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RESEARCH ARTICLE

Removal efficiency of storm water treatment techniques: standardized full scale laboratory testing

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ABSTRACT
Sedimentation devices have been widely implemented to remove suspended solids and attached pollutants from stormwater before entering surface waters. The treatment performance of these best management practices (BMPs) on fine particles is rarely investigated in a standardized way. To overcome this information gap a reliable and standardized testing procedure is formulated.
Four devices have been tested on their suspended sediments removal efficiency at different discharges and particle sizes, using the newly developed standardized full scale test method. The observed removal rates of the facilities with a storage volume in the order of 1.5 m^3 and settling surface around 1 m^2 drop to low removal efficiencies at flow rates of 10 l/s or more. For small sized sediments (up to 63 µm) the removal efficiency is below 50%. The results of the experiments can be used to improve both the design and the dimensions of stormwater treatment devices.

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Introduction

Contaminants are transported in runoff via stormwater networks to either sewer systems or directly to downstream aquatic ecosystems (Davis *et al*. 2001, House *et al*. 1993). Existing drainage networks can be retrofitted with prefabricated devices (e.g. vortex separators and filters) and detention systems facilitating infiltration (e.g. infiltration basins, raingardens, swales) are designed to reduce flooding and remove suspended solids (Hatt *et al*. 2008, Palhegyi *et al*. 2010).

Major pollutants include: nutrients, heavy metals, PAH, pesticides and bacteria (Bratieres *et al*. 2008). Many of these pollutants are adsorbed to particles and will come to settle under stagnant or low flow conditions. Well-known examples of settlement devices are sedimentation basins, ponds, lamella filters, sedimentation chambers and sedimentation pipes.

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). Settlement devices can be categorized as source control stormwater control measures (SCMs).

The settling efficiency of sedimentation devices highly depends on the characteristics of the pollution load, dimensions of the facility and implementation in the field (Wilson *et al*. 2004, Woods-Ballard *et al*. 2011). For detailed determination of the pollution removal efficiency of these sedimentation devices information is needed on:

- Quality of stormwater.
- Suspended solids, pollutant adsorption behavior, particle size distribution and settling velocities of particles.
- Hydraulic loading and geometry of the facility.

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 up more than 70% of the total suspended sediment (TSS) load carried by runoff by weight (Andral *et al*. 1999, Furumai *et al*. 2002, German and Svensson 2002, Roger *et al*. 1998). The studies showed that particles less than 20 µm accounted for more than 50% of the particulate mass for runoff samples with a TSS concentration of less than 100 mg/L. Based on observed average particle size distributions in stormwater runoff at 25 locations in the Netherlands about 50% of the mass of the suspended sediment consists of particles smaller than 90 µm (Boogaard *et al*. 2014) (Figure 1).

The finest particles in runoff have the highest concentration for many pollutants, especially heavy metals, oil and poly-aromatic hydrocarbons (PAH) (Li *et al*. 2006, Morquecho and Pitt 2003, Roger *et al*. 1998, Sansalone and Buchberger 1997, Viklander 1998). Nutrients (TP and TN) are less bound to particles and are mostly adsorbed to sediments between 11 µm and 150 µm. It is

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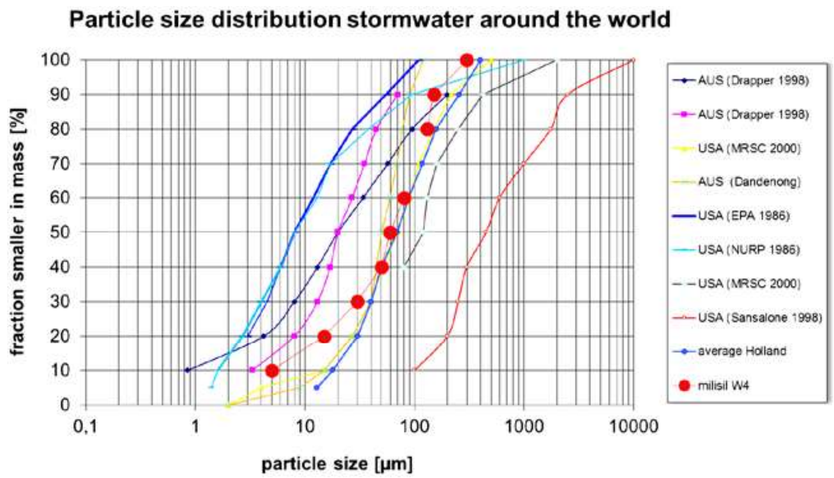

Figure 1. Cumulative particle size distribution of Millisil®W4 as compared to the observed average particle size distribution in urban storm water in the Netherlands and in storm water in the USA and Australia (Boogaard *et al*. 2014).

suggested that treatment facilities must be able to remove sediments down to 11 µm (Vaze and Chiew 2004).

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

Material and methods

Standardized test procedure

Regarding the formulation of a standardized monitoring protocol for testing these types of facilities in a comparable way, several lessons are to be learned from earlier laboratory research (Boogaard *et al*. 2010, Dierkes *et al*. 2013, Maniquiz-Redillas *et al*. 2014, Maus and Uhl 2010, Ngu *et al*. 2014, Welker *et al*. 2013, Uhl *et al*. 2013):

- Use sediment with representative, constant and well known particle size distribution and settling velocities. 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 (e.g., Howard *et al*. 2012, Kwon *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, 1999) and results of several tests are to be compared.
- Detailed monitoring on particles sizes being captured. Use a representative amount of particles. Tests that are run with higher concentrations than regularly occurring can overestimate the efficiencies of the devices (Uhl *et al*. 2013).
- Recirculation of the test water is to be avoided as this leads to fluctuating concentrations of suspended sediment in the influent.
- The test should be performed until a steady-state hydromorphological situation and a constant removal efficiency is reached with well-known hydraulic parameters. With residence times up to twice the water volume in the device decreasing removal efficiencies were observed. After a residence time >2 the efficiencies remained more or less constant (Uhl *et al*. 2013).

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

Table 1 presents an overview of the tests performed on each of the four devices as a standardized test procedure.

The general setup of the testing equipment is shown in Figure 2. The hydraulic capacity of the test facility was 400 l/s. This allows for testing of facilities that are capable of treating the stormwater of a connected impervious area in the range of at least 1–2 ha. This is a very common design range for drainage designers and manufacturers in the Netherlands (Boogaard *et al*. 2007).

Measurement equipment

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

Hydraulic performance

For gaining, an overall understanding on how a device functions hydraulically film footage can be very effective. By adding a tracer, $KMnO_4$ in our case, to the flow patterns, death zones and preferential flow paths can be visualized and recorded. Visualizations help with finding areas with relatively high flow velocities in a facility and finding measures to optimize the sedimentation performance of a device (Madhani *et al*. 2013, 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).

Sediment mixture for standardized testing

Settling properties of the facilities are to be tested in a standardized way. As mentioned, sediment particle sizes <60 µm have the

Table 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 death zones 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 hydraulic loadings. Visual removal efficiency test: visualization of sediment transport in transparent parts of the device (if available)	Standard suspended sediment mixture. Sampling 1 liter at 5 min intervals. By particle counting and (video-) camera

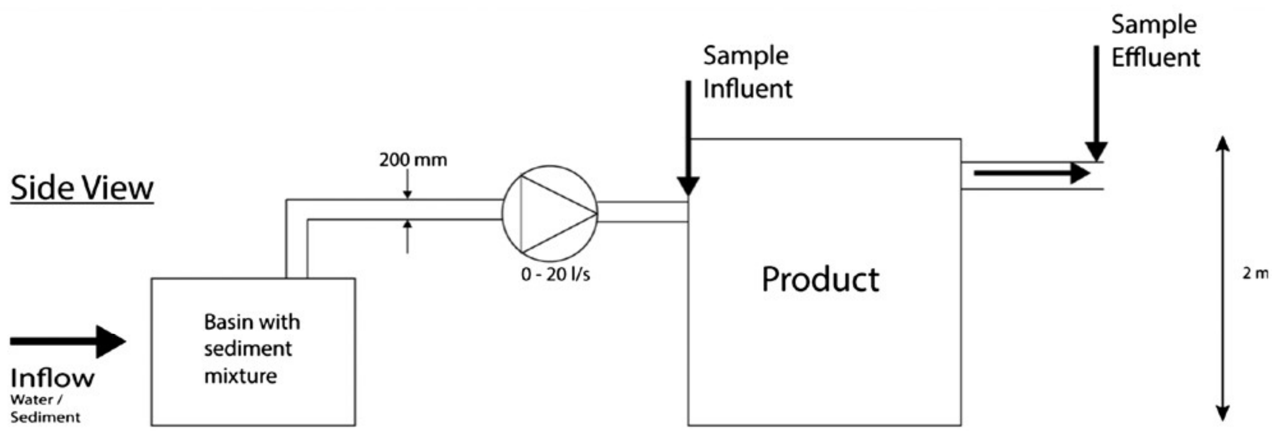

Figure 2. General setup of the testing platform.

Table 2. Equipment used in testing.

Measurement	Equipment type	Accuracy	Literature
Discharge	Endress+Hauser Prosonic flow 91	±0.5%	Endress+Hauser (2006)
Water height and water temperature	SchlumbergerMirco diver DI 501/ DI 500	0.05%[1]±0.5 cm H_2O± 0.1 °C	Schlumberger (2014)
Particle counting	HRLD-400HC	For particles 2–400 µm <10%[2]	Hach (2010)

Notes: 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).

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 within the range of 5–150 µm and a specific density of 2650 kg/m^3, pH of 7 and a specific surface of 1300 cm^2/g. The fractions 1–63 µm, with the water temperature in the lab between 15 and 20 °C will result in settling velocities ranging from 0.01 up to 13 m/h.

Figure 1 shows the particle size distribution of Millisil®W4 as compared to the observed particle size distribution in international urban stormwater.

Concentration

Suspended sediment concentration and particle size distribution in stormwater depends on location, type of connected paved area and specific activities on the site as well as on rainfall/runoff intensity. Stormwater monitored in the Netherlands shows an average of suspended solids 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 suspended solid concentration of 50 mg/l is chosen which is the 90% percentile value 50 mg/l of the Dutch database and close to international values. For example, 48 mg/l is the median value of TSS from the NSQD database that collected samples over nearly a ten year period from more than 200 municipalities throughout the USA (Pitt 2004).

Sampling

Each facility is tested over a range of hydraulic loads. Exactly every 5 minutes a grab sample of 1 liter was taken at both inflow

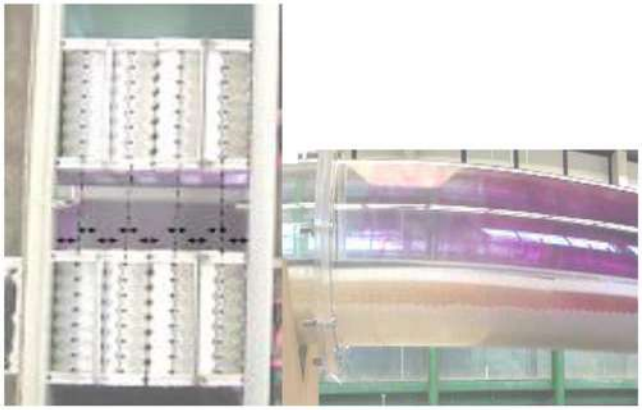

Figure 3. Visualization of preferential flow in lamella separator (top view: divided into nine parts where four parts have no visible current due to the construction bars of the lamella at the dotted lines), sedimentation pipe (right) where flow below the grid (sedimentation chamber) is observed.

and outflow point by two people for at least half an hour, producing at least 12 samples. Each sample is stirred to create and maintain a homogenous 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.

Settling velocity and removal efficiency

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

$$\eta = \frac{V_s}{(Q/A)} \qquad \text{(Hazen 1904)}$$

With:

ŋ 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.

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 2), * sampling uncertainty (uncertainty due to the potential temporal and spatial variability of the suspended sediment concentration), * storage uncertainty (samples are temporarily stored during the test for a maximum of 2 days; as the used aggregate is stable and inert this storage does not effect the results). The following actions have been taken to obtain a high accuracy of the results: * data processing (all data is stored in a database and recorded in a blog)* the discharge of the (calibrated) pump has been verified with timing the filling of the basin (900 dm^3)

- The volume of sediment calculated by the particle counter is verified by Imhoff cones and nflow of suspended sediment is checked by comparing the amount of particles per size at different influent samples (Figure 4). No sedimentation has been recorded by visual inspection in the inflow pipe. The Reynold number at the inflow pipe (200 mm) at 5 l/s and 10 l/s is 24.298 and 48.596 respectively.
- Most tests are repeated three times with the same hydraulic loading, and moving averaging (over five steps of 0.77 µm intervals) is used to smooth every removal efficiency curve.

Tested facilities

The sedimentation devices available in The Netherlands 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. The four selected devices have different separation techniques.

1) Sedimentation pipe: allows particles to drop through an open grid in the 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. Note that the sedimentation devices have different volumes and sizes, the largest being the sedimentation-pipe with a length of 24 meters and diameter of 600 mm. Facilities numbered 3 and 4 have more or less the same dimensions (cylinder shape with inner diameter of 0.995 meters) and are, in general, representative of many of the installed sedimentation devices used 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 m^3/h and 13.89 l/s).

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 sectional area (see colored flow in Figure 3). For the sedimentation-pipe 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.[1]

Observed removal efficiency by particle size

In Figure 4 the amount of particles of the influent and effluent is given for the cyclone filter 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 µm can be observed due to the fact that the amount of particles in each sample is limited.

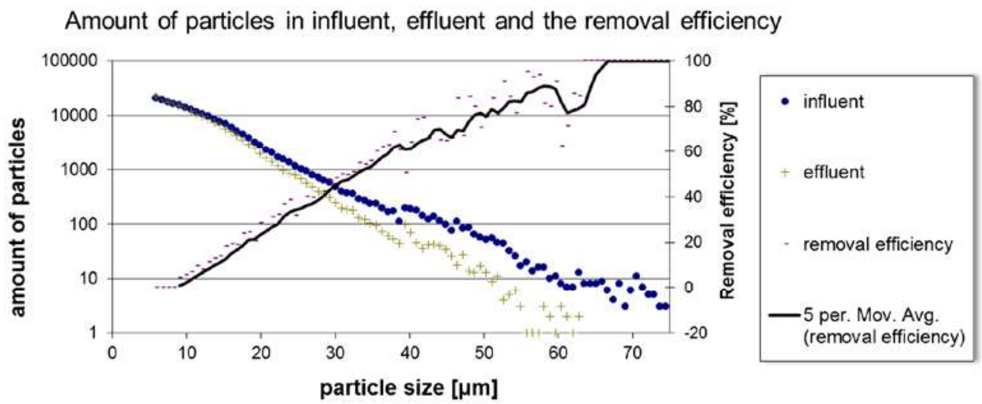

Figure 4. Amount of particles of the influent and effluent and removal efficiency of sedimentation slide (device no. 3 'cyclone filter') at 5 l/s (raw data).

Table 3. Properties of the four tested sedimentation devices for local treatment of storm water (detailed dimensions and drawings can be found in Appendix 1).

Treatment-process	Description of product	Storage volume(m^3)	Sedimentation surface (m^2)	Diameter Shaft(m)	Height(m)	Length(m)	Width(m)
Sedimentation pipe	Pipe between 2 shafts Grid in pipe to create sedimentation chamber	10.71	7.57	1	5	24	0.6
Lamella filter	Rectangular basin with lamella	2.75	1.83 without lamella, with 43.3 m2	-	1.5	3	0.61
Cyclone filter	A cylinder for cyclonic separation	1.40	2.27 (bottom and 2 rings)	0.995	1.8	-	-
Sedimentation filter	Cylinder with filter cartridges and sedimentation chamber	1.56	0.78 (bottom without filter substrate surface)	0.995	2	-	-

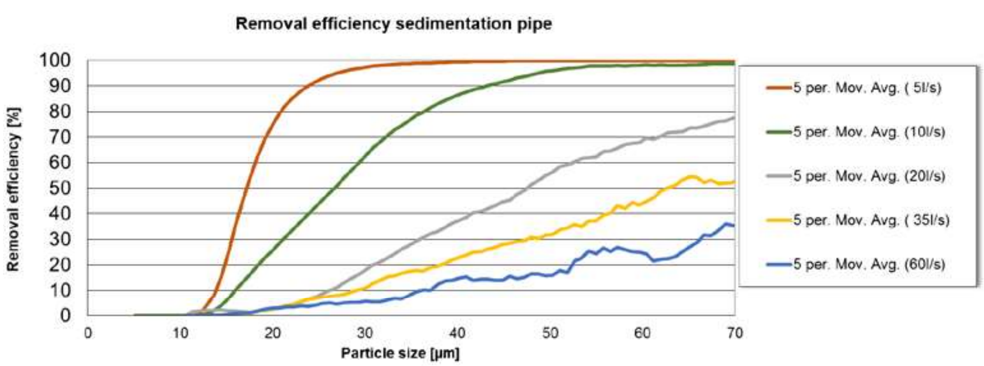

Figure 5. Removal efficiency of the sedimentation pipe (device no. 1) (moving an average of five steps) at inflow of 5, 10, 20, 35 and 60 l/s.

The observed removal efficiencies of the sedimentation-pipe for several flow rates are given in Figure 5. The data demonstrate the expected decreasing removal efficiency with increasing flow rate, as determined for all four sedimentation devices. Also the noise in the data increases as the flow rate increases, due to the turbulence the samples show more variable results.

The removal efficiency of the four devices varies with the characteristics of the device, such as volume, flow velocity and sedimentation surface (Figure 6). Given a flow rate of 10 l/s, even with a large facility like the sedimentation-pipe, small particle sizes, up to 25 µm, will not be removed by more than 50%. Particles over 60 µm are trapped with a removal efficiency higher than 80% but only by the larger sedimentation devices like the sedimentation-pipe and the lamella filter.

The observed removal rates of the facilities with a storage volume in the order of 1.5 m^3 (the cyclone filter and sedimentation filter) drop to low levels at a flow rate of 10 l/s. For sediments <60 µm, which contain the highest amount of pollutants, the removal efficiency is less than 50%.

Sedimentation efficiency

Figure 8 shows from all the performed tests the removal efficiency plotted against the settling velocity divided by the surface load So (So = 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 at 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

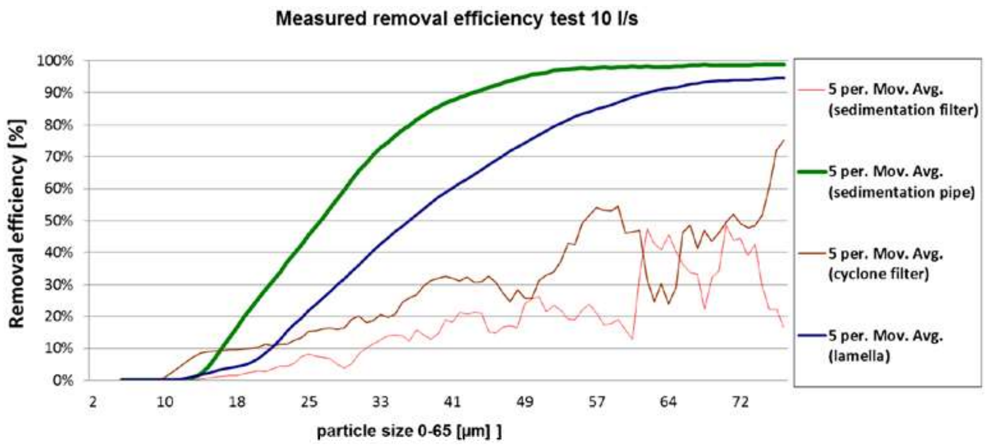

Figure 6. Removal efficiency of suspended sediments (Millisil®W4) observed in four sedimentation devices for storm water treatment at a flow rate of 10 l/s (five steps moving average of observed efficiency).

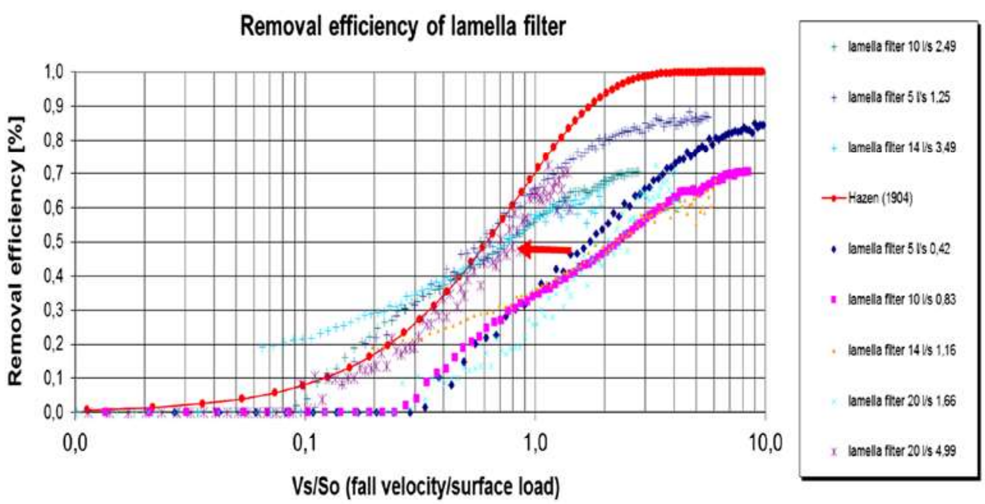

Figure 7. Removal efficiency of lamella filter related to the surface load against the theory by Hazen (red curve). In the legend the type of device is given with the discharge (l/s) and the surface load (m/h).

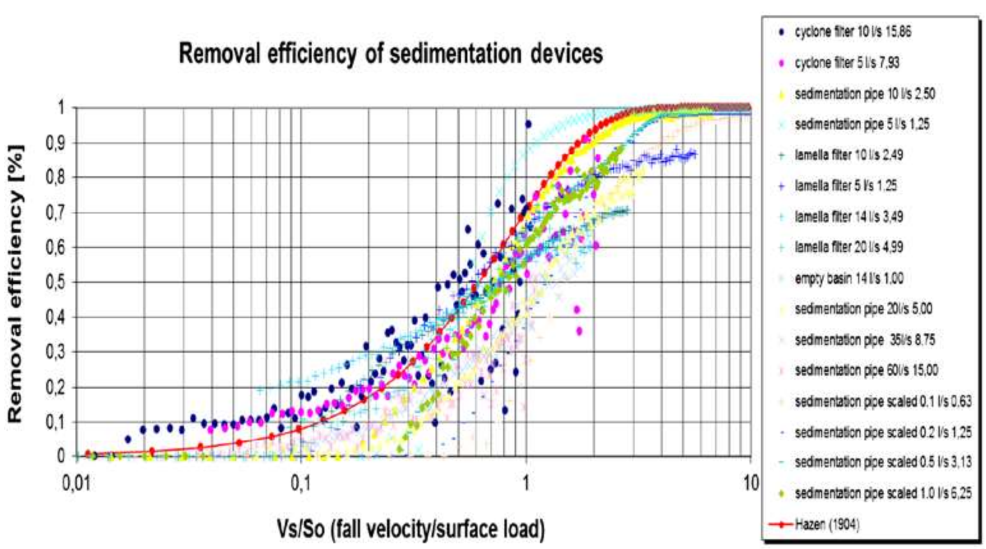

Figure 8. Total removal efficiency of all tests related to the surface load against the theory by Hazen (red curve). In the legend the type of device is given with the discharge (l/s) and the surface load (m/h).

earlier research (Boogaard *et al*. 2010) and tracer testing (Figure 3) it could be observed that due to the construction by far not all of the surface is contributing to the removal efficiency. If we take into account the minimum factor of 4/9 (45%) for the effective sedimentation surface the curves fits more closely to the theoretically expected sedimentation, see Figure 7 where the best fit is achieved when 33% effective sedimentation surface is applied.

In Figure 8 where the removal efficiency of all tests are related to Vs/So, the curves are close to Hazen's theory (red curve) but show individual deviances that can be caused by earlier discussed inaccuracy in measurement equipment or measurements but more likely the real 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.

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 Vs/So should be in the order of 0.7. Example: in order to remove more than 50% of particles smaller than 60 μm (settling velocity of 9 m/h) the maximum surface load should be 15.9 m/h, which would indicate a maximum hydraulic load of about 10 l/s for the cyclone filter. Any higher load should be by-passed.

Discussion

Although the particle size distribution of Millisil®W4 sediment shows a decent match with international particle size distribution it should be taken into consideration that the particle shape, specific density and coagulation properties are different.

The experiments show for the sedimentation devices with a sedimentation surface in the order of 1–2 m^2 flow rates should be minimized up to 10 l/s in order to capture more than 50% of fine particles up to 60 μm.

Conclusions and recommendations

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 Hazen's theory. From the relation between removal efficiency to Vs/So 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 the flush-out of earlier collected sediment at high discharges.

Recommendations

The standard test results provide insight into 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.

Further research could focus on the removal efficiency of substances that are less bound to suspended solids such as pathogenic microorganisms.

Note

1. Visual results of tracer experiments can be seen on the following urls: Tracertest Lamella filters: https://www.youtube.com/watch?v=uRkL0EZmqyc&list=UUdrVBHNrWAhkw4bxpzN4Ytw and tracertest Sedipipe: https://www.youtube.com/watch?v=i1GzDdTQdnY&index=3&list=UUdrVBHNrWAhkw4bxpzN4Ytw

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