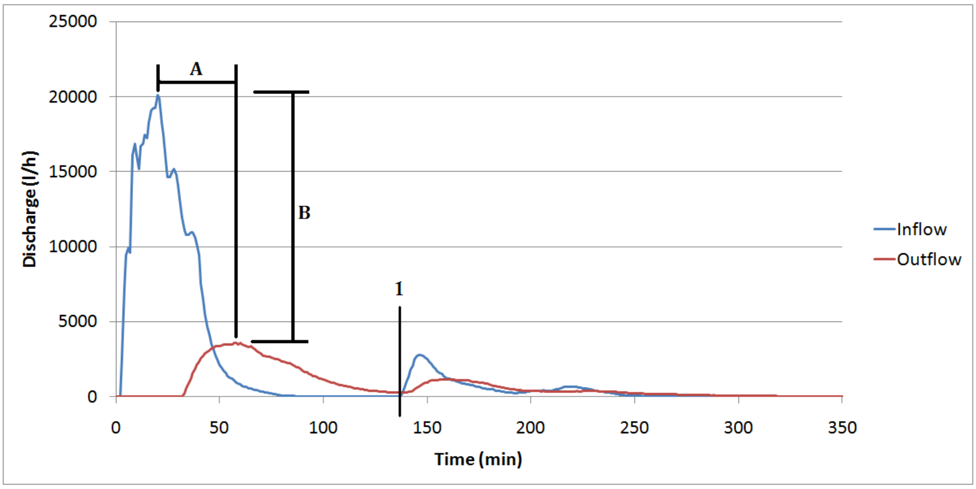


Figure 4.19 Discharge measured at the inflow and the outflow. This graph shows the data of event 9. '1' denotes the start of a new event. 'A' denotes the peak delay in minutes. 'B' denotes the peak reduction in *l/h*.

From the discharge data the cumulative volume may be determined. This gives information about the total volume of water that is discharged into the SFDS and the volume of water that is discharged through the drain from the SFDS. In figure 4.20 the cumulative volume of the inflow and the outflow is given in *l*. With this the volume reduction may be determined. In figure 4.20 the volume reduction is denoted by 'C'. The cumulative volume is converted from *l* to a percentage of the total cumulative volume of the inflow.

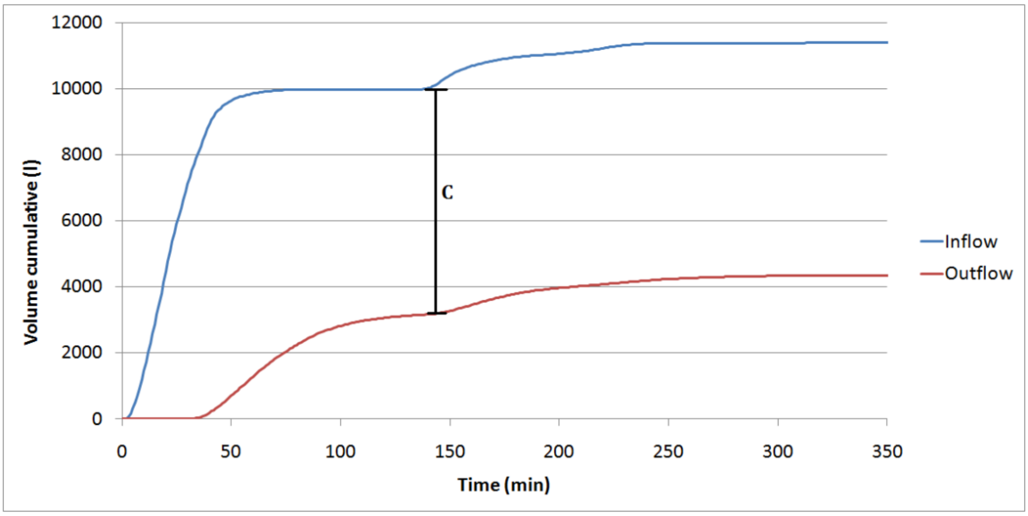


Figure 4.20 Cumulative volume measured at the inflow and at the outflow. This graph shows the data of event 9. 'C' denotes the volume reduction in *l*.

The delayed volume is defined here as the volume that is discharged by the drain at the moment the drain has a larger discharge value than the inflow. The difference between outflow and inflow discharge at that time we call the delayed volume. In figure 4.21 the grey shaded areas denote the delayed volume.

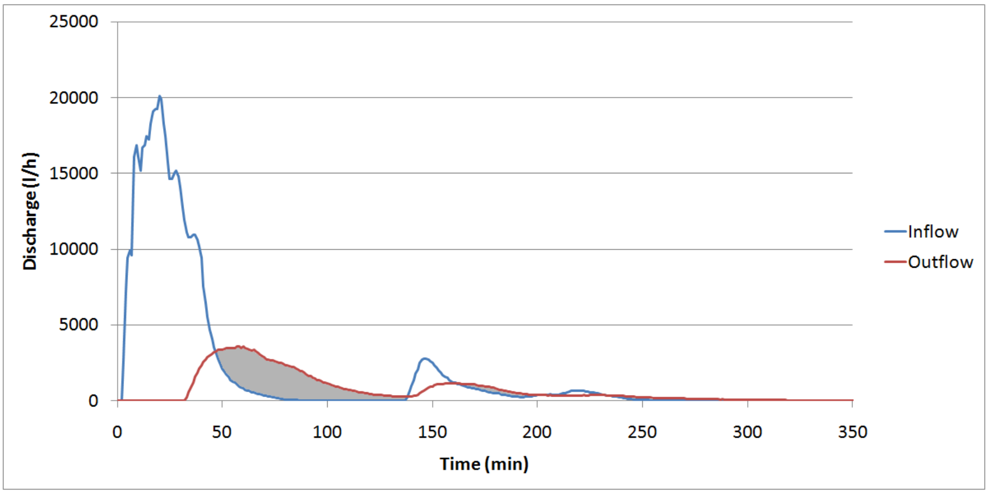


Figure 4.21 Discharge measured at the inflow and the outflow. This graph shows the data of event 9. The grey shaded area between the inflow and outflow lines denotes the delayed volume in *l*.

The data of the piezometers is shown in figure 4.23. The heads are presented with respect to the surface level at the location of pb2. Therefore the surface level at the location of pb2 is called the reference level. With this data it is possible to analyze the water level at three different places in the trench. This is done with pb2, pb3 and pb4 shallow. The heads of the aquifer underneath the SFDS are given by pb4 deep, pb7 and pb8. The locations of the piezometers are given in figure 4.22. Piezometer number 1 is not present in the graph. This is because of a malfunction in the measurement device.

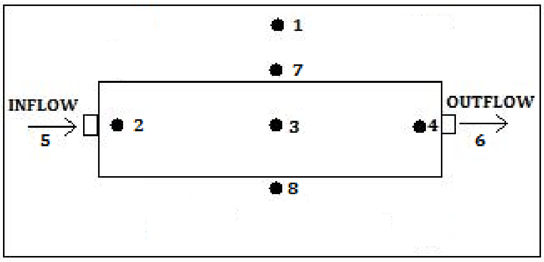


Figure 4.22 Locations of the piezometers.

The heads of the deep piezometers show a difference between the piezometer underneath the trench and nearby the water and the piezometers besides the trench. This difference is caused by the surface water that has got a higher level. Because of this the piezometer nearby the water shows a smaller depth of the head than the piezometers located further away from the surface water.

There is an infiltrating situation from the trench to the native soil. This is caused by the larger depth of the hydraulic head in the deep layer with respect to the depth of the hydraulic head in the trench. When it is vice versa there will be seepage to the SFDS which is not the case at this study location.

In the trench the water level reacts on the inflow. This is clearly visible in this graph.

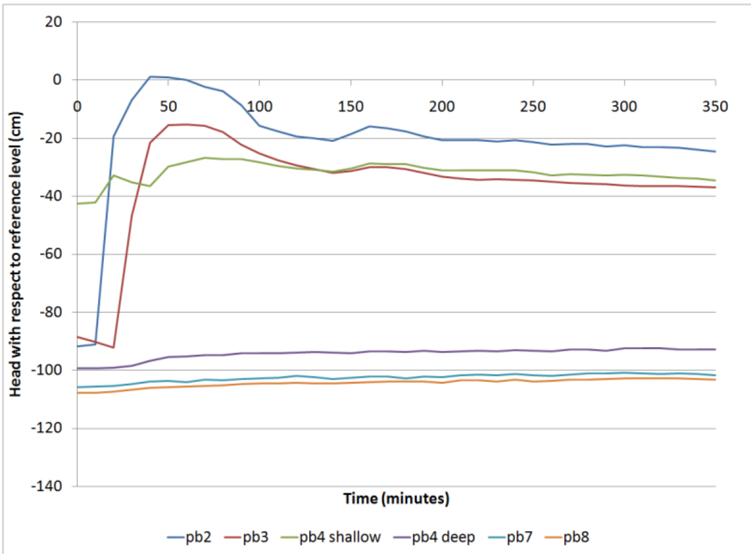


Figure 4.23 Heads in *cm* with respect to the reference level. This graph shows the data of event 9.

In paragraph 4.3.7 more events are shown in figure 4.35 and figure 4.36. This gives a more complete view on what kind of inflow – discharge measurements are used for the analyses. Furthermore some processes in the SFDS are determined with these figures. In these figures events are shown with a dry initial condition and a wet initial condition. They show inflow events with different distributions as well.

4.3.6 Extracted results from rough data

There are twenty measurements used to extract the results from the rough data as shown above. These measured events took place within the period from the 29th of April 2010 until the 3rd of July 2010.

4.3.6.1 Investigated inflow characteristics

The extraction of results from the rough data as shown in the latter paragraph results in some new graphs where the results are shown against four different values of quantities. The first is the intensity in *l/min*. It is defined as the total inflow volume divided by the duration of the inflow. The further values of quantities are the duration of the inflow in *minutes*, the total volume of the inflow in *liter* and the peak inflow in *l/h*. These values of quantities are used because it is expected that they could have their effect on the inflow – discharge relation.

The relation between the different values of quantities is shown in the appendix in figure 9.1. One has to take into account that these results give the relations for this measurements and therefore do not state that this relations are general for the inflow of SFDSs.

These graphs show that there are different relations for events with a short duration and a long duration. The short events have a duration between 75 minutes and 385 minutes. The long events have a duration between 1020 minutes and 1055 minutes. Based on this the difference between short and long events will be analyzed as well.

4.3.6.2 Peak delay, peak reduction and total volume reduction

In the appendix figure 9.2 shows the effect of the four above mentioned parameters on the peak delay. Figure 9.3 and figure 9.4 do the same for respectively the peak reduction and the total volume reduction.

The graphs in figure 4.24 show the three outflow characteristics plotted against the duration of the inflow. The data points of the long duration events show a different relation then the points of the short duration events. This is the case especially for the total volume reduction and the peak reduction. This substantiates the assumption that there is a difference between the behavior of the system on short duration and long duration events. There is a decrease of the values for events with a longer duration for the peak delay and the peak reduction. Due to the relation between the duration of the inflow and the total volume of the inflow this is the case for the total volume of the inflow as well.

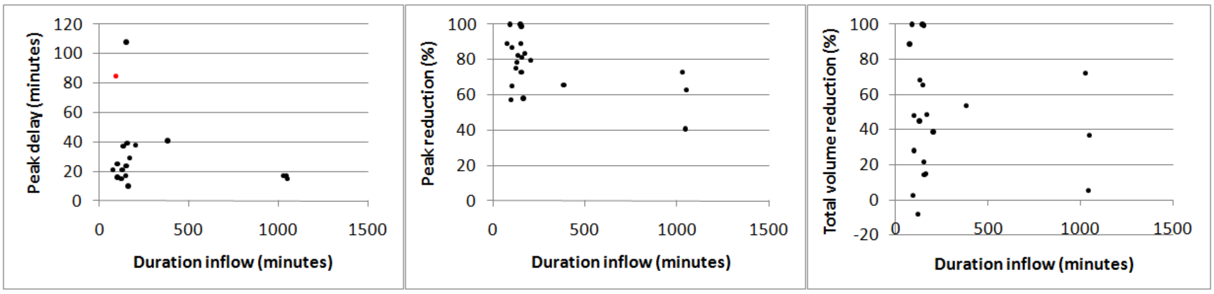


Figure 4.24 The peak delay in *min*, the peak reduction in *%* and the total volume reduction in *%.* The values are plotted against the duration of the inflow in *min*.

The majority of the peak delay values lies between 15 and 45 minutes. There are two different values of 85 minutes and 108 minutes. The first value is denoted with a red point. It is extracted from the experiment. The odd value may be clarified by the fact that the inflow discharge was constant and therefore reached the peak inflow immediately after the event started. At the time when the inflow stopped the outflow peak occurred. Due to the unnatural constant inflow this event shows a different value than the natural events. The second value of 108 minutes has a dry initial condition. This in combination with the largest inflow peak at the start of the event and another lower peak at the end of the event gives a relatively large peak delay. This event is shown in figure 4.35. The outflow of this event is denoted there with the character 'A'.

For the peak reduction the majority of the percentages is situated between 57% and 99%. One value that is different is the 40%. This value corresponds with an event that occurred about 400 minutes later than the end of the artificial inflow discharge. The relative low value of the peak reduction is probably caused by the very wet initial condition of the SFDS at the start of the event. This indicates that a larger initial moisture content probably causes a smaller peak reduction. Which is in agreement with the literature (Barber, King, Yonge, & Hathhorn, 2003). It substantiates what was described in the scenarios in paragraph 3.3 as well.

The total volume reduction shows wide spread values between -8% and 100%. The negative value is caused by the fact that for that event the outflow of the previous event was not stopped already. Due to this part of the water that flowed into the SFDS during the former event is discharged through the drain during this event. There is a large spread of the values, because of this no odd values may be pointed out.

The peak delay and the peak reduction decreases when the total inflow volume increases. Furthermore there is no clear relation for the different inflow characteristics. This may be caused by the fact that the initial water level in the trench is different for each precipitation event. This means that a different storage volume was available in the SFDS for the different events. Figure 4.25 shows the effect of a different initial available pore volume in the trench on the total volume reduction, the peak delay, the peak reduction and the difference between the start of the inflow and the start of the outflow. The latter is analyzed in paragraph 4.3.6.5.

First of all it should be noticed that the event with the initial available pore volume of 0.14 m^3/m is the experiment. This value is denoted with a red point. In the left graphs this event shows a different value than one probably expects. For all four graphs it may be stated that with an increasing initial available pore volume in the trench the values are increasing. They do not have a clear linear relation. This is probably caused by the different inflow characteristics.

Furthermore there are some events where no outflow is measured. These events do not have a peak delay and a difference between the start of the inflow and the start of the outflow. This is the reason why for these events no data is given in these graphs.

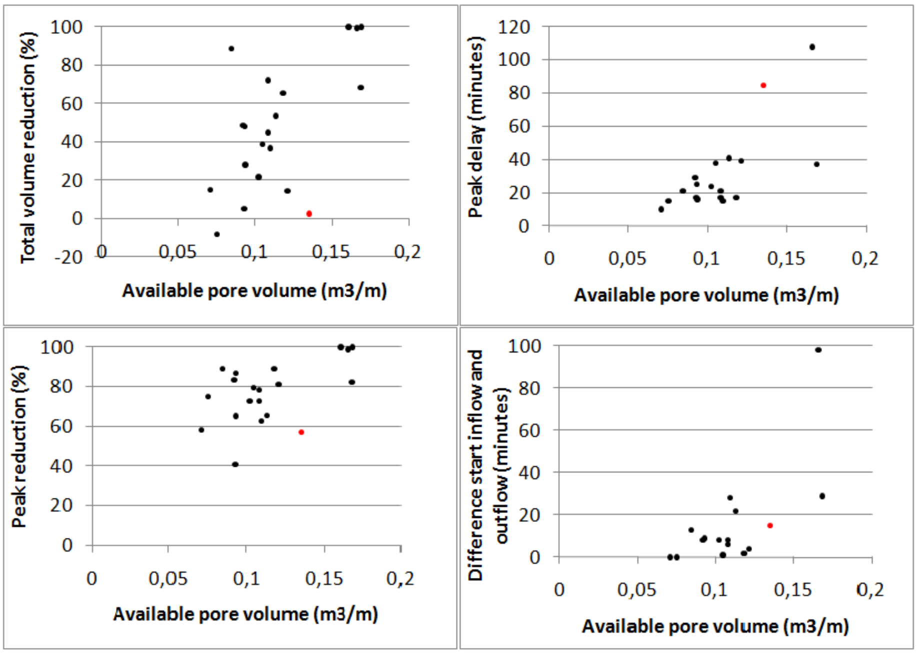


Figure 4.25 Relations of the initial available pore volume in *m^3/m* versus the total volume reduction in *%*, the peak delay in *minutes*, the peak reduction in *%* and the difference between the start of the inflow and the start of the outflow in *minutes*. The red point denotes the experiment.

To analyze the results with the same initial water level in the trench the events with an initial water level of 35 cm or less with respect to ground level are selected. For this selection piezometer 2 is used. This piezometer is used because it is the most close one to the inflow point. Here the initial water level will have the biggest effect because of the processes in the SFDS. These processes are shown in paragraph 4.3.7. The same graphs as shown in the appendix in figure 9.2, figure 9.3 and figure 9.4 are created for these selected events. These graphs are shown in the appendix in respectively figure 9.5, figure 9.6 and figure 9.7. In this figures the black data points denote the short duration events and the red data points denote the long duration events.

The peak delay is between 10 minutes and 42 minutes. Analyzing the results of the peak delay it still is difficult to define a relation. This is in contradiction with the literature where for an increasing duration an increasing peak delay and an decreasing peak delay is found (Barber, King, Yonge, & Hathhorn, 2003). This disagreement is probably caused by the different inflow distributions. The distribution used in literature does have one peak, the actual distribution of the measurements do have more peaks. The largest peak of the measured data is used to determine the peak delay.

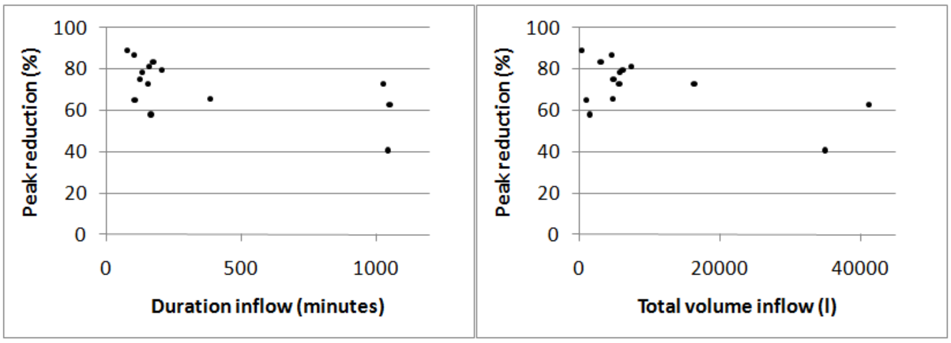


Figure 4.26 The peak reduction in % plotted against the duration of the inflow in *min* and the total inflow volume in *l*. The data points represent the events with an initial water level in the trench of 35 cm or less with respect to the surface level.

The values of the peak reduction are between 40% and 89%. An increase of the duration of the inflow and an increase of the total inflow volume show a small decrease of the peak reduction. This is shown in figure 4.26. The intensity and the peak inflow does not have any effect on the peak reduction.

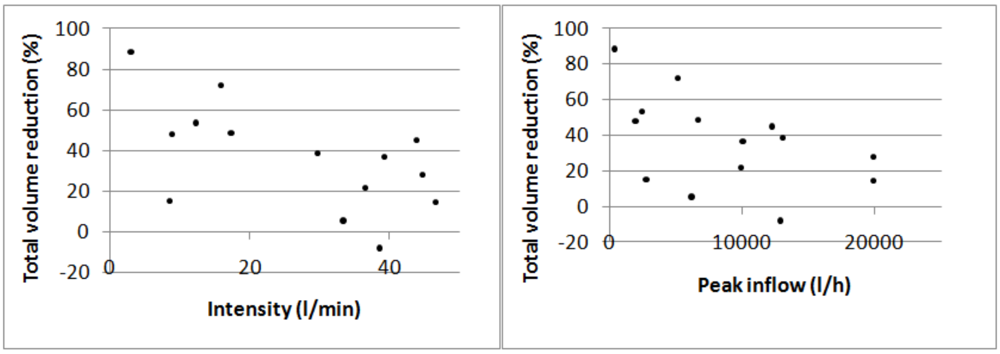


Figure 4.27 The total volume reduction in % plotted against the intensity in *l/min* and the peak inflow in *l/h*. The data points represent the events with an initial water level in the trench of 35 cm or less with respect to the surface level.

The total volume reduction values are situated between -8% and 89%. The duration of the inflow and the total inflow volume do not have a clear effect on the total volume reduction. However an increasing intensity and peak inflow cause a decreasing total volume reduction.

The duration of the inflow and the total volume inflow have a similar effect on the peak reduction. While the intensity and the peak inflow do not have a clear effect on this subject. On the other hand the intensity and peak inflow do have effect on the total volume reduction. While the duration of the inflow and the total volume do not have a clear effect on the subject. This may be related with the relations between these inflow characteristics. These are shown in the appendix in figure 9.1.

As mentioned before there is a difference between the short inflow events and the long inflow events. Therefore the data of the short events are compared to the data of all the events. The short events all have the peak inflow at the start of the event. This causes an increasing peak delay for an increasing duration of the inflow and an increasing total volume reduction. While the events with a long duration have a significant smaller peak delay. The range of the values for the short events is between 10 minutes and 42 minutes.

As well as for all the events the peak reduction decreases for an increasing duration of the inflow for the short event. Furthermore for the total inflow volume for short events there is no trend. While taking into account the events with a larger total inflow volume there is a decreasing peak reduction for an increasing total volume inflow. The range of the values for the short events is between 58% and 89%.

There is a decreasing total volume reduction for an increasing intensity and peak inflow. Which is the case when taking all the events into account as well. Furthermore for the short events there is a more clear decrease of the total volume reduction for an increasing total inflow volume. The range of the values for the short events is between -8% and 89%.

4.3.6.3 Duration outflow versus duration inflow

Besides the obvious characteristics to study like peak reduction, peak delay and total volume reduction more characteristics are studied in this research to get a more complete view on the actual working of the SFDS. Figure 4.28 shows the relation between the outflow duration and the inflow duration. At the left the graph is given for all the data points. At the right the graph is shown with the data points of the events with an initial water level in the trench of 35 cm or less with respect to the ground level.

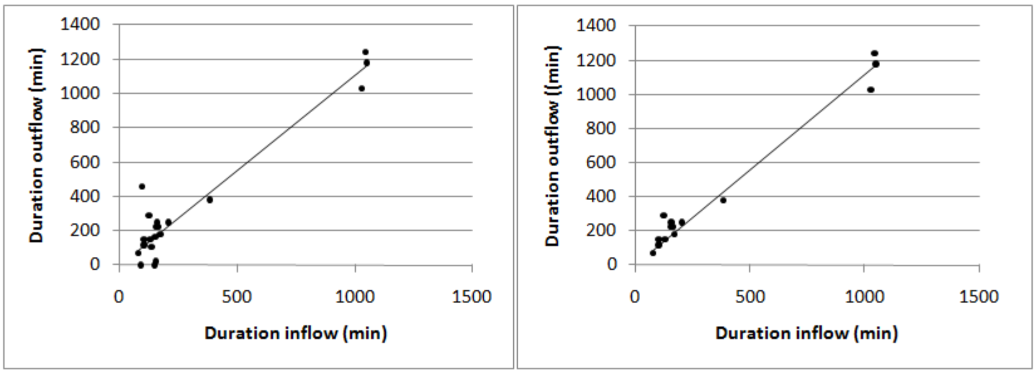


Figure 4.28 Duration outflow *min* versus duration inflow *min*. Left: All the data points. Right: The data points with an initial water level in the trench of 35 cm or less with respect to the surface level.

In both graphs the linear relation shows that the duration of the outflow takes 12.5% more time than the duration of the inflow. At the left graph the data points of the events with an initial water level in the trench of more than 35 cm with respect to the ground level are all underneath the linear relation line. This is because more water is stored underneath the drainage level by which less water has to be discharged by the drain. One data point is an exception on this. This point has an inflow duration of 95 minutes and an outflow duration of 460 minutes. These are the values of the experiment which is probably the reason of the exceptional position in the left graph.

The 12.5% increase of the outflow duration with respect to the inflow duration has a certain maximum. This is caused by the maximum outflow duration after an event where the SFDS is totally filled. This situation is created during the experiment. Here it took around 350 minutes before the outflow stopped after the inflow stopped. By this the maximum time the trench empties by means of the drain is determined. For the study site this means that even with a precipitation event of 2800 minutes (almost 2 days) it is still possible to have an outflow duration that is 12.5% longer than the inflow duration. With longer events this is not possible. The maximum increase will be smaller.

4.3.6.4 Total volume inflow versus total volume outflow

Like for the relation between the duration of the outflow and the duration of the inflow a relation between the total inflow volume and the total outflow volume is expected. In figure 4.29 this relation is demonstrated. At the left the graph is given for all the data points. At the right the graph is shown with the data points of the events with an initial water level in the trench of 35 cm or less with respect to the ground level.

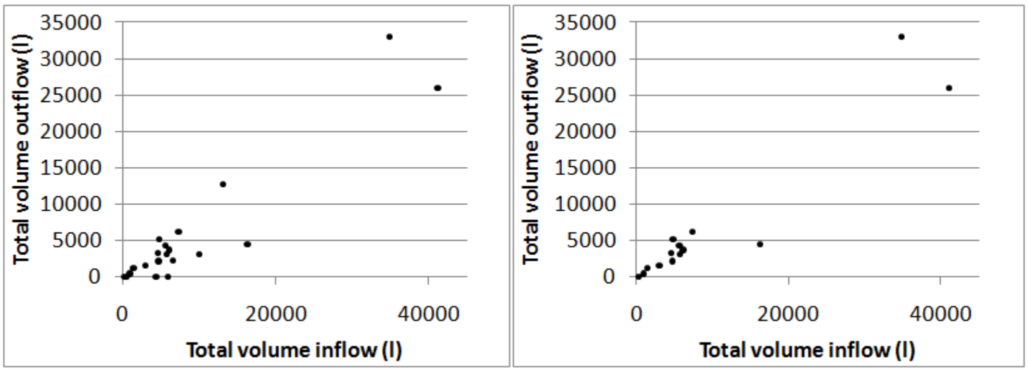


Figure 4.29 Total volume outflow in *l* versus total volume inflow in *l*. Left: All the data points. Right: The data points with an initial water level in the trench of 35 cm or less with respect to the surface level.

As for the duration of the inflow versus the duration of the outflow relation as expected there is a relation between the inflow volume and the outflow volume. The left graph which contains all the data points shows more smaller outflow volumes. This is caused by the larger storage capacity of the SFDS underneath the drainage level when the water level depth in the trench is larger. There is one value that is an exception on this. This is the value of the experiment. The unnatural distribution of the inflow of this measurement causes a large intensity from the beginning to the end. This will fade away the effect of the storage capacity underneath the drain. Furthermore the trench was not completely empty when the experiment started. Due to this there was no maximum storage capacity available underneath the drainage level.

The linear function shows a volume reduction of around 28%. This linear relation clarifies the fact that not a clear effect could be determined between the inflow volume and the total volume reduction in paragraph 4.3.6.2. The volume reduction shown in that paragraph is around 28% as well.

4.3.6.5 Difference start inflow and start outflow in minutes

How long it takes before the drain starts discharging after the inflow has started shows a delay between both. In figure 4.30 this delay in minutes is plotted against the initial available pore volume in m^3/m. There is a trend of an increasing delay for increasing initial water level depths in the trench. This is obvious because more water needs to be added to exceed the drainage level. The data shows the delay of events with different distributions of the inflow. This is why there is not a very clear relation visible. An event with a larger intensity will cause a smaller delay than an event with a smaller intensity and the same initial water level in the trench.

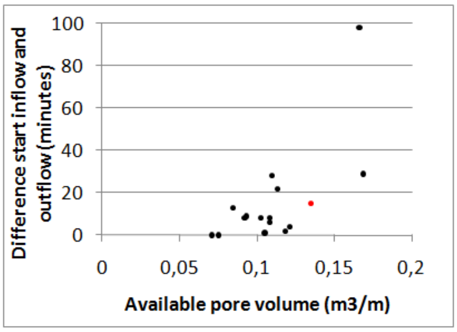


Figure 4.30 Difference start inflow and start outflow in *minutes* versus initial available pore volume in the trench in m^3/m.

4.3.6.6 Total delayed volume per total outflow volume

Not the whole volume of water that is discharged through the drain may be considered as a delayed discharge. During the outflow discharge when there is still an inflow discharge a part of the outflow discharge is not delayed. The definition of the delayed volume can be found in paragraph 4.3.5. Furthermore it is shown in figure 4.21. The part of the outflow volume that actually is delayed may be considered as a percentage of the total outflow volume. In figure 4.31 the total delayed volume per total outflow volume is given as a percentage versus the inflow intensity in l/min.

The left figure shows all the data points. The range of the percentages is between 0% and 72%. The intensity of 138 l/min is the experiment. That clarifies the very large intensity and thus the exceptional position in the graph. The right graph shows the data points with an initial water level in the trench of 35 cm or less with respect to ground level. The range of the percentages is from 0% to 65%. The range thus is somewhat smaller than the range of all the data points.

The right graph shows some relation of the total delayed volume per total outflow volume with the intensity. An increasing intensity causes an increasing delayed volume per total outflow volume. This relation is presented in the left graph as well.

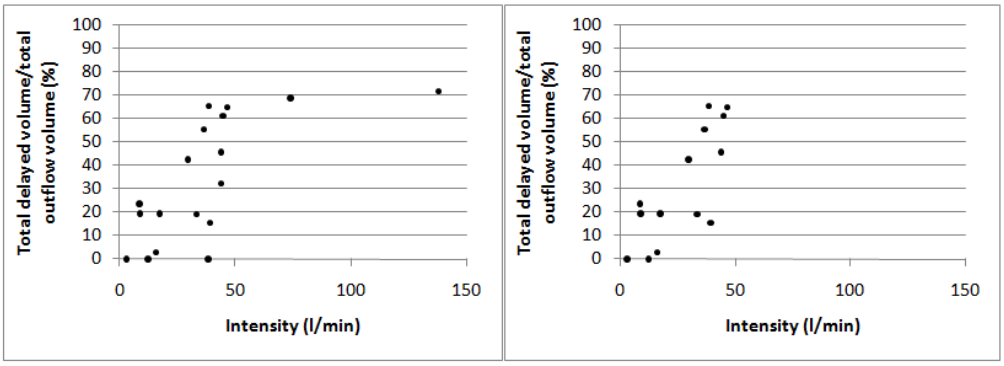


Figure 4.31 Total delayed volume per total outflow volume in *%* versus inflow intensity in *l/min*. Left: All the data points. Right: The data points with an initial water level in the trench of 35 cm or less with respect to ground level.

As can be seen in figure 9.1 for these measurements there is a relation between the intensity of the inflow in l/min and the peak inflow in l/h. An increasing intensity involves an increasing peak inflow. This explains why for a larger intensity the ratio between delayed volume and outflow volume is larger. When the peak inflow is smaller the intensity is smaller and the water inflow is more evenly spread in time. This causes a larger overlap between inflow and outflow. Which causes a smaller ratio between the delayed volume and the outflow volume.

Based on the latter it is clear that for an increasing peak inflow an increasing ratio between the delayed volume and the outflow volume is obvious. This is shown in figure 4.32 where the left graph shows all the data. The right graph shows the data points of the measurements with an initial water level in the trench of 35 cm or less with respect to ground level. Both graphs show the mentioned relation.

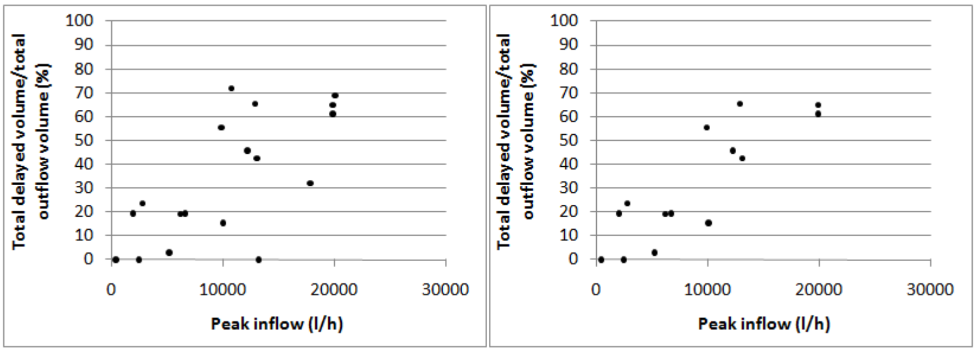


Figure 4.32 Total delayed volume per total outflow volume in *%* versus peak inflow in *l/h*. Left: All the data points. Right: The data points with an initial water level in the trench of 35 cm or less with respect to ground level.

The ratio of the total delayed volume and the total outflow volume is significant smaller for long duration events than for short duration events. The same is the case for the events with a large total inflow volume. This is shown in figure 4.33. In this figure the black points denote the short duration events and the red points denote the long duration events. The short duration events as well as the long duration events separately have an increasing trend in case of an increasing duration of the inflow and an increasing total volume of the inflow.

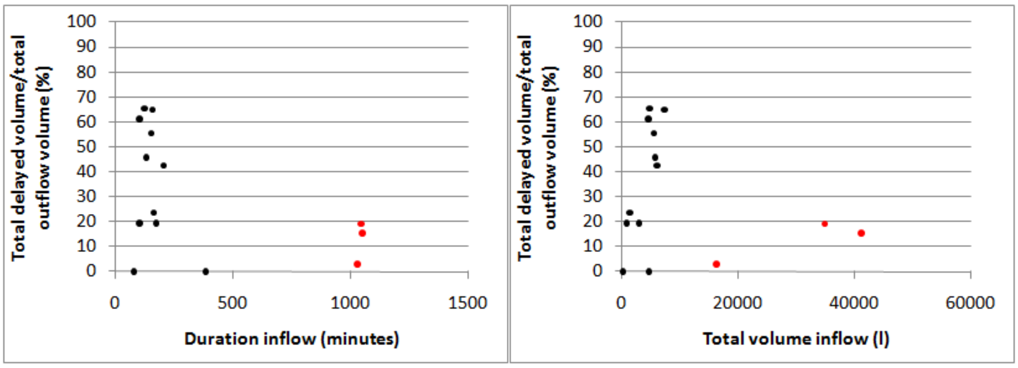


Figure 4.33 Total delayed volume per total outflow volume in *%* versus duration of the inflow in *minutes* and the total volume inflow in *l*. The data points that are presented have an initial water level in the trench of 35 cm or less with respect to ground level. The black points denote the short duration events. The red points denote the long duration events.

4.3.6.7 Peak outflow

The results of the peak reduction showed more or less constant values for the intensity and the peak inflow. Which indicates a linear relation between the peak outflow and the intensity and peak inflow. An increasing duration of the inflow and total volume inflow causes a small decrease of the peak reduction. This indicates a non-linear relation between the peak outflow and the duration of the inflow and total volume inflow. Figure 4.34 shows the results with respect to the peak outflow. The black points denote the short duration events. The red points denote the long duration events.

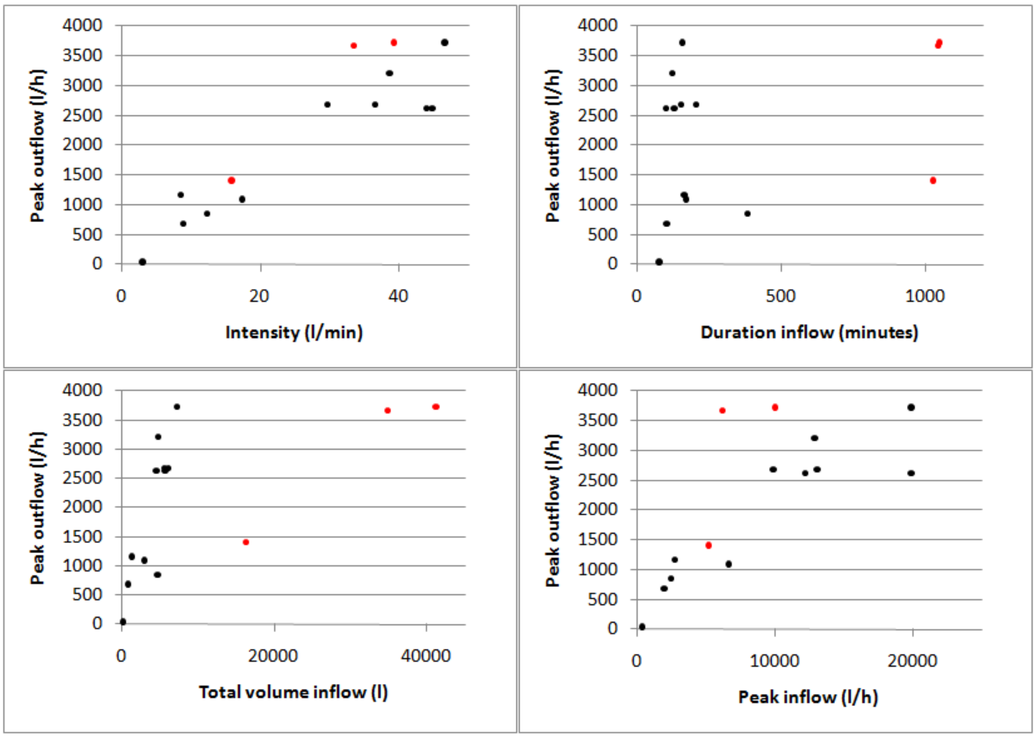


Figure 4.34 Peak outflow in *l/h* versus intensity in *l/min*, duration inflow in *minutes*, total volume inflow in *l* and peak inflow in *l/h*. Data points are extracted from events with an initial water level of 35 cm or less with respect to ground level. The black points denote the short duration events. The red points denote the long duration events.

In the graph of the peak outflow against the inflow intensity a clear linear relation is observed. An increase of the intensity causes an increase of the peak outflow. The size of the outflow peak is dependent on the reached water level in the trench. The higher the water level the larger the outflow peak is. With an intensity of the inflow which exceeds the discharge of the drain and the infiltration to the native soil the water level in the trench is able to rise. Due to this a larger peak outflow occurs. For the analyses of all the events this is the case as well as for the short and long duration events.

As observed in the appendix in figure 9.1 in practice the peak inflow is related to the intensity. Because of this for the peak inflow as well the same effect is noticed as for the intensity. A larger peak inflow causes a larger peak outflow. Although the relation is less clear for the peak inflow than for the intensity. In case of the short events the relation for the peak inflow is more clear than for all the events.

For the duration of the inflow and the total volume of the inflow on basis of the peak reduction it could be expected that there is no linear relation with the peak outflow. This is because of the small decrease of the peak reduction when the two characteristics increase. In both graphs of these characteristics in figure 4.34 it is clear that there is no linear relation when analyzing all the results. The short and long duration events separately have an increasing relation for an increasing duration of the inflow and an increasing total inflow volume.

4.3.6.8 Summary of the inflow characteristics

The above described analyses on all the events is summarized in table 4.5. In this table it is shown which inflow characteristics do or do not have any effect on the investigated outflow characteristics.

All events	Peak delay	Peak reduction	Total volume reduction	Total delayed volume per total outflow volume	Peak outflow
Intensity inflow	0	0	--	++	++
Peak inflow	0	0	--	++	++
Duration inflow	0	-	0	0	+
Total inflow volume	0	-	-	0	+

Table 4.5 Summary of the affecting characteristics drawn from the measurements. -- = A clear decrease when the changed characteristic is increased. - = A small decrease when the changed characteristic is increased. 0 = No effect. + = A small increase when the changed characteristic is increased. ++ = A clear increase when the changed characteristic is increased.

The summarizing tables may be given for the short duration events as well. This is done in table 4.6. For the long duration events it must be noticed that only 3 measurements were available. That makes that in this report only the trends for short duration events are given.

Short duration events	Peak delay	Peak reduction	Total volume reduction	Total delayed volume per total outflow volume	Peak outflow
Intensity inflow	0	0	--	++	++
Peak inflow	0	0	--	++	++
Duration inflow	+	-	0	0	+
Total inflow volume	+	0	-	++	+

Table 4.6 Summary of the affecting characteristics drawn from the short duration events. -- = A clear decrease when the changed characteristic is increased. - = A small decrease when the changed characteristic is increased. 0 = No effect. + = A small increase when the changed characteristic is increased. ++ = A clear increase when the changed characteristic is increased.

A more complete view on the investigated characteristics is given in table 4.7. Here the minimum, the median and the maximum values are summarized for the peak delay, the peak reduction, the total volume reduction, the total delayed volume per total outflow volume and for the peak outflow. The values are given for all the events and for the events with a shallow initial water level in the trench.

		Peak delay (min)	Peak reduction (%)	Total volume reduction (%)	Total delayed volume per total outflow volume (%)	Peak outflow (l/h)
All measured events	**Number of observations**	18	20	20	18	20
	Minimum	10	40	-8	0	0
	Median	23	79	47	28	1691
	Maximum	108	100	100	69	4515
Shallow initial water level in trench	**Number of observations**	14	14	14	14	14
	Minimum	10	40	-8	0	44
	Median	21	74	38	22	2628
	Maximum	41	89	89	66	3730
Short duration events	**Number of observations**	11	11	11	11	11
	Minimum	10	58	-8	0	44
	Median	24	79	39	43	2628
	Maximum	41	89	89	66	3730

Table 4.7 Minimum, median and maximum values of the measurement data. The values are given for all measured events and for the events with a shallow initial water level in the trench of 30 cm or less with respect to surface level.

4.3.7 SFDS processes

The measurements revealed some processes in the SFDS during the precipitation events. In figure 4.35 and figure 4.36 the measurement of respectively the 30th of May 2010 and the 8th of June 2010 are shown. The top graph of each figure shows the discharge of the inflow and the outflow. The bottom graph shows the heads with respect to the reference level. The black lines with the characters A to F show the different outflow events. These events start when the outflow starts and stops when the outflow stops as well. Both measurement periods have a dry initial condition of the SFDS. Pb4 shallow has a maximum measurement depth of 40 cm. This is why it looks like the water level at that place does not drop below this level. Furthermore the filter of pb3 is situated underneath the soil improvement. That is why these measurements give a somewhat different water level in the trench.

Measurement analyses

In figure 4.36 before there is outflow discharge measured there did some inflow events take place without any outflow discharge. The drainage level of 30 cm with respect to reference level is exceeded by pb2 for the second event while no outflow discharge is measured. This is probably caused by the water level at pb3. It is not exceeding the drainage level. The rising water level of pb2 and pb3 are clearly visible. At the moment of these two inflow events the drain is filled with water. From this drain probably the water is infiltrated to the dry soil surrounding the drain. Furthermore the water is spread over the trench by horizontal flow. This principle is visible at the beginning of the measurement shown in figure 4.35 as well.

At the time the water level at the locations of pb2 and pb3 are high enough the drain starts discharging a small amount of water. This is denoted with the A in figure 4.35. Pb4 at that moment is not exceeding the drainage level. The outflow period denoted with B starts when the water levels of pb2 and pb3 are high enough. After 90 minutes the water level of pb4 exceeds the drainage level. When the outflow stops the water level of pb4 is below the drainage level again. The next outflow period is denoted with C. Here the difference in water level rise is clearly visible. Pb2 rises the fastest and pb4 rises the slowest. Again here the outflow starts when pb4 is not exceeding drainage level. The outflow stops after pb4 drops below drainage level. Periods D and E both show that the saturation of the SFDS is large at the beginning. The three piezometers react fast to the inflow. During the main part of the outflow they all exceed the drainage level. In figure 4.36 the period F shows again that when pb2 and pb3 have a water level that is shallow enough to start the outflow discharge. This happens before pb4 exceeds the drainage level. At this location the water level is below drainage level when the outflow stops.

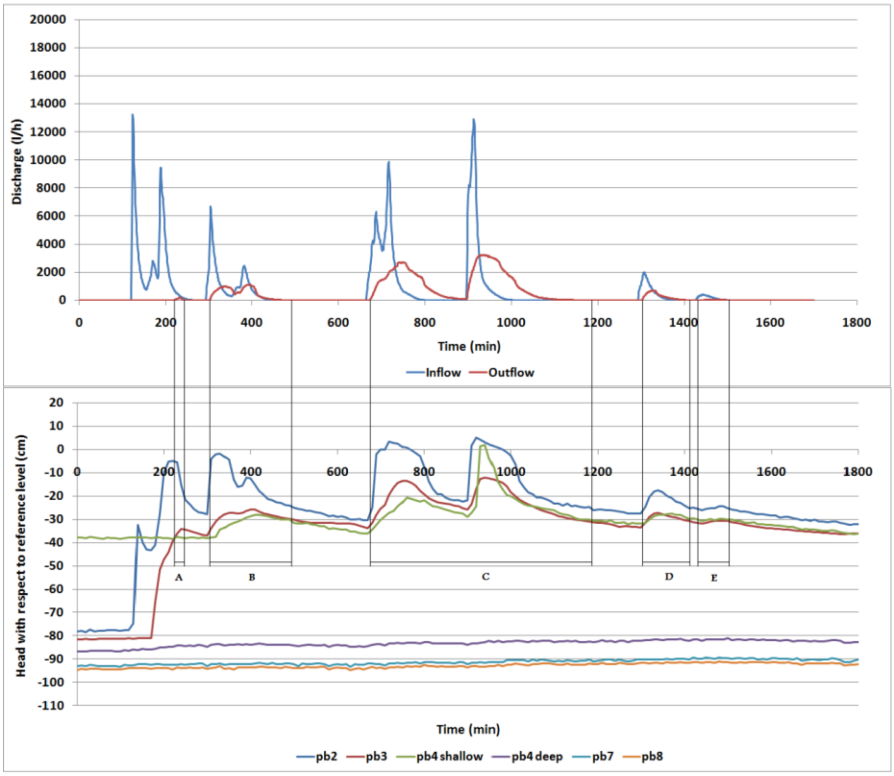


Figure 4.35 Events measured at the 30th of May 2010. The top graph shows the discharge in *l/h* of the inflow and the discharge of the outflow. The bottom graph shows the heads in *cm* with respect to reference level. The lines with the characters A, B, C, D and E denote the outflow events.

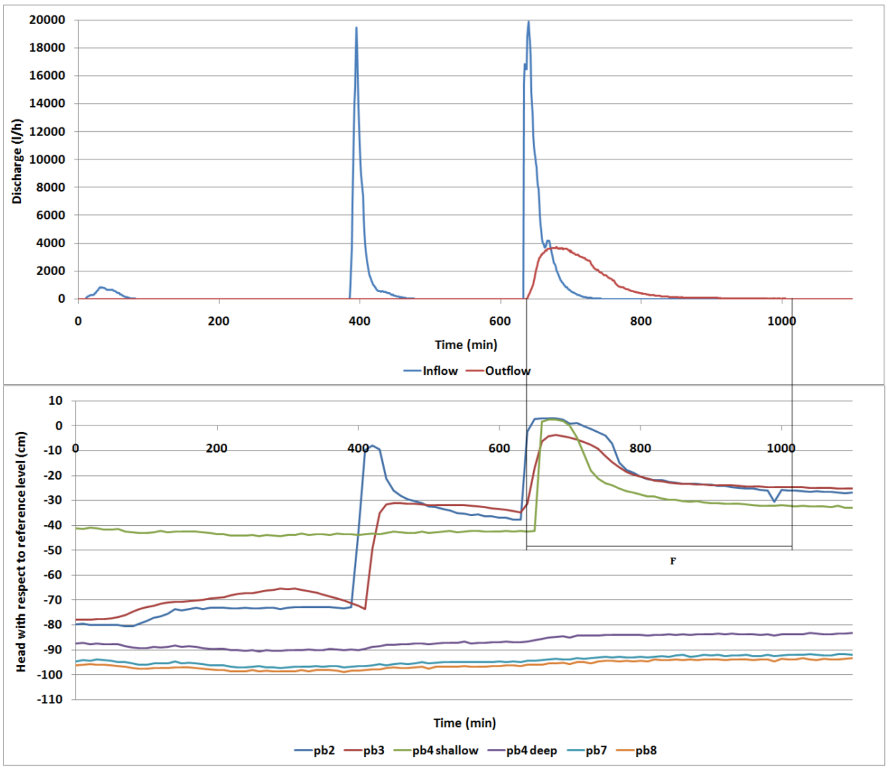


Figure 4.36 Events measured at the 8th of June 2010. The top graph shows the discharge in *l/h* of the inflow and the discharge of the outflow. The bottom graph shows the heads in *cm* with respect to reference level. The line with the character F denote the outflow events.

Schematic summary of processes

The processes as described above are shown in figure 4.37. In this figure the SFDS is empty in the beginning and at the end of the event. The processes described are typical for a SFDS with the inflow at the beginning of the SFDS.

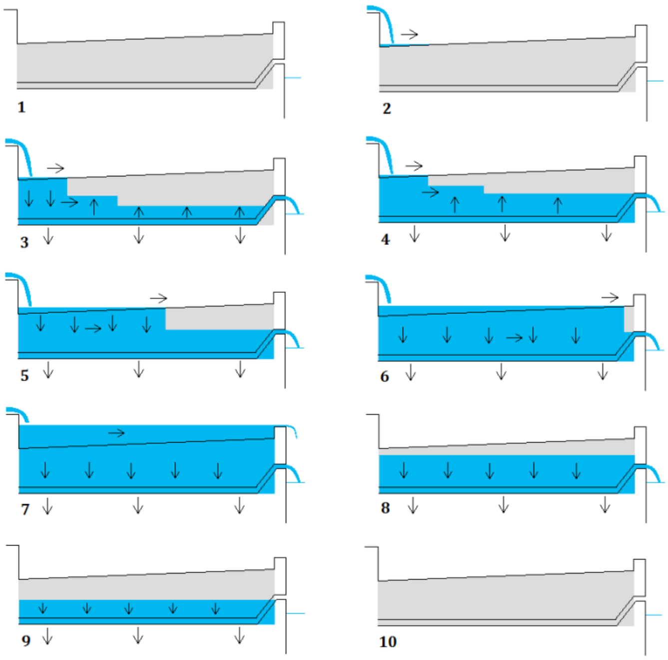


Figure 4.37 Processes in the SFDS during rain events.

Here an explanation is given for figure 4.37:

1. The SFDS is empty before the rain event.
2. It starts raining. Water is flowing into the SFDS.
3. Water infiltrates into the trench and reaches the drain. It starts flowing through the drain. The drain infiltrates water back to the trench. When the water level in part of the trench exceeds the drainage level the drain is not immediately discharging. This is the case when the same amount of water is entering the drain as is infiltrating from the drain back to the trench. The drain starts discharging when there is enough water to infiltrate back from the drain to the trench and to discharge to the surface water. Furthermore water is infiltrating to the surrounding soil.
4. From the drain water is infiltrating to the trench until the drainage level is exceeded, while the drain is still discharging and water is infiltrated to the surrounding soil.
5. The swale starts filling up. Water infiltrates over a larger surface.
6. Over the whole surface of the SFDS water infiltrates.
7. The swale is totally filled. The drain and the spill are discharging water. If the design is good this normally happens only during an extreme event. For instance once or twice a year.
8. The rain stops. In the trench the water level decreases by discharging the water through the drain and infiltrating the water to the surrounding soil.
9. The drain stops discharging. Only infiltration to the surrounding soil decreases the water level.
10. The SFDS is empty again.

Empirical conceptual model

Some of the processes as described above are tested by using an empirical conceptual model. Such a model is made for the SFDS at the study site. It simulates the actual processes in a very simple way. The modeled processes are the inflow, the infiltration, the horizontal flow through the trench and the flow through the drain. Here a short explanation of the model is given and some results are shown and analyzed. The schematic view of the SFDS like how it is used in the model is shown in figure 4.38.

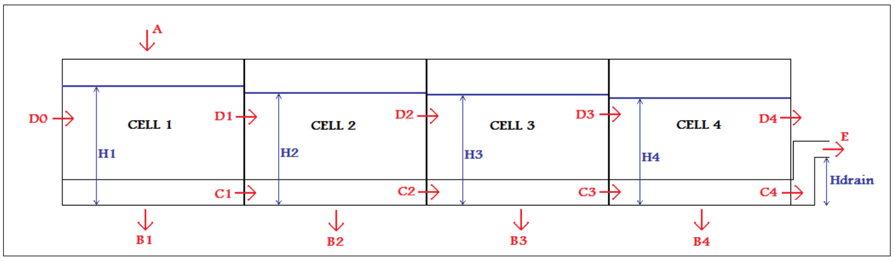


Figure 4.38 Schematic view of the SFDS as used in the empirical conceptual model. The SFDS is divided in n cells. In this example the SFDS is divided in 4 cells.

In the model the SFDS is divided in n cells. In figure 4.38 the SFDS is divided in 4 cells. For each cell a water balance is calculated for every time step. The water balance contains an inflow, an outflow and a change in storage. With the change in storage the new water level in the specific cell is calculated. Here the used formulas are shown. The first two formulas are used to calculate this change in water level. The formulas with the characters in front determine the flows as denoted in red in the figure.

$$F_{rates}(1) = F_{inflow}(1) + F_{redistribution}(1) + F_{infiltration}(1) + F_{drain}(1)$$

$$F_{rates}(2{:}n) = F_{redistribution}(2{:}n) + F_{infiltration}(2{:}n) + F_{drain}(2{:}n)$$

<u>A</u> F_{inflow} *(boundary condition)*

<u>B</u> $F_{infiltration}(1{:}n) = -K_{infiltration} \times H(1{:}n)$

C $F_{drain}(1:n) = -K_{drain} \times (H(1:n) - H_{drain})$ for $H > H_{drain}$

D $F_{redistribution}(0) = 0$ *(boundary condition)*

$F_{redistribution}(n) = 0$ *(boundary condition)*

$$F_{redistribution}(1:n-1) = K_{redistribution}\frac{H_{n+1} - H_n}{l_{cell}}$$

E $F_{out} = \sum F_{drain}(1:n)$

Where:

F	= Flux (m/day)
H	= Water level in trench with respect to the bottom of the trench (m)
H_{drain}	= Drainage level with respect to the bottom of the trench (m)
l_{cell}	= Length of cell (m)
$K_{infiltration}$	= Infiltration parameter (1/day)
K_{drain}	= Drain parameter (1/day)
$K_{redistribution}$	= Redistribution parameter (m/day)

The model as described above is made in Matlab. The model results are calibrated for the outflow discharge and the water levels in the trench. The measurement results of the 30th of May 2010 are used for this. The results of a run with the SFDS divided in 10 cells is compared with the results of a run with no division of the SFDS in cells. The parameters used for these calculations are presented in table 4.8. The results are shown in figure 4.39 and figure 4.40.

The water levels in case of the calculations with 10 cells are sometimes too large. Although, this is the case for 3 cells of the 10 cells. Furthermore the exceeding is especially the case during an event with a saturated SFDS. The first water level measurement, presented by the thin blue line in the graphs, is measured at 10 meter from the inflow point. This corresponds with the third cell in the model. The modeled water level results of the third cell show a better fit with the measurement results. Furthermore the rest of the modeled water levels lie within the range of the measured water levels.

During the period from 0 day until 0.4 day the results show that the calculations with 1 cell simulate the outflow better than the calculations with 10 cells. This is caused by the fact that no redistribution by means of the drain is in the model. When the water level in the first cell exceeds the drainage level the outflow starts immediately. Most of the SFDS at that time is still empty. Therefore the water in the drain in practice is distributed to the empty cells instead of discharged out of the SFDS. For the 1 cell simulation the water level exceeds the drainage level later. Due to this the start of the discharge and the peak delay is better simulated there. Furthermore the maximum discharge and the total amount of the discharged volume is better simulated.

During the period from 0.4 day until 0.8 day the SFDS was saturated. Due to this there is no significant difference between the two simulations. As mentioned before a saturated SFDS with the inflow at one point processes the water like a SFDS with a homogeneous inflow. The start of the discharge, the peak delay, the maximum discharge and the total amount of the discharge is simulated very well for this period.

During the period from 0.8 day until 1.1 day the outflow is better simulated with the 10 cells calculation. This is caused by the fact that the water level in the first cell exceeds the drainage level relatively fast. The water discharged by the drain is not needed for redistribution to other cells, because those cells contain water levels that are already at or around drainage level.

By using this simple empirical conceptual model it is tested and proven that the next processes are present in the SFDS:

- In case of an empty SFDS at the start of an event the water is slowly redistributed over the length of the trench. In this process it is very likely that the drain plays a role as well as the horizontal flow through the trench.
- When the initial water level of the total trench is around the drainage level the drainage starts short after the inflow starts. This is caused by the fact that the inflow let the water level at the head of the SFDS rise faster than the rest of the SFDS. Due to this the drainage level is exceeded relatively fast when it is compared with a situation with homogeneous inflow. The drain starts discharging when the drainage level is exceeded.
- In case of a saturated SFDS the inflow is processed the same way for an inflow at the head as for a homogeneous inflow.

Length SFDS (m)	Width SFDS (m)	H_{drain} (m)	Porosity (-)	$K_{infiltration}$ (1/day)	K_{drain} (1/day)	$K_{redistribution}$ (m/day)
35	0.75	0.5	0.4	0.8	25	7000

Table 4.8 Used parameters in the model results.

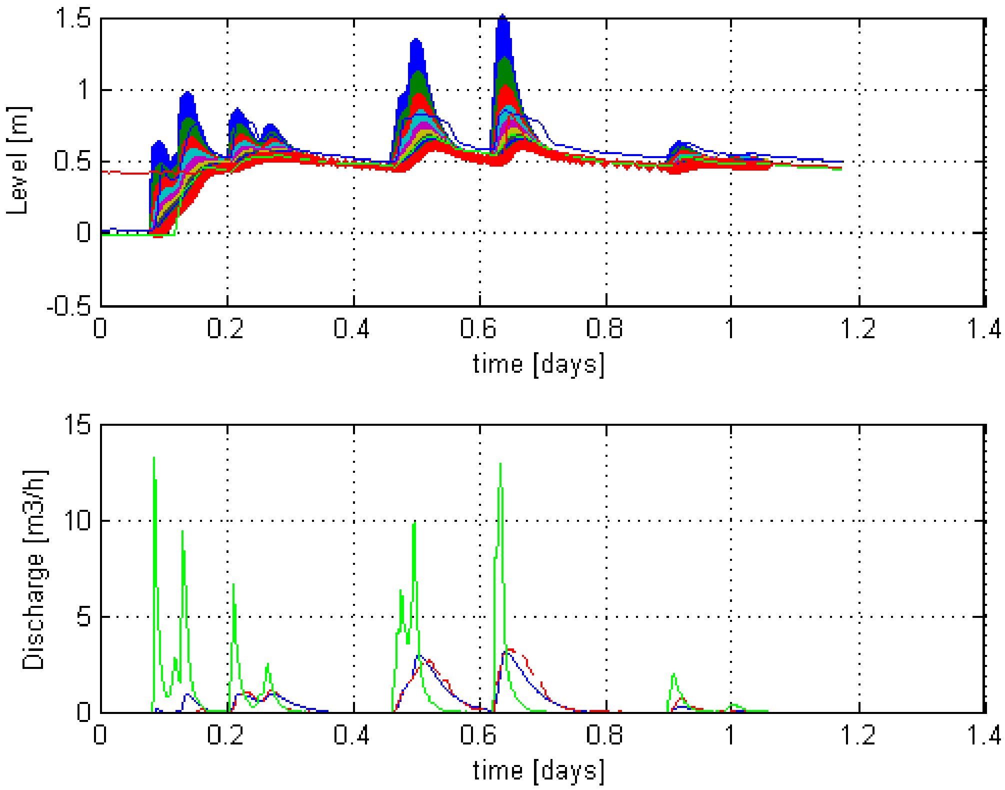


Figure 4.39 Results empirical conceptual model. Number of cells = 10. Measured events of the 30th of May 2010. The top graph shows the water levels in the trench. The thick lines denote the modeled water levels, the thin lines denote the measured water levels. The bottom graph shows the discharges. The green line is the measured inflow, the red line is the measured outflow and the blue line is the modeled outflow.

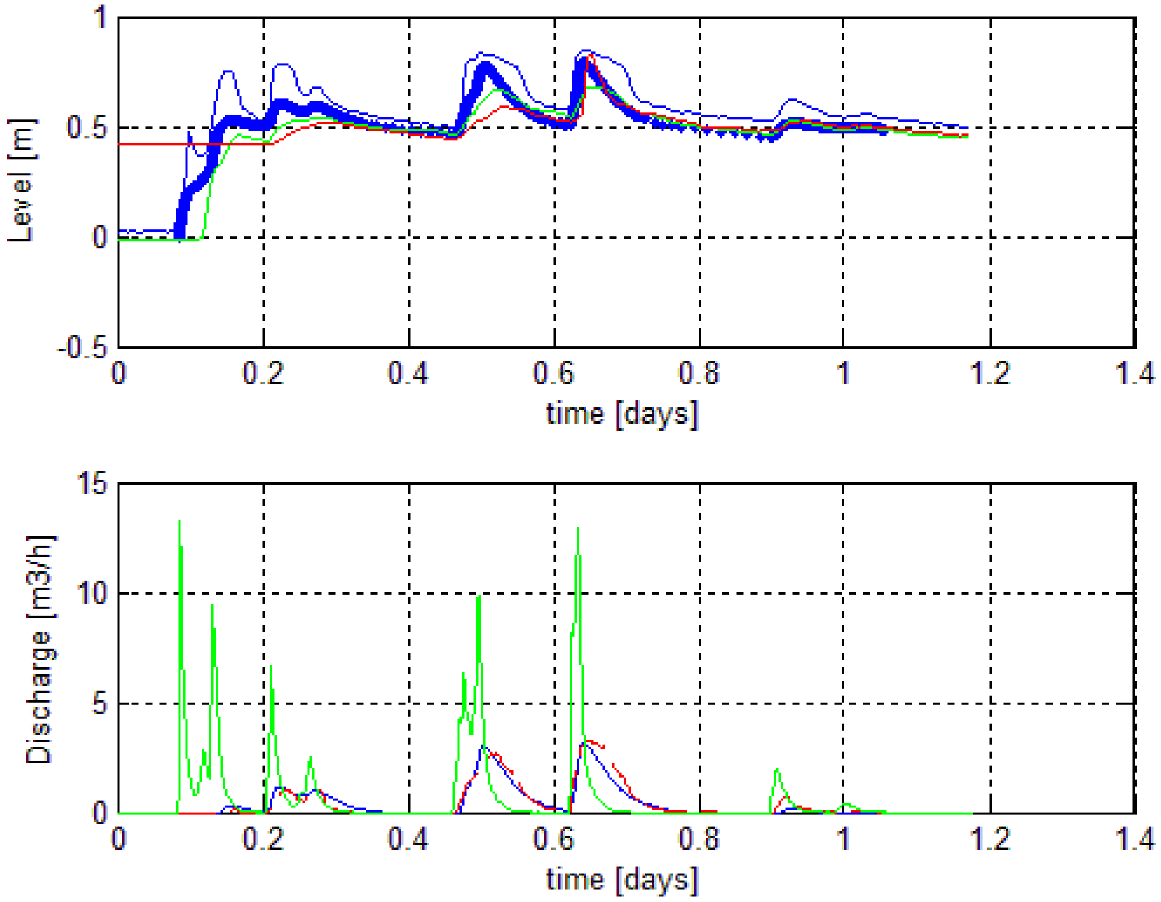


Figure 4.40 Results empirical conceptual model. Number of cells = 1. Measured events of the 30th of May 2010.The top graph shows the water levels in the trench. The thick lines denote the modeled water levels, the thin lines denote the measured water levels. The bottom graph shows the discharges. The green line is the measured inflow, the red line is the measured outflow and the blue line is the modeled outflow.

5 Model

In addition to the measurements a numerical model is used for investigating the inflow – discharge relation of SFDSs. The purpose of the model is to simulate more scenario's for the SFDS. The effect of different properties of the SFDS may be investigated. Hydrus 2D is used. In this chapter an explanation of the choice of Hydrus 2D and a basic description of Hydrus 2D is given. A detailed description is given in Simunek (2006). Furthermore the results of the simulations are given.

5.1 Model description

Hydrus 2D is a finite element based numerical model in two dimensions. The model domain is discretized into a triangular mesh grid. For each element in the network a water balance is solved every time step. An example of a triangular network is shown in figure 5.1.

Hydrus takes into account the saturated and unsaturated zone. In the SFDS as well as in the surrounding soil of the SFDS there is a variable saturation. This is a reason why this program is suitable for this research.

Furthermore Hydrus 2D was chosen for this research because the software is available at the Delft University of Technology where the modeling took place.

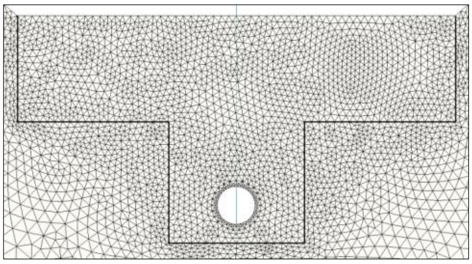


Figure 5.1 Division of a part of the calculation area into a triangular network.

To calculate the water balance for each small triangular area the following modified form of the Richards' equation is used:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j}+K_{iz}^{A}\right)\right]-S \qquad \text{(eq 7)}$$

where θ is the volumetric water content [L^3L^{-3}], *h* is the pressure head [L], *S* is a sink term [T^{-1}], x_i (i=1,2) are the spatial coordinates [L], *t* is the time [T], K_{ij}^A are components of a dimensionless anisotropy tensor K^A, and *K* is the unsaturated hydraulic conductivity function [LT^{-1}] given by

$$K(h,x,y,z)=K_s(x,y,z)K_r(h,x,y,z) \qquad \text{(eq 8)}$$

where K_r is the relative hydraulic conductivity [-] and K_s the saturated hydraulic conductivity [LT^{-1}]. The anisotropy tensor K_{ij}^A in (eq 7) is used to account for an anisotropic medium. The diagonal entries of K_{ij}^A equal one and the off-diagonal entries zero for an isotropic medium. If (eq 7) is applied to planar flow in a vertical cross-section, x_1=x is the horizontal coordinate and x_2=z is the vertical coordinate, the latter taken to be positive upward.

The Richards' equation is a nonlinear equation, therefore an iterative process is used to obtain solutions of the global matrix equation at each new time step. (Simunek, 2006)

Hydrus offers the possibility to use some preset parameters of different soil types. These preset parameters are shown in appendix III in table 9.1.

Θr denotes the residual water content, θs denotes the saturated water content, Ks is the saturated hydraulic conductivity. The parameters α and n are empirical coefficients affecting the shape of the hydraulic functions.

The used soil-hydraulic model implements the soil-hydraulic functions of van Genuchten who used the statistical pore-size distribution model of Mualem to obtain an equation for the unsaturated hydraulic conductivity function in terms of soil water retention parameters. The expressions of van Genuchten are given below.

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{eq 9}$$

$$K(h) = K_s S_e^l \left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{eq 10}$$

where,

$$m = 1 - 1/n, \quad n > 1 \tag{eq 11}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{eq 12}$$

Parameter *l* denotes the pore-connectivity. For Hydrus this parameter was estimated to be about 0.5 as an average for many soils. S_e denotes the effective water content. (Simunek, 2006)

5.2 Model setup

The model setup is based on the SFDS of the Castellumknoop where the measurements took place. The model is calibrated against the experimental results. This is done by comparing three quantities.

- The discharge of the drain.
- The total discharged volume of water between the time the water level in the trench was at surface level and the time the discharge from the drain stopped.
- The water level decrease in the trench after the discharge of the drain has stopped.

It should be noted that the inflow to the SFDS at the Castellumknoop is at the head of the SFDS. Accordingly the inflow is not divided homogeneously. When the SFDS is modeled in 2D the inflow is spread homogeneously over the length of the SFDS. Many of the SFDSs are designed with a homogeneous inflow. For the latter design a 2D model is suitable.

The translation from the actual 3D situation to the modeled 2D situation brings on some constraints. These constraints are for instance neglecting the processes in longitudinal direction. This is the case for processes within the trench and processes in the surrounding soil of the trench. Within the trench one of these processes is the transport of the water through the drain to infiltrate it back into the trench at another location. The other process within the trench is the horizontal flow of the water in longitudinal direction. One of the processes from the trench to the surrounding soil is the infiltration to the surrounding soil at the head of the SFDS in the longitudinal direction. This causes a more difficult calibration which has to be taken into account during the calibration process.

5.2.1 General

In figure 5.2 a schematic view is given of the SFDS that is modeled in Hydrus 2D. The number 1 denotes the trench, the number 2 denotes the drain and the number 3 denotes the surrounding soil. The modeled area is shown in figure 5.3. The top figure shows the different soil materials of the calibration model. The bottom figure shows the different boundary conditions. In this chapter an explanation will be given about the used soil types and the used boundary conditions.

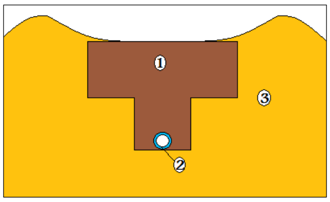


Figure 5.2 Schematic view of the SFDS. Number 1 denotes the trench with the soil improvement. Number 2 denotes the drain. Number 3 denotes the surrounding soil.

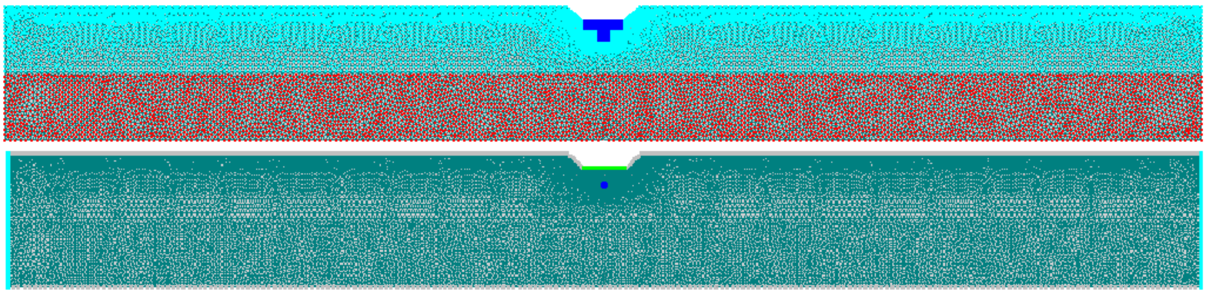


Figure 5.3 The top figure shows the different soil materials of the calibration model. The dark blue surface denotes the trench. The light blue surface denotes the top layer of the native soil and the red surface denotes the second layer of the surrounding soil. The bottom figure shows the different boundary conditions. The different colors denote different boundary conditions. These boundary conditions are described in paragraph 5.2.2.

Trench

In the top figure of figure 5.3 the trench is denoted with the dark blue color. The trench consists of coarse sand with a K_{sat} of 3 cm/min. This value is determined on the basis of the knowledge of the soil type and during the calibration of the model. In the actual situation there is a top soil layer situated on the sand of the trench to let the grass grow on. This soil layer is neglected in the model. This is done because of the lack of parameter values for this layer. Furthermore the thickness is relatively small. Because of the constraints caused by the translation from the actual 3D situation to the modeled 2D situation it is better to simplify the model. With this method the model represents a more general SFDS which is a benefit in this research. The shape of the trench is the same as the shape of the trench at the Castellumknoop.

Drain

The diameter of the drain is 125 mm. Around the drain in the model there is a layer of 2 cm to simulate a certain resistance around the drain. This layer is given a K-value of 0.02 cm/min. This value is determined during the calibration.

Native soil

In the top figure of figure 5.3 the native soil is denoted with the light blue and red color. The native soil denotes the soil that is surrounding the trench. It is the soil that already was present before the construction of the SFDS. Two layers represent the native soil. The soil types are determined by the municipality of Utrecht before this research. The top layer consists of silt. This soil type has a K-value of 0.0042 cm/min. The bottom layer consists of loamy sand with a K-value of 0.2432 cm/min. These values come from the earlier mentioned table 9.1 in appendix III. The k-value of the top layer is somewhat smaller than the measured k-value for that layer. This is because of the choice of a default soil type in Hydrus 2D.

The depth of the top layer is 230 cm with respect to the ground level. The total depth of the model is 425 cm with respect to the ground level. The width of the model is 42 m.

5.2.2 Boundary conditions

Trench

As shown in figure 4.37 during an event the SFDS has a certain inflow. This inflow infiltrates into the trench. Due to this the water level in the trench will rise. At a certain moment the water level in the trench will reach the surface level. When the water level still rises ponding occurs. On top of the trench two types of boundary conditions are used. First of all the atmospheric boundary condition is used to simulate the part where the water level of the trench is not exceeding the surface level. Second the variable pressure head boundary condition is used to simulate the ponding. Here an explanation of these boundary conditions and the constraints for this research is given. The location of this boundary condition is denoted with a light green line in the bottom figure in figure 5.3.

An atmospheric boundary condition is used to simulate the SFDS without ponding. With this boundary condition a potential flux may be specified. In Hydrus 2D it is not possible to define a maximum permissible pressure head for the atmospheric boundary. The default value is 0 m. Due to this it is not possible to simulate ponding. The difference between the potential flux and the actual flux is lost as runoff. A hypothetical soil layer with a large K-value of 1000 - 100000 cm/min, a saturated theta-value of 1 and a residual theta-value of 0.001 was tried. An example of the K-h relation and the theta-h relation is given in figure 5.4. Unfortunately no parameter set was found which kept the K-value large enough when the theta-value tended to 0. Therefore either the hypothetical soil layer holds too much water or this layer will act like an impermeable layer for negative pressure heads.

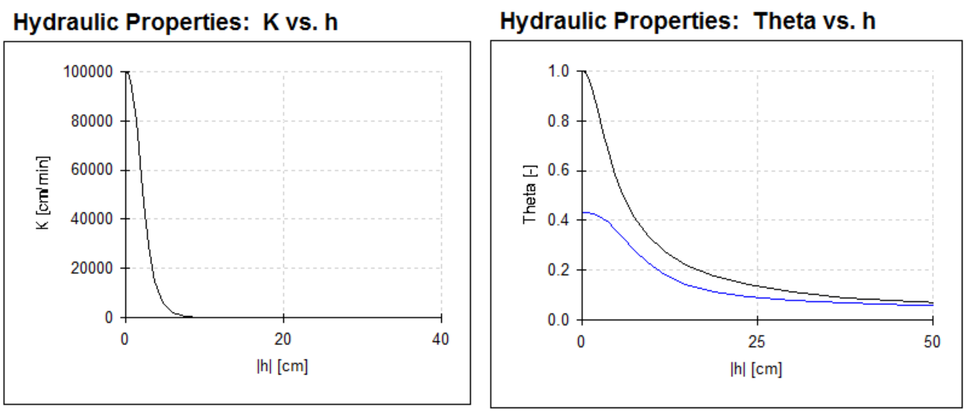


Figure 5.4 The K-h relation and the theta-h relation for the hypothetical soil layer (black line). With theta r = 0.001, theta s = 1, alpha = 0.3, n=2 and Ks=100000 cm/min.

Because of the lack of the ponding possibility in Hydrus 2D to still simulate this ponding a variable head boundary condition needs to be used. In this way it is possible to slowly increase and decrease the water level on top of the trench. This situation has to be simulated apart from the situation with the atmospheric boundary condition.

Drain

In practice the drain in the trench of a SFDS may be installed with a variable drainage level. In many cases the drain is installed near the bottom of the trench, the drainage level is regulated by a small weir. An example of a regulation device is shown in figure 5.5. With this regulation device it is possible to set the drainage level at the same level of the drain as well. In figure 5.6 a schematic view is given of the SFDS with a higher drainage level denoted with number 1 and the SFDS with a horizontal drain denoted with number 2. Two boundary conditions in Hydrus 2D are applicable to the drain for this research. For the drainage level on the level of the drain itself the seepage face boundary condition is used. The variable drainage level is simulated with a variable pressure head boundary condition. Here an explanation of these boundary conditions is given. The location of this boundary condition is denoted with a dark blue color in the bottom figure of figure 5.3.

Figure 5.5 Left: Top view on a drainage level regulation device. Right: Schematical view of the drainage level regulation. (Boogaard, Bruins, & Wentink, 2006)

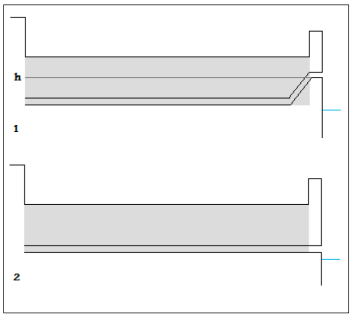


Figure 5.6 Schematic view of the SFDS in longitudinal direction. Figure 1 shows the SFDS that is modeled with a higher drainage level. In this figure 'h' denotes the drainage level. Figure 2 shows the SFDS that is modeled with the seepage face. It is a tile drain that is installed horizontally at the bottom of the trench.

The seepage face boundary condition is used for the horizontal drain. This situation is shown in the bottom figure in figure 5.6. The drain starts draining when the surrounding soil is saturated. The pressure head is set to 0m and it is not possible to specify another pressure head value. In unsaturated conditions there is no flux at the seepage face boundary. In this research a variable drainage level is needed. When the seepage face is used for a variable drainage level this may be implemented by physical relocation of the drain to a higher or lower level. However, with this approach the streamlines of the water in the trench are different from the actual situation.

For the simulation of the higher drainage levels it is possible to use a variable pressure head boundary. This will solve the constraint for this research of the not definable drainage level of the seepage face boundary condition. When specifying the time variable pressure head, the lowest located nodal point with this boundary condition is located. For this point the specified pressure head is applied to this node. To the other nodes pressure heads are adjusted according to the z-coordinates. The constraint of this boundary condition is that it is not possible to automatically stop the flux when the water level in the trench falls below the imposed drainage level. Hereby the drain will start recharging the trench when the drain level is above the trench water level. This problem may be solved by manually regulating the drain. For the variable pressure head a possibility is to let no flux occur when the specified pressure head is negative. As a result the drain can be switched on and off.

Native soil

The native soil denotes the soil that is surrounding the trench. It is the soil that already was present before the construction of the SFDS. A constant pressure head boundary condition is used for the sides of the model. With the constant pressure head boundary it is possible to specify the pressure head at the bottom of the model. From that point the pressure head decreases linearly with the z-coordinates. The location of this boundary condition is denoted with a light blue color in the bottom figure in figure 5.3. The bottom and top of the native soil have a no flux boundary. This is denoted with the grey lines in the bottom figure of figure 5.3.

5.2.3 Initial conditions

General

The initial condition is a known pressure head. This pressure head is specified the same way as the boundary pressure head at the sides of the model. The pressure head is defined for the bottom. From the bottom to the top the pressure head decreases linearly with the height.

5.2.4 Calibration

As mentioned before the model is calibrated with the results of the experiment at the SFDS. For this the discharge of the drain, the total discharged volume of water between the time the water level in the trench was at surface level and the time the discharge of the drain stopped and the water level decrease in the trench after the discharge of the drain has stopped is calibrated.

The discharge of the drain.

The model computes a drain discharge of 2.45 m^3/h at the time the trench is totally saturated. The water level at this time is at surface level. The measured discharge is 2.68 m^3/h. The difference between the modeled drain discharge and the measured drain discharge is 9%.

The total discharged volume of water between the time the water level in the trench was at ground level and the time the discharge of the drain stopped.

From the moment the water level of the piezometer ‘pb4 shallow’ drops below ground level till the end of the drainage 3.13 m^3 of water is discharged. The discharged volume between the total saturation of the trench and the end of discharging of the model is 2.97 m^3. The difference between the modeled result and the measured result is 5%.

The water level decrease in the trench after the discharge of the drain has stopped.

In the trench after the discharge of the drain has stopped the water level decreases by infiltration of the water to the native soil. The model gives a decrease of the water level of 0.008 cm/min as output. The measurements show a decrease of 0.01 cm/min. Therefore the difference is 20%. Taking into account the fact that there are some constraints in the model because of the 3D to 2D translation this shows that the infiltration to the native soil is simulated sufficiently.

With these steps it is proved that the model is calibrated. Therefore it can be used for the intended purpose in this study. Which is the research to the effect on the inflow – discharge relation of the change of certain physical characteristics of the SFDS and its surrounding.

5.3 Model scenarios

The objective of the model is to study the effect of different properties of the SFDS and its surrounding. The model simulations are performed with the model based on the SFDS of the Castellumknoop. The model is simplified by combining the two layers with the native soil types to one layer. This is because the model simulations will be done for a SFDS in one soil layer. To investigate the effect of different properties three reference models are used. Each of the reference models has its own native soil type. The characteristics of the reference models are given in table 5.1. This reference model is made for the native soil types sand, loam and silt. These soil types have different characteristics with respect to the hydraulic conductivity and water content. These different characteristics are shown in figure 5.7. In the left graph it can be seen that the saturated hydraulic conductivity for sand is much larger than those for loam and silt. When the negative pressure head in the unsaturated zone decreases the difference between the hydraulic conductivities of the soil types decreases. The water content is shown in the right graph. There is not a large difference in saturated water content for the different soil types. Although in the unsaturated zone there is a significant difference in the decrease of the water content for a decreasing negative pressure head. This causes much more available storage in the unsaturated zone for sand than for loam and silt.

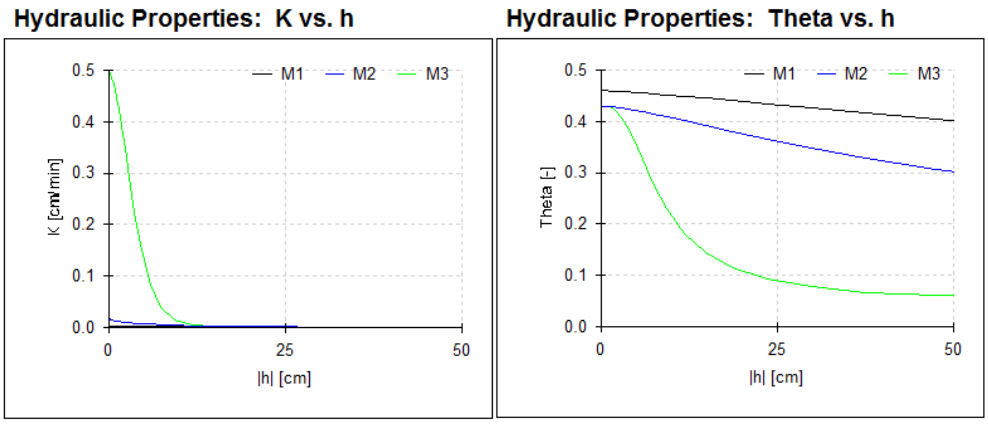


Figure 5.7 The h-K relation and the h-Theta relation of the three used native soil types. In the graphs M1 denotes silt, M2 denotes loam and M3 denotes sand.

In figure 5.8 the T-shaped trench and the rectangular shaped trench that are mentioned in the tables are shown.

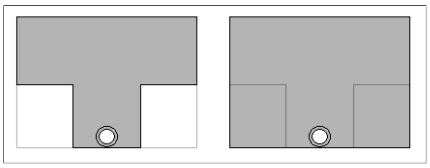


Figure 5.8 Schematic view of the different shapes of the trench used in the model. The grey shaded areas show the modeled trench. The grey lines show the other trench. Left: the T-shaped trench. Right: the Rectangular trench.

Trench soil type	Coarse Sand (K=3cm/min)
Drain diameter (cm)	12.5
Drainage depth (cm)	-30
Groundwater level (with respect to surface level) (cm)	-75
Trench shape	T-shape

Table 5.1 Characteristics of the SFDS used for the reference model.

The properties of the SFDS which are used to determine the effect of the parameters on the efficiency of the SFDS are summarized in table 5.2. These are the characteristics that are changed with respect to the reference situation. The rest of the characteristics remain the same during the different simulations. Therefore the trench soil type remains the same in all simulations as well. In figure 5.8 a schematic view of the T-shape trench and the rectangular shaped trench are shown. In figure 5.9 a schematic view of the different widths is shown.

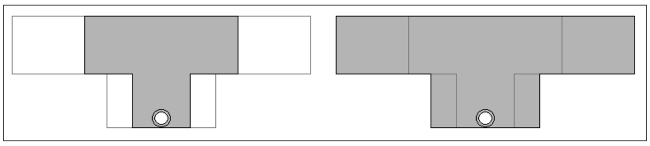


Figure 5.9 Schematic view of the different widths of the trench. The grey shaded areas show the modeled trench. The grey lines show the other trench. Left: width of 145 cm. Right: width of 290 cm.

Drain depth (with respect to surface level) (cm)	-30 (Reference)	-55	-68.5 (Seepage face)
Trench width (cm)	145 (Reference)		290
Trench shape	T-shape (Reference)		Rectangular
Groundwater level (with respect to surface level) (cm)	-30	-75 (Reference)	-125

Table 5.2 Properties investigated with model simulations.

Each simulation with the atmospheric boundary condition is done stepwise:

A potential atmospheric flux of 0.6 cm/min over a time period of 160 minutes for silt and loam and a time period of 400 minutes for sand is specified. For the simulation the following steps are taken:

- The first model run is done without a working drain. After this model run it is investigated when the water level in the trench is at drainage level. In figure 5.10 this is shown in the first figure.
- The second model run is done with a functioning drain from the moment the drainage level is reached by the water level in the trench. The atmospheric flux fills the trench until ground level is reached. The actual atmospheric flux may be different from the specified atmospheric flux when it is not possible to reach the defined atmospheric flux of 0.6 cm/min. When the run is completed the time when the drainage level is reached again is found. In figure 5.10 this is shown in the second and third figure.

- The third model run is done with a functioning drain from the moment the drainage level is reached by the water level until the moment the descending water level reaches the drainage level again. The rest of the time the drain does not do anything at all. In figure 5.10 this is shown in the fourth figure. This model simulates a period of 5 days.

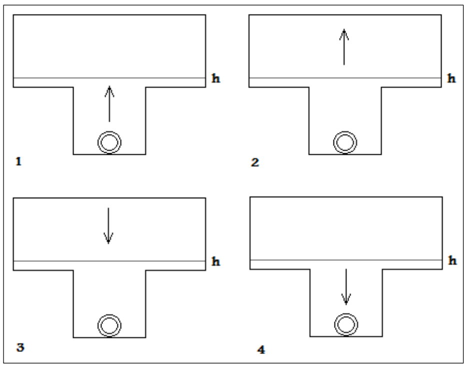


Figure 5.10 Schematic view of the stepwise simulation. The drainage level is denoted with 'h'. Number 1 denotes the filling of the trench until drainage level is reached. Number 2 denotes the filling of the trench during the discharging of the drain. Number 3 denotes the moment where the inflow has stopped and the water level is descending until the drainage level is reached. Number 4 denotes the descending water level after the drain has stopped discharging.

The maximum saturated capacity of the SFDS is investigated with a variable pressure head boundary which increases every 2 minutes 1 cm until 15 cm is reached.

5.4 Model results

In this paragraph the model results are shown and analyzed. The results are processed and analyzed with respect to the peak reduction and the total volume reduction.

5.4.1 Peak reduction

The peak reduction of the model simulations is determined in the same way as the peak reduction of the measurements. The peak reduction is expressed as a percentage of the maximum inflow peak. The results are shown for all four property changes which are the drainage level, the groundwater level, the width of the SFDS and the shape of the SFDS. In all four graphs the results of the reference situation is included to compare it with the results of the simulations with the property changes. In figure 5.11 the graphs are shown.

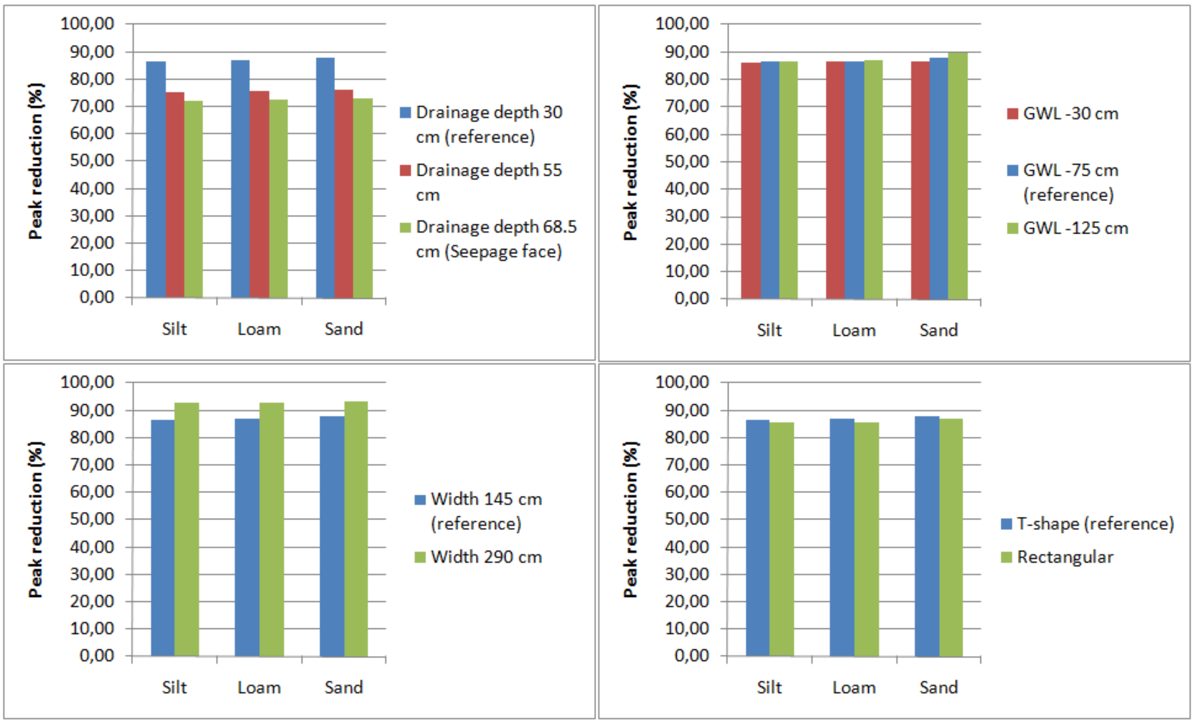


Figure 5.11 Model results for the peak reduction. In every graph the results of the reference situation is included to compare it with the different property variations. The different property variations are: Top left: drainage level. Top right: Groundwater level. Bottom left: Width of the SFDS. Bottom right: trench shape.

The peak reduction is affected by the drainage level. During the simulations the trench is completely filled with water. This is done with the same specified potential atmospheric flux of 0.6 cm/min. Due to the fact that the trench is completely filled with water the simulations with the same drainage level have more or less the same peak reduction. For the simulations of the SFDS with a width of 290 cm shown in the bottom left graph there is a difference in peak reduction with the reference situation. This is caused by the larger inflow discharge because of the same flux of 0.6 cm/min over a larger width.

A different drainage level causes a different maximum outflow peak. This is shown in the top left graph. Here the peak reduction is shown for different drainage levels. To visualize the relation between drainage depth and peak reduction the peak reduction is plotted against the drainage depth in figure 5.12. The relationship between the peak reduction and the drainage depth is given in table 5.3. This relationship shows that in this model simulations the peak reduction decreases with 0.44% to 0.47% when the drainage depth increases with 1 cm. This linear decrease is logical because of the linear decrease in maximum pressure difference when the drainage depth is increased.

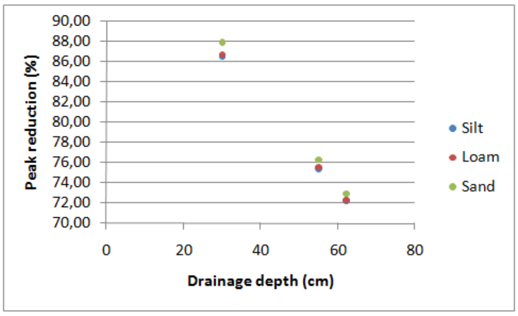


Figure 5.12 Peak reduction *%* versus drainage depth with respect to ground level *cm* for silt, loam and sand.

Native soil type	Function
Silt	y = -0,4422x + 99,781
Loam	y = -0,4469x + 100,13
Sand	y = -0,4646x + 101,87

Table 5.3 Relation between the peak reduction *%* represented by "y" and the drainage depth *cm* represented by "x".

Furthermore the groundwater level is affecting the peak reduction. When the groundwater level depth increases the peak reduction shows a small increase as well. This is the case for all native soil types. For sand it has the largest effect. This is caused by the larger permeability and larger available pore volume of sand in respect to silt and loam. Due to the larger groundwater level depth there is a negative pressure at the bottom of the trench and a larger negative pressure at the sides of the trench. As it was shown in figure 5.7 with a larger negative pressure head more volume is available for the storage of water. Due to this more water is able to infiltrate from the trench to the native soil and therefore less water is discharged through the drain. For sand the available storage volume is the largest. This means that for sand the effect of the groundwater level is the largest.

The difference in shape affects the peak outflow due to the fact that with a rectangular shape there is a larger area in the cross section that contains the soil improvement. This is shown in figure 5.8. Due to this the streamlines encounter less resistance than with a non-rectangular shape. This means that the SFDS with a rectangular shape has a larger peak outflow and therefore a smaller peak reduction.

5.4.2 Total volume reduction

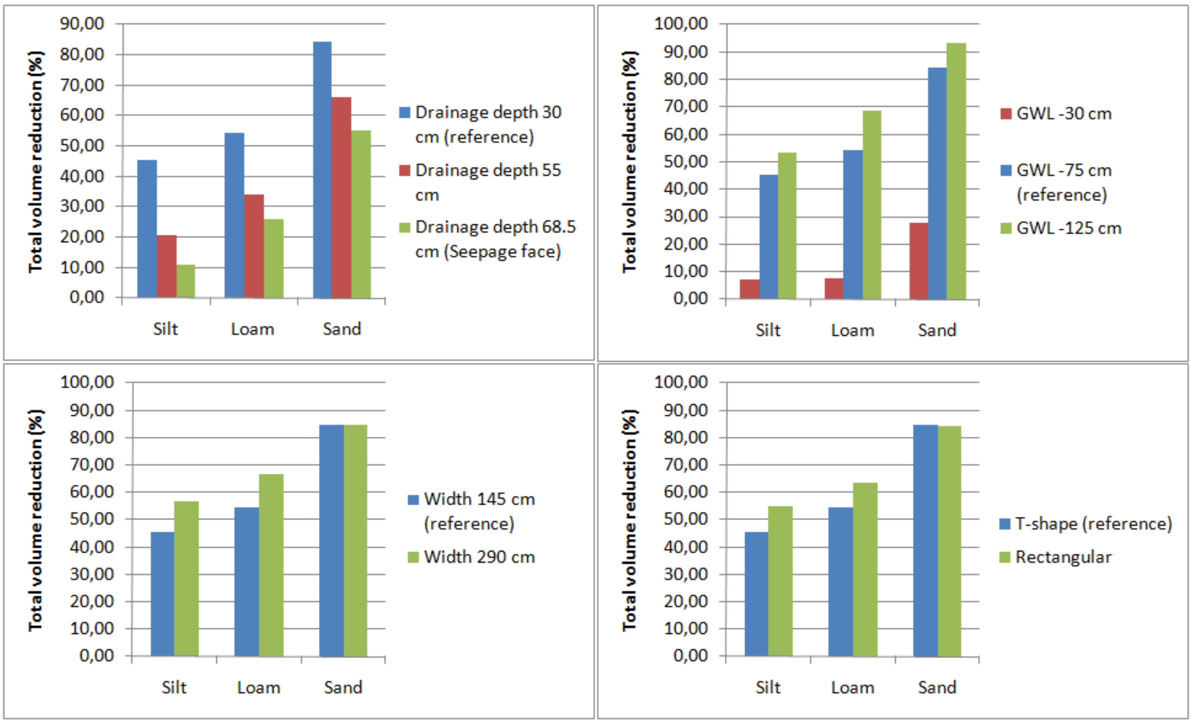


Figure 5.13 Model results for the total volume reduction. In every graph the results of the reference situation is included to compare it with the different property variations. The different property variations are: Top left: drainage level. Top right: Groundwater level. Bottom left: Width of the SFDS. Bottom right: trench shape.

The total volume reduction of the model simulations is determined in the same way as the total volume reduction of the measurements. This means that the volume reduction is the difference between the inflow volume and the outflow volume. The total volume reduction is expressed as a percentage of the total inflow volume. The results are shown for all four property changes which are the drainage level, the groundwater level, the width of the SFDS and the shape of the SFDS. In all four graphs the results of the reference situation is included. The graphs are shown in figure 5.13.

In all four graphs there is a significant difference visible. For the two graphs on top which represent the difference in drainage level and the difference in groundwater level for all native soil types a comparable relation is visible. The two other graphs which represent the difference in the width of the trench and the shape of the trench have the same relation for loam and silt. For sand the relation is different, both situations give the same total volume reduction.

To analyze the results better the results are plotted against the drainage depth, the groundwater level and the width. These graphs are shown in figure 5.14, figure 5.15 and figure 5.16.

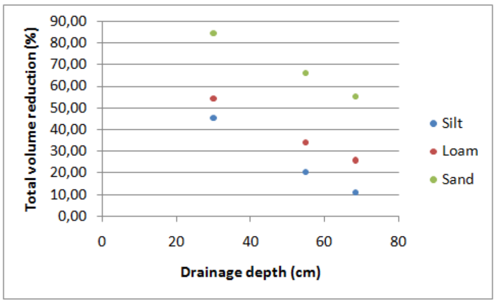


Figure 5.14 Total volume reduction (%) versus drainage depth with respect to ground level (cm) for silt, loam and sand.

An increasing drainage level causes a decreasing total volume reduction. This is shown in figure 5.14. Three linear relations may be drawn through the data points of the different native soils. The functions of these relations are given in table 5.4. The decrease of the total volume reduction is between 0.75% and 0.9% when the drainage depth increases with 1 cm. This linear relation is caused by the rectangular shape of the SFDS at the bottom. The storage underneath the drainage level is significant for the total volume reduction. When the width on each depth is the same the storage will increase linearly with a decreasing drainage depth. When the drainage depth is at a location with a larger width there is no linear relation anymore. The linear relation turns into a non-linear relation when the drainage depth is significant smaller than the drainage depth where the width still is constant.

Native soil type	**Function**
Silt	y = -0,9038x + 71,904
Loam	y = -0,7524x + 76,61
Sand	y = -0,7556x + 107,34

Table 5.4 Relation between the total volume reduction (%) represented by "y" and the drainage depth (cm) represented by "x".

The groundwater level affects the infiltration capacity from the trench to the native soil. This can be seen in figure 5.15 this clearly affects the total volume reduction. An increasing groundwater level with respect to surface level shows a higher total volume reduction. This is due to the larger infiltration that is possible with a larger groundwater level depth. As mentioned before this is caused by the larger initial storage capacity of the native soil. It is clearly not a linear function that can be drawn through the data points. What can be noticed is a decreasing effect on the total volume reduction by an increasing groundwater level depth.

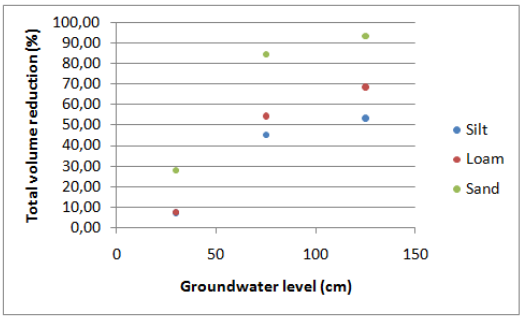


Figure 5.15 Total volume reduction (%) versus groundwater level with respect to surface level (cm) for silt, loam and sand.

The width of the trench has effect on the infiltration capacity of the trench to the native soil. When the width of the trench is increased the infiltration area is increased. Furthermore the storage capacity is affected by the width of the trench. A larger width of the trench causes a larger storage capacity with the same drainage depth. In figure 5.16 the effect of these characteristics is only visible for the native soil types silt and loam. For sand the total volume reduction in both cases is the same. The difference with the native soils silt and loam is the infiltration capacity from the trench to the native soil. This capacity is much larger for sand. Because of this the total volume reduction of silt and loam is more dependent on the storage capacity than the total volume reduction of sand. Probably for the native soils silt and loam the storage underneath the drainage depth is the most dominant characteristic by changing the width of the trench.

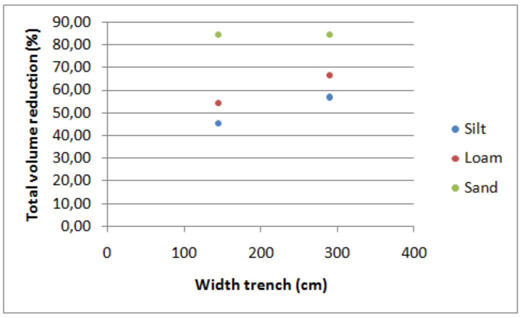


Figure 5.16 Total volume reduction (%) versus the width of the trench (cm) for silt, loam and sand.

The shape of the trench has effect on the storage capacity underneath the drainage depth. A rectangular shape contains a larger storage capacity than the non-rectangular shape as used at the reference SFDS. Like the change in width the change in shape shows for the native soil types silt and loam a dominant influence of the storage capacity. For sand no effect may be noticed. This is caused by the large infiltration capacity from the trench to the native soil.

5.4.3 Fluxes with atmospheric pressure head of 15 cm

The simulations with a boundary pressure head of 15 cm at the top of the trench give insight in the flux at surface level. With this simulation a 15 cm flooding of 200 minutes is simulated. This flux is affected by the flux through the drain and the infiltration to the native soil. To investigate these characteristics first the flux at ground level is shown figure 5.17 for the different simulations. In this graphs both characteristics are visible. Figure 5.18 shows the flux through the drain. In figure 5.20 the difference between the flux at ground level and the flux of the drain is shown. In this graphs the flux that is infiltrated from the trench to the native soil is visible. By analyzing these figures it is possible to investigate the effect of the different property changes to the infiltration capacity.

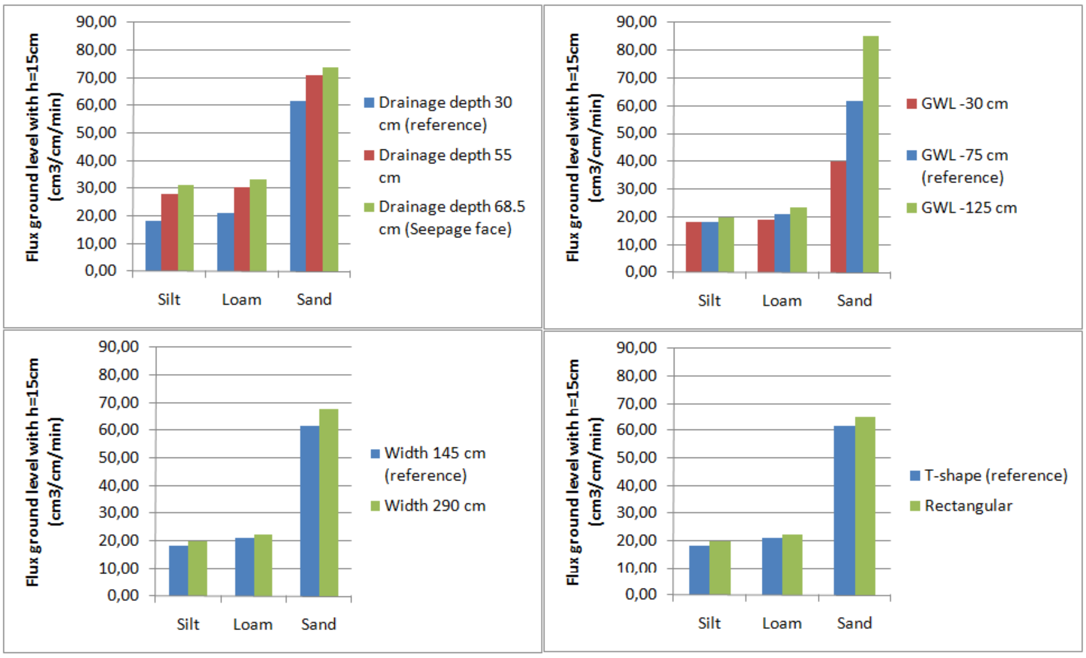


Figure 5.17 Infiltration (cm^3/cm/min) with a pressure head of 15 cm at ground level.

In figure 5.18 the flux of the drain is given for the different simulations. The drainage level as noticed before by analyzing the peak reduction is affecting the maximum drainage capacity. An increase in drainage depth causes an increase of the maximum drainage capacity.

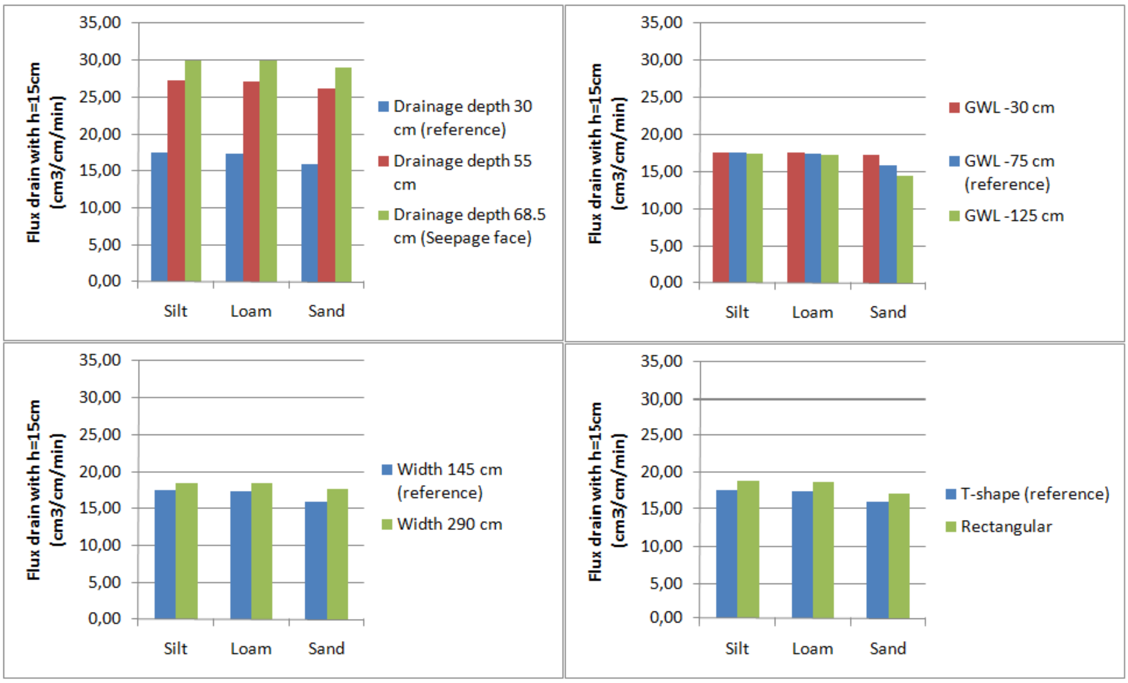


Figure 5.18 Flux of the drain (cm^3/cm/min) with a pressure head of 15 cm at ground level.

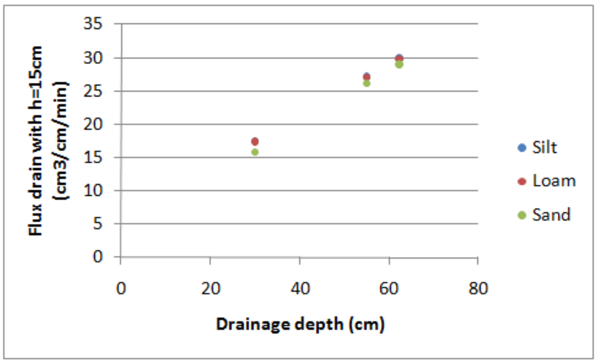


Figure 5.19 Flux drain (cm^3/cm/min) with 15 cm flooding versus drainage depth with respect to drainage depth (cm) for silt, loam and sand.

As shown before for the peak reduction the flux of the drain has a linear relation with the drainage depth. The graph exposed in figure 5.19 makes this relation visible. Silt is not visible because the points are behind the points of loam. Through the data points three lines may be drawn with the functions given in table 5.5.

Native soil type	Function
Silt	y = 0,3861x + 5,926
Loam	y = 0,3877x + 5,7703
Sand	y = 0,4067x + 3,7061

Table 5.5 Relation between the drain flux (cm^3/cm/min) with 15 cm flooding represented by "y" and the drainage depth (cm) represented by "x".

When the groundwater level is lowered for silt and loam it has a very small effect on the drain capacity. A larger groundwater level depth causes more infiltration. More water will infiltrate to the native soil. For sand the difference in infiltration capacity is larger when the depth of the groundwater level increases because of the larger available storage volume in the soil. That is the cause of the larger difference in the drainage flux for the simulations that contain sand as a native soil.

In case of an increasing width the drainage flux increases as well. This can be explained by the streamlines from the sides having less resistance because of the larger area around the drain with soil improvement.

The same effect as for an increased width of the SFDS is noticeable for the difference in trench shape. When the trench is rectangular the streamlines encounter less resistance due to the larger area that contains soil improvement.

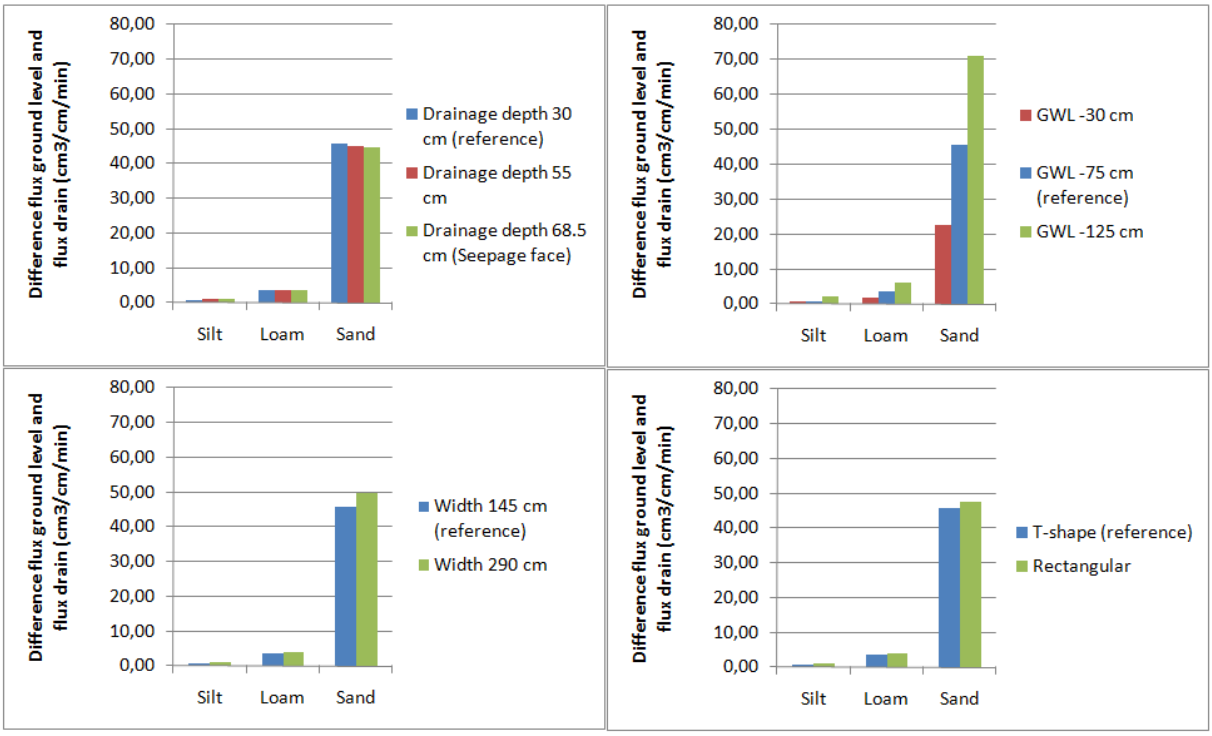


Figure 5.20 Difference between the flux at ground level and the flux of the drain. In short the infiltrated water from the trench to the surrounding (cm^3/cm/min) with a pressure head of 15 cm at ground level.

The graphs of figure 5.20 show the difference of the flux at ground level and the flux of the drain. In short it contains the infiltration to the native soil. First of all it is clear that for silt and loam the infiltration is much less important than it is for sand. This is because of the low permeability of silt and loam with respect to the permeability of sand.

The infiltration to the native soil is not significant affected by the drainage depth. This is logical because of the same physical setup of the model and the same groundwater level in the surrounding.

A change in groundwater level shows a significant change in infiltration. As noticed before a larger groundwater level depth causes a larger infiltration flux to the native soil. For the native soil types silt and loam this effect is less than for sand. While silt and loam have a much smaller permeability and water content difference in the unsaturated zone than sand.

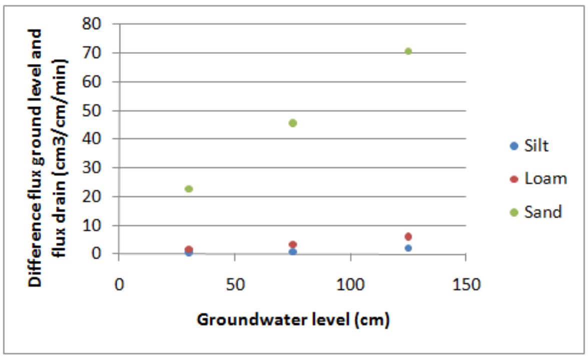


Figure 5.21 Infiltration flux (cm^3/cm/min) with 15 cm flooding versus groundwater level depth (cm) for silt, loam and sand.

The in figure 5.21 shown graph contains the linear relations as shown in table 5.6.

Native soil type	Function
Silt	y = 0,0155x + 0,035
Loam	y = 0,0475x + 0,1111
Sand	y = 0,5071x + 7,5402

Table 5.6 Relation between the infiltration flux ($cm^3/cm/min$) with 15 cm flooding represented by "y" and the groundwater level depth (cm) represented by "x".

By increasing the width of the trench the infiltration surface is increased as well. Due to this the infiltration capacity is increased. This may be seen in the graph. The absolute change is the largest for the native soil sand. The relative change is 9%. For loam the relative change is 10%. The relative change for silt is 58%. It should be noted that the infiltration values for silt are very small. This increases the vulnerability for the relative change calculation. A value with a certain derivation has much more effect on the values of silt than on the values of sand for instance. Probably the effect of the width increases with a decreasing permeability of the native soil. The ratio between the permeability of the soil improvement and the native soil is larger with a smaller permeability of the native soil. The boundary between the trench and the native soil vanishes slowly when the ratio approaches the value one.

The shape of the trench does have an effect on the infiltration capacity. By changing the shape the infiltrating surface stays the same. The only thing that changes is the location of the boundary between the trench and the native soil. The sides of the trench are more open with the rectangular shape which increases the infiltration flux. There is less of the native soil type between the bottom of the trench and the groundwater level. This increases the infiltration flux as well.

5.4.4 Time between end inflow and end outflow

The time the drain is discharging after the inflow stops gives insight in the extra time the system is discharging with respect to the situation without a SFDS. In the case a SFDS is used the system where the water is discharged to is burdened with a smaller flux although over a larger time. The time between the end of the inflow and the end of the outflow is shown in figure 5.22.

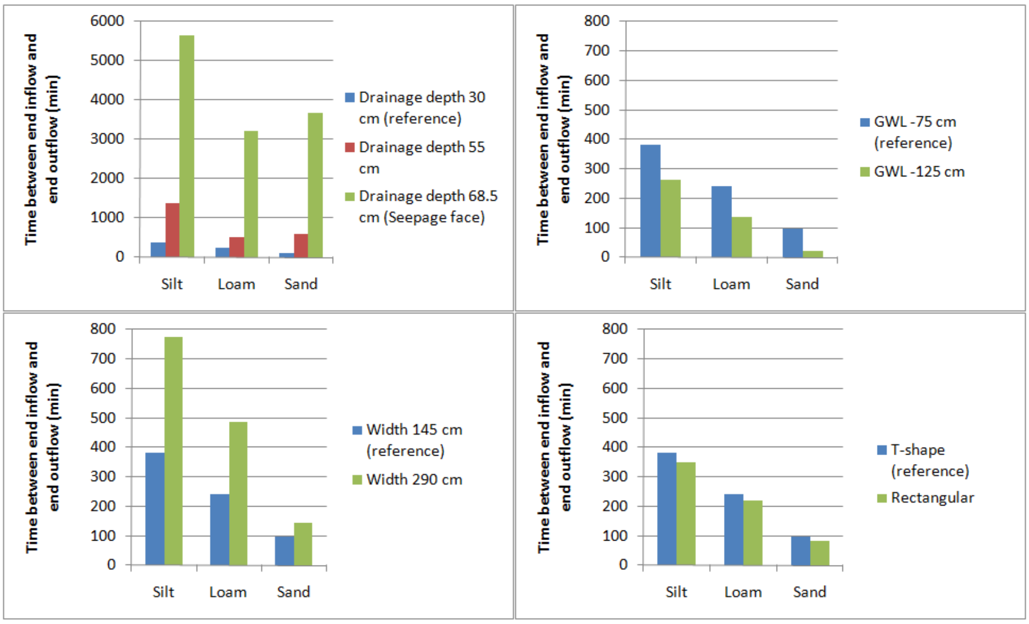


Figure 5.22 Time between the end of the inflow and the end of the outflow (min).

The drainage depth shows the most conspicuous results. First of all the drainage depth of 55 cm and the seepage face show for sand a longer time period than for loam. One could expect a reverse situation. This may be explained by the water that is infiltrated into the native soil during the inflow. After the inflow the trench and drain is draining water from the native soil as well. The time period of the inflow for loam is 160 minutes and for sand 400 minutes. Furthermore there is more available storage volume for sand than for loam. Due to this there is more water to drain after the inflow stops for the simulation with sand as native soil. This effect is not noticed for the drainage depth of 30cm. Due to the small drainage depth there will be less drainage from the native soil. The second conspicuous aspect for the drainage depth changes is the seepage face that needs far more time than the drainage depths of 30cm and 55cm. This large difference is caused by the fact that the groundwater level is at the bottom of the trench. Infiltrated water to the native soil causes an increase of the groundwater level. Because the water searches for the path with the least resistance it will recharge the trench when the water level in the trench is low enough. This low water level in the trench during outflow of the drain occurs in case of the seepage face. In figure 5.23 the volume that is discharged in 1365 minutes is 98% of the total discharged volume after 5500 minutes. Which means that the most significant part of the total outflow volume is discharged within 1365 minutes.

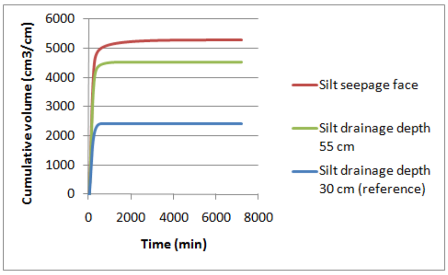


Figure 5.23 Cumulative outflow volume (cm^3/cm) versus time (min).

A deeper groundwater level causes a larger infiltration capacity from the trench to the native soil, this has a clear effect on the time between the end of the inflow and the end of the outflow. With a larger infiltration to the native soil the water level in the trench falls below the drainage level in a shorter time period. For sand it relatively affects this time the most. The results of silt are affected the least. Which indicates the difference of permeability and available pore volume are important characteristics. Native soils with a larger permeability and a larger available pore volume are more affected by the groundwater level depth than other native soil types.

Increasing the width of the trench leads to more water that has to be discharged. When the width is increased with a factor two the volume of water above the drain when the trench is saturated is increased with a factor two as well. For native soil types with a low permeability the infiltration is not affecting the time between end inflow and end outflow significant. One could expect that the time is increased with a factor two as well. This indeed is the case for the results of silt and loam as native soil. For sand this factor is 1.5 due to the larger infiltration from the trench to the native soil.

The shape of the trench is not affecting the volume above the drainage level with a drainage level depth of 30 cm. The difference shown in figure 5.22 is for all native soil types the same. In all cases 10% less time is needed.

5.4.5 Emptying time

One of the characteristics that affects the efficiency of the SFDS is the emptying time. Only when the trench is empty the total capacity is available during the next precipitation event. When the groundwater level is at a depth of 30 cm the trench will never empty. In case the groundwater level is at a depth of 75 cm the trench will empty very slow because the groundwater level is at the same depth as the bottom of the trench. Only the simulations with sand as native soil empty the trench within the simulated time of 7200 minutes. The groundwater level at a depth of 125 cm shows emptying times within the simulated time of 7200 minutes for all native soils. To give an indication of the time needed to empty the trench after the inflow is finished in figure 5.24 this time is given for silt, loam and sand. The values come from the simulations with a groundwater level at a depth of 125 cm. It has to be noticed that for the simulations for sand much more water is used to get the trench totally saturated. This probably increases the time needed for the sand simulation to empty the trench. That is why this graph gives a global view on the emptying time one could expect. For silt the emptying time is 3960 minutes (=2.75 days), loam has an emptying time of 1083 minutes (=0.75 day) and sand has an emptying time of 233 minutes (=0.16 day).

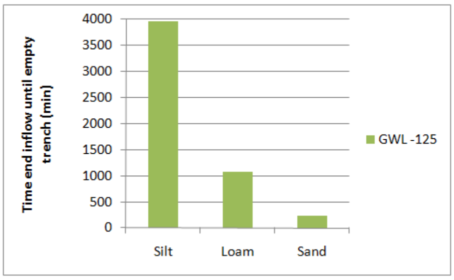


Figure 5.24 Time end outflow until empty trench (min) with a groundwater level at a depth of 125 cm for silt, loam and sand.

5.4.6 *Summary of the physical characteristics*

The analyses of the model results may be summarized in a table. This gives an overview of which property changes do and do not affect the outflow characteristics. In table 5.7 and table 5.8 this summary is given for respectively the simulations with native soil types silt, loam and sand. The majority of the relations is the same for the different native soil types. Only some relations of the groundwater level depth, the trench width changes and the trench shape changes are different for sand with respect to silt and loam.

For the trench simulations with a different width it needs to be noted that the total inflow volume is larger than for the other simulations. For silt and loam it is 80% larger and for sand it is 30% larger. This is caused by the larger available volume in the trench with the larger width. Which means that the capacity of the SFDS increases when the width increases.

Native soil type: silt and loam	Peak reduction	Total volume reduction	Flux drain	Infiltration from trench to native soil	Time between end inflow and end outflow
Drainage depth	--	--	++	0	++
Groundwater level depth	+	++	-	+	--
Trench width		+	+	+	++
Trench shape	-	+	+	+	-

Table 5.7 Summary of the affecting characteristics drawn from the model simulations with native soil types silt and loam. -- = A clear decrease when the changed characteristic is increased. - = A small decrease when the changed characteristic is increased. 0 = No effect. + = A small increase when the changed characteristic is increased. ++ = A clear increase when the changed characteristic is increased. For the trench shape it is not an increase, though it is the change from non-rectangular to rectangular.

Native soil type: sand	Peak reduction	Total volume reduction	Flux drain	Infiltration from trench to native soil	Time between end inflow and end outflow
Drainage depth	--	--	++	0	++
Groundwater level depth	+	++	-	++	--
Trench width		0	+	+	+
Trench shape	-	0	+	+	-

Table 5.8 Summary of the affecting characteristics drawn from the model simulations with native soil type sand. -- = A clear decrease when the changed characteristic is increased. - = A small decrease when the changed characteristic is increased. 0 = No effect. + = A small increase when the changed characteristic is increased. ++ = A clear increase when the changed characteristic is increased. For the trench shape it is not an increase, though it is the change from non-rectangular to rectangular.

A more complete view on the investigated characteristics is given in table 5.9, table 5.10 and table 5.11. Here the minimum and maximum values of the model results are summarized for respectively silt, loam and sand.

Native soil type: silt		Peak reduction (%)	Total volume reduction (%)	Flux drain (cm^3/cm/min)	Infiltration from trench to native soil (cm^3/cm/min)	Time between end inflow and end outflow (min)
Drainage depth	**Minimum**	72.3	11.1	17.5	0.8	381.5
	Maximum	86.5	45.4	29.9	1.1	5636.0
Groundwater level depth	**Minimum**	86.3	7.3	17.4	0.6	264.7
	Maximum	86.7	53.3	17.5	2.2	381.5
Trench width	**Minimum**	86.5	45.4	17.5	0.8	381.5
	Maximum	92.8	57.0	18.5	1.2	773.5
Trench shape	**Minimum**	85.5	45.4	17.5	0.8	349.5
	Maximum	86.5	55.1	18.7	1.2	381.5

Table 5.9 Minimum and maximum values of the model data for the native soil silt. The values are given for all the studied SFDS characteristics.

Native soil type: loam		Peak reduction (%)	Total volume reduction (%)	Flux drain (cm^3/cm/min)	Infiltration from trench to native soil (cm^3/cm/min)	Time between end inflow and end outflow (min)
Drainage depth	**Minimum**	72.3	25.8	17.4	3.5	243.0
	Maximum	86.7	54.5	29.9	3.5	3205.0
Groundwater level depth	**Minimum**	86.5	7.5	17.2	1.6	137.0
	Maximum	87.1	68.5	17.5	6.2	243.0
Trench width	**Minimum**	86.7	54.5	17.4	3.5	243.0
	Maximum	92.8	66.8	18.5	3.8	485.0
Trench shape	**Minimum**	85.7	54.5	17.4	3.5	220.5
	Maximum	86.7	63.6	18.6	3.9	243.0

Table 5.10 Minimum and maximum values of the model data for the native soil loam. The values are given for all the studied SFDS characteristics.

Native soil type: sand		Peak reduction (%)	Total volume reduction (%)	Flux drain (cm^3/cm/min)	Infiltration from trench to native soil (cm^3/cm/min)	Time between end inflow and end outflow (min)
Drainage depth	**Minimum**	73.0	55.3	15.9	44.7	95.5
	Maximum	88.0	84.5	29.0	45.7	3672.7
Groundwater level depth	**Minimum**	86.7	28.0	14.4	22.7	20.0
	Maximum	89.6	93.4	17.2	70.9	95.5
Trench width	**Minimum**	87.9	84.5	15.9	45.7	95.5
	Maximum	93.2	84.5	17.7	49.9	142.7
Trench shape	**Minimum**	87.1	84.4	15.9	45.7	84.7
	Maximum	87.9	84.5	17.0	47.7	95.5

Table 5.11 Minimum and maximum values of the model data for the native soil sand. The values are given for all the studied SFDS characteristics.

6 Discussion

During the research some specific findings were done about the SFDS of the Castellumknoop. Based on these findings here a discussion is given for the study side.

Inflow point

The inflow point at the location of the Castellumknoop is at the head of the SFDS, the outflow is at the end of the SFDS. Because of this the outflow starts discharging faster than when the inflow is spread homogeneous over the full length of the SFDS. More water is discharged by the drain at the beginning of the event. While the drain is discharging it is used as well to fill the storage underneath the drainage level where no water is infiltrated from surface level. During long precipitation events when the SFDS is totally saturated and there is water above ground level it makes no significant difference where the water inflow is situated.

When the purpose of the SFDS is to retain water and delay the discharge of the inflow it is now known that with the inflow at one point the drain starts discharging relatively fast. One manner to reduce this effect is to create more storage at the inflow point, which is not always possible because of the groundwater level in the surrounding. The change from a point inflow to a homogeneous inflow will increase the time before the drain starts discharging as well. This is due to the fact that the water level in the trench will raise less fast when the inflow is over the full length than when it is at one point and thus is not spread over the full length at the head of the inflow.

The drain that is installed in the trench can be halved. This is shown in the middle figure in figure 6.1. When the drain is halved it will take more time before the drain is reached by the water. This will give a larger delay before the outflow will start. Although the maximum capacity of the drain will be reduced because there is a smaller area where water may enter the drain.

The top layer of the native soil where the SFDS is constructed has a low permeability. At the head of the SFDS the top layer of the native soil may be excavated and replaced with a soil improvement. This is shown in the right figure in figure 6.1. This will improve the infiltration to the aquifer underneath the layer with a low permeability. Due to this is takes more time to fill the trench with water until the drainage level is reached. Which will increase the total volume reduction and the peak reduction.

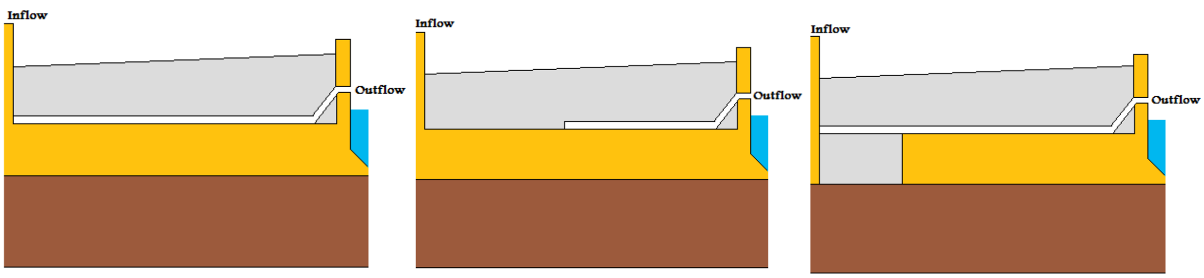


Figure 6.1 A schematic longitudinal view on the SFDS of the Castellumknoop. At the left the current situation is shown. The middle figure shows the halved drain. At the right the extra soil improvement at the head of the SFDS is shown.

Drainage level

At the Castellumknoop the drainage level is not at the bottom of the trench but higher. Due to this a large storage is available. This storage has to be filled before the drain starts discharging. A larger storage underneath the drain means a larger time period between the start of the inflow event and the start of the outflow discharge.

The drainage level apparently affects the storage and with this the time before the SFDS starts discharging through the drain and the total amount of infiltration to the native soil. The actual storage underneath the drainage level at the beginning of the precipitation event is important for the amount of infiltration to the native soil. This actual storage is dependent on the precipitation events that took place before the new event. How large they were and how long before the new precipitation event they took place. Those are aspects that have to be taken into account during the design of a SFDS.

Native soil

The native soil has a small hydraulic conductivity, so that the infiltration capacity from the trench to the native soil is low. A long time in the range of a few days is needed to have an empty trench again. Accordingly when a precipitation event occurs within this emptying time from another precipitation event the total storage is not available. This affects the time before the drain starts discharging with respect to the start of the inflow.

The total discharged volume is in the case of a native soil with a small hydraulic conductivity highly dependent on the storage in the trench and the time between the precipitation events. The storage may be created by a larger depth or width of the trench underneath the drainage level. Naturally this storage is dependent on the groundwater level as well. In case of a high groundwater level above or at drainage level there will be less storage or no storage at all.

Connection to surface water

In the original situation of the Castellumknoop the drain is in contact with the surface water most of the time. It discharges to the surface water during precipitation events. The drainage level is below the surface water in this case. In the trench the water level is at or even above drainage level most of the time. During precipitation events there is no storage possible underneath the drainage level. The drain starts discharging almost immediately when water infiltrates to the trench. There is almost no volume reduction. Especially in dry periods in summer the surface water is kept high. In these periods the drain fills the trench with water until the surface water level is reached. During these periods the most intensive precipitation events occur which means that the mentioned drawbacks are important especially for this period.

A benefit of this situation is that more infiltration takes place to the native soil because the trench is used as infiltration area as well. The whole time the water level of the surface water is above the drainage level the infiltration is larger than when it is not.

A choice can be made about what is more important for the users of the SFDS. When infiltration to the native soil is the most important then it is a good option to put the drainage level underneath the surface water level. If it is more important to have volume reduction it is better to construct the drainage level above the surface water level.

7 Conclusions

In this chapter the conclusions of the results are drawn and the research questions of chapter 1 are answered.

7.1 The effect of inflow characteristics to the inflow – discharge relation

There is no clear inflow – discharge relation found within this study. This is caused by the different initial conditions of the SFDS during the measurement period. The natural precipitation events have different distributions which makes it difficult to determine one relation as well. The measurements give insight in the effect of different inflow characteristics. This is shown in this paragraph. Some conclusions are drawn from the measurements and some quantitative conclusions are drawn.

Peak delay

The peak delay has a range between 10 minutes and 108 minutes for all the analyzed events. For the events with a shallow initial water level in the trench the range is between 10 minutes and 41 minutes. None of the studied inflow characteristics based on all the events have effect on the peak delay. Although, in case of the short events there is an increasing peak delay for an increasing duration and total volume of the inflow. These short events have a minimum duration of 77 minutes and a maximum duration of 385 minutes.

It was noticed that the distribution of the inflow for a dry initial condition may enlarge the peak delay significantly. When there is a dry initial condition and the largest inflow peak occurs at the start of the event it may happen that another smaller peak occurs after it. This second inflow peak may cause the outflow peak. Which enlarges the peak delay.

Peak reduction

The peak reduction in case of all the measurements is between 40% and 100%. The reduction for the events with a shallow initial water level in the trench are between 40% and 89%. The peak reduction decreases with an increasing duration and total volume of the inflow. In case of short events there is only a decreasing peak reduction for an increasing duration of the inflow.

Total volume reduction

Values between -8% and 100% are found for the total volume reduction. The negative value is because of the initial condition that is very wet due to a precipitation event short before the specific event. The outflow of this event did not end before the specific event started. The events with a shallow initial water level show total volume reductions from -8% to 89%. An increasing intensity and peak of the inflow causes a clear decrease of the total volume reduction. The same relation but less clear is found for the total inflow volume. There is no difference in effect for the short duration events.

Total delayed volume per total outflow volume

The total delayed volume per total outflow volume is between 0% and 69% for all analyzed events. For the events with a shallow initial water level in the trench the maximum value is 66%. For all measurements an increasing intensity and peak inflow causes an increasing total delayed volume per total outflow volume. For short duration events the same effects are found. Although, for short duration events an increasing total inflow volume causes an increasing ratio as well.

Peak outflow

The peak outflow has values between 0 l/h and 4515 l/h for all events. For the events with a shallow initial water level in the trench the values are between 44 l/h and 3730 l/h. For all measurements the peak outflow clearly increases with an increasing intensity and peak inflow. The peak outflow increases less for an increasing duration and total volume of the inflow.

Duration inflow versus duration outflow

There is a linear relation between the duration of the inflow and the duration of the outflow. In this research it is shown that the outflow duration was 12.5% larger than the inflow duration. Even with the measurements with larger water level depths in the trench this relation was clear, although there was a larger spread. Furthermore there is a certain maximum to the increase of the duration because of the outflow duration after the inflow stops. For the SFDS of the study site this maximum has an inflow duration of 2800 minutes.

Total volume inflow versus total volume outflow

Like for the duration of the inflow versus the duration of the outflow there is a linear relation between the total inflow volume and the total outflow volume. The outflow volume is 28% less than the inflow volume.

Difference start inflow and start outflow in minutes

The results show a difference between the start of the inflow and the start of the outflow between 1 minute and 100 minutes. This large range is caused by the difference in storage that is available underneath the drainage level at the start of the inflow and the intensity of the inflow. In case only the results of the events with an initial water level depth of 35 cm in the trench are analyzed the range is between 1 minute and 28 minutes.

Maximum inflow volume before outflow discharge

Within this study there are two values found for the maximum inflow volume before any outflow was measured. These events both had an initial water level at the depth of the bottom of the trench. Therefore they had a dry initial condition. The inflow volumes before the outflow started are 5700 l and 5900 l. This is 2.9 mm for the sealed area of 2000 m^2.

7.2 The effect of physical characteristics to the inflow – discharge relation

The model simulations give insight in the effect of certain property changes of the SFDS and its surrounding. This in addition to the measurement results gives a total view on the characteristics affecting the inflow – discharge relation of the SFDS. Again it is noted that the modeled SFDS is in 2D and therefore simulates a homogeneous inflow. The measurement results for the calibration come from a SFDS with the inflow at the head of the SFDS. The drain discharge is underestimated by 9%with respect to the measurement. For the total discharged volume there is a 5% underestimation of the model results with respect to the measured volume. The water level decrease in the trench after the discharge of the drain has stopped is underestimated by 20%.

In this paragraph the conclusions are drawn about what the effects of different SFDS characteristics on the inflow – discharge relation are. The minimum and maximum values of the model results are presented in table 5.9 in paragraph 5.4.6.

Drainage level

A larger drainage level depth causes a decrease in the peak reduction, a decrease in the total volume reduction, an increase in the drain flux and an increase in the time between the end of the inflow and the end of the outflow. For all native soil types there is a clear effect.

Groundwater level

In case of an increase in the depth of the groundwater level the peak reduction increases, the total volume reduction increases, the flux of the drain decreases, the infiltration from the trench to the native soil increases and the time between the end of the inflow and the end of the outflow decreases. This is the case for all native soil types.

Trench width

The drain flux and the infiltration from the trench to the native soil increased a small amount when the trench width is increased. This is the case for all three native soil types. The time between the end of the inflow and the end of the outflow increases more clearly for silt and loam than for sand. For silt and loam the total volume reduction increases a small amount as well.

Trench shape

When the trench shape is changed from a non-rectangular to a rectangular shape the drain flux and the infiltration from the trench to the native soil increases a little. The peak reduction and the time between the end of the inflow and the end of the outflow decreases a little. This counts for all the studied native soil types. For the native soil types silt and loam the total volume reduction increases a little.

Emptying time of the SFDS

The emptying time of the trench from the moment the outflow stopped is determined. This is done for the situation where the drainage level is at a depth of 35 cm with respect to the surface level. Furthermore the groundwater level is at a depth of 125 cm. Three native soil types are analyzed again. For silt the emptying time is 3960 minutes (=2.75 days), loam has an emptying time of 1083 minutes (=0.75 day) and sand has an emptying time of 233 minutes (=0.16 day).

7.3 Consequences for the design of a SFDS

In this paragraph the consequences of the knowledge about the characteristics that have effect to the inflow – discharge relation are presented for the main outflow characteristics.

Peak delay

There is found a minor effect for some studied characteristics in case the peak delay is the most important outflow characteristic. Only for short events there is an effect of the duration of the event and the total inflow volume of the event. This means that during the design period this may be taken into account. When a certain peak delay is found during modeling this peak delay is different with for instance another duration of the event. Although the effect is very small.

Peak reduction

The inflow characteristics have no or not much effect on the peak reduction. When a large peak reduction is purposed one may use a shallow drainage level. Furthermore it is recommended to use a t-shaped trench instead of a rectangular shaped trench. The groundwater level has a certain effect on the peak reduction as well. When the groundwater level is deeper the peak reduction is larger. This may be important for calculations during the year. The groundwater level may change during the year.

Total volume reduction

When the total volume reduction has the priority during the design phase the intensity and the peak inflow of the event have an effect to it. A larger intensity and peak inflow causes a smaller total volume reduction. This means that when the design is modeled with a certain event the results are different when the design is modeled with an event with a larger intensity. This needs to be taken into account during the design phase to prevent for overestimation of the volume reduction by the system. The total inflow volume has a minor effect to the total volume reduction. During the design phase it still may be taken into account.

In case a large total volume reduction is purposed a shallow drainage level may be used. The groundwater level has an effect as well. This means that the fluctuation of the groundwater level during the year needs to be taken into account. By enlarging the volume of the soil improvement the total volume reduction is increased as well.

For all outflow characteristics it must be noted that the emptying time of an SFDS for the native soils with a small hydraulic conductivity is relatively large. Because of this it takes more time after a precipitation event to get back to the maximum storage capacity of the SFDS. Because of this, simulations with a series of events may be used. This will simulate the designed SFDS with different initial conditions caused by the former events.

7.4 Processes within the SFDS

The processes that are determined by means of the measurement results and the empirical conceptual model are presented here.

- In case of an empty SFDS at the start of an event the water is slowly redistributed over the length of the trench. In this process it is very likely that the drain plays a role as well as the horizontal flow through the trench.
- When the initial water level of the total trench is around the drainage level the drainage starts short after the inflow starts. This is caused by the fact that the inflow let the water level at the head of the SFDS rise faster than the rest of the SFDS. Due to this the drainage level is exceeded relatively fast when it is compared with a situation with homogeneous inflow. The drain starts discharging when the drainage level is exceeded.
- In case of a saturated SFDS the inflow is processed the same way for an inflow at the head as for a homogeneous inflow.

8 Recommendations

Within this research some aspects that were outside the scope of this study showed up. These aspects are described in this chapter. Furthermore some aspects to take into account in the future during the design of SFDSs or further research to SFDSs are presented here.

8.1 Design phase of a SFDS

When a SFDS is designed there are some purposes to fulfill. For instance a maximum total volume reduction is declared to be the most important purpose. During the design phase it is recommended to take a look at the summarizing tables in paragraph 4.3.6.8 and 5.4.6. These tables give information on which inflow characteristics and SFDS properties have effect to the different outflow characteristics.

8.2 Clogging

Clogging is one of the most important subjects that may have effect on the lifespan of a SFDS. It possibly occurs around the drain, between the trench and the native soil or at the swale. To investigate the lifespan of a SFDS better, clogging should be taken into account.

When measurements are done over a longer time period of five to ten years the effect of clogging can be investigated. Not only inflow and outflow discharge measurements and water level measurements but also soil research should be undertaken to compare the differences in quality of the soil. Infiltration capacity tests may be undertaken to investigate clogging of the swale.

By making use of a model the effect of clogging on the efficiency of the SFDS may be determined. Also the different effects of clogging on the different places in the SFDS may be investigated. These different places are the drain, the swale and between the trench and the native soil.

8.3 Extreme precipitation events

The research described in this thesis relies on part of the measurements that are actually done in the study period. This is because of the elimination of some measurements that were not reliable. The measurements that were not reliable were those of extreme events. The SFDS flooded too much trough which the inflow discharge measurements were not accurate. When more measurements are undertaken it is recommendable to improve the measurements in a way also the extreme events may be investigated.

8.4 Measurements of homogeneous inflow

The study site contains a SFDS with the inflow at the head of the SFDS. The model is calibrated by the measurements of this SFDS. Though the model that is used is a two dimensional model. Due to this a homogeneous inflow measurement is more realistic to calibrate the model with than an inflow at one point. By doing experiments with a homogeneous inflow the model may be better calibrated.

Furthermore it is a good addition to this research to undertake measurements on a SFDS with a homogeneous inflow and compare those results with the results of this research. Obviously it is even better to measure more SFDSs with those two types of inflow to avoid typical results for one specific SFDS.

8.5 Measure more SFDSs

Investigating one SFDS in practice by measuring is not enough to draw conclusions for all sorts of SFDSs in all kinds of areas. To draw the right conclusions about the quantitative efficiency of the SFDS in practice more SFDSs should be investigated.

For instance the different types of inflow is an interesting characteristic to do research on. This thesis depicts a SFDS with the inflow point at the head of the SFDS, while other SFDSs have their inflow over the full length. The processes of the researched SFDS as described in paragraph 4.3.7 are probably different from the processes of a SFDS with the inflow over the full length. It is interesting to investigate the effect of this.

Furthermore different areas where SFDSs are constructed have different native soil types. Measurements on SFDSs situated in different areas will give more insight into the effect of those different soil types on the efficiency of the SFDS. The same counts for the difference in groundwater level, drainage level and soil improvement.

The model results in this thesis show that the groundwater level, the drainage depth and the native soil are affecting characteristics on the inflow – discharge relation. This knowledge may be used to find study sites that differ from each other in that characteristics. In this way the model results can be further investigated.

8.6 Measurements during a whole year

During a whole year there are different weather periods. To investigate the effect of this different periods it is recommendable to undertake measurements on a SFDS during a whole year. Aspects that may be considered to have their effect on the processes within the SFDS are for instance long drought periods versus long wet periods, snow versus rain, a frozen swale versus a non-frozen swale and a change in groundwater level.

8.7 Different vegetation in the swale

While doing the measurements for this research some conversations took place with inhabitants of Leidsche Rijn. Some of these inhabitants put forward the idea of making use of different vegetation in the SFDSs. In addition it is noticed that in the SFDS that was measured not only grass was present. A lot of other different vegetation (weeds) are present.

It is known that the municipality of Utrecht is undertaking an experiment with different vegetations used in the SFDS. More of these research could take place to investigate the effect of different vegetations in the swale of the SFDS. For instance the infiltration may be affected by the roots and the transpiration may be very different for different kinds of vegetation.

8.8 Sealed area function

The areas where SFDSs are constructed in do have different functions. Some of the functions are residential districts, traffic roundabouts, industrial areas and busy roads. These functions all may have their own effect on the quantitative and qualitative efficiency of the SFDS. For instance the waste materials that are transported to the SFDS. For roundabouts this effect probably is more noticeable than for a road where the traffic does not have to brake and accelerate every time they pass it.

8.9 Translation actual situation to an empirical conceptual model

In this research the purpose was to find out what the effects are of different characteristics to the quantitative efficiency of the SFDS. In practice this gives a rough view on what could be expected from this efficiency in different area’s with different native soil types and groundwater levels. It will be an improvement if a simplified empirical conceptual model is made and tested that may be used in urban water management programs. When this kind of application is available it is possible to integrate the SFDS in a substantial manner into an urban water management system.

9 Appendix

Appendix I. Bibliography

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Appendix II. Graphs

Inflow and outflow graphs

Graphs with the extracted results

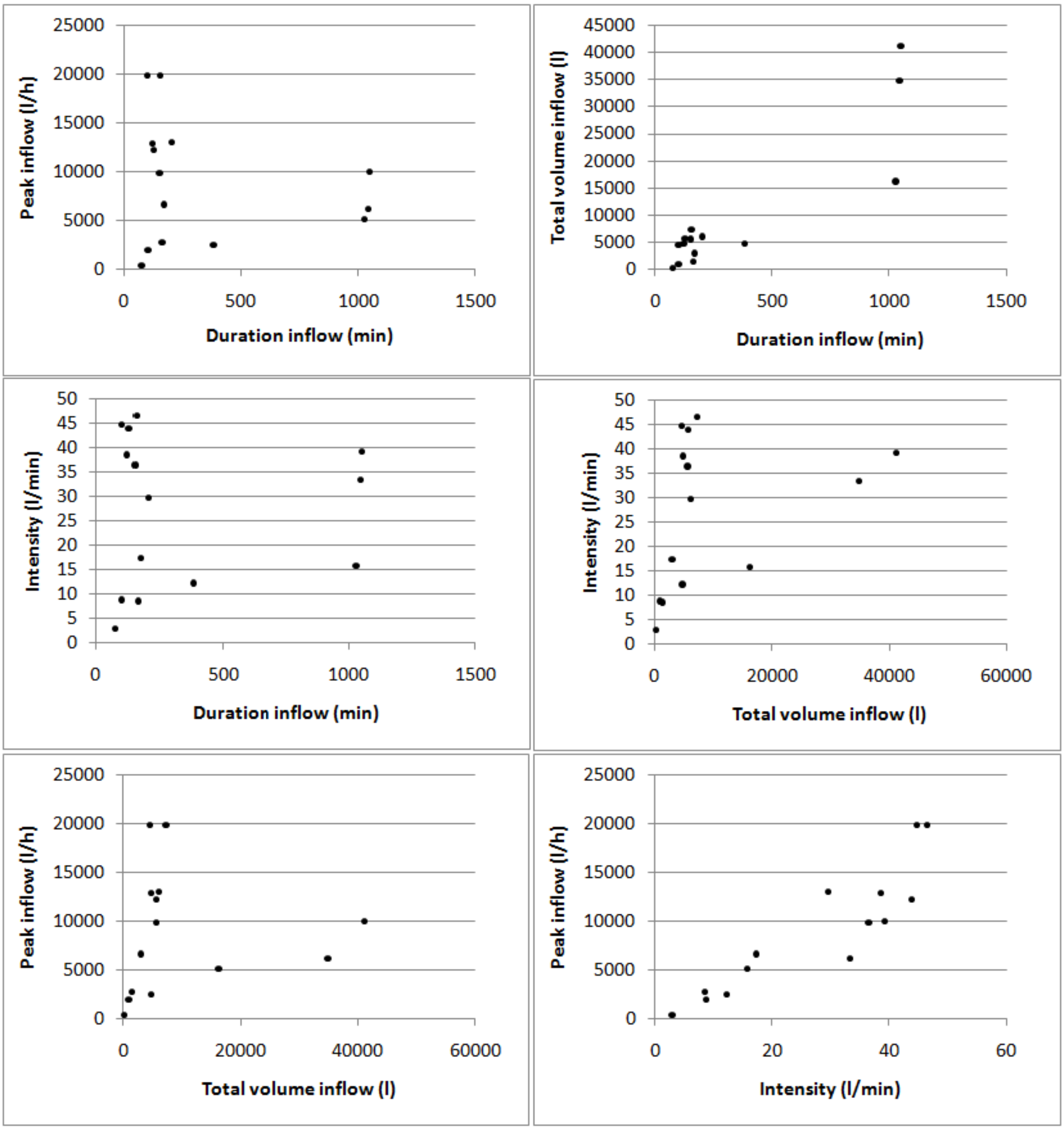

Figure 9.1 Relations between the investigated inflow characteristics.

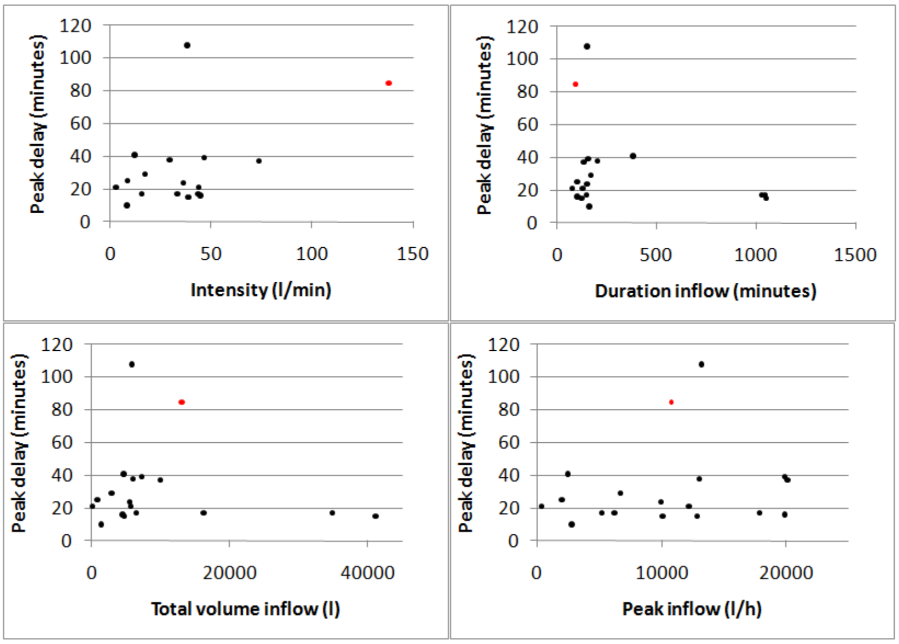

Figure 9.2 Extracted peak delay results from the data as shown in paragraph 4.3.5. The peak delay is expressed in *min*. The values are plotted against the intensity of the inflow in *l/min*, the duration of the inflow in *min*, the total volume of the inflow in *l* and the peak inflow in *l/h*. The red point denotes the peak delay of the experiment.

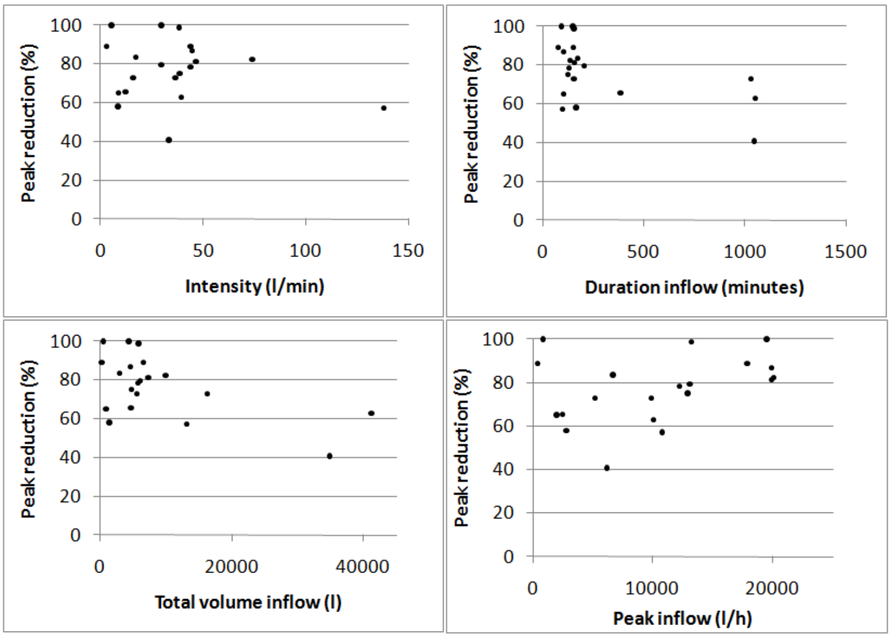

Figure 9.3 Extracted peak reduction results from the data as shown in paragraph 4.3.5. The peak reduction is expressed in a percentage of the maximum inflow peak. The values are plotted against the intensity of the inflow in *l/min*, the duration of the inflow in *min*, the total volume of the inflow in *l* and the peak inflow in *l/h*.

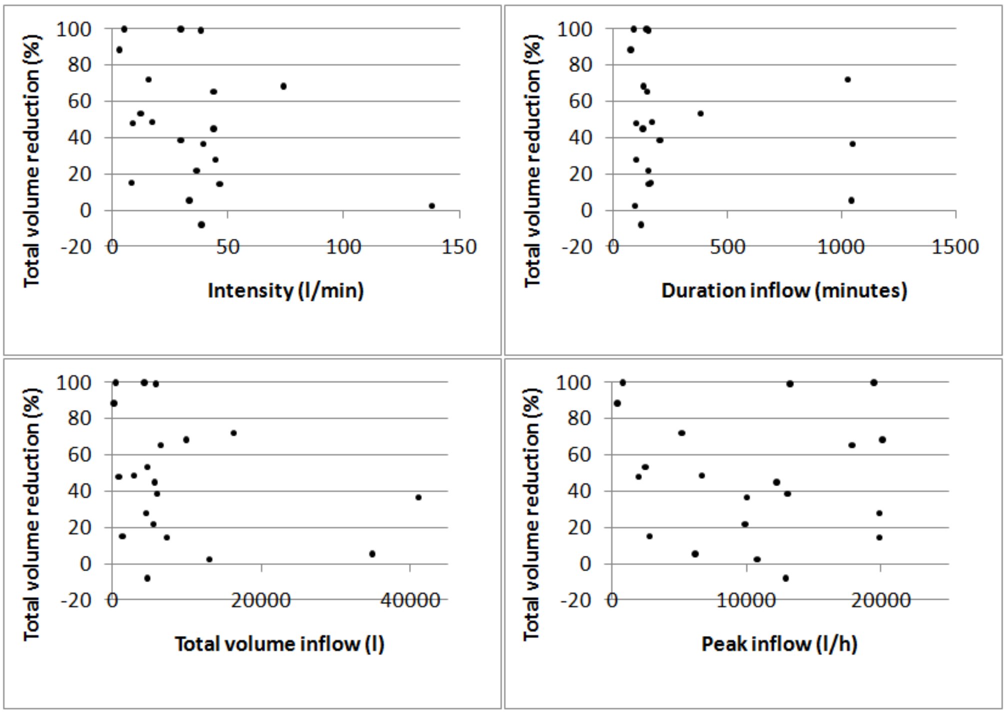

Figure 9.4 Extracted volume reduction results from the data as shown in paragraph 4.3.5. The total volume reduction is expressed in a percentage of the total inflow volume. The values are plotted against the intensity of the inflow in *l/min*, the duration of the inflow in *min*, the total volume of the inflow in *l* and the peak inflow in *l/h*.

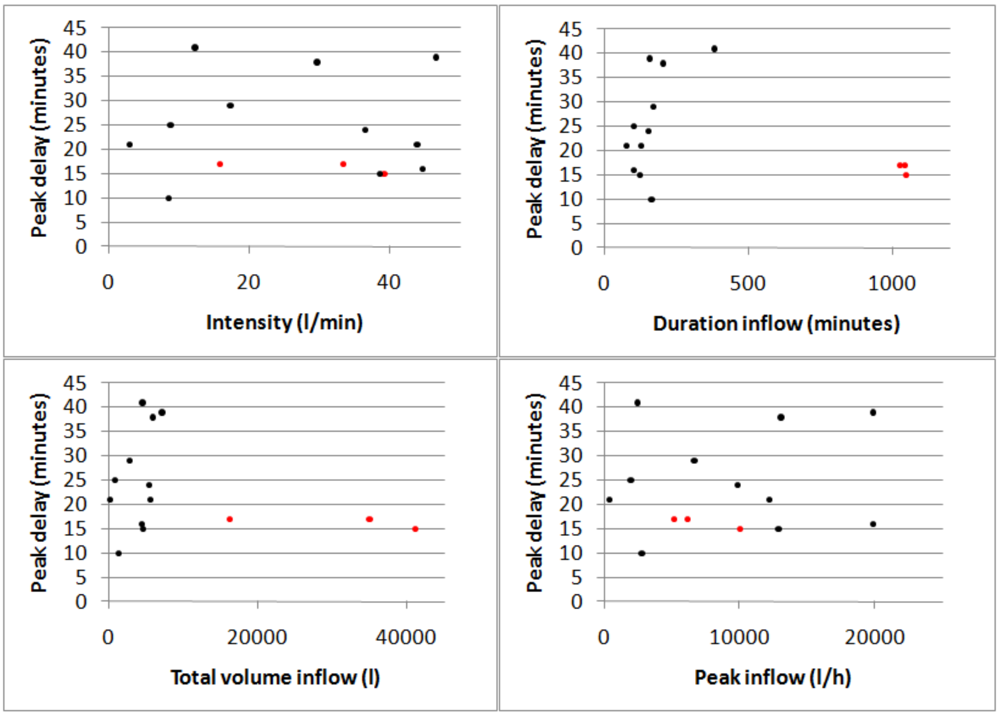

Figure 9.5 Events with an initial water level of 35 cm or less with respect to ground level. The black points denote the short duration events. The red points denote the long duration events.

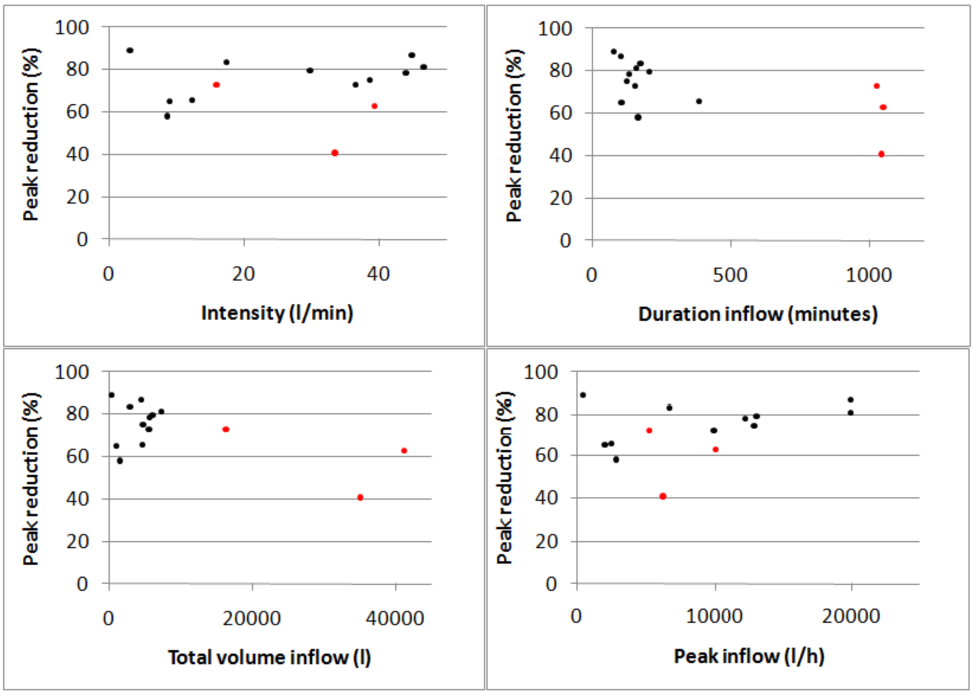

Figure 9.6 Events with an initial water level of 35 cm or less with respect to ground level. The black points denote the short duration events. The red points denote the long duration events.

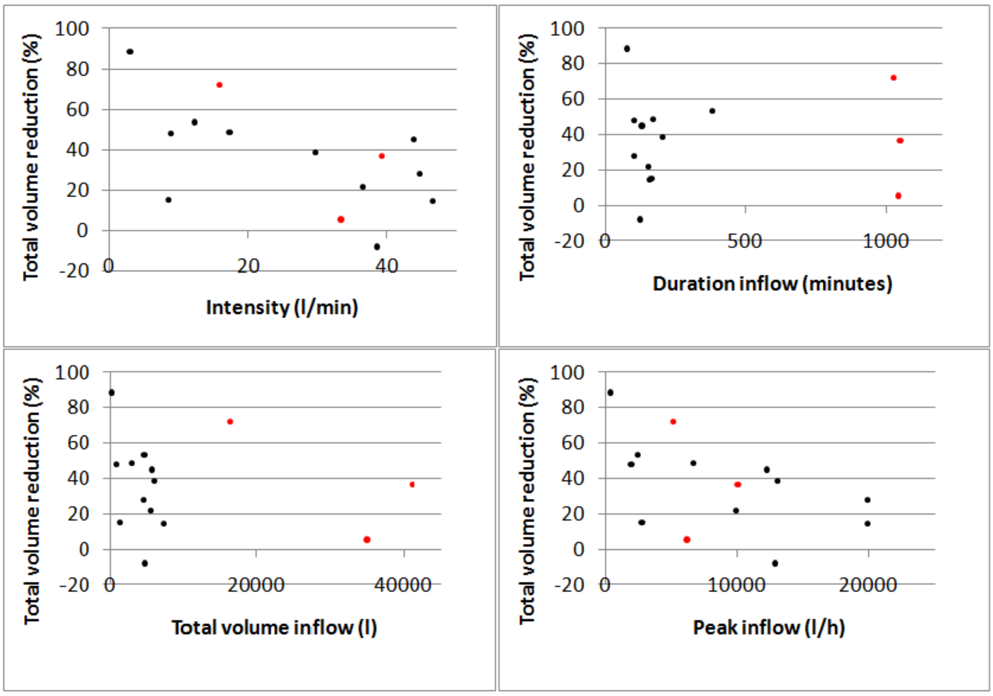

Figure 9.7 Events with an initial water level of 35 cm or less with respect to ground level. The black points denote the short duration events. The red points denote the long duration events.

Appendix III. Tables

In table 9.1 the default parameters of different soil types in Hydrus are presented.

Textural class	Θ_r [L^3L^{-3}]	Θ_s [L^3L^{-3}]	α [cm^{-1}]	n [-]	K_s [$cm\ min^{-1}$]
Sand	0.045	0.430	0.145	2.68	0.4950
Loamy Sand	0.057	0.410	0.124	2.28	0.2432
Sandy Loam	0.065	0.410	0.075	1.89	0.0737
Loam	0.078	0.430	0.036	1.56	0.0173
Silt	0.034	0.460	0.016	1.37	0.0042
Silty Loam	0.067	0.450	0.020	1.41	0.0075
Sandy Clay Loam	0.100	0.390	0.059	1.48	0.0218
Clay Loam	0.095	0.410	0.019	1.31	0.0043
Silty Clay Loam	0.089	0.430	0.010	1.23	0.0012
Sandy Clay	0.100	0.380	0.027	1.23	0.0020
Silty Clay	0.070	0.360	0.005	1.09	0.0003
Clay	0.068	0.380	0.008	1.09	0.0033

Table 9.1 Preset parameters for different soil types in Hydrus. (Simunek, 2006)

Appendix IV. List of figures

Appendix V. List of tables