

Stormwater characteristics and new testing methods for certain sustainable urban drainage systems in The Netherlands

Proefschrift

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Door
Floris Cornelis BOOGAARD
civiel ingenieur geboren te Uithoorn.

Dit proefschrift is goedgekeurd door:
Promotor: Prof. dr. ir. N.C. van de Giesen
Copromotor: Dr. ir. F.H.M. van de Ven

Samenstelling van de promotiecommissie:

Rector Magnificus, voorzitter
Prof. dr. ir. N.C. van de Giesen, Technische Universiteit Delft, promotor
Dr. ir. F.H.M. van de Ven, Technische Universiteit Delft, copromotor

Onafhankelijke leden:
Prof.dr.ir. J.B. van Lier, Technische Universiteit Delft
Prof.dr.ir. C. Zevenbergen, Technische Universiteit Delft /UNESCO-IHE
Prof.dr. R.M. Ashley, University of Sheffield, UK
Prof.dr.ir. A.E. Mynett, Technische Universiteit Delft /UNESCO-IHE
Prof.dr.ir. B. Schultz, UNESCO-IHE/ Universiteit Wageningen, HGL
Prof.dr.ir. H.H.G. Savenije, Technische Universiteit Delft, reservelid

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Summary

Climate change and urbanization will increase the frequency and magnitude of urban flooding and water quality problems in many regions of the world. In coastal and delta areas like The Netherlands, where urbanization is often high, there has been an increase in the adoption of sustainable urban drainage systems (SUDS). These have been installed with the expectation to reduce urban flooding and reduce the pollution impact of urban stormwater discharges on receiving waters. However, the performance of SUDS in delta areas such as the Netherlands (with high groundwater tables and low permeability soils) is often questioned and monitoring results on their long term efficiency are limited. Therefore, research results on the hydraulic performance and removal efficiencies of Dutch SUDS will improve the local design, implementation, maintenance and performance of these facilities.

Numerous research studies in the past have used laboratory-based experiments to model and predict the performance of SUDS field installations. However, the results of these studies were generally not calibrated or verified against reliable field performance data. Many factors can affect the performance of SUDS and some of these are extremely difficult to simulate in a laboratory. These factors can include: clogging, climate and seasonal effects, water table variations, maintenance and numerous site environmental conditions. For example, measured infiltration parameters such as hydraulic conductivity can have a spatial variation of up to two orders of magnitude which can result in laboratory and model outcomes with great uncertainty. There is a significant knowledge gap in the research information available pertaining to the performance of frequently applied SUDS devices such as sedimentation facilities, swales and permeable pavement systems. The research presented in this thesis has therefore focused on an in-depth investigation into the operational performance of 'old' SUDS installed in low-lying areas in The Netherlands.

In order to address this knowledge gap new standardized test procedures for full-scale testing are set up and tested to study the behaviour of these SUDS in

The Netherlands. In the hydraulics laboratory of the TU Delft the removal efficiency of several sedimentation devices was tested in a standardized way.

This research into the performance of SUDS in the Netherlands included:

- Characteristics of stormwater (chapter 2)
- Laboratory testing of sedimentation devices (chapter 3)
- Field tests of:
 - Permeable pavements (chapter 4)
 - Bioretention swales (chapter 5)

For testing each of these facilities new monitoring methods have been developed, tested and evaluated.

Characteristics of stormwater

Detailed information on stormwater quality characteristics is essential to rate the efficiency of sustainable urban drainage systems (SUDS). Stormwater, flowing into storm sewers, is known to contribute to pollutant loads entering urban receiving waters; this can result in significant degradation of the receiving water quality. Knowledge of the characteristics of stormwater pollution would enable urban planners and drainage engineers to incorporate the most appropriate stormwater management strategies in their plans and to mitigate the effects of stormwater pollution on downstream receiving waters. This requires detailed information on stormwater quality and treatability of the storm water. This study gathered stormwater pollution data at over 150 locations throughout the Netherlands. In 15 years a total of 7,652 individual storm events have been monitored. This makes the database the largest stormwater quality database in Europe. The study compared the Dutch data to those presented in contemporary international stormwater quality research literature. The study found that the pollution levels at many of the Dutch sites did not meet the requirements of the European Water Framework Directive (WFD) nor Dutch Water Quality Standards. To meet these standards additional sedimentation, filtration or adsorption capacity is needed to capture small particles with attached pollutants. Detailed information on suspended sediment characteristics in stormwater is essential to be able to rate the efficiency of sustainable urban drainage systems (SUDS).

Efficiency of sedimentation devices

In the hydraulic laboratory of the TU Delft four sedimentation devices were tested on removal efficiency of suspended solids in stormwater by sedimentation. The treatment performance of these sedimentation facilities is investigated in a standardized way in order to compare their hydraulic performance and removal efficiency. In the tests, Dutch stormwater is simulated with a standardized mixture of water and sediment with a well-known particle size distribution and fall velocity of these particles. The new test method proved to be a good method to compare the removal efficiency of small particles in the range of 5-60 μm of several sedimentation devices. The observed removal rates for sediments up to 60 μm of the facilities with a storage volume in the order of 1,5 m^3 and settling surface around 1 m^2 drop to levels below 50 % at a flow rate of 10 l/s and higher. Given a flow rate of 10 l/s, small particle sizes up till 20 μm will not be removed by more than 10%. Particles over 60 μm are trapped with higher removal efficiency but these particles contain less adsorbed pollutants. Since most of the tested facilities have no protection from hydraulic overloading, flush-out of earlier collected sediment at moments of higher discharges was observed.

In order to comply with the Dutch maximum acceptable concentration (MAC) and or WFD standards, SUDS that contain a treatment step with filtration or adsorption can be advised. Two SUDS that are widely implemented in the Netherlands are: permeable pavements and swales. However, the effectiveness of these SUDS is sometimes questioned, especially in the low lying parts of the Netherlands with the soil consisting mainly of clay and peat and its high groundwater tables. Research on the hydraulic performance of these SUDS in the Netherlands is scarce, in particular on their resistance to progressive clogging in the years after implementation.

Permeable pavements

Permeable pavements are specifically designed to promote infiltration of stormwater through paved surfaces in order to reduce runoff volumes and to improve water quality by filtering sediment and other pollutants. This research evaluates the performance of permeable pavements using a new experimental

test method developed to more accurately determine the surface infiltration rate. The method is a full-scale falling head method which involves inundating a large area of the pavement in order to determine the infiltration rate through the pavement surface. The method has been tested on 8 locations in 5 Dutch municipalities to achieve measurements on the infiltration capacity of permeable pavement over seven years after construction and without maintenance.

Infiltration rates of newly installed permeable pavement systems are generally very high, but rates can decrease significantly over time due to clogging. Newly installed permeable pavements in the Netherlands should demonstrate a minimum infiltration capacity of 194 mm/h (270 l/s/ha). In field tests on older pavement infiltration rates ranging between 29 and 342 mm/h were determined. Permeable pavement guidelines in the Netherlands recommend that maintenance should be undertaken on permeable pavements when the surface infiltration falls below 20.8 mm/h. According to this guideline, none of the 8 pavements tested in this study would require immediate maintenance. Clogging of permeable pavements over time is inevitable due to its filter function. However; over 80 % of the pavements evaluated in this study were found to have an infiltration capacity of more than 70 mm/h after over seven years of continuous service without maintenance.

Swales

Bioretention swales (in Dutch called “wadi’s”) have been introduced in the Netherlands around 1998. Swales are one type of SUDS device that has been used globally for well over two decades now to provide stormwater retention and conveyance and improve stormwater quality. The main design objectives of swales, and the purpose of their installation, can however vary considerably. Even under conditions of high groundwater tables (up to 0.5m under the swale) and low permeable soil such as clay the emptying time of the swales should be less than 48 hours.

This research demonstrated that 75% of the swales tested in the study meet the required hydraulic performance levels even after years in operation and without maintenance. The individual swales show a variation of the infiltration capacity of 0.08 to 2.16 m/d.

SUDS in the Netherlands and around the world

The results obtained in this study are encouraging and important for the implementation of permeable pavement and swales in The Netherlands, since the performance of SUDS in delta areas and in areas in the world with comparable hydraulic circumstances has been viewed with skepticism. The research undertaken on Dutch SUDS field installations has demonstrated with new, full scale monitoring methods that most of the bioretention swales and permeable pavements tested in this study meet the required hydraulic performance levels even after years in operation and without maintenance. Standardized tests of sedimentation devices however demonstrated that these facilities have a limited effectiveness for particles smaller than 60 μm while receiving a normal hydraulic loading.

The applied methods of full scale testing of SUDS can easily be applied to observe the hydraulic performance of swales and permeable pavement after years of operation. Innovative monitoring methods and visualization of these experiments using video footage allows real-time observation of the entire infiltration process. Recording these observations in a logbook can provide insight in their demand of maintenance and can also help to improve their design.

1 Introduction

Impacts on the natural catchment hydrological process caused by urbanization have been widely acknowledged and, in many regions of the world, can lead to an increase in the frequency and the magnitude of urban flooding, as well as deteriorating downstream water quality [Zhou, 2014]. Urbanization predominantly takes place in coastal and river plains [Adger et al., 2005] where increased resilience to extreme weather events is needed. In these areas, it is essential to combine enhanced storage capacity in periods of water surplus with periods of water scarcity [Voskamp et al., 2014].

1.1 Water quality

Given the worldwide increase in urbanization, and the impact of urban stormwater on both humans and aquatic ecosystems, the management of urban drainage is a critically important challenge [Fletcher et al., 2013]. Urbanization increases the variety and quantities of pollutants found in downstream receiving waters [Hatt et al., 2004]. Urban stormwater drainage systems are known to contribute significantly to annual pollutant loads and to cause degradation of urban receiving waters [House et al., 1993, Pitt et al., 2004]. The European Water Framework Directive (WFD) advises enhanced protection of the aquatic environment. As a consequence, the WFD advises to address the emissions from drainage systems adequately and to take action when these emissions affect the quality of receiving waters [WFD, 2000]. Moreover, climate change can have a significant impact on both the hydraulic performance of water management systems in municipalities and on quality of receiving water bodies. Most stakeholders do not realize that climate change can also have a (significant) impact on sewer flow quality [Ashley et al., 2008] and on the performance of Sustainable Urban Drainage Systems (SUDS).

1.2 Sustainable Urban Drainage Systems (SUDS)

1.2.1 Definition of SUDS

Surface water drainage systems that have been developed in line with the ideals of sustainable development are collectively referred to as Sustainable Drainage Systems (SUDS). Appropriately designed, constructed and maintained SUDS are more sustainable than conventional drainage methods because they can mitigate many of the adverse effects of urban stormwater runoff on the environment [Woods-Ballard et al., 2011]. They can achieve this through:

- * reducing runoff rates, and reducing the risk of downstream flooding,
- * reducing the additional runoff volumes and runoff frequencies that tend to be increased as a result of urbanisation, and which can exacerbate flood risk and damage receiving water quality,
- * encouraging natural groundwater recharge (where appropriate) to minimise the impacts on aquifers and river baseflows in the receiving catchment,
- * reducing pollutant concentrations in stormwater, and protecting the quality of the receiving water body,
- * acting as a buffer for accidental spills by preventing direct discharge of high concentrations of contaminants to the receiving water body,
- * reducing the volume of surface water runoff discharging to combined sewer systems, and reducing discharges of polluted water to watercourses via Combined Sewer Overflow (CSO) spills,
- * contributing to the enhanced amenity and aesthetic value of developed areas,
- * providing habitats for wildlife in urban areas and opportunities for biodiversity enhancement.

The appropriate use of sustainable urban drainage systems (SUDS) can reduce urban surface water flooding as well as reduce the impacts of urban stormwater pollution discharges on receiving waters. However, the performance of SUDS is not yet well understood by many stakeholders, and

their efficacy is often questioned when compared with more traditional engineering solutions [Viavattene et al., 2013].

The focus of urban stormwater management has changed over the last few decades and it now covers more than just flood mitigation and public health protection aspects. The stormwater industry has developed and adopted new terms to describe these new approaches [Fletcher et al., 2014] including: best management practices (BMPs); green infrastructure (GI); integrated urban water management (IUWM); low impact development (LID); low impact urban design and development (LIUDD); source control; stormwater control measures (SCMs); water sensitive urban design (WSUD) and sustainable urban drainage systems (SUDS).

Descriptions of SUDS, including their design, purpose and performance can be found in a variety of reference material [e.g. Lawrence et al., 1996, Wilson et al., 2004, Woods-Ballard et al., 2011]. However, research on the hydraulic performance and removal efficiencies of SUDS are scarce, particularly for those that have been operating for some time [Al-Rubaeia et al., 2014], and for those in delta areas with high groundwater tables and low permeability soils. Most documents advise that the site area for SUDS should be characterised in terms of the potential for infiltration, but little specific guidance or test results are given on sites with very low infiltration capacity and high groundwater levels. An exception is the new SUDS manual (Woods-Ballard et al., 2015 *in press*) that offers specific guidance on sites with high groundwater levels. The SUDS manual describes that *'infiltration may not be suitable where there is not an adequate depth of unsaturated soils (i.e. greater than 1m) between the infiltration surface and the groundwater'* and describes one example of SUDS on a site with high groundwater levels (the Henry Box site in Witney) with groundwater 400mm to 700mm below the surface of the site. In the low lying parts of The Netherlands this is not an exception, the distance between the bottom of implemented SUDS and the groundwater level will mostly vary between 0-1 metres

The performance of SUDS in delta areas such as the Netherlands, is often questioned, e.g because basic information on maintenance requirements to mitigate clogging is unavailable [Lemmen et al., 2008, Boogaard et al., 2012]. The performance of SUDS under these circumstances is mostly predicted by

models [RIONED, 2015] that cannot be verified since long-term monitoring results from SUDS field installations is scarce. Therefore, research findings on the hydraulic performance and pollution removal efficiencies of (Dutch) SUDS that have been in service for many years will improve design, implementation, maintenance and performance of these facilities.

1.3 SUDS in the Netherlands

Almost half of the Netherlands lies below sea level (figure 1-1) and more than half of its population, and its capital, are concentrated in this heavily urbanized area [De Graaf et al., 2009]. Water levels are managed artificially in this area by installing water storage capacity and pumping capacity in a so-called polder system.

Climate change, sea level rise and ongoing urbanization result in increased vulnerability of these low-lying areas in the Netherlands. Important implications of these changes are the increased flooding frequency [De Graaf et al., 2009] and deteriorating water quality, as in many other delta cities around the world [Molenaar et al., 2013, World Bank, 2010].

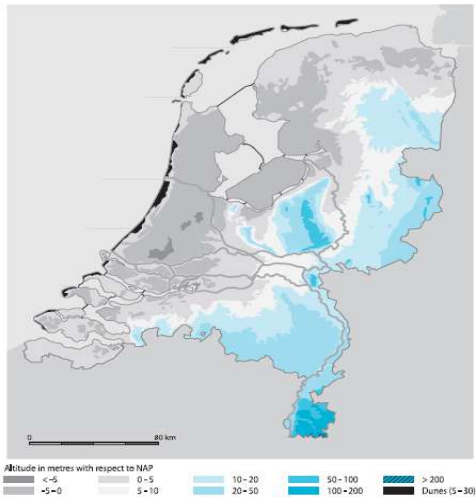


Figure 1-1 Surface topography of the Netherlands; elevation relative to NAP = Normaal Amsterdams Peil, approximately mean sea level (source: Dufour, 2000).

Over recent years many Dutch cities have combined an integrated future vision on urban development and liveability with urban drainage, water management and climate adaptation strategies. Technical measures can be seen in plans from cities such as Rotterdam and Amsterdam which include the application of SUDS like bioretention swales, green roofs, water retention squares and additional water storage capacity [De Graaf et al., 2008]. The first SUDS in the Netherlands were implemented around 1998 [Beenen et al., 2007, RIONED, 2006] primarily to retain and treat stormwater by sedimentation and/or filtration processes. Examples are sedimentation basins (figure 1-2a), lamellar settlers (figure 1-2b), sedimentation ponds (figure 1-2c) and regular urban canals and ponds. An interesting development in the more recent use of SUDS includes the installation of units in series to form treatment trains. Their capacity to treat and attenuate runoff is still explored [Bastien et al., 2010].

The implementation of SUDS has been widely accepted in many countries. For an accurate estimation of the pollution removal efficiency of these systems, detailed knowledge of the quality and characteristics of the stormwater is essential.



Figure 1-2 (a) Empty sediment basin filled with sludge from a stormwater system after 8 years of operation, (b) sludge from stormwater sewer clogging a lamella settler and c) sedimentation pond

Examples of well-functioning SUDS devices are numerous, although failing SUDS can be more educational. The poor functioning of SUDS in The Netherlands is often caused by a reduction in the infiltration or storage capacity, a reduction of the discharge capacity, or is due to pollution of the soil

and groundwater [Boogaard et al., 2012] (figure 1-3). Interviews and field inspections conclude that continuous monitoring of SUDS is required throughout the full lifespan of the systems, including the construction stage, to guarantee that the intended pollution and stormwater reduction targets are achieved [Boogaard et al., 2008]. A review of constructed SUDS systems showed that the uncertainties in design can have a large effect on the performance of the systems [Wilson et al., 2004, Boogaard et al., 2012]. In addition, a lack of monitoring and maintenance leads to reduced SUDS performance which can result in flooding or in pollution of ground- and surface waters [Lemmen et al., 2008, Boogaard et al., 2008].



Figure 1-3 insufficient hydraulic capacity of a swale (left) and clogged infiltration system.

From experiences in Europe and the USA it can be derived that the efficiency of SUDS depends highly on the dimensions of the facility and on its implementation in the field [Al-Rubaeia et al., 2014, Wilson et al., 2004, Clary et al., 2012]. Acquiring the following information on storm water quality is required to understand their treatment performance:

- Stormwater quality levels, which determine the need for stormwater treatment techniques based on the removal of solids.
- Behavior of pollutants, which pollutants are bound to which particles sizes and how much is dissolved.
- Particle size distribution, which gives an indication on what particles are likely to be removed by sedimentation and filtration

1.4 Research on SUDS

Filtration SUDS that are widely implemented in the Netherlands are permeable pavement and Bioretention swales [RIONED, 2014]. The applicability of these SUDS in the Netherlands is however questionable since the lowlands of the Netherlands have high groundwater tables and the soil consists mainly of low permeable clay soil [Boogaard et al., 2012].



Figure 1-4 a) Bioretention swale after rainstorm, b) permeable pavement.

Bioretention swales have been used for well over two decades globally to provide stormwater conveyance and improve stormwater quality. Bioretention swales (figure 1-4a) have been introduced in the Netherlands around 1998 [RIONED, 2006]. Swales are commonly used and preferred because of simplicity of design and maintenance, because of their treatment performance (filtration of micro-pollutants) and because of their landscape quality. The main design objectives of these swales, and the purpose of their installation, vary considerably from country to country [Boogaard et al., 2014, Wilson et al., 2004, Clary et al., 2012]. Records of their long term performance with high groundwater levels and low permeable soil are scarce.

Permeable pavements (figure 1-4b) are used around the world to enhance infiltration and treatment of urban stormwater runoff and to minimize runoff volumes [Beechem et al., 2009, Wilson et al., 2004, Clary et al., 2012]. Urban stormwater runoff contains suspended sediments that can cause clogging and reduce the infiltration capacity and effectiveness of permeable pavements

[Lucke et al., 2014]. It is important for stormwater managers to be able to determine when the level of clogging has reached an unacceptable level so that they can schedule maintenance or replacement activities (chapter 4) [Lemmen et al., 2008].

1.5 Existing testing methods

Numerous research studies in the past have used laboratory-based experiments and models to predict the performance of SUDS field installations. The results of these studies were generally not calibrated or verified against reliable field measurement performance data [Lucke et al., 2014, RIONED, 2015]. Measured infiltration parameters such as hydraulic conductivity can have a spatial variation of up to two orders of magnitude in swales [Gulliver et al., 2014, RIONED, 2006]. Using small areas for testing permeable pavements could potentially lead to erroneous results as a number of studies have demonstrated a high degree of spatial variability between different infiltration measurements undertaken on the same pavement installation [Van Dam & Van de Ven, 1984; Bean et al., 2004; Lucke & Beecham, 2011]. Dutch results from 4 infiltrometer tests taken within 10 m² on one location in 'Meijel' showed a variation of 34 to 596 mm/h (chapter 4). Even in engineered soil (swales and permeable pavement) this will result in measurements and model outcomes with great uncertainty.

Many factors can affect the performance of SUDS field installations and some of these are extremely difficult to simulate in a laboratory. These factors can include:

- Climate and seasonal effects – the performance of SUDS field stormwater infiltration devices can be significantly affected by weather conditions in cold climatic regions [Fach et al., 2011, Roseen et al., 2009].
- Clogging – the sediment accumulation processes that occur in SUDS field installations due to soil erosion, atmospheric pollutant deposition, and pollution entrainment and transport in stormwater runoff are extremely complex and difficult to model accurately in the laboratory, particularly during the construction and operational phase [Borgwardt, 2006, Siriwardene et al., 2007].

- Water table variations – the performance of SUDS field installations can be significantly affected by seasonal variations in groundwater levels and hydraulic conditions in the saturated and unsaturated zone. It is difficult to simulate these in a laboratory [Roseen et al., 2009].
- Maintenance - maintenance procedures of SUDS installations and the surrounding surface areas can vary significantly and this should be accounted for appropriately in modelling studies [Wilson et al., 2004].
- Site environmental conditions – the effects of surrounding vegetation and biodiversity can influence the performance of SUDS field installations. For example, permeable pavements installations often have trees and other vegetation surrounding them and this has been shown to affect the surface infiltration rate of pavements [Kazemia et al., 2009; Fassman and Blackburn, 2010].

Due to these difficulties in simulating real-world conditions and SUDS performance in the laboratory, the research methods presented in this thesis are primarily based on investigations on actual SUDS field installations that have been functioning for several years. Results of studies can be different to those presented in the literature [Lucke et al., 2014]. The practical implications of this are that modelling studies undertaken by industry professionals to predict SUDS performance based on research literature results, may not be truly representative of real-world conditions. Long-term SUDS performance predictions obtained using these models may not be accurate.

Another obstacle that had to be overcome in this research project was the lack of standardized testing procedures. Very few countries have developed SUDS device testing protocols for pollutant removal [Dierkes et al., 2014] or hydraulic performance,

In many documents the need for adequate testing for infiltration facilities is discussed. For example: '*One of the main risks to soakaway performance is inadequate infiltration testing, because of time constraints at the planning stage or cost*' [Woods-Ballard B et al., 2015]. The infiltration tests should be carried out at the location, depth and with a head of water that replicates the proposed design. For larger systems the tests should provide sufficient coverage across the entire area to be occupied by the infiltration system [Woods-Ballard B et al., 2015].

To make testing results of several SUDS installations comparable, a specific testing procedure was developed for both compact settling SUDS and filtration SUDS.

Treatment by settling is incomparable to treatment by soil filtration and adsorption. In order to comply with quality standards, SUDS that contain a treatment step with filtration or adsorption are mostly recommended above sedimentation devices because of higher removal efficiencies [Wilson et al 2004, Jianghai et al 2013]. SUDS that have these multiple treatment steps are regarded in this research: permeable pavement (chapter 4) and swales (chapter 5). As mentioned, many factors can affect the long term performance of SUDS field installations and some of these are extremely difficult to simulate in a laboratory. For this reason a full scale testing method for field experiments is set up. Visualisation should be included in the new test method since visualization of the hydraulic behavior of SUDS infiltration can be effective for understanding the conducted research and can contribute a better understanding of SUDS by many actors (e.g. urban planners from water authorities and municipalities etc). This visualisation should allow real-time monitoring of the entire infiltration process, can be useful as a logbook for the conducted experiments and also facilitate verification of other measurements.

1.6 Research questions

In delta areas like the Netherlands or similar locations with high groundwater tables and low permeable soil, some have questioned the performance of SUDS such as Woods-Ballard et al. (2015) who state *'infiltration may not be suitable where there is not an adequate depth of unsaturated soils between the infiltration surface and the groundwater'*. But what is an inadequate depth or what is suitable? In most parts of the low lying parts of the Netherlands the groundwater level is less than 1 meter below the surface level. The question is whether this is an inadequate depth? Is the Netherlands simply not a 'suitable' location for infiltration of stormwater *at the surface* with swales and permeable pavement? Does suitable mean that these SUDS should empty their storage capacity within 24 or 48 hours? And will these SUDS stay 'suitable' years after implementation?

The overall objective of this research is to review the performance of SUDS in the Netherlands with high groundwater tables and low permeable soils. Research findings on the characteristics of Dutch stormwater and the hydraulic performance and pollution removal efficiencies of (Dutch) SUDS that have been in service for many years can improve design, implementation, maintenance and performance of these facilities.

Main hypothesis: The hydraulic performance of swales and permeable pavement that have been in service for many years are *suitable* in high groundwater tables and low permeable soil.

'Suitable' can be defined as the ability to infiltrate a certain amount of stormwater in an acceptable time, for instance; *'the empty time of a swale should be less than 24 hours to have a full storage capacity before the next stormwater event'*. This acceptable infiltration rate could depend on the infiltration method, location or actors involved. Therefore this is in detail discussed in the chapters 4 (permeable pavement) and 5 (swales).

1.6.1 Research method

As mentioned, many factors can affect the long term performance of SUDS field installations and some of these are extremely difficult to simulate in a laboratory. For this reason a full scale testing method for field experiments is set up with visualisation of the infiltration process that can contribute to a better understanding of Dutch SUDS by many actors (e.g. urban planners from water authorities and municipalities).

The next questions will be addressed in this thesis:

- Which SUDS device testing method can accurately describe the performance of SUDS?
- Can we apply these new methods in laboratory and in the field to SUDS in the Netherlands?
- Which cost effective visual monitoring methods are preferred for this method?

- What test results can be acquired from SUDS (swales and permeable pavement) in low permeable soil and high groundwater levels after several years?

1.6.2 Research on sedimentation devices in laboratory

First the characteristics of Dutch stormwater are evaluated. A standardized testing procedure was developed to obtain detailed insight in the performance of SUDS that use settling as their main treatment technology (chapter 3). This procedure is characterized by using:

- Suspended sediment with a representative and well-known particle size distribution
- A non-coagulating suspended sediment with constant and known specific density
- Particle counting for detailed analyses
- A representative concentration of suspended sediment particles

1.6.3 Full scale testing method for field experiments

As previously discussed, there is a significant knowledge gap in the research information available pertaining to the performance of SUDS devices, operating under real operational conditions; this is particularly the case for compact settling SUDS, swales and permeable pavement systems. The research presented in this thesis has therefore focused on an in-depth investigation into the operational performance of these SUDS systems installed in low-lying areas in the Netherlands in order to address this knowledge gap with new test procedures as full-scale testing. In order to evaluate the performance of the new full-scale infiltration testing method, the method was first trialled on several locations and SUDS throughout The Netherlands. The new method could be used to accurately measure infiltration rates of several SUDS in-situ; swales and permeable pavement (figure 1-5) as well as watersquares and filter drains (figure 1-6).

The new testing method was therefore used on existing permeable pavements and swales at different municipalities evaluated in this study (chapter 4 and 5).



Figure 1-5 Full scale test at swale (left) and full scale test at permeable pavement (right).



Figure 1-6 Full scale test at watersquare (left) and full scale test on filter drains (right).

1.6.4 Visualisation monitoring methods

The hydraulic behavior of SUDS is primarily studied by hand measurements and pressure transducers for recording the reduction in water levels over time. While pressure transducers and loggers provide an abundance of data and allow informative and attractive graphs to be compiled, much care needs to be taken to ensure that the pressure transducers readings are verified and accurate. Pressure transducers can be unreliable and inaccurate due to external influences such as wind effects and changes in atmospheric pressures (Lucke et al., 2014). Therefore, it is highly recommended that transducer readings are calibrated and verified using visual recording of the SUDS as cameras and time lapse photography.

The different measurement methods (Figure 1-7) in this study are:

1. Pressure transducers
2. Hand Measurements
3. Calibrated Underwater Camera
4. Time-Lapse Photography



Figure 1-7 Underwater camera set-up at permeable pavenment (left), timelapse camera (middle), camera set up for monitoring infiltration transport drainage (right).

Calibrated Underwater Camera: a high definition video camera was used at a number of strategic locations to record the decrease of water levels over the duration of the (Figure 1-7).

Time-Lapse Photography: time-lapse photography was used at most test location to record all research activities and to enable verification of the pressure transducer and hand measurements. The time-lapse photographs were also used to compile an accelerated video of the entire pavement testing. All timelapse movies can be found on www.climatescan.nl.

1.7 Thesis outline

In chapter 2 the quality characteristics of stormwater are discussed. Detailed information on stormwater quality is given, relevant for the efficiency of sustainable urban drainage systems.

In chapter 3 a new method is given for detailed testing of compact settling SUDS performance in settling suspended sediments in the laboratory. In the laboratory of the TU Delft, the sediment removal efficiencies of several SUDS were tested under standard circumstances.

A new full scale test method for the performance of permeable pavements is discussed in chapter 4. In chapter 5 the results from field-tests on Bioretention swales is converted to guidelines for design, construction and maintenance. Test results using the new monitoring techniques are found in chapter 3, 4, and 5 and discussed in every chapter. Finally chapter 6 is used to discuss and evaluate the results of testing and provide recommendations and gives suggestions for further research.

1.8 Bibliography

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2 Stormwater Quality Characteristics in Dutch Urban Areas and Performance of sedimentation devices

This chapter is primarily based on:

Boogaard F, van de Ven F, Langeveld J, van de Giesen N, Selection of SUDS based on storm water quality characteristics, Challenges 2014, 5(1), 112-122; doi:10.3390/challe5010112

Langeveld, J.G., Geelen F, Boogaard F, Uncertainties of stormwater characteristics and removal rates of stormwater treatment facilities: Implications for stormwater handling, Water Research, 2012,

<http://dx.doi.org/10.1016/j.watres.2012.06.001j.watres.2012.06.001>



2.1 Stormwater quality

This chapter discusses stormwater characteristics, which are derived from the Dutch national stormwater quality database combined with international literature data, in the light of the potential efficiency of sedimentation devices.

For this research monitoring data is collected over a fifteen-year period (the earliest measurement in the database is from 1999) from more than 60 municipalities and over 150 locations throughout the country. The total number of individual events included in the database now is 7,652. The national database of all collected stormwater monitoring data allows for a scientific analysis of the data and information and recommendations for improving the quality monitoring. Each data set has gone through a quality assurance/quality control review based on reasonableness of data, extreme values, relationships among parameters, sampling methods and a review of the analytical methods [Boogaard et al., 2007].

Most data on the characterization of stormwater quality (contaminants concentration, particle size distribution of suspended sediment, fraction bound to suspended solids) was found by sampling stormwater during stormwater events. Most of the samples were analyzed in certified laboratories according to standard methods and standard quality control/assurance procedures (see table 2-1).

Table 2-1 Water quality parameters.

Water Quality Problem Related	Parameter	Reference Method
General parameter	Total Suspended Solids (TSS)	NEN-EN 872
Oxygen depletion	Biochemical Oxygen Demand (BOD)	NEN-EN 1899 1&2
	Chemical Oxygen Demand (COD)	EN 6633:2006
Eutrophication	Total Kjeldahl Nitrogen (TKN)	NEN-ISO 5663:1993
	Total Phosphorus (TP)	NEN 6663
Toxicity	Lead (Pb)	NEN-EN-ISO 17294-2:2004
	Zinc (Zn)	
	Copper (Cu)	
Microbiological quality	<i>E. coli</i>	NEN 6571:1982
Particle size analysis	HRLD-400HC	NEN-ISO 13320-1

Preferably data from well-described stormwater research sites have been used for the database (peer reviewed journals). In addition the following information was entered: Aim of the research, site descriptions (state, municipality, land use components), and sampling information (date, season, sampling method, sample type) with links to the original research reports and articles.

The database has its focus on urban areas, divided into residential areas (roofs and roads) and commercial areas; industrial areas were not represented.

Different water quality parameters were characterized through the calculation of minimum, maximum, mean, median, and 90th percentile values.

Distribution between dissolved and particle-bound pollution loads were determined by comparing the total concentration in samples with the filtered sample (0.45 µm).

Particle size distribution was determined by a particle counter (HRLD-400HC).

The particle counter measured the absolute amount of particles for every particle size (quantified intervals of 0.77 µm) between 0 and 1000 µm.

2.2 Stormwater quality

The recorded concentrations of the pollutants from the database have been compared to Dutch quality standards such as the maximum acceptable concentration (MAC) for receiving waters [van der Beesen et al., 1998]. The mean stormwater quality measurements for nutrients (TKN and TP) and for copper and zinc exceeded the MAC Table 2-2. In addition, the microbiological parameters showed that stormwater by far exceeds the standards of 200 E. coli/100 mL for swimming water [Langeveld et al., 2012].

Table 2-2 Concentrations of pollutants in stormwater runoff from Dutch residential areas, roofs and roads [Boogaard et al., 2014].

	Cd	Cr	Cu	Hg	Pb	Ni	Zn	PAH10	PAH16
	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
mean	0.27	6.2	19	0.05	18	5.6	102	0.8	60.9
median	0.15	1.1	11	0.06	6	3.6	60	0.8	1.5
90 percentile	0.50	12.0	35	0.08	43	10.0	250	1.1	1.5
n measurements	152	141	686	118	682	155	684	145	106
MAC solved	0.4	8.7	1.5	0.20	11.0	5.1	9.4	2.3	
MAC total	2.0	84	3.8	1.2	220	6.3	40	4.3	4.3
required R	0.0%	0.0%	80.5%	0.0%	0.0%	0.0%	60.7%	0.0%	
	Oil	Cl	Fe	BOD	COD	Ptot	N-kj	SS	E. coli
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	kve/100 mL
Mean Dutch	37	18.3	1.8	5.7	32	0.4	1.9	29.9	1.9E + 04
median	1	11.0	1.1	3.1	20.0	0.3	1.1	11	6.7E + 03
90 percentile	90.8	33	2.9	12.5	60	1.0	3.1	50	3.5E + 04
n measurements	149	321	60	219	681	107	590	1,262	116
MAC dissolved						0.15	2.2(N-tot)		1.0E + 03 (swimming water)
required R						64.5%	0.0%		94.8%

Green concentrations are under total MAC value, orange is exceeding MAC value and red is exceeding the MAC by 2 times or more. "Required R" is the required removal efficiency to MAC values.

Table 2-2 shows the required removal efficiency (“required R”) to achieve the quality standard. To achieve the MAC for copper and zinc, the stormwater treatment facilities must have a removal efficiency of about 80% and 60%.respectively. For phosphate the removal efficiency needs to be in the order of 65%.

The quality and characteristics of stormwater can strongly differ per country, location and even between and during stormwater events [Gobel et al., 2007]. A comparison with international data from USA, Australia, and Europe is given in Table 2-3.

Table 2-3 (inter-)national stormwater quality data from residential areas.

substance	unit	Dutch ^a	USA NSQD ^b	Europe/Germany ATV Database ^c	Worldwide ^d
		Mean	Median	Mean	Mean
TSS	mg/L	17	48	141	150
BOD	mg/L	5.7	9	13	
COD	mg/L	32	55	81	
TKN	mg N/L	1.9	1.4	2.4	2.1
TP	mg P/L	0.4	0.3	0.42	0.35
PB	µg/L	18	12	118	140
Zn	µg/L	102	73	275	250
CU	µg/L	19	12	48	50

Notes: ^a [Boogaard et al., 2014] Dutch STOWA database (Version 3.1.2013) based on data monitoring projects in the Netherlands, residential and commercial areas, with n ranging from 26 (SS) to 684 (Zn);

^b [Pitt , 2004] NSQD monitoring data collected over nearly a ten-year period from more than 200 municipalities throughout the USA. The total number of individual events included in the database is 3.770 with most in the residential category (1.069 events);

^c [Fuchs et al., 2004] ATV database, partly based on the US EPA nation wide urban runoff programme (NURP), with n ranging from 17 (TKN) to 178 (SS);

^d [Bratieres 2008] Typical pollutant concentrations based on review of worldwide [Duncan, 1999] and Melbourne [Stone 1996] data.

The data from the Dutch database shows that the stormwater monitored in the Netherlands is relatively low in suspended solids. BOD, COD and heavy metals show low concentrations compared to international data, whereas the nutrient concentrations are within the international range.

2.3 Fraction of Pollutants Attached to Particles

Treatability of stormwater runoff by sedimentation depends to the degree on which pollutants are bound to particles. Therefore, the distribution between dissolved and particle-bound pollution loads has been determined. Up to 90 measurements were taken by several organizations from stormwater sewers at 25 different locations in the Netherlands. Distribution between dissolved and particle-bound pollution load was determined by comparing the total concentration in samples with the filtered sample (0.45 µm).

Figure 2-1 shows the average values of pollutants bound to suspended solids in stormwater from roofs and roads in residential areas (yellow bars on chart). The plus and minus gives the range of the data values which indicates a large variability in the ability of pollutants to bind to suspended solids. The red dot gives the typical average value found throughout the world, which was taken from comparable international studies [Walker et al., 1997].

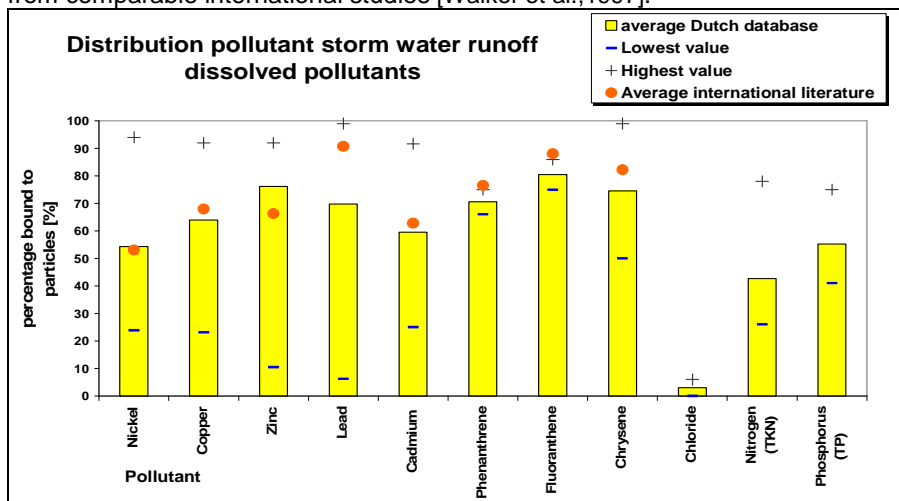


Figure 2-1 Distribution of pollutants in Dutch stormwater (90 samples from 25 locations) [Boogaard et al., 2014]

From figure 2-1, the pollutant behavior can be derived. Nutrients are less bound to particles than most of the heavy metals and PAH and therefore harder to retain than other contaminants. Within a certain pollutant group, such as metals, the individual pollutants have their own specific behavior. The average Dutch research results are similar to the average from international data [Gromaire-Mertz et al., 1999, Grant et al., 2003].

Figure 2-1 gives an indication of the maximum removal efficiency rate that can be achieved by using settlement devices. To get a detailed insight of the removal efficiency, knowledge of particle size distribution of suspended sediment in stormwater is required in order to find out which particles can be captured by settlement facilities.

As heavy metals are bound in the order of 65% (lead up to 90%) a higher removal rate with settlement basins (remove only suspended solids and not solved pollutants) should not be expected but is rarely determined in the field (see table 2-4). If 80% removal rate is needed to achieve MAC for copper, which is bound on average at 65 % to suspended solids, then it is unlikely that this quality standard will be achieved with sedimentation basins only.

2.4 Research on suspended solids

Field data on composition of the suspended material, particle size distribution, and settling velocities are essential to rate the efficiency of sedimentation devices. Several studies demonstrated that particles less than 50 μm make more than 70% of total suspended sediment (TSS) load carried by runoff by weight [German and Svensson et al., 2002; Roger et al., 1998; Andral et al., 1999]. Furumai et al., (2002) showed that particles less than 20 μm accounted for more than 50% of the particulate mass for runoff samples with TSS concentration less than 100 mg/L. Based on observed average particle size distributions in storm water runoff at 25 locations in the Netherlands about 50% of the mass of the suspended sediment consists of particles smaller than 90 μm (see figure 3-3).

The finest particles in runoff have the highest concentration for many pollutants, especially heavy metals, oil and poly-aromatic hydrocarbons (PAH) [Sansalone et al., 1997; Roger et al., 1998; Viklander et al., 1998, Morquecho et al., 2003, Li et al., 2006]. Nutrients (TP and TN) are less bound to particles

and are mostly adsorbed to sediments between 11 and 150 μm , it is suggested that treatment facilities must be able to remove sediments down to 11 μm [Vaze et al., 2004].

2.5 Particle Size Distribution

To get detailed information on the achievements of settlement and filtering sustainable urban drainage systems an examination of particle size distribution is needed. Measurements at 25 locations in The Netherlands were taken in stormwater sewers and the particle size distribution was determined. The results are given in figure 2-2.

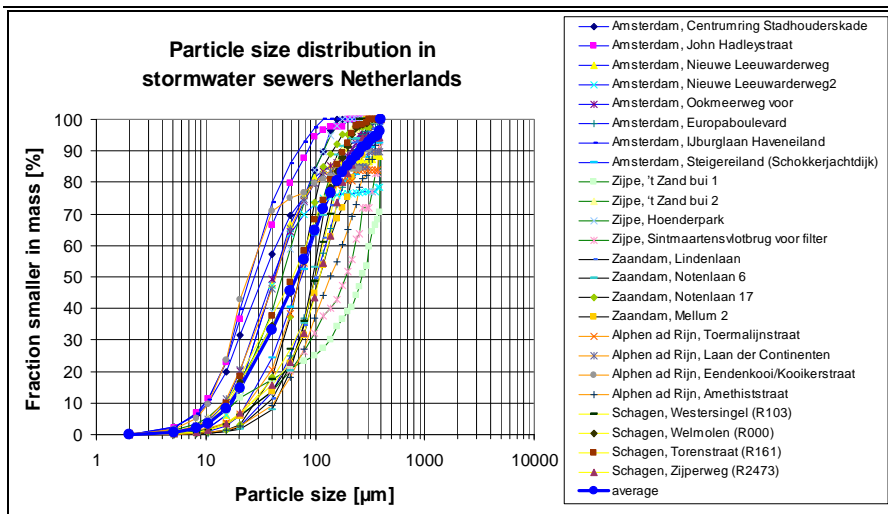


Figure 2-2 Particle size distributions observed in Dutch stormwater sewer systems.

The particle size distribution varies with each different stormwater sewer location. Half of the mass consists of particles smaller than 90 μm . Compared to other international research it seems that Dutch stormwater is within the range of international data [Walker et al., 1997] see Figure 2-3).

2.6 Stormwater Characteristics and Conclusions on Removal Efficiency

The stormwater quality data showed that to achieve the Dutch MAC for copper and zinc the stormwater treatment facilities must have a removal efficiency of 80% and 60% and for nutrients in the order of 65%. The characterization of stormwater contaminants (particle size distribution, fraction bound to suspended solids, etc.) showed that it is not likely to achieve this. Observed removal efficiencies in the field are shown in Table 2-4.

In the overview of the 'BMPs orders of preference for the removal of identified pollutants' [Schueler, 2000] settlement tanks were ranked the lowest for removal of heavy metals.

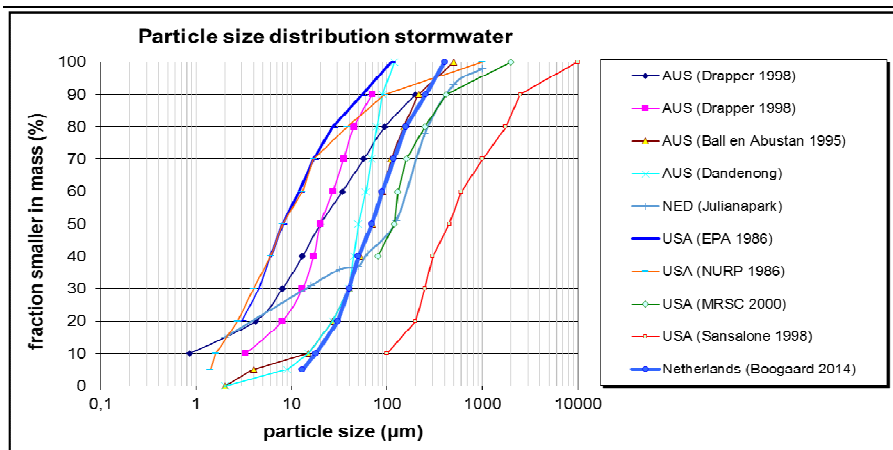


Figure 2-3 Particle size distributions in several stormwater sewer systems around the world [Boogaard et al 2007].

Research results on removal efficiency of sedimentation devices are scarce in the Netherlands. However, recent research has been done on lamella settlers and the treatability of stormwater. At three lamella settlers with a design surface loading of 1 m/h. the specific pollutants concentration levels on influent and effluent side (heavy metals, TSS, COD, BOD) have been monitored in the Dutch area Krimpenerwaard [Liefing et al., 2015], This has resulted in more than 75 storm events being monitored at the lamella settler, during a 3 year monitoring period. The same method of testing is being used as a research in

Arnhem where more than 75 samples were taken by the automatic samplers before and after a lamella settler to estimate the volume weighed removal rate [Langeveld et al. 2012].

Table 2-4 Removal efficiencies from sedimentation facilities with lamella settlers.

	Required Removal Efficiency to MAC values [Boogaard et al., 2014]	Bound to Particles [Boogaard et al., 2014]	Schoonhoven [Liefing et al. 2015]	Krimpen a/d IJssel [Liefing et al. 2015]	Haasdrecht [Liefing et al. 2015]	Arnhem Dordrechtweg [Langeveld et al. 2012]	International literatuur [Daligault et al. 1999]
Amount of samples			21-24	28-30	23-25	66-75	n
Copper ($\mu\text{g Cu/l}$)	80%	65%	24%	9%	6%	21%	29% - 40%
Lead ($\mu\text{g Pb/l}$)			19%	19%	46%	36%	28% - 44%
Zinc ($\mu\text{g Zn/l}$)	60%	55%	20%	10%	36%	23%	-38% - 27%
COD (mg O ₂ /l)			8%	3%	17%	18%	30%
Suspended solids (mg/l)			30%	24%	13%	34%	30% - 54%

Table 2.4 summarizes the removal rates of lamella filters from the locations Schoonhoven, Krimpen aan de IJssel and Haasdrecht [Liefing et al., 2015] and Arnhem [Langeveld et al. 2012]. The removal rates of the lamella settlers are around the lower limit reported by [Daligault et al., 1999], which was to be expected given the stormwater characteristics discussed in previous paragraphs. The results of lab testing showing that not a high percentage of small particles is being captured at the design surface loading of 1 m/h.

2.7 Discussion

Detailed data on the percentage of contaminants bound to a specific particle size fraction in urban stormwater are rare.

From the research it can be concluded the distribution can vary substantially per location, which is expected since the particle size distribution and (un)bound fractions show a large variation too. Most contaminants are bound to smaller fractions of particles [Taylor et al., 2005, Scholes et al., 2007]. In characterization of solid and metal element distributions in urban highway stormwater more than 50% of copper, zinc, and lead are bound to particles smaller than 75 μm [Pitt et al., 2004]. Since the removal efficiency of suspended solids is in the order of 60% for zinc in order to achieve the MAC quality standard, a high amount of particles <70 μm needs to be removed.

2.8 Conclusions

From the acquired data on stormwater quality and characteristics it can be concluded that to achieve the WFD and Dutch quality standards for copper and zinc, the stormwater treatment facilities must have a removal efficiency of 80% and 60%, and for nutrients in the order of 65%.

These removal efficiencies are unlikely to be achieved by settlement basins due to the distribution between dissolved and particle-bound pollution loads of these pollutants. As heavy metals are bound for about 65% (lead up to 90%) a higher removal rate with settlement basins should not be expected and is rarely observed in the field.

If 80% removal rate is needed to achieve MAC for copper, which is bound on average for 65% to suspended solids, then it is unlikely that this quality standard will be achieved with sedimentation basins.

Comparing Dutch stormwater characteristics to international data the average percentage of pollutants bound to suspended solids are comparable. Data on particle size distribution are less coherent. The particle size distribution demonstrated that about 50% of the mass of stormwater measurements (average of 25 locations) consists of particles smaller than 90 μm . As the fine fraction is responsible for most of the pollution load, it is important to know

whether SUDS are capable of removing the finer solids. With the insight of particle distribution, further research can focus on the ability of different SUDS or sedimentation devices of capturing these fine particles (chapter 3). To conclude, regarding the characteristics of stormwater quality and required removal efficiency for achieving MAC demands, SUDS based on settling as the primarily treatment process, will not be able to achieve the required removal efficiencies. An additional stormwater treatment step with filtration or adsorption will be necessary in order to comply with the MAC and or WFD.

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3 Settlement efficiency of sedimentation devices: standardized full scale testing

This chapter is primarily based on:

Boogaard F.C, Blanksby J., Kregting P., Bakker W., Poole A., Developing new perspectives on approaches to the management of inlets to traditional urban drainage systems. SUDSnet International Conference Coventry, (keynote) 2012, pg 26.

Boogaard F.C., Langeveld J.G., Liefiting H.J., Kluck J., Storm water quality and removal efficiency rates of lamella filters, NOVATECH 2010.

Boogaard F., van de Ven F., Langeveld J., Kluck J., van de Giesen N., Removal efficiency of storm water treatment techniques: standardized full scale laboratory testing, Urban water 2015 (under review)



3.1 Introduction

Storm sewers are known to contribute significantly to the annual pollutant loads into the receiving waters and to ecological degradation [House et al., 1993, Davis et al., 2001]. As discussed in chapter 2, major pollutants include suspended solids, nutrients, heavy metals, PAH, pesticides and bacteria [Bratieres, et al., 2008]. Fortunately, most of these pollutants are adsorbed on particles and will come to settle under stagnant flow conditions.

Existing drainage networks can be retrofitted with prefabricated devices (e.g. vortex separators and filters) and detention systems facilitating infiltration (e.g. infiltration basins, rainwatergardens, swales) are designed to reduce flooding and remove suspended solids [Hatt et al., 2008; Palhegyi et al., 2010].

The stormwater industry has developed and adopted new terms to describe new approaches and technologies of urban drainage [Fletcher et al., 2014] including: best management practices (BMPs) and sustainable urban drainage systems (SUDS).

A number of proprietary stormwater treatment devices that use multiple chambers to help trap and retain sediments and floating substances are manufactured with pre-treatment units [Sample et al., 2012]. Examples are lamella filters; sedimentation chambers and sedimentation pipes. Some examples are shown in figure 3-1.



Figure 3-1(a) Sediment basin in Amsterdam (sludge from stormwater system during maintenance after 8 years) and (b) lamella settler in Krimpenerwaard, The Netherlands.

To achieve Dutch surface water quality standards (Maximum Allowable Concentration, or 'MAC') for copper, zinc and nitrogen, storm water treatment facilities should obtain a removal efficiency of 80%, 60% and 65%, respectively

[Boogaard et al., 2014]. As shown in chapter 2, this can be concluded from observed concentrations collected in the Netherlands' stormwater quality database. According to the same database some 65%, 55% and 40% percent of this copper, zinc and nitrogen is bound to particles. These figures are comparable to the figures found in international literature [Sansalone et al., 1997, Scholes et al., 2014, Taylor et al., 2005].

The settling efficiency of sedimentation devices highly depends on the characteristics of the pollution load, the dimensions of the facility and implementation in the field [Woods-Ballard et al., 2015, Wilson et al., 2004]. For detailed determination of the pollution removal efficiency of these sedimentation devices information is needed on:

- **Quality of storm water**, as the concentration of the pollutants determines the need for storm water treatment and acquired removal efficiencies.
- **Suspended solids, pollutant adsorption behavior, particle size distribution and settling velocities of particles**, which determine the potential of treatment techniques based on settling.
- **Hydraulic loading and geometry of the facility**, as this determines flow velocity which affects the settling process of particles.

Urban water managers can use this information to identify the most appropriate stormwater management strategy for a specific drainage area.

As the fine fraction is responsible for a substantial part of the pollution load (chapter 2), it is important to know whether our sedimentation devices are capable of removing the finer solids. Therefore the focus of this chapter is to determine the ability of a number of frequently applied sedimentation devices to capture these fine particles. To this end a standardized full scale testing procedure was developed.

3.2 Test procedures

Comparison of sedimentation devices' treatment performance in terms of capturing suspended sediment and adsorbed pollutants is impeded by the variety of variables that could be included in test procedures. In order to compare the removal efficiency of sedimentation devices, a standardized test procedure has been set up. Regarding the formulation of a standardized monitoring protocol for testing this type of facilities in a comparable way, several lessons are to be learned from earlier research [Schmitt et al., 2011, Maus et al., 2010, Uhl et al., 2013, Dierkes et al., 2013, Boogaard et al., 2010, DIBt, 2011, Ngu et al., 2014, Maniquiz-Redillas et al 2014]:

- Use sediment with representative, constant and well known particle size distribution and settling velocities. In several investigations undefined materials (particle sizes, settling velocities) have been used. For example, when using road sediment from the field it is important to know the particle size distribution and the settling velocities for a clear understanding of the performance of hydraulic separators [eg Kwon et al., 2012, Howard et al., 2012]. The use of a standardized non- coagulate sediment with well-defined spherical particles and density is required, especially if particle counting is used [NEN-ISO 13320-1] and results of several tests are to be compared.
- Detailed monitoring on particles sizes being captured. Sometimes Imhoff cones have been used to quantify settled solids [e.g. Gunawardana et al., 2012]. An Imhoff cone is a cone-shaped container marked with graduations. The cone is used to measure the volume of settleable solids in a specific volume (usually one liter) of water or wastewater. But the estimated volume with these cones doesn't provide insight in the sizes of the particles that are removed. Volume, weight and amount of particles can be determined in more detail by particle counting.
- Use a representative amount of particles. E.g. it is not representative to use a once in 10 years extreme suspended sediment load to assess the long term achievements of the sediment facility. Tests that are run with higher concentrations than regularly occurring in storm water runoff can overestimate the efficiencies of the devices [Uhl et al., 2013].
- Recirculation of the test water is not advised because this could leads to fluctuating concentrations of suspended sediment in the influent.

- The test should be performed until a steady-state hydro morphological situation and a constant removal efficiency is reached. Within residence times up to 2 (water volume is not refreshed at least 2 times) decreasing removal efficiencies were observed. After a residence times > 2 the efficiencies remain to be more or less constant [Uhl et al., 2013].
- Checking resistance to litter and trash. Some facilities can capture small particles but clog when trash (plastic bags, cans, lollipop sticks) enters the sediment facility.

Based on these lessons a standardized test procedure has been formulated.

3.3 Standardized test procedure

Table 3-1 presents an overview of the tests performed on each of the four devices as a standardized test procedure. The stepwise testing procedure can be divided in two blocks:

- Hydraulic performance testing (step 1-2).
- Removal efficiency assessment by particle size (step 3).

The testing was done at the Hydraulic Laboratory of the TU Delft.

Table 3-1 Overview of experiments for assessment of sediment removal efficiency of sedimentation devices

No	Name experiment	Purpose of experiment	Used measurement-tools
1	Hydraulics test: visualization of flow	Visualizing flow with color tracer to study the hydraulic performance (research conditions as and preferential flow paths)	Visualizing flow with potassium permanganate captured on video camera. Water pressure and discharge measurements included
2	Hydraulics test: Visualization and testing maximum hydraulic performance	Insight in 'extreme' hydraulic performance; assessment of maximum hydraulic capacity and evaluation of performance if this inflow capacity is exceeded	Bypass and overflow will function: (video-) camera, water pressure and discharge measurements
3	Suspended sediment removal efficiency test at different flow rates	Removal efficiency is determined on the difference between amount of particles per particle size at inflow and at outflow, at three different flow conditions. Visual removal efficiency test: visualization of sediment transport in transparent parts of the device (if available)	Standard suspended sediment mixture. Sampling 1 liter at intervals of 5 min). By particle counting and (video-) camera

The general setup of the testing equipment is shown in Figure 3-2. The hydraulic capacity of the test facility in TU Delft was limited to 400 l/s. This allows testing of all facilities that are capable to treat the storm water of a connected impervious area in the range of 1-2 ha. This is a very common design range for urban planners and manufacturers [Boogaard et al., 2007].

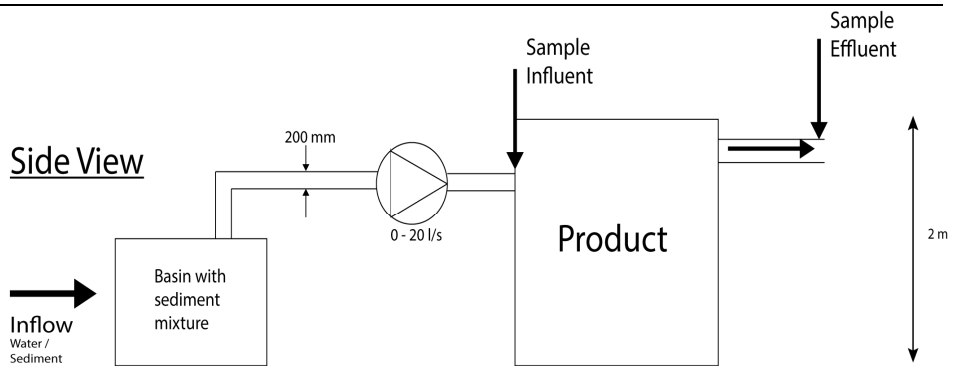


Figure 3-2 General setup of the testing platform.

Testing equipment

The equipment that has been used in the testing of the sedimentation devices and its reported accuracy is listed in table 3-2.

Table 3-2 Equipment used in testing.

Measurement Type	Equipment	Accuracy	Literature
Discharge	Endress+Hauser Prosonic flow 91	±0.5%.	[Endress + Hauser, 2006]
Water height and water temperature	Schlumberger Mirco diver DI 501/ DI 500	0.05% ¹ ±0.5 cmH ₂ O ± 0,1 °C	[Schlumberger, 2014]
Particle counting	HRLD-400HC	For particles 2 – 400 µm <10% ²	[Hach, 2010]

For a constant and reliable rate of flow, an acoustic flow meter (Prosonic flow 91) was used during the experiment. For the test a basin has been used for pre-mixing water. The basin had a volume of 0.900 m³. For a constant suspended sediment concentration (keeping particles in suspension) during the experiment a mixer is used with a frequency of 700 rounds per minute.

The accuracy of the particle counter depends on the concentration of a certain fraction. For high amounts of particles smaller than about 20 µm there is a risk of multiple scattering, where light is scattered subsequently at more than one particle [NEN-ISO 13320-1]. With a suspended sediment concentration of 50 µg/l, the amount of particles in the fraction < 20 µm is over 10.000 particles per liter which is in the order of the concentration limit of the HRLD-400 particle counter. This can lead to inaccurate results due to multiple scattering. Above 60 µm the amount of particles can be less than 10 particles per liter, leading to sampling inaccuracy.

¹ > 67% of the measurements are within 0.05% of value [Schlumberger, 2014]

² Typically, sample-to-sample reproducibilities of better than 10% can be expected for on-line and laboratory sampling applications. Calibration rapport] showed 0% difference after calibration at 20 ml/min of expected and measured particle sizes between 1,99 and 160 µm in 11 steps [Telstar, 2013.]

3.4 Hydraulic performance

For gaining an overall understanding on how a facility functions hydraulically digital film footage can be very effective. By adding a tracer, KMnO_4 in our case, to the flow patterns, preferential flow paths can be visualized and recorded.

Visualizations with tracers can be effective in locating areas with relatively high flow velocities in a facility and finding measures to optimize the sedimentation performance of a device³ [Morin et al., 2008]. Three of the four tested sedimentation devices are constructed with a transparent window to provide a view on the actual flow in the system (figure 3-5).

3.5 Sediment mixture for standardized testing

Settling properties of the facilities are to be tested in a standardized way. As mentioned, sediment particle sizes $< 60 \mu\text{m}$ have the most contaminants attached and are therefore the focus of this research. Particle shape and specific density are other important factors for a standardized suspended sediment mixture. Organic particles and clay particles have disadvantages such as electrical loading, irregular shapes, coagulation; these properties make it impossible to produce and reproduce a suspended sediment mix with constant properties. To allow for comparability of the tests we have to make use of silica particles. With these preconditions a small range of suitable, regulated and controlled substances are available on the market, such as Millisil®W4. This silica material has an evenly distributed, constant particle size distribution with a specific density of 2650 kg/m^3 (table 3-3) and within the range of $5 - 150 \mu\text{m}$ (see figure 3-3). Vortex separators are most effective where the materials to be removed from runoff are able to be settled, they cannot remove small diameter solids (e.g. $< 115 \mu\text{m}$) with poor settleability, emulsions or dissolved pollutants [Woods-Ballard et al., 2015]. The fractions $1-63 \mu\text{m}$, with the water temperature in the lab between 15 and $20 \text{ }^\circ\text{C}$ will result in settling velocities ranging from 0.01 up to 13 m/h based on stokes law.

Table 3-3 characteristics Millisil W4 [Quarzwerkegruppe Frechen, 2009]

Density	2,65 g/ml
pH	7
Specific surface	1300 cm ² /g
Chemical Analysis (weight.-%)	
SiO ₂	99
Al ₂ O ₃	0,3
Fe ₂ O ₃	0,05
CaO + MgO	0,1
Na ₂ O + K ₂ O	0,2

Figure 3-3 shows the particle size distribution of Millisil®W4 as compared to the observed particle size distribution in urban storm water in the Netherlands and distributions observed elsewhere.

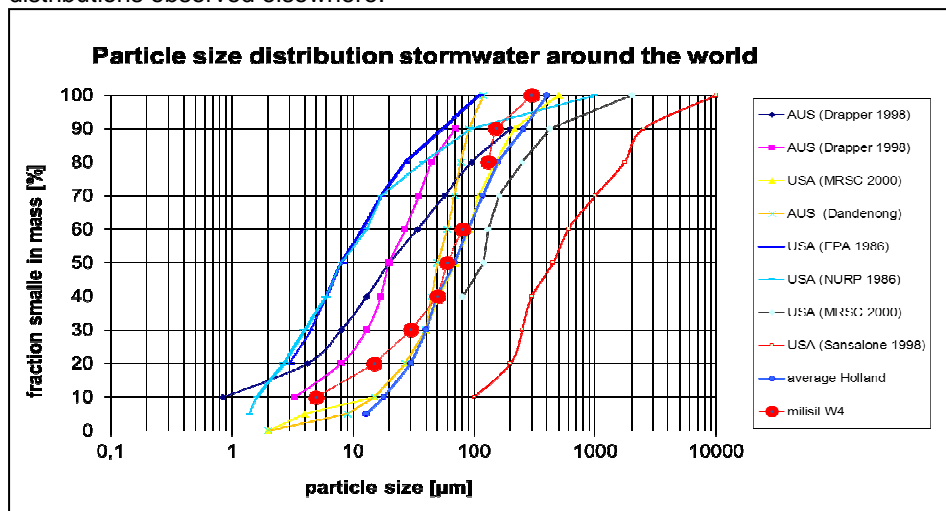


Figure 3-3 Cumulative particle size distribution of Millisil®W4 as compared to the observed average particle size distribution in urban storm water in the Netherlands and in storm water in the USA and Australia. [Boogaard et al., 2014].

Suspended sediment concentration and particle size distribution in storm water depends on location, type of connected paved area and specific activities on the site as well as on rainfall / runoff intensity. Storm water monitored in the Netherlands show an average of 29.5 mg/l (ranging from 1.5 to 950 mg/l in 1236 observations) in residential areas [Boogaard et al., 2014, Langeveld et al., 2012]. For the test a SS concentration of 50 mg/l is chosen which is the 90% percentile value 50 mg/l of the Dutch stormwater database and close to international values (chapter 2). For example, 48 mg/l is the median value of TSS from the NSQD database that collected samples over nearly ten year period from more than 200 municipalities throughout the USA [Pitt et al., 2004].

3.6 Sampling

Each facility was tested over a range of hydraulic loads. Exactly every 5 minutes a grab sample of 1 liter was taken at both inflow and outflow point by 2 persons for at least half an hour, producing at least 12 samples. Each sample was stirred to create and maintain a homogeneous mixture to be tested with the particle counter. The particle counter measured the absolute amount of particles for every particle size (with intervals of 0.77 μm) between 0 and 100 μm .

3.7 Settling velocity and removal efficiency

The settling velocity v_s depends on the density, the diameter and the shape of the particle. The settling velocity for spherical particles in water can be computed with the well-known Stokes' law:

$$[1] \quad v_s = \frac{(\rho_p - \rho_w) g d^2}{18 \mu} \quad [\text{Stokes, 1851}]$$

where v_s is the settling velocity, ρ is density (the subscripts p and w indicate particle and water respectively), g is the acceleration due to gravity and μ is the dynamic viscosity of the fluid. Stokes' law applies for spherical sized sand particles smaller than 100 μm , where the Reynolds number of the particle is less than 0.1, which is the case in these experiments.

In fluid mechanics, the Reynolds number (Re) is a dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations:

$$[2] \quad v_s = \frac{(\rho v L)}{\mu} \quad [\text{Reynolds, 1883}]$$

where:

- v is the mean velocity of the object relative to the fluid (m/s)
- L is a characteristic linear dimension, (travelled length of the fluid; hydraulic diameter when dealing with river systems) (m)
- μ is the dynamic viscosity of the fluid (Pa•s or N•s/m² or kg/(m•s))
- ν is the kinematic viscosity (m²/s)
- ρ is the density of the fluid (kg/m³).

The theoretical sedimentation efficiency of a sedimentation device for a specific particle can be estimated with Hazen's formula:

$$[3] \quad \eta = \frac{v_s}{(Q/A)} \quad [\text{Hazen, 1904}]$$

With:

η the sedimentation efficiency; v_s the settling velocity and Q/A the surface load with Q the hydraulic load and A is the sedimentation surface.

The performance of water quality treatment devices has traditionally been measured in terms of the removal efficiency for a given determinant of interest (e.g. suspended solids SS of a particular particle size range). This is assessed by determining the proportion of the influent concentration of the determinant removed by the device as follows:

$$[4] \quad \text{Removal efficiency [\%]} = \frac{[\text{Influent SS} - \text{Effluent SS}]}{[\text{Influent SS}]} \times 100$$

3.8 Measurement uncertainties and verification

The accuracy of the results obtained in the test procedure is determined by the accuracy of the equipment, as specified in Table 3-2.

- Sampling uncertainty. This uncertainty is due to the potential temporal and spatial variability of the suspended sediment concentration at the sampling location being not representative for the 'true' concentration. Every 5 minute a manual grab sample is taken simultaneously from influent and effluent until a constant performance is observed.
- Storage uncertainty. The samples are temporarily stored during the test until the particle counter was available for a maximum of 2 days. As the used aggregate is stable and inert, this storage does not affect the results.
- The discharge of the (calibrated) pump has been verified with timing the filling of the basin (900 dm³).
- The volume of sediment calculated by the particle counter is verified by Imhoff cones. Imhoff cones are used to determine the volume of the particles in a sample and are compared with the estimation of volume of particles of the particle counter. The inflow of suspended sediment is checked by comparing the amount of particles per size at different influent samples (figure 3-6). The homogeneity of the contents of the Millisil®W4 bags has been checked. Different samples from a bag showed slightly different numbers of particles at specific particle sizes. The bags are mixed before using the sediment.
- No sedimentation has been recorded by visual inspection in the inflow pipe. The tests are repeated 3 times with the same hydraulic loading, and moving averaging (over 5 steps of 0.77 µm intervals) is used to smooth every removal efficiency curve (figure 3-7).
- Data processing. All data is stored in a database and all actions have been recorded and stored in a blog.

3.9 Tested facilities

Sedimentation devices available on the Netherlands' market show much similarity in general. They consist of an inlet and an outlet; a compartment at the bottom of the facility is used as a trap for storing the solids that have settled.

Four different sedimentation devices have been tested, using the test method discussed above.

The four selected devices have different separation techniques:

1. Sedimentation pipe: allows particles to drop through an open grid in lower zone of a pipe.
2. Lamella filter: designed to remove particulates from liquids with inclined plates that reduce the hydraulic surface load.
3. Cyclone separation: cyclonic separation is a method of removing particulates from water, by establishing a high speed rotating flow within a cylindrical or conical container called a cyclone.
4. Sedimentation filter: separation of suspended solids with a sedimentation area and the use of a filter media.

The characteristics of these facilities are stated in Table 3-4. Note that the sedimentation facilities have different volumes and sizes, the largest being the 'Sedipipe' with a length of 24 meters and diameter of 600 mm.

Facilities number 3 (cyclone) and 4 (Sedimentation filter) have more or less the same dimensions (cylinder shape with inner diameter of 0.995 meter) and are in general representative for many of the installed sedimentation devices in practice serving a connected area between 0.5 and 2 ha. The tested discharge for these sedimentation devices (cyclone and filter) was up to 15 l/s (connected surface of 0.5 ha and stormwater event of 10 mm/h results in 50 m³/h and 13.89 l/s).

Table 3-4 Properties of the four tested sedimentation devices for local treatment of storm water.

Treatment process	Product	description of Product	Storage volume	Sedimentation surface	Diameter shaft	Height, length, width.
			m ³	m ²	m	m
Sedimentation pipe	sedippe	Pipe between 2 shafts. Grid in pipe to create sedimentation chamber	10.71	7.57	1	5, 24, 0.6
lamella filter	M Pack	Rectangular basin with lamella	2.75	1.83 without lamella, with lamella 43.3 m ²	-	1.5,3,0.61
cyclone filter	Certaro	A cylinder for cyclonic separation	1.40	2.27 (bottom and 2 sedimentation rings)	0.995	H=1.8
Sedimentation filter	Hydro 400	Cylinder with filter cartridges and sedimentation chamber	1.56	0.78 (bottom without filter substrate surface)	0.995	H=2

Construction drawings, pictures and some further footage of the tests of each of the four facilities are found in Appendix 8.



Figure 3-4 Pictures of the four products: a) Lamella filter, b) Sedipipe, c) Certo and d) Hydro400 (detailed info can be found in appendix 8).

3.10 Results

Flow visualization

First the flow is visualized in the transparent models by adding potassium permanganate as a tracer. The visualization at the lamella filter showed that due to the connection bars (that hold the lamella at a certain distance) the flow is in practice limited to approximately 45% (4/9) or less of the total cross section area (see colored flow in figure 3-5).

For Sedipipe we can see a preferential flow above the grid and a lower velocity under the grid where sedimentation can take place. Results can be seen on Youtube.⁴

⁴ Visual results of tracer experiments can be seen on the following urls:

[Tracertest Lamella filters;](https://www.youtube.com/watch?v=uRkL0EZmqyc&list=UUdrVBHnrWAhkw4bpxzN4Ytw)

<https://www.youtube.com/watch?v=uRkL0EZmqyc&list=UUdrVBHnrWAhkw4bpxzN4Ytw> and [tracertest Sedipipe :](https://www.youtube.com/watch?v=i1GzDdTQdnY&index=3&list=UUdrVBHnrWAhkw4bpxzN4Ytw)

<https://www.youtube.com/watch?v=i1GzDdTQdnY&index=3&list=UUdrVBHnrWAhkw4bpxzN4Ytw>



Figure 3-5 Visualization of preferential flow in lamella separator (divided in 9 parts where the upper 4 parts have no visual current due to the construction bars of the lamella at the dotted lines), Sedipipe (right) where the flow above the grid is dominant.

3.11 Observed removal efficiency by particle size

In figure 3-6 the amount of particles of the influent and effluent is given for Certaro at 5 l/s as an example of one test. From the amount of particles the removal efficiency is calculated at every particle size. For the presentation raw data is used: the less stable removal efficiency for particles $> 50 \mu\text{m}$ can be observed due to the fact that the particles in each sample is limited. A moving average of 5 steps is used to extrapolate the removal efficiency for higher particle fractions for this and the other tests.

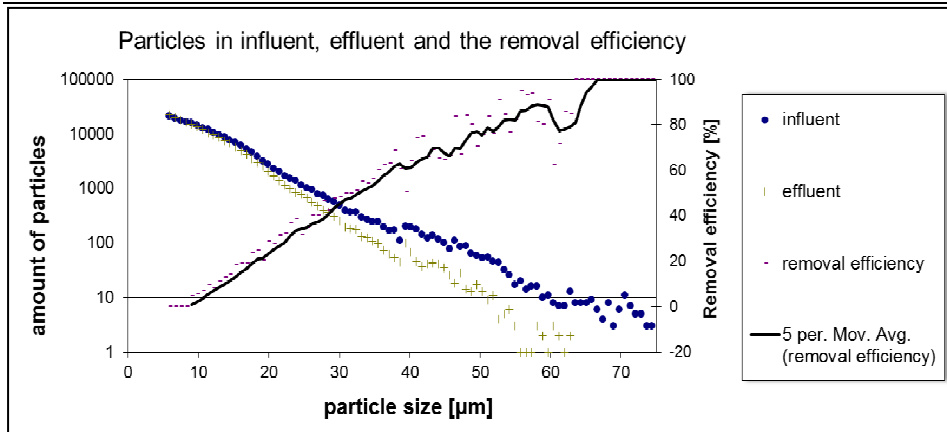


Figure 3-6 Amount of particles of the influent and effluent and removal efficiency of the Certaro sedimentation device at 5 l/s (raw data).

The observed removal efficiencies of Sedipipe for several flow rates are given in figure 3-8. The data demonstrate the expected decreasing removal efficiency with increasing flow rate, as determined at all four sedimentation devices. Also the noise in the data increases as the flow rate increases. This is mainly due to the fact that the flow pattern becomes more turbulent and the samples taken show more variable results, in particular for larger particles.

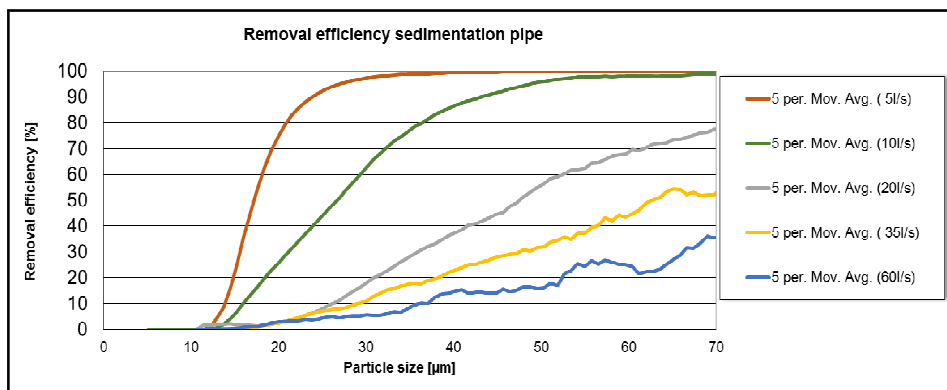


Figure 3-7 Removal efficiency of the SediPipe XL 600/24 (moving average 5 steps) at inflow of 5, 10, 20, 35 and 60 l/s (leading to surface loads of 1.25 to 15 m/h).

The removal efficiency of the four products varies with the characteristics of the device such as volume, flow velocity and sedimentation surface. Given a flow rate of 10 l/s (figure 3-9), even with a large facility like the Sedipipe small particle sizes up to 25 μm will not be removed by more than 50%. Particles over 60 μm are trapped with removal efficiency higher than 80% only by the larger sedimentation devices Sedipipe and the lamella filter.

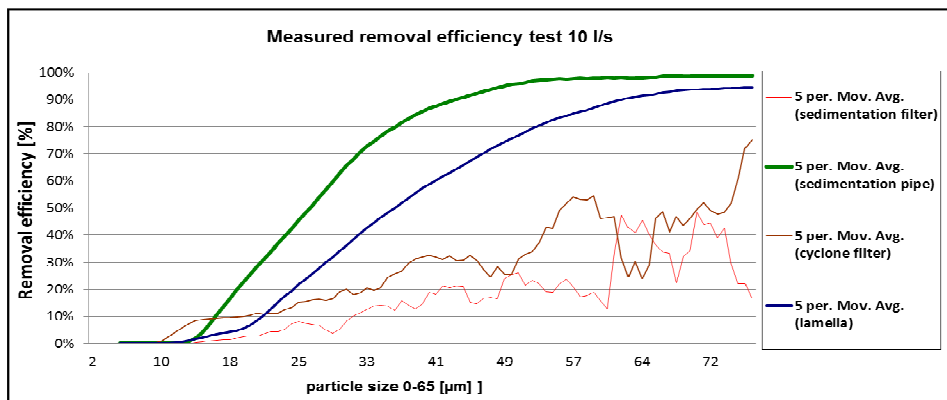


Figure 3-8 Removal efficiency of suspended sediments (Millisil®W4) observed in four sedimentation devices for storm water treatment at a flow rate of 10 l/s (5 steps moving average of observed efficiency).

The observed removal rates of the facilities with a storage volume in the order of 1.5 m³ (Certaro and Hydro400) drop to low levels at a flow rate of 10 l/s (see figure 3-9). For sediments < 60 μm , which contain the highest amount of pollutants, the removal efficiency is less than 50%.

3.12 Sedimentation efficiency

Figure 3-10 shows from all the performed tests the removal efficiency plotted against the settling velocity divided by the surface load S_o ($S_o=Q/A$). Presenting the removal ratio curves of the different settlement devices in this way should be comparable and be close to the red theoretical curve of Hazen's formula for spherical silica particles in water of 18°C. The surface load in some of these devices is hard to estimate due to the assessment of the effective sedimentation surface A.

The lamella settler for example, has a theoretical surface load of 0.83 m/h at 10 l/s when all the surface of the lamellas is taken into account. However, from earlier research [Boogaard et al., 2010] and tracer testing (figure 3-5) it could be observed that due to the construction by far not all of the surface is contributing to the removal efficiency.

When the minimum factor of 4/9 (45%) is taken into account as an effective sedimentation surface the curves fits more closely to the theoretically expected sedimentation. The best fit is achieved when 33% effective sedimentation surface is applied (see figure 3-9).

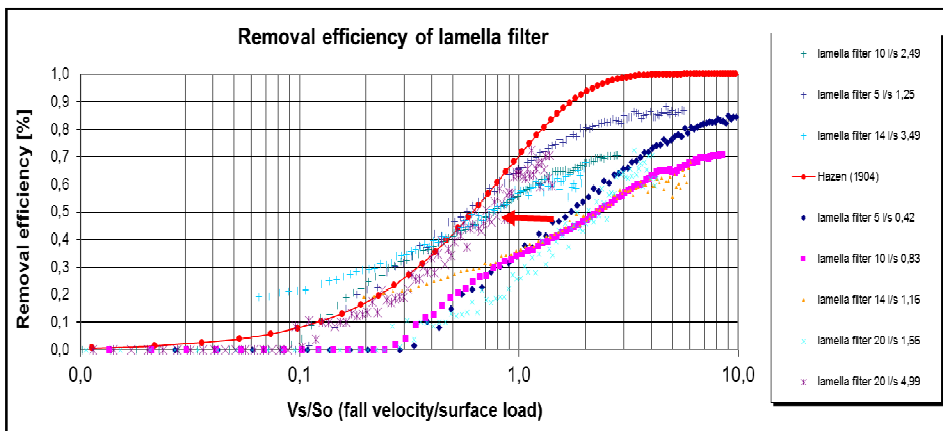


Figure 3-9 removal efficiency of lamella filter tests related to the surface load against the theory of Hazen (red curve). In the legend the type of device is given with the discharge (l/s) and the surface load (m/h).

In figure 3-10 where the removal efficiency of all tests are related to v_s/S_o , the curves are close to theory of Hazen (red curve) but show individual deviances that can be caused by earlier discussed inaccuracy and actual surface of the devices that is contributing to sedimentation. More detailed tests are advised to get detailed insight of the individual devices to optimize the individual performance and further development of knowledge on the removal efficiency of fine particles.

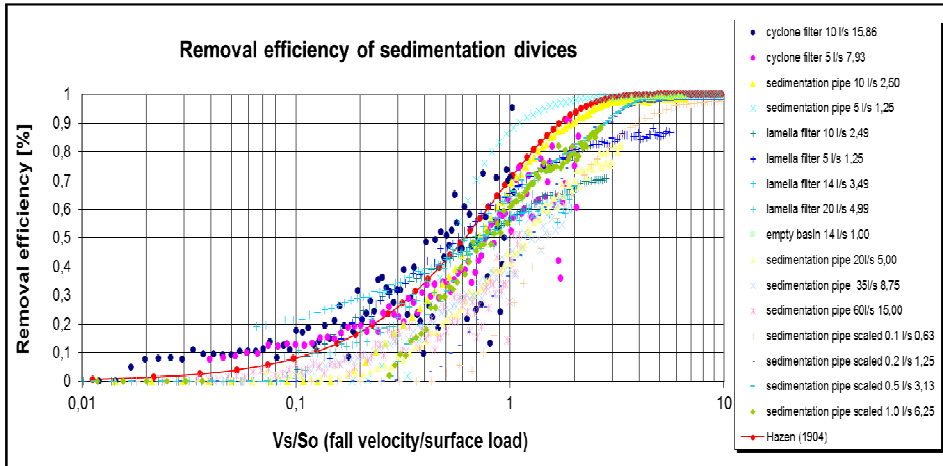


Figure 3-10 Total removal efficiency of all tests related to the surface load against the theory of Hazen (red curve). In the legend the type of device is given with the discharge (l/s) and the surface load (m/h).

The bandwidth of the observed curves can be used for an indication of the performance of sedimentation devices and to design their hydraulic loading. When a suspended sediment removal efficiency of 50% is needed, the surface load V_s/S_o should be in the order of 0.7.

3.13 Discussion

The Millisil®W4 sediment used in the tests shows a representative particle size distribution for suspended sediment found in the Dutch storm water. But although the particle size distribution shows a decent match it should be taken into consideration that the particle shape, specific density and coagulation properties are different. In practice, part of the suspended particles will be organic material or clay minerals, which would make it harder to make these sediments settle. As a result, our tests could overestimate the performance of such sedimentation SUDS in practice. On the other hand, due to the fact that the silica particles of Millisil do not coagulate, the settling properties of the four tested facilities could be underestimated by the testing procedure we have used.

The experiments show for the sedimentation devices with a sedimentation surface in the order of 1-2 m² flow rates should be minimized up to 10 l/s in order to capture more than 50% of fine particles up to 60 µm. This result is similar to the literature on suspended solids (paragraph 2.4) and the description in the SUDS manual; 'Vortex separators cannot remove small diameter solids (eg < 115µm) with poor settleability, emulsions or dissolved pollutants' [Woods-Ballard et al., 2015].

The frequency of occurrence of a 10 l/s flow rate on a total catchment area of 0.5-2 ha (as a typical connected total catchment size) will be more than once per year in the Netherlands, while the maintenance frequency of these devices is in most cases once every 2 years (or not at all).

This means that remobilization and a flush out of collected suspended solids is likely to take place quite frequently, with hardly any effective sediment removal in practice. For this reason, a by-pass facility is strongly recommended.

Most of the sedimentation facilities in The Netherlands are implemented to achieve Dutch surface water quality standards (Maximum Allowable Concentration, or 'MAC'). To achieve these MAC values, the removal efficiencies for copper, zinc and nitrogen should be in the order of 80%, 60% and 65% respectively when only 65%, 55% and 40% percent of copper, zinc and nitrogen is bound to particles (Boogaard et al., 2014). So, even with capturing all the suspended sediment particles the required reduction objectives cannot be met. With the conclusions of this research that the smallest particles with the most pollutants are not captured and the knowledge that most of these facilities are not protected from hydraulic overloading it is not likely that the required removal efficiencies to meet MAC standards will be achieved by the application of the sedimentation devices we have investigated.

The experiments in this research can be reproduced in other laboratories with the proposed test procedure. Some scaled test with gross material on other facilities are available but cannot be compared with the results of these tests. Full scale testing with silica is strongly advised for detailed insight on the removal efficiency of small particles and the ability to compare different sedimentation devices on the market.

3.14 Conclusions and recommendations

Four facilities have been tested in a standardized test procedure on their suspended sediments removal efficiency at different discharges and for a range of particle sizes. As expected the research data demonstrate a decreasing removal efficiency of the facilities with an increasing flow rate.

The observed removal rates for small sized sediments (up to 60 μm) of the facilities with a storage volume in the order of 1,5 m^3 and settling surface around 1 m^2 drop to levels below 50 % at a flow rate of 10 l/s and higher. Given a certain flow rate of 10 l/s, small particle sizes up till 20 μm will not be removed by more than 10%.

Particles over 60 μm are trapped with higher removal efficiency but these particles contain less adsorbed pollutants.

Observed removal efficiencies were related to the surface load of the devices and show coherence. Large deviations from the theoretical removal efficiency according to Hazen (1904) could be explained by the constructive properties of the devices.

The tracer testing for example was effective in finding the effective sedimentation surface of lamella to fit the theory of Hazen. From the relation between removal efficiency and v_s/S_o can be derived that, when a removal efficiency of 50% is needed, the settle velocity divided by the surface load should be in the order of 0.7.

From this relation a maximum design flow for a device can be determined. Since most of these facilities have no protection from hydraulic overloading, a bypass is strongly recommend to prevent flush-out of earlier collected sediment at high discharges.

3.15 Recommendations

The standard test results provide insight in the efficiency of sedimentation devices under laboratory circumstances. Due to differences between field and laboratory environment, additional measurements should take place in field studies to determine the efficiency in practice.

Additional research is needed regarding the true characteristics of suspended sediment in stormwater. The composition, size and shape of the particles, their coagulating properties, distribution of the settling velocities and the adsorptive binding of pollutants are all relevant to the effectiveness of treatment facilities, Removal efficiencies claimed by manufacturers without this information should be taken with skepticism.

Other sedimentation devices can now be tested in the same procedure and under similar circumstances for an adequate comparison their performance. The testing method as presented has proven to be effective and can be a good starting point for an internationally standardized testing procedure.

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4 Comparing Results of a New Permeable Pavement Infiltration Test Method with International Requirements

This chapter is primarily based on:

- Boogaard F., Lucke T., Beecham S., Effect of Age of Permeable Pavements on their Infiltration Function, clean soil air water 2013.
- Lucke T., Boogaard F., van de Ven F., Evaluation of a new experimental test procedure to more accurately determine the surface infiltration rate of permeable pavement systems, 15 March 2014, <http://www.tandfonline.com/doi/full/10.1080/21650020.2014.893200>
- Boogaard F., Lucke T., Giesen N., Ven F., Evaluating the Infiltration Performance of 10 Dutch Permeable Pavements Using a New Full-scale Infiltration Testing Method, Journal Water 2014.



4.1 Introduction

Permeable (or porous) pavements are a type of sustainable urban drainage system (SUDS) treatment device that are used around the world to infiltrate and treat stormwater runoff. Permeable pavements are specifically designed to promote the infiltration of stormwater through the paving and basecourses where it is filtered through the various layers (Figure 4-1). This can significantly reduce runoff volumes and discharge rates from paved surfaces [Pratt et al., 1995; Hunt et al., 2002; Fletcher et al., 2005; Bean et al., 2004; Collins et al., 2008] which can potentially minimize the risk of downstream flooding. Permeable pavements also provide considerable water quality improvements by treating and trapping stormwater pollutants [Pratt et al., 1995; Dierkes et al., 2002; Siriwardene et al., 2007, Clary et al., 2012], permeable pavements show a removal efficiency of suspended solids (depending on structure and local circumstances) from 60 to 90% [Wilson et al 2007].

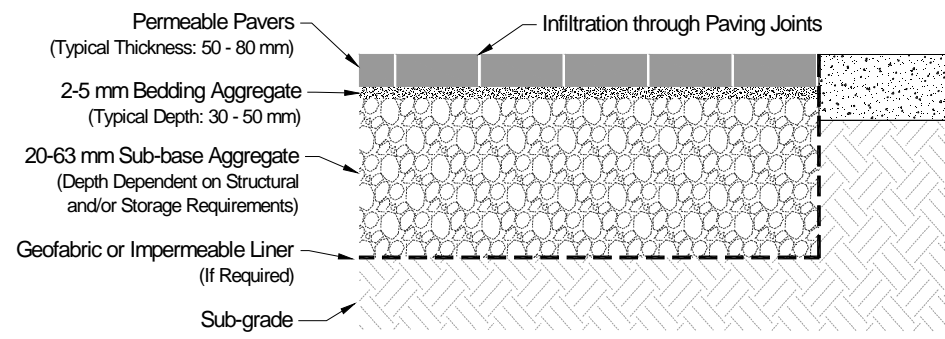


Figure 4-1 Typical Permeable Pavement Structure

Several types of permeable pavement are used around the world. In the USA for example, 35 porous pavement are included in the BMP Database. Of these, 11 are modular block (including various types interlocking pavers and 3 modular turf types), 6 are pervious concrete, 1 is porous aggregate, 8 are porous asphalt, 3 are porous turf and 6 are permeable friction course applications [Clary et al., 2012]. There are several types of permeable pavements typically used in Europe including concrete pavers with wide joints or apertures (Figure 4-2a), and porous concrete pavers, either with or without wide joints (Figure 4-2b). These are usually

manufactured as blocks and are generally referred to as permeable concrete interlocking pavers (PCIP). Concrete and plastic grid pavers (CGP and PGP) have more open void spaces to promote infiltration. Stormwater is able to infiltrate through the large gaps in these pavers which are usually filled with gravel, or topsoil planted with grass (Figure 4-2c).



Figure 4-2(a) Impermeable Concrete PICP; (b) Porous Concrete PICPs; (c) Grass-filled PICPs.

There is a perception that permeable pavements that are used as source control devices, and designed to infiltrate runoff, will tend to clog quickly and result in high maintenance and replacement costs. Clogging is a result of fines, organic matter and traffic-caused abraded particles, blocking the gaps and surfaces of permeable pavement systems due to physical, biological and chemical processes [Siriwardene et al., 2007]. This clogging decreases the porosity/permeability of the paving surface and hence the infiltration rate of a system [Borgwardt, 2006; Gerrits and James, 2002; Yong and Deletic, 2012].

It is important for stormwater managers to be able to determine when the level of clogging has reached an unacceptable level so that they can schedule maintenance or replacement activities as required. In order to assess the reduction in infiltration capacity that occurs in permeable pavements over time due to clogging, a variety of infiltration test procedures have been utilised in the past. However, the results have generally been inconsistent, and have shown a large variation in the range of infiltration rates measured [Dierkes et al., 2002; Colins et al., 2008; Pezzaniti et al., 2009; Lucke and Beecham, 2011, Beeldens and Herrier 2006; Fassman and Blackbourn, 2010]. The number of global permeable pavement installations increases, and could benefit from a more reliable and more accurate method to measure surface infiltration rates is needed [Li et al., 2013].

4.2 Current methods of infiltration rate testing

A number of previous permeable pavement infiltration studies [Gerrit and James, 2002; Bean et al., 2004; Fassman and Blackbourne, 2010; Lucke and Beecham, 2011] have been based on results using a modified version of either the single or double-ring infiltrometer test (ASTM D3385-09). In these tests, rings are sealed to the pavement surface and filled with water. The time taken for the water to infiltrate through the permeable surface area is used to estimate an average infiltration rate (usually in mm/h) for the test location. Both the constant head and the falling head methods can be utilized in these testing procedures. Double-ring infiltrometer tests (DRIT) have generally been the preferred method in the past. This is because the outer ring is thought to reduce measurement errors and prevent lateral flow from occurring beneath the rings. However, on pavements where the infiltration rate is so high that it is difficult to supply enough water to both rings, the single ring Surface Infiltration Test [Bean et al., 2004] has been used (Figure 4-3c).



Figure 4-3 Modified Ring Infiltrimeters used for Permeable Pavement Testing (a) DRIT (Fassman & Blackbourn, 2010); (b) Square, Double Ring (Lucke & Beecham, 2011); (c) Single Ring Surface Inundation Test (Bean et al., 2004).

Three variations of ring infiltrometers used in past permeable pavement studies are shown in Figure 3. Other permeable pavement infiltration research has been undertaken using specially fabricated rainfall simulation infiltrometers [Dierkes et al., 2002; Borgwardt, 2006]. A new Standard Test Method for Surface Infiltration Rate of Permeable Unit pavement Systems (ASTM C1781M-13) has been published by ATSM. However, to date there have been no studies published using this method. The permeable pavement infiltration testing methods described above are based on the infiltration rate through a very small area of the pavement that is used to

represent the total pavement area infiltration. For example, the area of the inner ring of the ASTM D3385-09 DRIT test is 0.0707 m². The minimum area recommended by the Dutch guidelines [Kiwa, 2014] is even smaller, at only 0.01 m². Using such small areas for testing could potentially lead to erroneous results as a number of studies have demonstrated a high degree of spatial variability between different infiltration measurements undertaken on the same pavement installation [Van Dam & Van de Ven, 1984; Borgwardt, 2006; Bean et al., 2004; Lucke & Beecham, 2011]. In the Netherlands several infiltrometer tests have been performed on one location within 2 m² from each other leading to a high variation of results (fig 4-4). Dutch results from 4 infiltrometer tests taken within 10 m² on one location in ‘Meijel’ showed a variation of 34 to 596 mm/h (and 60 and 151 mm/h in between). In Heerhugowaard only 2 tests are taken showing an infiltration rate of 825 and 3511 mm/h.

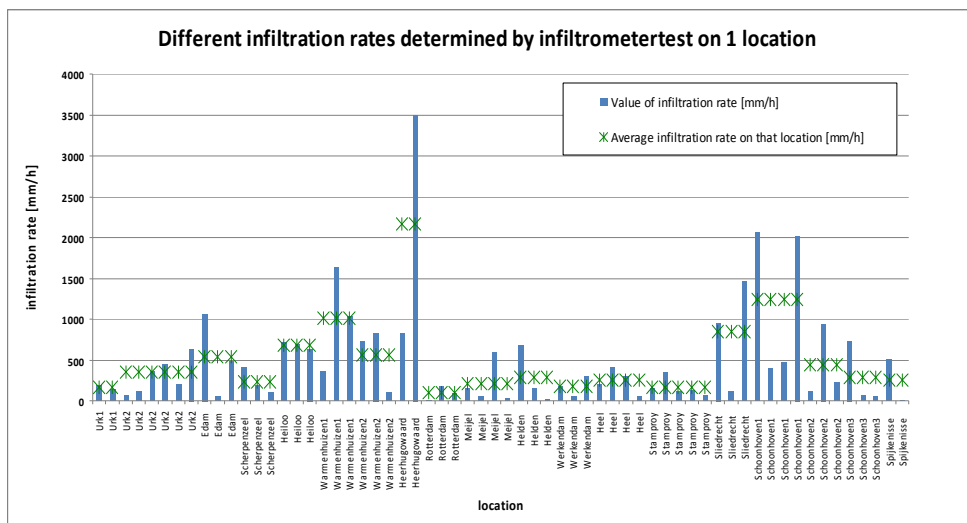


Figure 4-4 variation of infiltration rates measured by infiltrometer test on several locations with a minimum of 3 tests per location.

It was hypothesized that more accurate infiltration results may be produced by significantly increasing the area of the pavement surface being tested. By inundating a much larger area of pavement during testing, it was anticipated that

any spatial variations in infiltration capacity would be averaged-out and this would produce more reliable infiltration data.

In order to test this hypothesis, this study developed and trialed a new full-scale infiltration testing method. Using the new method, it was possible to test the infiltration capacity of large sections of existing permeable pavements at one time. This chapter describes the new experimental test procedure developed in the Netherlands to more accurately determine the surface infiltration rate of existing permeable pavement installations. The results from 8 different test locations in the Netherlands using the new infiltration testing method are presented and compared to national guideline requirements.

4.3 Materials and methods

In order to evaluate the performance of the new full-scale infiltration testing method, the method was first trialed on an existing permeable pavement street installation that had been in service for over seven years in Utrecht in the Netherlands. The results of the initial testing were successful [Lucke et al., 2014] and showed that the new method could be used to accurately measure infiltration rates of permeable pavements in-situ. The new testing method was therefore used on the 8 existing pavements in 5 different municipalities evaluated in this study.

The initial study identified a number of issues that need to be considered when using the new test method. It also highlighted potential improvements that could be incorporated to optimize the new infiltration testing method. These included:

1. Selection and isolation of pavement section for testing;
2. Various methods of containing the water within the pavement test section;
3. Water supply alternatives; and
4. Accurate determination of surface infiltration rate.

The different issues and options are described in the next sections. Many of the identified improvements were incorporated into the testing methodology in the current study for the 10 test locations in the Netherlands.

4.3.1 Test Area Selection

To enable an accurate estimation of the average surface infiltration rate using the new test method, a permeable pavement area of approximately 50m² was recommended for all tests. However, achieving this was dependent on site practicalities such as pavement width, length, slope and cross-fall, location of

drainage gullies, parked cars and resident access requirements. It should be noted that in order to undertake the testing, it was necessary to close the section of pavement for a number of hours. It is therefore recommended that local Dutch council permission be obtained before any testing is conducted.

4.3.2 Water Containment

To accurately define the infiltration testing area, and to contain the water used to infiltrate the pavement, it was necessary to construct small, temporary dams at the ends of the pavement test sections. The roadway kerb and gutter system retained the water on the sides of the pavement test sections. A number of dam variations were trialled at the 8 different test locations (Figure 4-5). These included:

1. Soil core wrapped in plastic sheeting
2. Sand core wrapped in geotextile
3. Soil- or sand-filled plastic bags
4. Impermeable barriers inserted into paving gaps; and
5. Use of existing traffic calming devices (speed-humps)



Figure 4-5 Various Dam Variations Used at the Different Test Locations (a) Impermeable barriers; (b) Plastic wrapped soil core; (c) Soil-filled plastic bags.

Recommendations

Where possible, one of the preferred methods of containing the water within the test site is to choose a section with an existing raised traffic calming device (speed hump) at one (or both) ends. This saves considerable setting-up time and also minimizes leakage problems during testing. It is also advisable to select the section of pavement with the least number of existing drainage gullies within the pavement surface or gutter. Drainage gullies need to be properly sealed to prevent water from leaking from the test area and entering the underground stormwater drainage system. This can be both difficult to accomplish and time consuming. Of all the methods trialled to create temporary dams, the soil-filled were found to be the most effective.

This was due to their ability to properly seal the test sections, the rapid filling and emptying characteristics of the bags, the ability to reuse the material, and the ease of construction by hand without the need for heavy machinery.

4.3.3 Water Supply

The new infiltration test requires large volumes of water to be discharged onto the test paving section in order to inundate the pavement surface. Depending on the site location, a number of different water supply options were trialled in this study, including transporting water directly to site with water trucks (Figure 4-6a) or water tanks (Figure 4-6b), and pumping water directly from nearby canals (Figure 4-6c).



Figure 4-6(a) Water truck supply; (b) Water tank supply; (c) Pumping from canal.

After the pavement test area had been selected and sealed with temporary dams, the pavement area was inundated with water to the maximum allowable water level possible that would not cause overtopping of the roadway kerb and gutter system. The maximum inundation depth was dependent on the type of construction. However, this was generally between 50 and 90 mm from the lowest point in the pavement to the top of the gutter. Due to the different levels of the pavement surface, this meant that the depth of water in the inundated test section was dependent on the measurement location, with the lowest pavement elevation generally having the highest inundation water levels.

Recommendations

Of the three water supply methods trialled, it was found that pumping the water from a nearby canal was the easiest option, where this option was available. This method offered total flexibility with types of testing, and also offered an unlimited availability of water. It is recommended to include a flowmeter in the water supply line to allow accurate monitoring of water inflow rates. Water trucks were the second easiest option. However, these had the disadvantages of being expensive and difficult to arrange, difficult to manoeuvre and park, and they generally had only limited water supply capacity. When a water truck must be used, it is advisable to ensure that the outlet is fitted with a flowmeter to measure flowrate into the test pavement area.

4.3.4 Determining Pavement Infiltration Rates

Pressure transducers were used in the study as the primary method of measuring and recording the reduction in water levels over time at various locations on the pavement surface. Two wireless, self-logging, pressure transducers (Minidiver: <http://www.slb.com>, described in chapter 3 and appendix 2) were installed at the lowest points of each test pavement area (Figure 4-6a). The transducers continuously monitored the static water pressures at those locations and transmitted this information to a laptop computer. The static water pressure was then converted to an appropriate depth of water above the pavement. This process produced accurate and reliable data over the duration of the tests. It also enabled visual representation of the pavement infiltration process.

Three different measurement methods (Figure 4-7) were used in conjunction with the pressure transducers in order to calibrate and verify the transducer readings.

The three methods were:

- Hand Measurements
- Calibrated Underwater Camera
- Time-Lapse Photography

These three methods are explained in more detail below.



Figure 4-7(a) Minidiver installed at lowest point of pavement; (b) Hand measurement point; (c) Underwater camera set-up; (d) Underwater camera view.

Hand Measurements

Water level measurements were taken using a simple 300 mm hand ruler (Figure 4-7b) at strategic locations on the pavement surface throughout the duration of the testing. These measurements were used to verify the functionality and accuracy of the self-logging pressure transducers as described above. Photographs of each hand measurement were also taken for documentation and verification purposes.

Calibrated Underwater Camera

A high definition video camera was also used at a number of strategic locations to record the decrease in pavement water levels over the duration of the tests. The camera was placed inside a waterproof, calibrated, transparent box so that it could capture the entire infiltration process (Figure 4-7c). This system allowed real-time monitoring of the entire infiltration process and also facilitated precise verification of the pressure transducer measurements.

Time-Lapse Photography

Time-lapse photography was used at each test location to record all research activities and to enable verification of the pressure transducer and hand measurements. The time-lapse photographs were also used to compile an accelerated video of the entire pavement testing.

Recommendations

While pressure transducers and loggers provide an abundance of data and allow informative and attractive graphs, much care needs to be taken to ensure that the pressure transducers readings are verified and accurate. Pressure transducers can be unreliable and inaccurate. They have also been shown to be sensitive to external influences such as wind effects and changes in atmospheric pressures (Lucke et al., 2014). Therefore, it is highly recommended that transducer readings are calibrated and verified using at least one of the other methods described above.

4.3.5 Study Test Locations

The infiltration rates of eight existing permeable pavements in the Netherlands were tested in the current study. The locations and details of the pavements are listed in Table 4-1. All test locations are located in residential areas (30 km/h zones). No maintenance other than street sweeping has taken place at the locations. All testing has taken place in dry periods.

Table 4-1 Permeable Pavement Locations Tested in the Netherlands.

Test Location	Streetname	Type of pavement	Year of Construction	Test area (m ²)	Test Date
Zwolle 1	Pieterzeemanlaan	Porous Concrete PICPs	2006	44.2	15/11/2013
Zwolle 2	Pieterzeemanlaan	Porous Concrete PICPs	2006	39.9	15/11/2013
Dussen 1	Groot Zuideveld	Impermeable Concrete PICP	2006	59.5	23/10/2013
Dussen 2	Groot Zuideveld	Impermeable Concrete PICP	2006	69.7	23/10/2013
Effen 1	Baanakker	Impermeable Concrete PICP	2006	29.4	30/10/2013
Utrecht 1	Nijeveldsingel	Impermeable Concrete PICP	2006	51.9	28/11/2012
Utrecht 2	Brasemstraat	Impermeable Concrete PICP	2006	60.0	13/06/2013
Delft 1	Drukkerijlaan	Impermeable Concrete PICP	2005	74.0	19/06/2013

4.3.6 Calculating Infiltration Rates

All eight test pavements (Table 4-1) were sealed, inundated and monitored as described above. The pressure transducer readings were then plotted against time to generate precise infiltration curves for each of the test sites (Figure 4-8). Simple linear regression analysis was used to generate lines of best fit for the transducer readings from each site. The equations of the linear regression lines were then used to calculate the average infiltration rate in mm/h for each test site (Table 4-2).

4.4 Results

The surface infiltration rates recorded for each of 8 test pavements using the new experimental test procedure are shown in Figure 4-8.

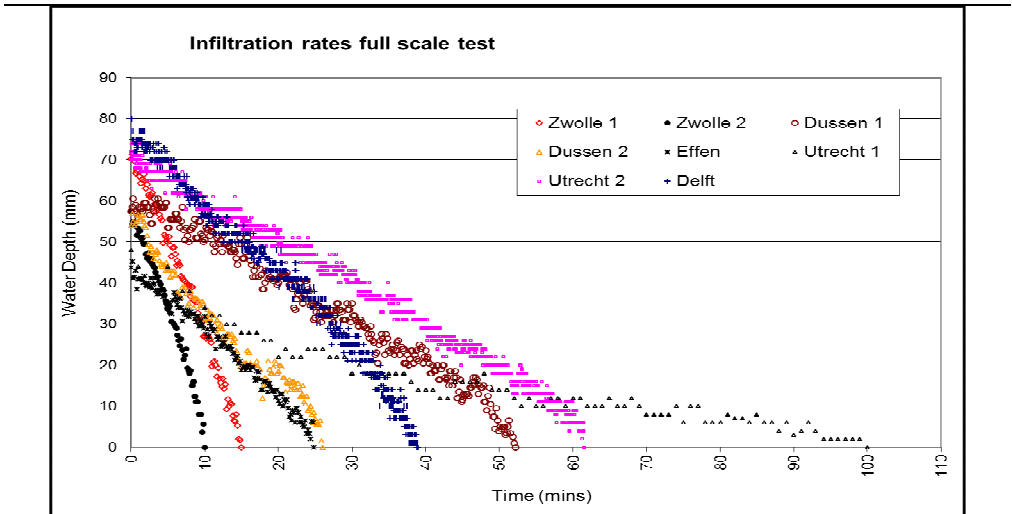


Figure 4-8 Infiltration curve results for the 8 permeable pavements tested in the study.

The linear regression analysis results for the 8 test pavement measurements are listed in table 4-2.

Table 4-2 linear regression analysis results for the 8 test pavements.

Test Location	R ²	Eqn.	Slope	Max Level (mm)	Total Time (mins)	Calculated	% of recommended	% of recommended
						Infiltration (mm/h)	EU value (194 mm/h)	EU value (97,2 mm/h)
Zwolle 3	0.984	$y = -5.21x + 58.935$	-5.21	57	10	342	176%	352%
Zwolle 1	0.992	$y = -4.63x + 73.373$	-4.63	71	15	284	146%	292%
Dussen2	0.962	$y = -1.85x + 52.742$	-1.85	57	26	132	68%	135%
Delft 1	0.982	$y = -1.82x + 77.848$	-1,81	80	38,76	124	64%	127%
Effen 1	0.983	$y = -1.61x + 44.451$	-1.61	45	24,8	109	56%	112%
Utrecht 2	0.979	$y = -1,03x + 70,576$	-1,03	72	61,2	71	36%	73%
Dussen 1	0.979	$y = -1,06x + 61,858$	-1,06	60	52,2	69	35%	71%
Utrecht 1	0,882	$y = -0,36x + 34,154$	-0,36	48	100	29	15%	30%

4.5 Discussion

Although the 8 permeable pavements tested in this study were of a similar construction type and of similar age, Table 4-2 shows a large variation in the calculated infiltration rates between the 8 study pavements. This variation in results is similar to findings of a number of previous studies that have attempted to quantify the infiltration rates of permeable pavements [Lucke et al., 2014; Bean et al., 2004; Lucke & Beecham, 2011; Kayhanian et al., 2012; Li et al., 2013; Boogaard et al., 2013]. The infiltration rates of the 8 test pavements differed from between 29 and 342 mm/h. There are a number of potential reasons for the observed variations in surface infiltration rates between the test pavements including:

- Age. Although most of the pavements were generally of a similar age range, small variations can be expected in surface infiltration capacity in the older pavements
- Construction. While the construction of the test pavements were generally similar to that shown in Figure 1, there were slight differences between the

sites. These included the size of the paving joints, different types of bedding aggregates and different pavement laying processes

- Maintenance. There were distinct variations in the pavement maintenance procedures between the different municipalities. All municipalities conducted regular street sweeping of their permeable pavements as other pavements but no attempts were made reduce clogging of the pavements
- Variations in Hydraulic Ground Conditions. The water table was higher at some pavement test locations (particularly in the western areas of the Netherlands), while the permeability of soils in the eastern test locations were generally higher
- Environmental Site Conditions. The type and amount of trees surrounding the pavements are not the same. Trees are known to affect the infiltration rate of permeable pavements [Fassman, 2010]. Pavement Usage. There are variations observed between the type and number of vehicles using the different pavements on a daily basis

4.6 Dutch Permeable Pavement Infiltration Guidelines

Guidelines for the construction and performance of permeable pavements are generally limited in the Netherlands. However, guidelines on acceptable infiltration rates for newly installed permeable concrete pavement systems in the Netherlands have been developed by Kiwa Nederland B.V. [2014] and local government engineers and designers often refer to these guidelines when designing new permeable pavement systems. Recently published Kiwa permeable pavement infiltration testing guidelines stipulate the following:

- A minimum of three infiltration tests shall be performed. If all three tests demonstrate an average infiltration rate of equal to or greater than 194.4 mm/h (540 L/s/ha), the pavement is deemed to comply
- Every test should demonstrate a minimum infiltration rate of 97.2 mm/h (270 L/s/ha)

A number of other European countries also have construction and infiltration guidelines for concrete permeable pavements. Permeable pavements in the Netherlands, Belgium and Germany all need to demonstrate an infiltration capacity of 194.4 mm/h [Probeton, 2009; FGSV, 1998].

The overall infiltration rates calculated for six of the eight pavements tested in this study were below the Kiwa recommendation of 194 mm/h (Table 4-2). Other permeable pavement guidelines in the Netherlands [RIONED, 2006] recommend

that maintenance is undertaken on permeable pavements when the infiltration falls below 0.5 m/d (20.8 mm/h). According to these guideline values, none of the tested pavements in Table 4-2 would require immediate maintenance. Previous studies have demonstrated that infiltration rates that have diminished over time due to clogging can be restored by undertaking pavement maintenance such as street sweeping and vacuum cleaning [Dierkes et al., 2002; Bean et al., 2004; Beecham et al., 2009].

Infiltration rates of newly installed permeable pavement systems have been shown to be very high. However, this has been shown to decrease significantly over time [Borgwardt, 2006, Pezzaniti et al., 2009, Lucke and Beecham, 2011, Boogaard et al, 2013] and it is the long-term infiltration performance of a pavement that determines their ultimate success or failure [Yong and Deletic, 2012]. Whether the surface infiltration rate obtained from testing is considered acceptable or not depends on a number of factors, including the location of the pavement, the intended purpose of the pavement and the stakeholder expectations.

If we compare all tests results from the Netherlands (full scale tests and infiltrometer tests) we see that after an age of about 4 years the infiltration capacity of the systems is likely to drop under the EU ambition of 194.4 mm/h (figure 4-9). German results [Nolting et al., 2005] and Belgium results [Beeldens et al., 2006] show a more positive view on this: the test results show higher infiltration capacities at the age of 4-6 years.

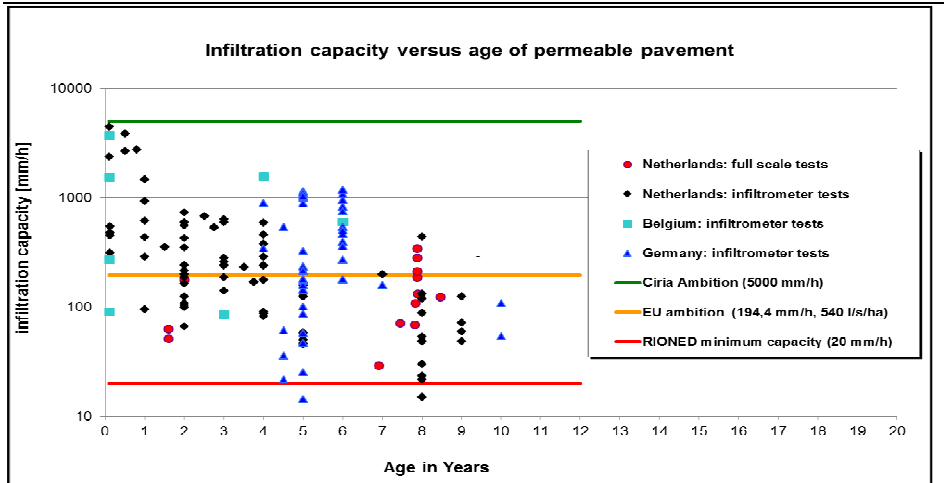


Figure 4-9 international research results on infiltration capacity of permeable pavement.

In the municipality Werkendam (test location Dussen) two different sections of the permeable pavement have been tested. Tests have been performed before and after maintenance to conclude the effectiveness of maintenance of the pavement conducted after 7 years.

The results showed an infiltration capacity on the two sections of 111 and 245 mm/h after maintenance improving the capacity with a factor 2.8 and 2.2.

4.7 Conclusions

This study used a newly developed, full-scale infiltration test to evaluate the infiltration performance of eight permeable pavements in five municipalities that had been in service for over seven years in the Netherlands. Traditional permeable pavement infiltration testing methods generally base results on the infiltration rates obtained through a very small area of the pavement, which is then used to represent the total pavement area infiltration. This approach of using small areas for testing could potentially lead to erroneous results being obtained.

Infiltration rates of newly installed permeable pavement systems are generally very high, although they have been shown to decrease significantly over time. Newly installed permeable pavements in the Netherlands must demonstrate a minimum

infiltration capacity of 194 mm/h. This study found that only two of the measured infiltration results of the eight pavements tested were above the 194 mm/h requirement. Other permeable pavement guidelines in the Netherlands recommend that maintenance should be undertaken on permeable pavements when the surface infiltration falls below 20.8 mm/h. According to this guideline none of the 8 pavements tested in this study would require immediate maintenance.

Visualisation of the hydraulic behavior of SUDS infiltration is effective for understanding the conducted research and contributed for a better understanding of SUDS by many actors (e.g. urban planners from water authorities and municipalities etc). This visualisation allowed real-time monitoring of the entire infiltration process, is useful as a logbook for the conducted experiments and also facilitated precise verification of the pressure transducer measurements.



Figure 4-10 visualisation by timelapse camera showed the infiltration capacity before and after maintenance of permeable pavement at the same time on video. (<http://www.climatecan.nl/page?details=60>).

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5 Comparing results of a new swale infiltration test method

This chapter is primarily based on:

- Boogaard F.C., Lucke T., Sommer H., de Beer J., van de Giesen N.C., van de Ven F.H.M. Lessons learned from over two decades of global swale use, (13th International Conference on Urban Drainage, Sarawak, Malaysia, 7-12 September 2014), ICUD 2014.
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5.1 Introduction

Bioretention swales are one type of SUDS that have been used for well over two decades globally to provide stormwater conveyance and water quality treatment. Swales are shallow (often < 0.3 m deep), vegetated (generally grass-lined) channels that receive stormwater runoff through gentle side slopes and convey this stormwater downstream by way of longitudinal slopes that are typically less than 5% [Davis & Jamil 2008; Davis et al. 2012; Stagge et al. 2012]. Water quality treatment in a swale occurs through the process of sedimentation, filtration, infiltration and biological and chemical interactions with the soil [Winston et al. 2012]. Swales have been shown to be very efficient in removing sediment particles from urban runoff [Barrett et al. 1998; Deletic 2005].

Swales are relatively simple SUDS devices and they are installed for a variety of reasons including: stormwater transport, water quality improvement, infiltration for groundwater or aquifer recharge, flood mitigation, aesthetics and cost. There are generally two main types of swales: 1) grassed or densely vegetated swales with natural soils below; or 2) swales with filter media or porous soils whose major treatment mechanism is infiltration. Sometimes swales may be used as conveyance structures with impermeable liners to pass the runoff to the next stage of a treatment train. The type of swale selected depends on site physical conditions (soils, slopes, land use, water table depth, depth to bedrock), contaminants of concern and maintenance infrastructure.

The main design objectives of swales, and the purpose of their installation, can vary considerably from country to country. Local environmental conditions are obviously very different across the world and the rationale for selecting a swale SUDS option in one country may not be appropriate in another country. This chapter presents an overview of the characteristics and performance of swales in the Netherlands after (full scale) testing. Special attention is given to the oldest swale in the Netherlands build in 1998 which has been monitored from that time.

The results are related to three different swale case studies from Germany (oldest swale in Germany or even Europe), Norway and Australia and research results from other countries, for example from the American BMP database that presents 41 biofilter/grass swales [Clary et al., 2012]. They are mainly selected for their age, the

difference in climate and the availability of research results (see table 5-3, row 'significance').

The environmental conditions at each of the swale locations, the main design objectives, the swale performance, and the results of monitoring are examined. The outcomes of each of the case studies are discussed and compared, and main lessons learned are presented in guidelines.

5.1.1 Guidelines for swales

This chapter lists construction and monitoring guidelines and their background. Results from monitoring of infiltration facilities in the Netherlands have formed the basis for the guidelines. Emphasis is placed on the importance of tailoring the design, construction and maintenance of infiltration facilities to location-specific situations. Therefore the presented guidelines should be regarded as tools to support design, rather than fixed requirements. The incentives behind the guidelines are clarified so that the user may deviate from them in a justified manner. Furthermore, it should be borne in mind that some guidelines are based on local experiences that are not representative for all locations. Knowledge of certain aspects of infiltration facilities is still limited, which means that new research and monitoring is needed, alongside period revisions of these guidelines.

This chapter focuses on four of these guidelines, including:

1. Swale water depth
2. Safety
3. Slope and maintenance
4. Time to empty

Swale water depth. The primary function of a swale is to ensure natural infiltration of stormwater runoff. The rainfall intensity often exceeds the infiltration capacity of the soil, which makes it necessary to temporarily store stormwater. The amount of available space for construction of swales is often limited, especially in existing dense urban areas. The limited horizontal space is often compensated by implementing infiltration facilities with a greater depth. However, a deeper swale with a relatively smaller infiltration surface and lower hydraulic conductivity will require more time to empty, and therefore has less available storage capacity for subsequent rainfall events. In the Netherlands the maximum depth is often set at 0.30 meters, allowing a (slightly clogged) top soil with a permeability of 0.3 m/d to

empty within approximately 24 or a maximum of 48 hours [RIONED, 2006]. To limit the water level height, an overflow structure is used, typically consisting of a gully pot in the slopes of the swale (figure 5-1 left) or direct overflow to surface water (figure 5-1 right).



Figure 5-1 Dutch overflow structure to ensure a maximum water depth in swale (left). Overflow of water from swale directly to surface water during full scale testing in Purmerend (right).

Safety: is an important issue, especially with regards to children who have a higher risk of drowning in deeper swales. This concern is factored into the design of swales, with limitations placed on depth and slope gradient. In addition, the swale needs to be completely visible to enable residents to observe and act immediately if an accident occurs. Low vegetation within and surroundings of the swale is therefore advised [RIONED, 2006].

Side slope of swales and maintenance

The slope of the swale is important for the expression of the infiltration facility in the landscape. A gentler slope will result in a more smooth landscape expression, but will require much more space. Maintenance aspects should be taken into account. Mowing the swale from the swale bed upward may, certainly under wet conditions, increase the risk of soil compaction and clogging [RIONED, 2006]. Mowing during dry conditions and from the slopes downward is in those situations preferable (figure 5-2b).



Figure 5-2 a) clogging of the top soil and b) maintenance of the swale

Emptying time: most guidelines advise a design that enables the swale to infiltrate stormwater within one day [e.g. DWA, 2005] however, some construction guidelines use a maximum emptying time of 48 hours [RIONED, 2006].

Such guidelines in the Netherlands are based on a number of factors such as the limited availability of space in urban areas; the low permeability of the soil; the shallow groundwater tables; limited public health concerns as well as a safety factor, given that the infiltration capacity of swales may reduce over time by clogging. Figure 5-4 shows emptying times of swales in the Netherlands. Some of the swales have an emptying time more than 48 hours when the total storage volume is reached (20-30 cm) [RIONED, 2006].

5.2 Materials and methods

The new testing method was used on the 12 existing swales evaluated in this study (table 5-1). As for applying the test method at permeable pavement (chapter 4) a number of issues need to be considered when using the new test method:

- Selection swale for testing;
- Water supply alternatives; and
- Accurate determination of surface infiltration rate.

The different issues and options are described in the next sections.

5.2.1 Test Area Selection

To enable an accurate estimation of the average surface infiltration rate using the new test method, a swale should be filled up with water to the maximum water level or at least 20 cm. The new infiltration test requires large volumes of water to inundate the swale. When the storage volume of the swale was higher than approximately 3 or 4 times the content of the available truck (in practice a volume close to 50 m³), pressure transducers and a raingauge were installed to determine infiltration rates after a stormwater event (long term monitoring).

5.2.2 Water Supply

Depending on the site location, a number of different water supply options can be undertaken, including transporting water directly to site with water trucks and pumping water directly from nearby canals.

After the swale test area had been selected, the swale was inundated with water to the maximum allowable water level possible. The maximum inundation depth was dependent on the type of construction. However, this was generally between 20 and 30 cm from the lowest point in the swale to the overflow structure.



Figure 5-3 Full scale test for monitoring the hydraulic behaviour of swales

5.2.3 Determining Infiltration Rates

Pressure transducers were used in the study as the primary method of measuring and recording the reduction in water levels over time at various locations. Two wireless, self-logging, pressure transducers (Minidiver: <http://www.slb.com>, described in chapter 3 and 4) were installed at the lowest points of the swale. The transducers continuously monitored the static water pressures at those locations and transmitted this information to a laptop computer.

Three different measurement methods were used in conjunction with the pressure transducers in order to calibrate and verify the transducer readings. The three methods were:

- Hand Measurements
- Calibrated Underwater Camera
- Time-Lapse Photography

These three methods are explained in more detail in chapter 4.

5.2.4 Study Test Locations

The infiltration rates of 12 existing swales in the Netherlands were tested. The locations and details of the swales are listed in Table 5-1. All test locations are located in residential areas (30 km/h zones), except no 2 and 11. No maintenance other than mowing of the grass has taken place at the locations.

Table 5-1 Swale locations tested in The Netherlands

Municipality	location	year of construction	runn off type	type of test	Age of construction during test(s)	literature/ background information
Oostzaan	Doktersbuurt	2004	residential area	Water-logger	2	Lohman 2005
Noord-oostpolder	Bant	2007	residential area	full scale	8	Boogaard 2015
Haren	Vondellaan	2013	residential area	Water-logger	2	Boogaard 2015
Haren	Mellensteeg	2013	residential area including schoolyard	Water-logger	2	Boogaard 2015
Purmerend	Bloemfontein	2004-2005	residential area	full scale	10	Graaf et al., 2014
Purmerend	Ismailiastraat	2004-2005	residential area	full scale	10	Graaf et al., 2014
Purmerend	Saidweg (oost)	2004-2005	residential area	full scale	10	Graaf et al., 2014
Purmerend	Saidweg (west)	2004-2005	residential area	full scale	10	Graaf et al., 2014
Enschede	Ruwenbos	1998-1999	residential area	Water-logger	3	RIONED 2006
Almelo	Kleef	2002	residential area	Water-logger	5	Wentink 2007, Boogaard 2007
Utrecht	Castellumdreef	2009	road and roundabout	Water-logger	5	Donkers 2010, Boogaard et al., 2011
Arnhem	Burgemeester Matsersingel	2005	residential area	Water-logger	5	Langeveld 2012, Boogaard 2007

5.2.5 Case studies

To present different applications of swales that will require different guidelines for design, construction and maintenance, four different swale case studies from the Netherlands, Germany, Norway and Australia are reviewed. They are selected on their age (oldest swales in Netherlands and Germany), in different climates (Norway and Australia) and the availability of (long term) research results (see table 5-3).

5.3 Results

Figure 5-3 shows emptying times of swales in the Netherlands on different sites. The infiltration curves show different gradients leading to different infiltration capacities (table 5-2). When monitoring data is available from stormwater event over several years, possible clogging can be determined by comparing the slope of the emptying curves. This has been done for the data of the swale in Ruwenbos and Arnhem where no clogging was determined [Langeveld et al 2012], Vegetation that is resistant to long inundation can prevent clogging of the topsoil [Lewis et al., 2008, RIONED, 2006].

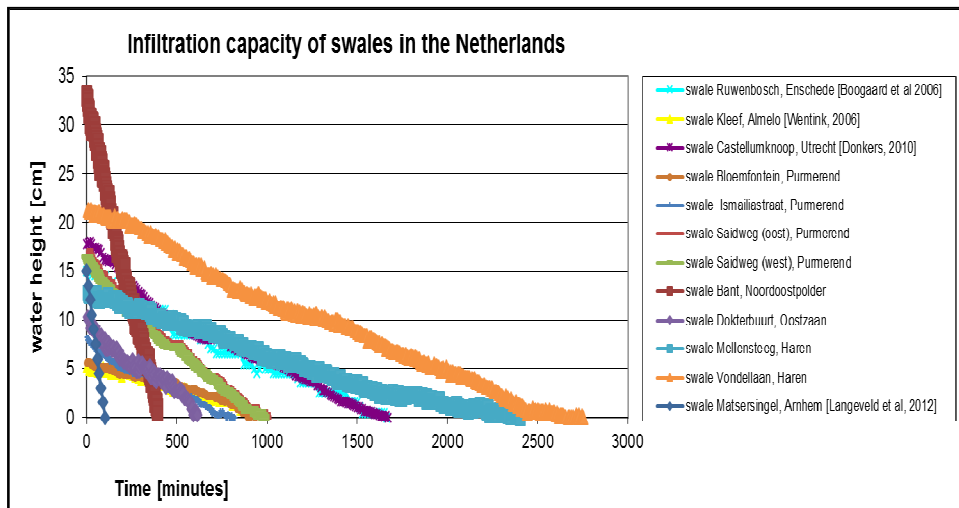


Figure 5-4 empty times swales on different locations in the Netherlands.

The full scale tests at 4 different swales in Purmerend are all performed in the same district with similar geohydrological circumstances not more than 30 meters from each other. Still, the individual swales show a variation of the infiltration capacity of 0.09 to 0.25 m/d (table 5-2). The tests were performed after 10 years without any maintenance has been done by the municipality except mowing the grass.

Table 5-2 infiltration rates swales

Municipality	location	type of test	waterlevel [cm]	empty time [min]	infiltration rate [m/day]**
Oostzaan	Doktersbuurt	l.t.m.	10.3	615	0.24
Noordoostpolder	Bant	full scale	33.1	393	1.21
Haren	Vondellaan	l.t.m.	21.2	2755	<u>0.11</u>
Haren	Mellensteeg	l.t.m.	12.8	2400	<u>0.08</u>
Purmerend	Bloemfontein	full scale	5.6	937	<u>0.09</u>
Purmerend	Ismailiastraat	full scale	8.2	823	0.14
Purmerend	Saidweg (oost)	full scale	17	990	0.25
Purmerend	Saidweg (west)	full scale	16.5	981	0.24
Enschede	Ruwenbos	l.t.m.	15.0	1665	0.13
Almelo	Kleef	l.t.m.	5.1	855	<u>0.09</u>
Utrecht	Castellumdreef	l.t.m.	17.7	1670	0.15
Arnhem	Burgemeester Matsersingel	l.t.m.	15	100	2.16

*l.t.m.= long term monitoring (waterloggers installed for longer period of time).

**Underlined infiltration rates are lower than 0,125 m/d which is needed to empty 25 cm in 48 hours.

The infiltration capacities of the test locations vary between 0.08 to 2.16 m/d. These values are comparably to values found in literature on infiltration capacity of swales monitored after 10 to 20 years. Ingvertsen et al, 2010 found in German swales infiltration capacities between 0.1 and 3.1 m/day using the open-end infiltration test [BMVBS, 2008].

Four out of the twelve swales have an emptying time more than 48 hours when the total storage volume is reached (mostly between 20 and 30 cm at the test locations). For example, the swale in Enschede has an infiltration capacity of 0.13 m/d, when the average waterlevel exceeds 13 cm the swale will probably take more

than a day to empty. The swale has a storage volume of 6 mm (see appendix 10). Long term measurements of 3 years showed that only 19 days in 3 years the water level exceeded 15 cm [RIONED, 2006].

Eight out of twelve swales in this research will empty its storage volume within 48 hours (with a maximum waterlevel of 25 cm).

5.4 Case studies

The main design objectives of swales, and the purpose of their installation, can often vary considerably from country to country. Local environmental conditions are obviously very different across the world and the rationale for selecting a swale SUDS option in one country may not be appropriate in another country. Table 5-3 presents four different swale case studies from the Netherlands, Germany, Norway and Australia. They are selected for their age and or the difference in climate (see table 5-3, row 'significance').

The overview from the case studies is not meant as a detailed scientific study but to present different applications of swales in different climates that will require different guidelines for design, construction and maintenance. As an introduction, the environmental conditions at each on the four swale locations and the main design objectives are stated in table 5-3. The summary of the case studies is presented in appendix 9.

Table 5-3 summary of international pilots

	Case study 1	Case study 2	Case study 3	Case study 4
country	The Netherlands	Germany	Norway	Australia
Name	Wadi	Mulden-Rigolen-System	Swale	swale
literature	RIONED, 2006	Sieker et al.,2001, Boogaard et al., 2014	Boogaard et al., 2014, Harvold et al., 2015	Kachchu et al., 2013
significance	Oldest swale in The Netherlands. Intensive monitoring	One of the oldest swales in Germany. Intensive monitoring	Young swale in wet and cold climate (rain and snow) at Unesco heritage site	swale in dry climate primarily used for sedimentation
rainfall [mm/yr]	800	600	2100	1464
Location	Enschede	Hoppegarten	Bergen	Sunshine Coast (SSC)
Constructed	1997-2000	<1992-1998	2012	2008-2009
Main purpose	Natural water balance, storage of rainwater	Retention and Purification	Stop decay of cultural deposits	Treatment of stormwater
Hydraulic situation	High groundwater table Low permeability	Low permeability, Clay soil from Ice Age	Rain/snow, mean temperature of 7.6°C (-30 till 25C)	Temperatures range 15.8 to 25.2C°.
Area	new development, residential	new development, commercial	Existing area, residential	new development sporting complex
Monitoring plan	1999-2006 Hydraulic, pollutants	1996 to 2000 water balance	2008-2014 Hydraulic, pollutants	Hydraulic, SS and pollutants
Connected area [ha]	4 ha, 400 houses and roads	100 ha	1-2 ha	Parking lot

5.5 Results and discussion on case studies

The main design objectives of swales, and the purpose of their installation, can often vary considerably from country to country. The four case studies discussed in this chapter and appendix 9 from the Netherlands, Germany, Norway and Australia are therefore hard to compare directly. The environmental conditions, the main design objectives, the swale's construction and performances are different at each of the four swale locations. It shows the variation in functions and performance that should be considered in design, construction and maintenance guidance.

The removal efficiencies of swales are relatively high compared to facilities based on sedimentation. The main outcomes and lessons learned for each of the studies included: the **Dutch** study swale was primarily installed for storage of stormwater. The study showed that design parameters were not met after construction and flexibility in the design and operation (real time control) is strongly advised. The study results also showed that nearly all residents surveyed (98%) were satisfied with the performance of the swales and preferred to live in a housing district with swales. From the hydraulic monitoring data the emptying time is determined in 1999 and 2002; no clogging was found in Ruwenbos in these first 4 years after construction.

The **German** study swale was primarily installed to mitigate potential flooding due to the runoff from a new development. The study showed that incorporating infiltration swales is an effective way of reducing stormwater runoff from catchments with low-permeability soils.

The **Norwegian** swale is primarily installed to preserve cultural deposits by improving wet conditions by infiltration. The research results on the characteristics of stormwater resulted in a treatment train (rainwater garden, swale and permeable pavement) to ensure that the concentrations (higher than at other locations in the world) will meet MAC and WFD guidelines. The study showed that the use of shallow SUDS to protect and preserve subsurface organic cultural deposits is not only cost-effective, but also a robust and practical solution.

The primary use of the swale in **Australia** is to easily convey stormwater runoff and to provide basic stormwater treatments by sedimentation.

The main lessons learned from the case study was that the installation of excessively long swales to treat stormwater TSS pollution may not be the most cost

effective solution as between 50% and 75% of TSS is removed within the first 10 m of the swale length.

The case studies show variation in functions and performance of swales around the world that should be considered in design, construction and maintenance guidance. Evaluating these case studies we must emphasize the importance of tailoring the design, construction and maintenance of infiltration facilities to location-specific situations. We should keep in mind that some guidelines (table 5-4) are based on local experiences that are not representative for all locations. Therefore the presented guidelines should be regarded as tools to support design, rather than fixed requirements.

5.5.1 General international design guidelines for swales

It is recommended that designers follow the basic design guidelines given in table 5-4.

Table 5-4 General international design guidelines for swales

Design Parameter	Unit	The Netherlands	Germany	UK	Belgium
Organization/literature		RIONED, 2006	DWA,2005	CIRIA, 2004	VLARIO, 2005
Swale area/drained area	m ² /m ²	5 – 10	> 7	--	5 – 10
Distance to houses	m	>1	1.5 depth		
Swale water depth till overflow	m	<0.3	<0.3	<0.1	<0.3
Width of bottom	m	>0,5	0.6	--	0.5 - 1
Longitudinal slope	V:H	1 : 3 or less	1:4 or less	--	1:3 or less
Max velocity	m/s	--	--	1 - 2	--
Thickness of filter soil	m	0.3 – 0.5	>0.1	--	0.3 – 0.5
Humus in top layer	%	3-5		--	
Infiltration capacity Kd	m/day	> 0.5	0.86 < Kd < 86.4	--	> 0.086
Overflowing frequency	1/yr	1 to 2	0.2	--	0.2 – 0.5
Time to empty	hour	<24	<24	> 10 min	<24

5.6 Conclusions swales

This research undertaken on swale field installations with the new full scale test in urban areas demonstrated that most of the swales tested in the study meet the required hydraulic performance levels even after years in operation and without maintenance. The individual swales show a variation of the infiltration capacity of 0.08 to 2.16 m/d. These values are comparably to values found in literature on infiltration capacity of swales monitored after 10 to 20 years. Eight out of twelve swales in this research will empty its storage volume within 48 hours under conditions of high groundwater tables (up to 0.5m under the swale) and low permeable soil (such as clay). These results are encouraging and important for the implementation of SUDS in the Netherland, but also for their applicability in other delta cities around the world.

From the research in the Netherlands and other locations regarding the differences between design and practice, it is advised to follow basic guidelines and build in possibilities to regulate the flow after construction. For instance: the overflow height can be changed to a lower level if the emptying time of the swale is too high. For this purpose and a general evaluation of SUDS, hydraulic monitoring is strongly advised to judge and optimize the performance.

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6 Concluding Remarks

6.1 Conclusions

The overall objective of this research is to review the performance of SUDS in the Netherlands with high groundwater tables and low permeable soils. Research findings on the characteristics of Dutch stormwater and the hydraulic performance and pollution removal efficiencies of (Dutch) SUDS that have been in service for many years can improve design, implementation, maintenance and performance of these facilities.

To evaluate the effectiveness of SUDS, this thesis first provides a detailed insight of the water quality characteristics of stormwater. New test methods were given for lab experiments and full scale field experiments to determine the efficiency of the tested SUDS. Test results showed the effectiveness of the most commonly used SUDS in the Netherlands and compact settling facilities, bioretention swales and permeable pavements. Sedimentation devices were tested in particular for their performance regarding water quality improvement. Porous pavements and bioswales were evaluated for their long term hydrological performance.

6.2 Characterization of stormwater and sedimentation devices

From the acquired data on stormwater quality and characteristics it was concluded that to achieve the European (Water Frame Directive) and Dutch (Maximum Allowed Concentration) quality standards for surface water, stormwater treatment facilities must have a removal efficiency of 80% for copper and 60% for zinc. As most of these pollutants are particle-bound, in particular to the finest particle size fraction, settling and filtration seem appropriate treatment technologies.

Most of the earlier research on sedimentation devices does not give a detailed analysis on which particles are removed at different flow rates. A testing procedure was formulated to achieve this comparison to obtain a detailed insight in the performance of these facilities. This procedure is characterized by:

- Using suspended sediment with a representative and well-known particle size distribution;
- Using a non-coagulating suspended sediment with constant and known specific density;
- Using a representative concentration of suspended sediment particles;
- Using particle counting for detailed analyses of suspended sediment in in- and outflow.

Four sedimentation devices were tested for their suspended sediments removal efficiency by particle size. As expected, the research data demonstrated a decreasing removal efficiency of the facilities with an increasing flow rate. Removal efficiency for particles smaller than 63 μm was less than 40 % for hydraulic loadings of 10 -15 l/s (surface load >25 m/h) and even less than 20 % for particles smaller than 30 μm .

Most of these facilities are not protected from hydraulic overloading. Without the implementation of by-pass constructions, remobilization of sedimented particles and a flush-out of earlier collected sediment is likely to take place during full hydraulic loading and the required removal efficiencies to meet WFD or MAC standards will not be achieved.

6.3 Infiltration facilities

Many factors can affect the long term performance of SUDS field installations and some of these are extremely difficult to simulate in a laboratory. For this reason a full scale testing method for field experiments was set up with visualisation of the infiltration process that can contribute to a better understanding of Dutch SUDS by many actors (e.g. urban planners from water authorities and municipalities).

6.3.1 Permeable pavements

Permeable pavements are a type of SUDS that are becoming more common in the Netherlands to allow infiltration, to minimize runoff volumes and to treat urban stormwater by soil filtration. However, urban stormwater runoff contains significant concentrations of suspended sediments that can cause clogging and reduce the infiltration capacity and effectiveness of permeable pavements. It is important for stormwater managers to be able to determine when the level of clogging has

reached an unacceptable level so that they can schedule maintenance or replacement activities.

This study used a newly developed, full-scale infiltration test procedure to evaluate the infiltration performance of 8 permeable pavements that had been in service for over seven years in the Netherlands. Newly installed permeable pavements in the Netherlands easily demonstrate a minimum infiltration capacity of 194 mm/h (540 l/s/ha). Permeable pavement maintenance guidelines in the Netherlands recommend that maintenance is undertaken on permeable pavements when the infiltration capacity falls below 0.50 m/d (20.8 mm/h). The observed infiltration capacities range between 29 and 342 mm/h. Two of the 8 pavements showed an infiltration capacity higher than 194 mm/h and all infiltration capacities are higher than 20.8 mm/h, consequently none of the pavements would require maintenance even after seven years.

6.3.2 Swales

Bioretention swales were first introduced to the Netherlands in 1998. Swales are one type of SUDS device that has been used globally for well over two decades now to provide stormwater retention and conveyance and improve stormwater quality. The main design objectives of swales, and the purpose of their installation, can vary considerably.

This research on swale field installations demonstrated that most of the swales tested in the study met the required hydraulic performance levels even after many years in operation and without maintenance. Eight out of twelve swales in this research will empty its storage volume within 48 hours under conditions of high groundwater tables (up to 0.5m under the swale) and low permeable soil (such as clay). The individual swales show a variation of the infiltration capacity of 0.08 to 2.16 m/d. These values are comparable to values found in literature on infiltration capacity of swales monitored after 10 to 20 years. These results are encouraging and important for the implementation of SUDS in the Netherland and other areas in the world with comparable hydraulic circumstances.

6.3.3 Are SUDS suitable in The Netherlands?

Answer to the hypothesis: *The hydraulic performance of swales and permeable pavement that have been in service for many years are suitable in high groundwater tables and low permeable soil.*

The performance of SUDS in delta areas such as the Netherlands has been viewed with scepticism. However, this research undertaken on Dutch SUDS field installations in urban areas has demonstrated that most of the bioretention swales and permeable pavements tested in the study have met the required hydraulic performance levels even after years in operation and without maintenance.

Regular monitoring of the facilities is required to check their need for maintenance. Full scale testing of these SUDS with the methods that were developed and tested in this research project can accurately visualise and quantify their actual performance. Maintenance needs and effectiveness can be checked by keeping a logbook of the testing results.

6.4 Recommendations

The foremost recommendation resulting from this research is that porous pavements and bioretention swales are acceptable for use in lowland areas with high groundwater tables and low permeability soils. Their long term performance is, in general, problem free assuming adequate monitoring and maintenance is provided. In order to improve our knowledge and understanding of performance of SUDS the following actions are advised:

- Monitor the performance of SUDS facilities and keep detailed records of design, construction and maintenance activities of SUDS. Analyze these logs annually to improve construction and maintenance practice.
- Using a treatment train approach achieves increased efficiencies that are generally not possible using single SUDS devices. For example, gross pollutant traps (GPS) can be used as the first treatment step to remove larger sediment particles followed by permeable pavement which can remove smaller sediment particles and nutrients to meet the required water quality standards. Clogging of the permeable pavements should be prevented since tests on the effectiveness of maintenance showed an improvement of the infiltration capacity with (only) a factor of 2.5.
- Performing full scale testing experiments in the field to evaluate the performance of facilities.
- For testing settling SUDS it is recommended to use a standardized test method for testing their settling performance under a range of hydraulic loadings, using

Glossary

Term	Explanation⁵
Basin	A ground depression acting as a flow control or water treatment structure that is normally dry and has a proper outfall, but is designed to detain stormwater temporarily.
Best Management Practice (BMPs)	A range of measures designed to reduce the rate and quantity of surface water runoff from developed areas and to improve runoff water quality. Stormwater BMPs are techniques, measures or structural controls used to manage the quantity and improve the quality of stormwater runoff. Term used in USA although often with less emphasis on amenity and biodiversity.
Catchment	The area contributing surface water flow to a point on a drainage or river system. Can be divided into sub-catchments.
Climate change	Climate change refers to any significant change in measures of climate (such as temperature, precipitation, or wind) lasting for an extended period (decades or longer).
Contributing area	The area that contributes storm runoff or other output to the receiving system.
Conventional drainage	The traditional method of draining surface water using subsurface pipes and storage tanks.
Design criteria	A set of standards agreed by the developer, planners, and regulators that the proposed development should satisfy. See drainage design criteria.
Detention basin	A vegetated depression that is normally dry except following storm events. Constructed to store water temporarily to attenuate flows. May allow infiltration of water to the ground.
Detention pond/tank	A pond or tank that has a lower outflow than inflow. Often used to prevent flooding.
Discharge	The flow rate of liquid passing through a conduit.
Drainage design criteria	A set of performance levels agreed by the developer, planners, and regulators that the proposed drainage system should satisfy.
Dry swale	Shallow vegetated channel with filter in the base to convey surface runoff to the sewer network or infiltrate into the surrounding soils.
Event (rainfall)	Single occurrence of a rainfall period before and after which there is a sufficient dry period for runoff and discharge from the drainage system to cease.
Filter drain	A linear drain consisting of a trench filled with a permeable material, often with a perforated pipe in the base of the trench to assist drainage.
Filtration	The act of removing sediment or other particles from a fluid by passing it through a filter.

⁵ Source: <http://www.susdrain.org/>

First flush	The initial runoff from a site or catchment following the start of a rainfall event. As runoff travels over a catchment it will pick up or dissolve pollutants and the "first flush" portion of the flow may be the most contaminated as a result. This is especially the case in small or more uniform catchments; however, in larger or more complex catchments pollution wash-off may contaminate runoff throughout a rainfall event.
Flow control device	A device used for the control of surface water from an attenuation facility, eg a weir.
Geotextile	A plastic fabric that is permeable.
Green infrastructure	A strategically planned and delivered network of natural and manmade green and blue spaces that sustain natural processes. It is design and managed as a multifunctional resource capable of delivering a wide range of environmental and quality of life benefits for society.
Groundwater	Water that is below the surface of ground in the saturation zone.
Heavy metal	Loosely, metals with a high atomic mass (sometimes given as metals with an atomic mass greater than that of calcium), often used in discussion of metal toxicity. No definitive list of heavy metals exists, but they generally include cadmium, zinc, mercury, chromium, lead, nickel, thallium, and silver. Some metalloids, eg arsenic and antimony, are classified as heavy metals for discussion of their toxicity.
Hydrodynamic separators	Proprietary systems designed to remove floating debris, sediments and other associated pollutants from surface water, using fluid dynamics to separate the solids from liquids.
Impermeable/ Impervious	Will not allow water (or any liquid) to pass through it.
Infiltration (to the ground)	The passage of surface water into the ground.
Infiltration basin	A dry basin designed to store and promote infiltration of surface water to the ground.
Infiltration device	A device specifically designed to aid infiltration of surface water into the ground.
Infiltration trench	A trench, usually filled with permeable granular material, designed to promote infiltration of surface water to the ground.
Low Impact Development (LID)	An approach to land development (or re-development) that works with nature to manage stormwater as close to its source as possible.
Management train	The management of surface water runoff in stages as it drains from a site (see SuDS Management Train).
Pathogen	An organism that causes disease.
Percolation	The passing of water (or other liquid) through a porous substance or small holes (eg soil or geotextile fabric).
Permeability	A measure of the ease with which a fluid can flow through a porous medium. It depends on the physical properties of the medium, for

	example grain size, porosity, and pore shape.
Permeable pavement	A permeable surface that is paved and drains through voids between solid parts of the pavement.
Permeable surface	A surface that is formed of material that is itself impervious to water but, by virtue of voids formed through the surface, allows infiltration of water to the sub-base through the pattern of voids, for example concrete block paving.
Pervious surface	A surface that allows inflow of rainwater into the underlying construction or soil.
Pond	Permanently wet depression designed to retain stormwater and permit settlement of suspended solids and biological removal of pollutants.
Porosity	The percentage of the bulk volume of a rock or soil that is occupied by voids, whether isolated or connected.
Porous asphalt	An asphalt material used to make pavement layers pervious, with open voids to allow water to pass through (previously known as pervious macadam).
Porous paving	A permeable surface that drains through voids that are integral to the pavement.
Rain garden	A planted basin design to collect and clean runoff (normally from a roof, or hardstanding with low risk of pollution).
Rainfall event	A single occurrence of rainfall before and after which there is a dry period that is sufficient to allow its effect on the drainage system to be defined.
Receiving waters	Water body (river, lake or watercourse) which receives a discharge from point or non-point sources.
Retention pond	A pond where runoff is detained for a sufficient time to allow settlement and biological treatment of some pollutants.
Retention time	The length of time that runoff is stored or detained to allow for settlement, or possibly biological action, to occur.
Runoff	Water flow (including flow from snow and other precipitation) over the ground surface which has not entered the drainage system. This occurs if the ground is impermeable, is saturated or rainfall is particularly intense. (Sometimes referred to as surface water runoff, surface runoff).
Sediments	Sediments are the layers of particles that cover the bottom of waterbodies such as lakes, ponds, rivers and reservoirs.
Silt	The generic term for waterborne particles with a grain size of 4-63 mm, ie between clay and sand.
Soakaway	A sub-surface structure into which surface water is conveyed, designed to promote infiltration.
Source control	The control of runoff at or near its source.
Stormwater control measures (SCMs)	Includes both structural (like bioretention systems) and non-structural (e.g. downspout disconnection programmes encouraging householders to manage their stormwater differently) control measures.
SuDS management	The management of runoff in stages as it drains from a site. A

train	range of SuDS components are used to maximise the hydraulic and water quality management benefits.
Substrate	An underlying layer; a substratum
Surface water	Water from precipitation which has not seeped into the ground and which is discharged to the drainage system.
Suspended solids	General term describing suspended material. Used as a water quality indicator.
Sustainable drainage systems (SuDS)	A sequence of management practices and control structures designed to drain systems (SuDS) surface water in a more sustainable fashion than some conventional techniques. Sometimes referred to as SuDS or Sustainable Urban Drainage.
Treatment	Improving the quality of water by physical, chemical and/or biological means.
Treatment train	A series of SUDS components, each designated to treat a different aspect of runoff that are implemented together to maximise their effectiveness. (See SuDS management train)
Turbidity	Reduced transparency of a liquid caused by the presence of undissolved matter.
Vortex flow control	The induction of a spiral/vortex flow of water in a chamber used to control or restrict the flow.
Water Framework Directive (WFD)	A Directive designed to integrate the way waterbodies are managed across Europe. It requires all inland and coastal waters to reach "good status" by 2015 through a catchment-based system of river basin management plans, incorporating a programme of measures to improve the status of all natural water bodies.
Water Quality Treatment volume	The permanent volume of water in a pond between rainfall events which is designed to provide dilution and adequate detention of surface water runoff to allow sedimentation along with other treatment processes to occur to provide partial treatment of the runoff before it is discharged from the site.
Water Sensitive Urban Design	A process that integrates the different water streams (surface water, waste water and water supply) within the water cycle and places water management at the heart of urban design (and vice-versa). SuDS make a contribution to WSUD, but they are not WSUD in its entirety.
Water quality	The chemical and biological content of water, usually compared to defined standards, set by legislation and enforced by environmental regulators.
Water table	The point where the surface of groundwater can be detected. The water table may change with the seasons and the annual rainfall.
Wetland	Flooded area in which the water is shallow enough to enable the growth of bottom-rooted plants.

Appendix 7 Curriculum Vitae

Employee ir. F.C. Boogaard

Family name Boogaard

First names Floris

Nationality Dutch

workfield Water management

Present position Senior consultant
researcher TU Delft
Professor (lector) Applied Science

Years of experience 16

introduction Floris Boogaard (1972) joined Delft University of Technology in 1992 and graduated in 1998 in water management with an additional graduation on working in third world countries. After graduating as Civil Engineer he joined the consulting agency Tauw BV to do work on urban drainage and water management for municipalities, water authorities, project developers, special planners, universities and other consulting agencies. In addition to his research he is group manager since 2007 for the water management group at Tauw BV in Amsterdam dealing with hydrology, ecology, waste and surface water. His research and advice fields include stormwater drainage and infiltration, complex monitoring and optimizing sewer systems, design of drainage facilities, water supply and groundwater pollution, urban water quality management and urban water management planning. He aims at making sustainable cities in terms of water management. In 2008 he joined the university of Delft to do PhD research on the quality of stormwater and optimizing SUDS in the international research group 'Skills integration and New Technologies (SKINT) in order to integrate the worlds of spatial planning and water management and to encourage the implementation of innovative technical and sustainable solutions. Floris accepted 1 April 2013 a professorship (in Dutch: lector) Spatial Transformations at the school of Architecture, Built Environment & Civil Engineering, NoorderRuimte Centre of Applied Research and Innovation on Area Development at Hanze University of Applied Sciences in Groningen. Floris is one of the founders of the company INDYMO (innovative dynamic monitoring systems) that monitors watersystems with innovative techniques as submerged waterdrones or aquabots.

Education 1992 – 1998 Delft University of Technology, water management (including additional graduation on working in third world countries)

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Appendix 8 sedimentation devices

Sedipipe

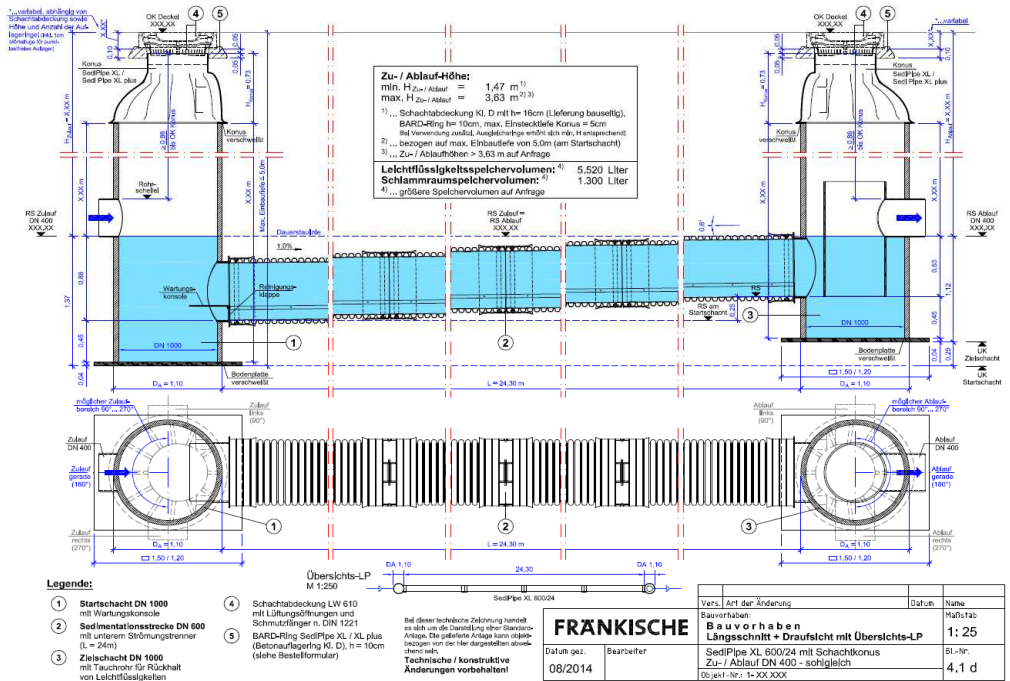


Figure 8-1 sedi pipe 600/24 (Frankische, 2014)

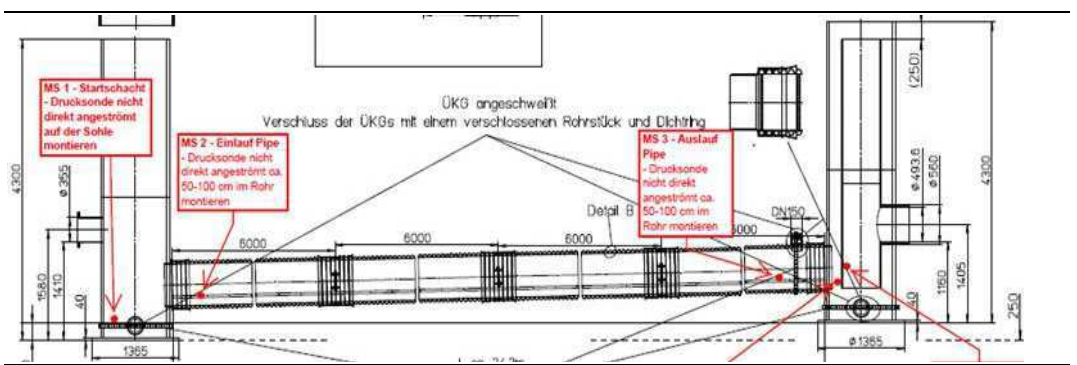


Figure 8-2 The set up full scale test of Sedi pipe with a length of 24 meters.

Lamella filter

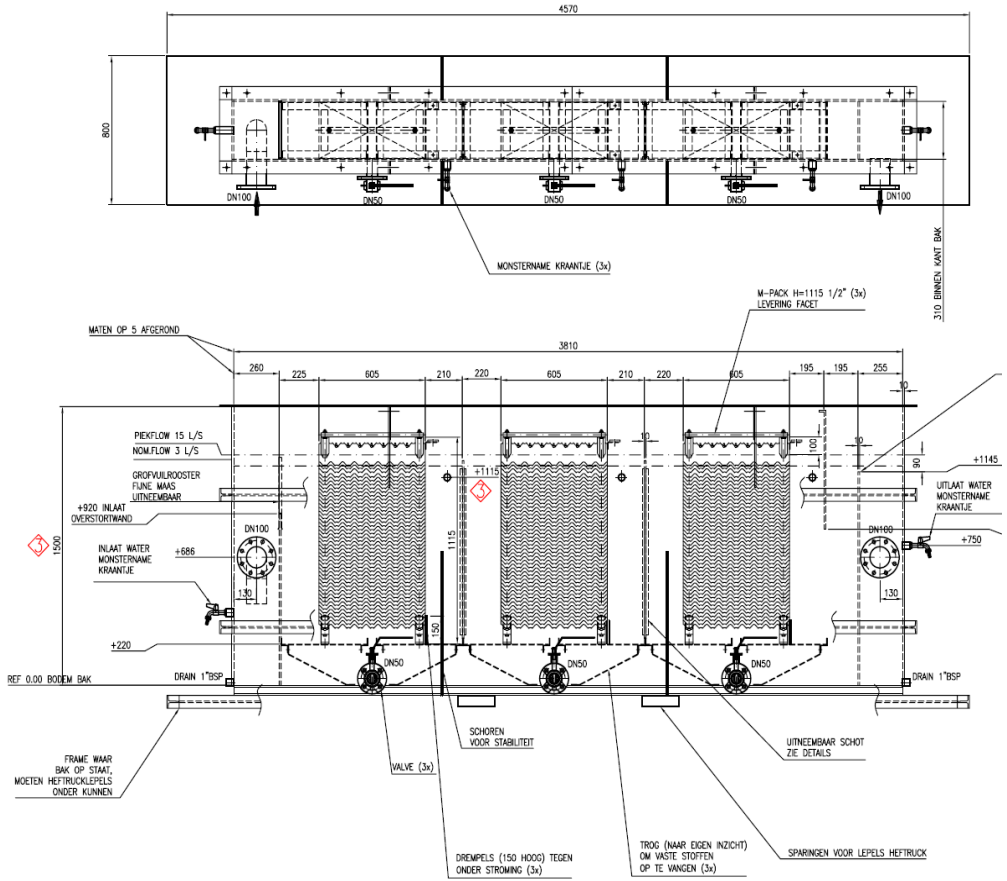


Figure 8-3 measurement set up Lamella filter (Facet international, ref 21C-42477 ref3, 11/6/2008)

Certaro filter

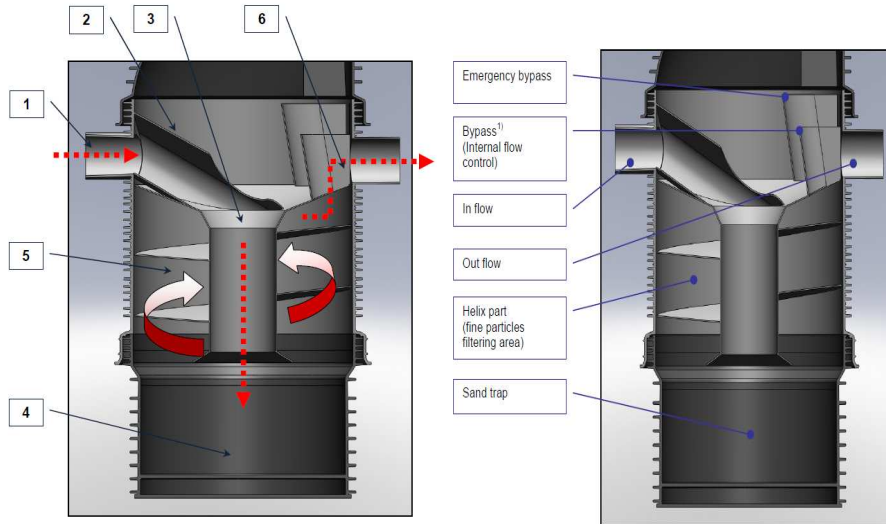


Figure 8-4 a+b 1 Working of Certaro HDS filter and Parts of Certaro HDS filter

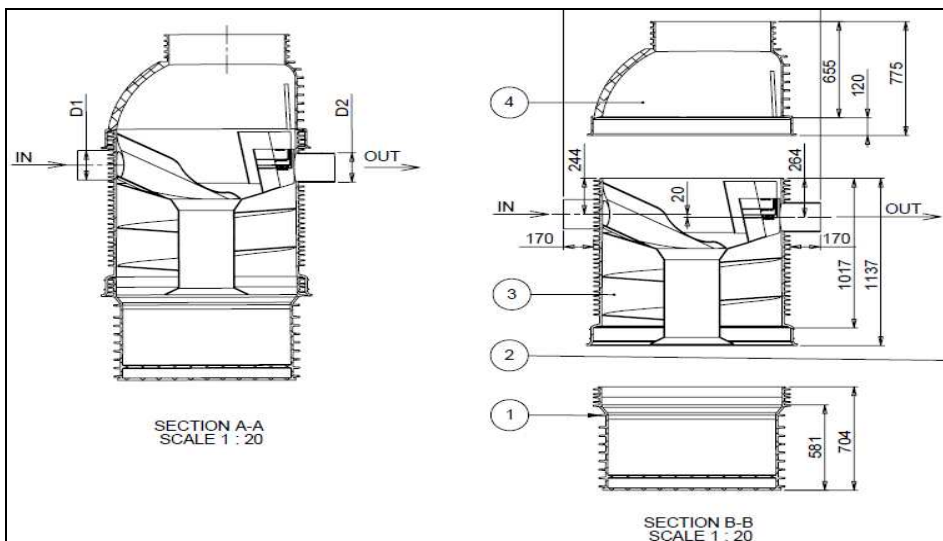


Figure 8-5 Certaro filter (Wavin, 2012)

Hydro 400

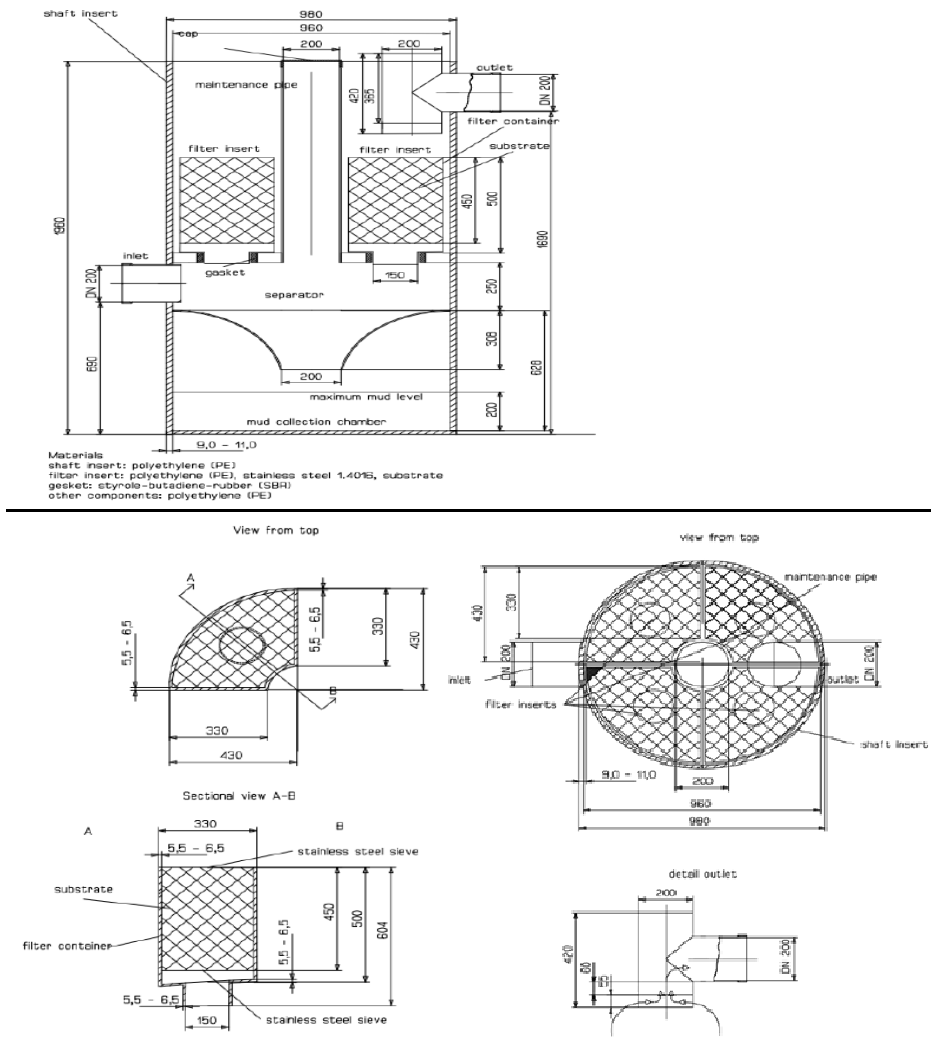


Figure 8-6 Hydro 400⁶

⁶ DIBt, Deutsches Institut für Bautechnik, (Registration centre for building projects and design Technical examination authority),

Applicant : 3P Technik Filtersysteme GmbH Date: 12 May 2010 II 32-1.84.2-1/07, Reference: Z-84.2-4 11 May 2010

Appendix 9 international casestudies swales

Case study 1 – Enschede, The Netherlands

Swale Location, Description and Objectives

Enschede is a municipality in the eastern part of The Netherlands, built on sandy soils. The infiltration capacity of the soil is reasonably high but groundwater levels are quite high (0.8 to 1.5 meters below street level). In 1994 development of a new housing, area called *Ruwenbos* has been started with high ambitions regarding storm water drainage system. The 400 new houses in this urban area are built respecting sustainability principles. The housing estate is designed as a garden district, maintaining existing trees and slopes. The storm water is drained by bioretention swales [RIONED, 2006].

Situation

All run-off in Ruwenbos is guided through gutters along the streets and is in this way kept visible on the surface. The gutters guide the rain water to the bioretention swales (figure 9-1b). In each swale the water is stored to a level of approximately 0.25 meters, a level designed to be exceeded only once every two years. Above this level gullies, also called 'gluttons', discharge the surplus to a subsoil infiltration body made up of expanded clay marbles wrapped in a geo-textile. Would the water level exceed 0.50 meter above the bottom to the swale then the ponding water can be discharged into the next swale and, in the end, directly into the surface water.

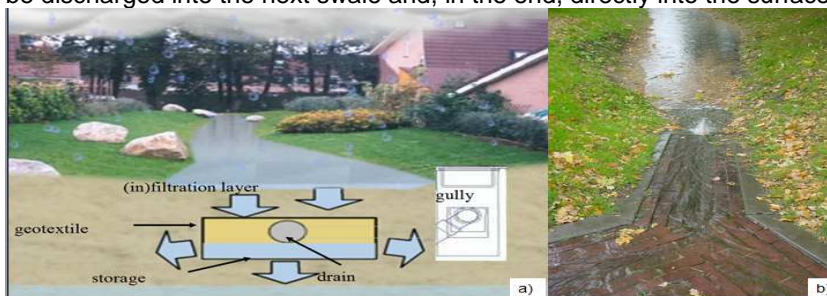


Figure 9-1 Swale (a) and gutters guide stormwater to the swales (b)

At the bottom of the infiltration device underneath the swale drainpipes spread the water through the infiltration body and drain the area when ground water tables are high (figure 9-1a). To manage the groundwater in combination with storm water infiltration a special regulating device has been installed in every downstream manhole to lower the level of drainage during winters and to store groundwater in summers. In this manner the swale system combines the drainage of ground and rain water in the wet winter periods with storage and infiltration during the dry summer periods.

According to the design requirements, all runoff from houses and roads is conveyed through street gutters to a system of swales, soakaways and infiltration units located at the end of the streets (see Figure 5-4 and Table 5-2 for details) [RIONED, 2006].

Study Methodology and results

From 1998 to 2006 the hydraulic performance of three of the bioretention swales was monitored by the use of waterloggers and weatherstation. Quantity and quality of precipitation, run-off, groundwater and overflows were analyzed. Local residents were also surveyed to establish their level of appreciation and general perceptions pertaining to this innovative urban drainage system.

The study found that the swales, soakaways and infiltration units generally emptied within 24 hours [Boogaard, 2012]. This was confirmed by observations by the local residents. However, the monitoring results showed that the observed hydraulic performance of the swales was significantly different to the design expectations. The main difference is shown in Table 9-1.

Table 9-1: Storage volume swale in Ruwenbos (the Netherlands)

Design Parameter	Design	Actual
Connected roof and paved surface/ house	65 m ²	83 m ²
Storage swale (against impermeable connected area) before discharge to gutter	20 mm	6 mm
Storage depth till street level	40 mm	19.4 mm

Although the actual storage is substantially less than planned, pluvial flooding has so far never occurred in Ruwenbos.

Maintenance

Due to the use of mowing machines, playing children, and the sedimentation of suspended sediment in the stormwater some parts of the grassed surface of the swales have become bare. Mowing when the soil is still moist has led to tracks. Using heavy machinery also causes reduction of the infiltration capacity of the upper layer of the bottom due to compaction. Furthermore experience showed that the slope between the swale and the surrounding field should not exceed the average slope of 1:3 in order to allow mowing machinery to enter the swale. For good functioning and appreciation of the swale system, clearing of fallen leaves and rubbish is recommended. The municipality cleans the gutters twice a year and the drainpipes once every year. Maintenance of the swale systems needs good tuning of the different activities to one another.

Conclusion and Lessons Learned

- The swales reduced the stormwater runoff significantly, 99% of the stormwater is infiltrated in the first 3 years (RIONED 2006)
- Any increases in groundwater levels due to the SUDS devices were localized and minimal. At peak storage capacity, a maximum increase of only 2 cm was recorded around the swales and this did not cause any problems for the houses on site
- The measured concentrations of pollutants found in stormwater runoff were higher than the Dutch MAC values. However, these were improved to acceptable levels by the swale treatment capacity. The concentrations of pollutants in the drainage water were lower than MAC values
- With the hydraulic monitoring data the emptying time is compared in 1999 and 2002, no clogging was determined in Ruwenbos (similar result for the swale in Arnhem), No significant accumulation of pollutants was found after six years of monitoring of the soil. All measured concentrations were below the Dutch MAC values limiting values [RIONED, 2006].

Case study 2 – Hoppergarten, Germany

Swale Location, Description and Objectives

In 1992 a new 100 ha commercial area development was constructed in Hoppergarten (east of Berlin). The case study area contains small and medium sized business plots with bio retention swales (details see table 5-3). The infiltration capacity of the site soil is relatively low and the ground water table is relatively deep. A modern stormwater management approach was required due to the limited capacity of a small existing creek which drains the entire catchment area. Swale-trench-systems are therefore widely used in the streets, as well as on the privately-owned properties (Figure 9-2). Due to a local planning regulation private properties require on-site stormwater management [Sieker et al., 1998].



Figure 9-2 retention measures on private properties (a) and public roads (b)

Study Methodology and Results

From 1996 to 2000 the complete hydrology of the system was monitored and evaluated by comparing the expected results from the planning phase with the results from the observed measurements. No specific water quality analysis was performed. However, the influence of one minor oil spill on the site was evaluated by soil and trench runoff samples.

Conclusion and Lessons Learned

The results suggest that the observed performance of the system was comparable to the anticipated design performance [Panning et al 2002]. In addition:

- The water balance achieved with the decentralized stormwater management systems was close to the natural pre-development conditions
- The infiltration sites were not clogged
- The reduction in runoff volumes and velocities agreed with design predictions
- The temporary ground water can be adequately managed by the swale system;
- The swale system is capable of retaining maximum discharge volumes from the site
- The system worked satisfactorily in during both summer and winter; and
- The water regime in the small river (Wernergraben) downstream of the development has improved in both dry and wet weather conditions
- The case study shows that a modern stormwater management approach incorporating infiltration swales is an effective way of reducing stormwater runoff from catchments with low-permeability soils

Case study 3 – Bergen, Norway

Swale Location, Description and Objectives

The swale described in this case-study is part of the historical World Heritage Site: Bryggen in Bergen, on the west coast of Norway (details see table 5-3). The average annual rainfall in Bergen is 2,250 mm/y and annual mean temperature of 7.6 °C, varying from 1.3 to 14.3 °C average daily temperature. Dry swales in this area are predominately used to increase the groundwater level and humidity in the top soil cost-effectively to avoid oxygenation and loss of highly organic cultural deposits in the subsurface. The study swales consist of two grassed areas positioned side by side. Each swale is approximately 20 m long, 6 m wide and has an average slope of 1:2 (Figure 9-3b). The swales are primary installed to capture and treat stormwater runoff from upstream roofs and roadway areas and convey most of the water to the groundwater and the further downstream underground infiltration-transport system.

Study Methodology and Results

Since the primary target of the swale system at Bryggen is to increase groundwater infiltration for preservation of organic archaeological assets, particular focus was placed on removal efficiency of oxidizing agents such as oxygen and sulphate, as those may induce increased decomposition of organic material. A baseline study was performed to characterize the stormwater quality from the upstream roofs and road areas. Results showed a large variation in the amount of pollutants bound and unbound to suspended solids compared to previous study results (chapter 3). The concentrations measured were higher than found in literature (Pb 35 ug/l, Zn 326 and Cu 70 ug/l). Pollutants appeared to be more dissolved than previous research results, which could be the result of mobilization by road salt. This may inhibit single-step treatment performance. Therefore, a "treatment train" of several SUDS devices was developed in order to achieve high pollution removal rates and prevents loss of valuable archaeological assets and consequential subsidence.



Figure 9-3 a) Site plan; b) Swales on Unesco world heritage site

Conclusion and Lessons Learned

The concentrations and characterization of pollutants can vary at different research locations. In most situations the removal efficiency of a swale would be sufficient to stay under MAC or WFD values. In Bryggen the monitoring has led to the design of a treatment train (rainwater garden, swale and permeable pavement). The use of shallow SUDS to protect and preserve subsurface organic cultural deposits in a historical urban area with significant legal limitations for (modern) constructions and deeper excavations is not only cost-effective, but also a robust and practical solution [Beer et al., 2012].

Case study 4 - Sunshine Coast, Australia

Swale Location, Description and Objectives

The swale described in this case-study is part of a sporting field complex on the Sunshine Coast (SSC) in Australia. The SSC is an urban area in South East Queensland and experiences frequent, short-duration, high-intensity rainfall events. The average annual rainfall on the SSC is 1,464 mm/y and annual mean temperatures range from 15.8 to 25.2C°. The study swale was grassed, approximately 40 m long, 10 m wide and had an average side slope of 1.25% (Figure 9-4a (details see table 5-3)). The swale was installed to capture and treat stormwater runoff from adjacent car parking and roadway areas and convey it to the downstream underground stormwater drainage system. Swales (including the case-study swale) are predominately used on the SSC to convey large runoff volumes quickly and cost-effectively, while at the same time providing some basic water quality treatment functions.

Study Methodology and Results

A series of controlled field experiments was undertaken to quantify the effect that swale length had on the pollutant removal performance of total suspended solids (TSS) from the synthetic stormwater used in the study.

Pollutants were introduced into the synthetic stormwater based on literature values for typical Australian urban runoff quality data [Duncan 1999; Wong 2006]. A control test was performed without any pollutants to determine the background concentrations found in the swales. The TSS concentrations of Test 2 replicated typical urban Australian concentrations. The third and fourth tests were five times, and ten times the typical TSS concentrations, respectively. These two tests were included to ensure measurable results would be obtained in the results. However, these pollutant concentrations are not representative of typical Australian stormwater conditions.

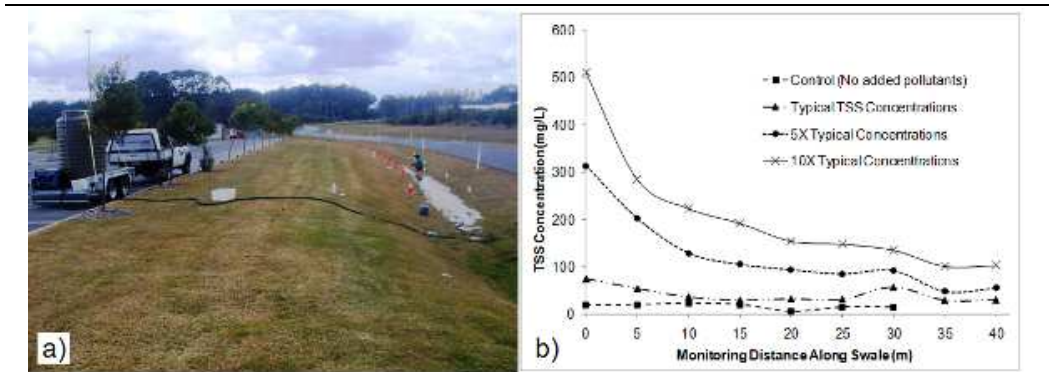


Figure 9-4 a) Water quality monitoring; b) Monitoring Results.

Figure 9-4b shows that between 50% and 75% of the TSS was removed within the first 10 m of the swale length. It can also be seen that there was a significant decline in the TSS removal efficiency after the first 10 m and the removal rate was minimal from that point on.

Conclusion and Lessons Learned

The study, where the primary goal of the swale is sedimentation, showed a distinctive exponential decrease of TSS concentration along the grass swale and that between 50% and 75% of the TSS was removed within the first 10 m of the swale length. These results suggest that installation of excessively long swales to treat stormwater TSS pollution may not be the most cost effective solution. Beyond 10 m, only a further approximately 20% reduction can be expected, regardless of the total length [Kachchu et al, 2013].