# Particle separation from road runoff by a decentralised lamella system – laboratory tests and experiences in the field

J. Fettig, V. Pick and H. Liebe

## ABSTRACT

A new decentralised settling system based on the principle of lamella separation was developed for the treatment of road runoff. Two different laboratory test methods, the DIBt (Deutsches Institut für Bautechnik) procedure and our own approach, were applied in order to evaluate the efficiency of the system based on the separation of fine mineral particles and a mixture of mineral and organic particles, respectively. Overall efficiencies (88% after DIBt and 61% according to our own method) were comparable to results obtained for commercial systems. The lamella system was then applied in the field for 1 year to treat runoff from a road area of 420 $m^2$. The amount of solids separated that was calculated from a mass balance (10.1 kg) was consistent with the amount of sediments measured (8.6 kg). However, the average separation efficiency was only 30% in the field study. This is related to the size and composition of the particles in runoff, which are not represented well by the material used for the test procedures. It is concluded that the test methods should be improved, and that more field studies are needed in order to obtain a better understanding of the settling behaviour of particles in road runoff.

**Key words** | lamella settler, particle separation, road runoff, test methods

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## INTRODUCTION

In industrialised countries both combined sewer overflows and discharges from storm water sewers are a major source of aquatic pollutants (Sieker 2013). Since storm water runoff from traffic areas (roads, streets and parking lots) contributes significantly to overflows, several states of Germany now plan to require pre-treatment of polluted runoff before local discharge or infiltration. Besides semi-central facilities, decentralised systems treating runoff from traffic areas of 100–500 $m^2$ in size will play an important role in this concept.

According to a recent review of European studies (Huber *et al.* 2015), the following median concentrations of heavy metals in runoff from motorways were found: 230 μg/L for zinc, 52 μg/L for copper, and 17 μg/L for lead, respectively. The data reveal that a considerable amount of these metals is bound to particulate matter. Similar findings were reported for North America (Kayhanian *et al.* 2012). Other investigations have shown that polycyclic aromatic hydrocarbons are also associated with particles to a large extent (Nielsen *et al.* 2015; Ozaki *et al.* 2015). Therefore mechanical treatment for the removal of particles from runoff can reduce significantly the load of pollutants. However, there is evidence that runoff from traffic areas contains a substantial fraction of fine particles with $d < 63$ μm (Li *et al.* 2005, 2006; Kim & Sansalone 2008). Thus the removal efficiencies obtained by applying mechanical processes might be limited.

The development of decentralised systems for runoff areas between 250 and some 1,000 $m^2$ that can be integrated into street inlets started some 10–15 years ago (Fettig *et al.* 2007). They can be grouped into settling systems, filtration systems or a combination of both. At present 14 different systems are on the German market (Sommer *et al.* 2015); however, it is difficult to predict their performance under field conditions. In order to overcome this problem, test methods have been suggested that will simulate the separation of fine mineral particles (DIBt 2011) and both mineral and organic particles (Fettig *et al.* 2008). Recent work has indicated that particle separation efficiencies obtained in the field differ considerably from the test results (Barjenbruch *et al.* 2016). Therefore one specific goal of our work was the comparison of particle

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removal results obtained in laboratory tests and under field conditions.

In this study a new decentralised settling system based on the principle of lamella separation was developed. This principle has been applied in semi-central treatment of storm water, i.e. units for runoff areas of more than 5,000 $m^2$, for a number of years (Clark *et al.* 2009; Hermann *et al.* 2010; Langeveld *et al.* 2012; Fuchs *et al.* 2014; Weiss 2014). The system was first tested under laboratory conditions and then applied in the field over a period of 1 year. The results are discussed with respect to the validity of the test methods. Hence the main objective of our study was to demonstrate whether lamella separation is a suitable method at the scale of decentralised systems with respect to both hydraulic properties and particle removal efficiency.

## MATERIAL AND METHODS

The lamella plate settler developed by our group is shown in Figure 1. The water flows from the inlet at the top through a small half-open container from which influent samples are withdrawn. Then it falls down about 10 cm to the water column, moves to the lower part of the manhole and then upwards through the lamella plate pack to the outlet. The lamella separator is made of 2 mm PVC plates, 28 cm in width and 25–39 cm in length. Altogether 11 plates are arranged at an angle of 60° and a distance of 2.1 cm, giving 10 flow channels with a total cross-sectional area of about 0.06 $m^2$. The particles are supposed to settle onto the upper surface of the plates and eventually slide down on them and settle further to the bottom of the manhole.

The effective settling area of the system, i.e. the projected lamellae area seen from above, is 0.41 $m^2$ and thus about 2.5 times larger than the cross-sectional area of the chamber. The minimal filling volume of the system is 133 L. Inflowing water causes an increase of the filling level, which determines the flow rate through the system. The bypass is activated when a filling volume of 198 L corresponding to a flow rate of 3 L/s is reached; i.e. the water flow in excess of 3 L/s will not pass through the lower part of the system. Thus turbulences close to the bottom sediment are limited and the sediment is prevented from being washed out at very high hydraulic loadings.

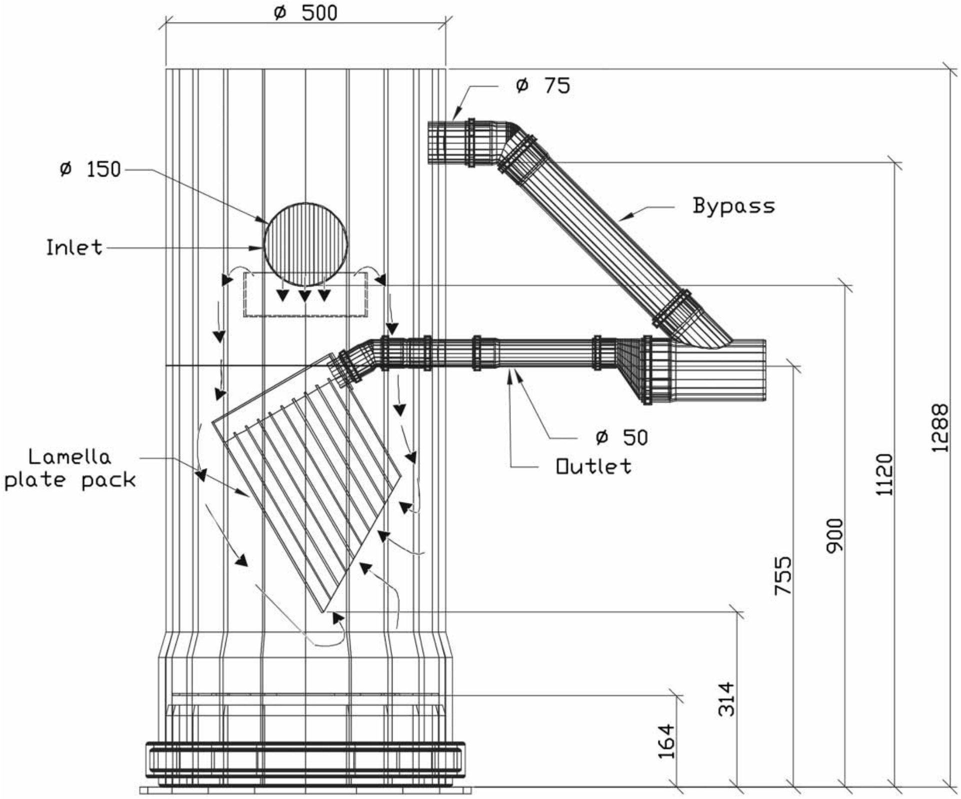


**Figure 1** | Decentralised lamella plate settler developed in this study (unit: mm).

The DIBt (Deutsches Institut für Bautechnik) laboratory test procedure (DIBt 2011) is based on the loading of a system with fine mineral particles (Millisil W4, Quarzwerke Gruppe, Germany). Characteristic diameters of the material by weight are: $d_{10} = 7$ µm, $d_{50} = 63$ µm and $d_{90} = 160$ µm, respectively; and its density is 2.7 g/cm$^3$. Three flow rates of 0.1 L/s (for 480 min), 0.24 L/s (for 200 min) and 1 L/s (for 48 min), respectively, are applied in the first part of the test. Here, altogether 20 kg of solids are fed into the system, resulting in total suspended solids (TSS) concentrations in the inflow of 1.2–3.5 g/L. This part of the test will simulate the solids load of 1 year. Finally a maximum water flow of 4 L/s is applied for 15 min without the addition of solids in order to estimate remobilisation of the sediment. For each flow rate at least 10 time-proportional effluent samples of 1 L are taken in order to obtain a representative composite sample. Individual separation efficiencies for each flow rate are determined from the ratio of the measured solids load in the effluent and the calculated solids load in the influent, respectively. By taking the results of the remobilisation test into account, the overall separation efficiency is calculated (DIBt 2011).

For our own test method (called HS-OWL test method) that was developed independent of the DIBt approach, a mixture of 42% of fine mineral particles and 58% of dried and sieved potting soil is used. The mineral particles have the characteristic diameters $d_{10} = 36$ µm, $d_{50} = 120$ µm and $d_{90} = 500$ µm, while the soil particles' diameters are <800 µm. Since the latter also contain inorganic compounds, the test material has a total organic content of 30%. The flow rates used (0.2 L/s, 0.5 L/s, 2 L/s for loading and 5 L/s for remobilisation, respectively), are higher than proposed by DIBt. Meanwhile, the total solids load (153 g) is lower because influent concentrations of 150 mg/L are applied, and the test period (28 min) is considerably shorter. About 25 time-proportional effluent samples of 100 mL are taken for each flow rate. As with the DIBt test, the overall separation efficiency is calculated (Fettig *et al.* 2008). In both tests, the particles are quantified as TSS according the German Standard DIN 38409 H2.

In addition to the lamella plate settler, two commercial decentralised settling systems, the Centrifoel Separator (Roval Umwelt Technologien, Germany) and the Aco System (ACO Tiefbau, Germany) that are designed to treat runoff from areas of 400–500 m$^2$ like our system, were tested in the laboratory in order to compare their performance with the lamella plate settler. The Centrifoel Separator has three settling compartments which are flowed through successively, while the Aco System is a sludge trap with a deflecting plate and other devices that minimise turbulences in the water flow. Details are given by Sommer *et al.* (2015).

For the field study the lamella system was connected to an inlet that received runoff from a road area of 420 m$^2$ frequented by about 12,000 vehicles daily. The inflow had to pass through a sieve first which removed leaves and other coarse material. The chamber of the system was equipped with a device for continuous flow measurement that calculates the flow rate from the storage depth recorded in intervals of 10 s based on a corresponding calibration curve (UFO-Ex, W.A.S. GmbH, Germany). Flow-proportional samples were taken from the half-open container at the inflow pipe and from the outflow pipe (TP 5, MAXX Mess- und Probenahmetechnik GmbH, Germany). A sample of 50 mL was collected after each 50 L of throughput, from which weekly composite samples were prepared. The system was cleaned twice (after 6 and 12 months), and the sediments were quantified.

Rainfall intensity data for the period of the field study are given in the Supplementary Material (available with the online version of this paper). For different events, rainfall data were compared with the flow through the system, resulting in event-related runoff coefficients between 0.6 and 1.0. As documented in the Supplementary Material, the runoff coefficient was 0.76 on average. A time series of the recorded storage depths in the system for the whole period as an indirect result of runoff variation is shown in Figure 6. The corresponding statistical evaluation of the hydraulic loading of the system is given in Figure 7.

## RESULTS AND DISCUSSION

Figure 2 illustrates that the individual separation efficiency of the lamella system according to the DIBt test procedure

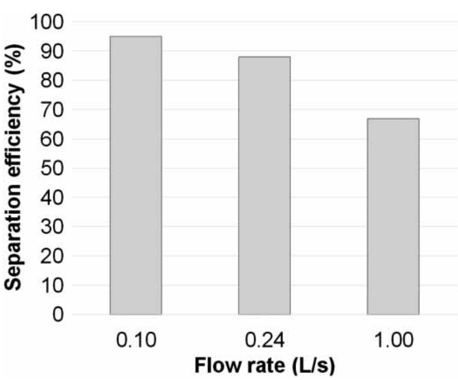


**Figure 2** | Separation efficiencies of the lamella system at different flow rates according to the DIBt test method.

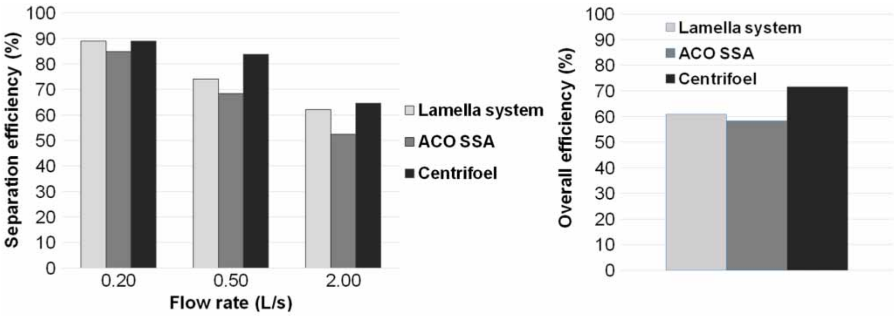


**Figure 3** | Separation efficiencies of the lamella system and of two commercial systems at different flow rates according to the HS-OWL test method.

is 95% at low and 88% at medium flow rate, while it decreases to 67% at high flow rate. The overall efficiency is 88% since the amount of remobilised material at a flow rate of 4 L/s was very small.

In Figure 3 separation efficiencies of the lamella system according to the HS-OWL test method are compared with results for the two commercial systems tested. In general the efficiencies are lower compared with the DIBt method. This can be attributed in part to the flow rates of the HS-OWL method, which are about twice as high. The lamella system is as efficient as the Centrifoel system at low and high flow rate and a bit less efficient at the medium level. The overall efficiency of the lamella system is lower than that of Centrifoel because the amount of remobilised material at a flow rate of 5 L/s was higher.

The results for all three systems are summarised in Table 1. The average removal efficiencies obtained are 65% (HS-OWL) and 74% (DIBt), respectively. According to the HS-OWL method the lamella system is comparable to the commercial systems, whereas it is clearly better based on the DIBt procedure. However, the Centrifoel system shows a less favourable performance in the DIBt test, whereas opposite results are obtained for the other systems. Thus there seem to be shortcomings with the test procedures, in particular with the DIBt test method, which might be partly caused by the results of the remobilisation test.

In order to study remobilisation in more detail, 2 kg of Millisil W4 were put onto the bottom of the manhole of the lamella system as mineral sediment. After 16 h the system was flushed with water for 1 min at different flow rates, the effluent was collected and the particles that had been washed out were analysed by wet sieving. The amounts of solids found in the effluent were between 3.4 g and 5.3 g, corresponding to less than 0.3% of the sediment, and thus relatively small. A possible reason is a certain agglomeration of the silica particles. Furthermore the flow rates were causing an overflow via the bypass that limited the washout effect to some extent. As illustrated by the data shown in Figure 4, fractionation takes place; i.e. relatively more fine particles are remobilised. This effect can be expected; however, it can be questioned whether the small quantity of solids washed out from the mineral sediment is representative for practical conditions where the sediment also contains light organic particles. In the remobilisation test phase of the HS-OWL method a fraction of up to 11.2% of the sediment was washed out.

In the field study, weekly composite samples from the influent and effluent of the system were analysed for TSS and heavy metals. TSS concentrations as a function of time are shown in Figure 5 for the winter half-year (Phase I) and the summer half-year (Phase II). Although high influent values are buffered by the system, overall particle separation

**Table 1** | Overall separation efficiencies of the lamella system and of two commercial systems

| Test method | Lamella system | ACO SSA | Centrifoel |
|---|---|---|---|
| HS-OWL | 61% | 58% | 72% |
| DIBt | 88% | 77%[a] | 60%[a] |

[a]Werker et al. (2012).

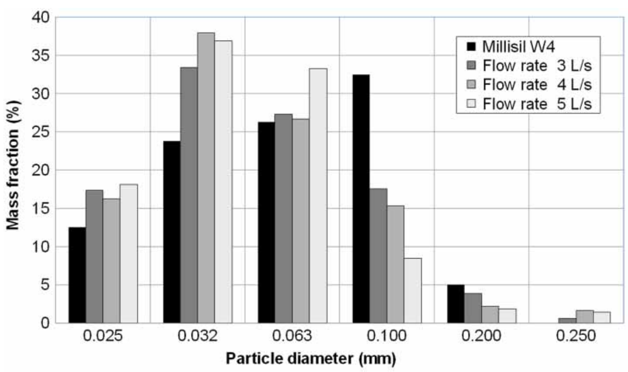


**Figure 4** | Mass fractions of different size ranges of Millisil W4 washed out from the manhole of the lamella system at high hydraulic loadings.

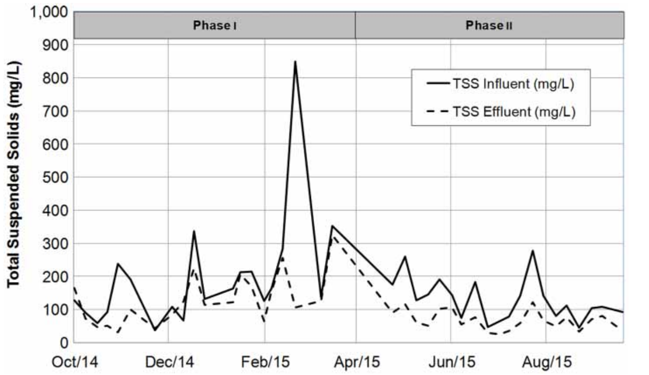


**Figure 5** | Influent and effluent TSS concentrations of the lamella system during the field study.

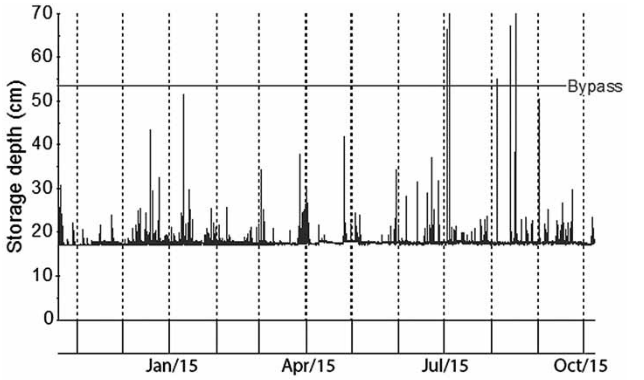


**Figure 6** | Time series of the recorded storage depths in the decentralised system during the field study.

was not as efficient as expected. Flow-weighted average influent concentrations were 210 mg/L in Phase I and 100 mg/L in Phase II, with an organic fraction between 35% and 43%. The corresponding flow-weighted average effluent concentrations were 164 mg/L in Phase I and 52 mg/L in Phase II.

After both phases the sediment was removed, dried and weighed. From about 230 $m^3$ of runoff passing through the system during 1 year, altogether 8.6 kg of solids with an average organic content of $35 \pm 9.8\%$ were separated. When calculated from flow-weighted TSS concentrations the mass of solids that was separated should have been 10.1 kg. In view of the conditions of sampling, these data are consistent. Moreover, no deposits which could have affected the flow were detected on the lamella plates.

The average TSS removal efficiency for the whole period was 30% and thus similar to the removal efficiency for zinc, whereas the other metal compounds were removed to a lesser extent (Table 2). However, TSS removal in the field study was clearly lower than in the laboratory tests. A possible reason is the fraction of fine particles in road runoff. During 5 weeks $TSS_{fine}$ concentrations ($d < 63$ μm) were determined in addition to the total TSS. In influent samples $TSS_{fine}$ amounted to 50% of total TSS. While the average separation efficiency during this period was 34% for TSS, the result was only 24% for $TSS_{fine}$. These findings indicate that the efficiency of a settling system for the removal of fine particles might be limited. In order to find a conclusive explanation, the hydraulic conditions are evaluated in more detail first.

**Table 2** | Removal efficiencies for TSS and heavy metals in the field study

| Parameter | Phase I | Phase II | Whole period |
|---|---|---|---|
| TSS | 22% | 48% | 30% |
| Zn | 21% | 47% | 31% |
| Cu | 10% | 16% | 12% |
| Pb | 19% | 7% | 16% |
| Ni | 6% | 25% | 13% |

The storage depths in the system during the field study were recorded in time intervals of 10 s by the data logger. The time series for the whole period shown in Figure 6 illustrates that the bypass was activated quite seldom. Average flow rates were calculated for time intervals of 10 s, 1 min and 5 min, respectively, and grouped in classes. As a result, the number distribution of the metered flow events was dependent on the interval width, while the volume distribution (=amount of water that passed through the system) was almost constant for all three intervals. Figure 7 shows the cumulative volume distribution of water flow rates through the system for a time interval of 1 min as a function of surface loading based on an effective area of the system of 0.41 $m^2$. Accordingly, 54% of the total runoff passed through the system at a surface loading of less than 2 $m^3/(m^2\,h)$, another 30% at values between 2 and 5 $m^3/(m^2\,h)$, 14% at

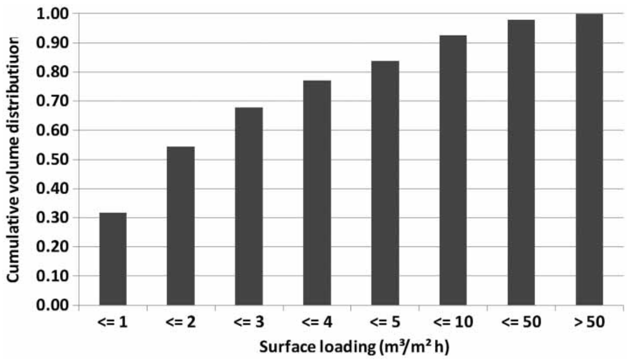


**Figure 7** | Cumulative volume distribution of water flow rates through the system derived from 1 min average values as a function of surface loading.

values between 5 and 50 $m^3/(m^2 h)$ and only about 2% at values higher than 50 $m^3/(m^2 h)$.

For the design of lamella settlers in semi-central systems, Weiss (2014) and Fuchs et al. (2014) recommend a maximum surface loading of 4 $m^3/(m^2 h)$, equivalent to a storm intensity of 15 L/(s ha). In our study 78% of the total water flow passed through the system under these conditions. If we assume a surface loading of 5 $m^3/(m^2 h)$ as a design value, the corresponding storm intensity will be about 18 L/(s ha), based on a runoff area of 420 $m^2$ and an average runoff coefficient of 0.75. Fuchs et al. (2014) derived a maximum surface loading of 5.6 $m^3/(m^2 h)$ and a mean surface loading of 1.9 $m^3/(m^2 h)$ from their data. With a mean inflow concentration of 134 mg/L they obtained 49% removal of TSS. In other recent studies with settling systems for storm water treatment, particle removal has also been only moderate. For a hydrodynamic separator operated at surface loadings of 16–40 $m^3/(m^2 h)$, Lee et al. (2014) found TSS removal efficiencies between 9% and 43%. Langeveld et al. (2012) investigated a semi-central lamella separator designed for a surface loading of 1 $m^3/(m^2 h)$ and obtained these results: 34% removal of TSS, 23% removal of zinc, 21% removal of copper and 36% removal of lead. Thus it is concluded that the operating conditions of our system were not much different from those of semi-central systems. Taking into account that the removal efficiency for TSS might be improvable by up to 6% using a nozzle distributor for the inflow into the lamella plate pack (Salem et al. 2011), the efficiencies are also in the same range.

When looking at removal efficiencies the hydraulic conditions are interconnected with the size of the particles to be separated. As stated before, our grab samples showed a fraction of 50% of fine particles (d < 63 μm). Fuchs et al. (2014) found even larger fractions of 70–90% of $TSS_{fine}$, while Selbig et al. (2016) measured a fraction of about 70% (mean value) in runoff from a parking lot and referred to data from the US Nationwide Urban Runoff Program where a generalised particle size distribution with a $TSS_{fine}$ fraction of even 88% is reported. On the other hand, Charters et al. (2015) observed a mean value of 39% for the fraction of $TSS_{fine}$ in urban runoff (TSS concentration of 158 mg/L), and Herr & Sansalone (2015) reported a value of 85 μm for the mean particle diameter ($d_{50}$). However, in both studies a large variation of particle size distributions measured for different events was observed: the diameter $d_{50}$ varied between 12 μm and 103 μm (Charters et al. 2015) and its standard deviation was ±76 μm (Herr & Sansalone 2015). Thus there seems to be some evidence that the fraction of fine particles in road runoff can be quite high during certain periods.

The removal of particles from road runoff by sedimentation can furthermore be affected by the following circumstances:

(a) A low density of the solids. For road dust, a particle density of 2.2 $g/cm^3$ was found in an orienting analysis in the field study. However, organic matter can take up water which will result in a reduction of the density (negative effect) but on the other hand in a swelling of the particles and thus in a positive size effect on sedimentation.
(b) The shape of the particles in combination with a certain roughness of their surface. Particles with irregular shapes are likely to settle more slowly. However, in this respect there is still a lack of knowledge, so the effect of shape cannot be assessed at this stage.
(c) The first flush effect. According to Kayhanian et al. (2012) the so-called concentration first-flush has been observed in numerous studies; i.e. the concentrations of solids and dissolved pollutants in road runoff tend to be higher during the first minutes after rain has started because of drag effects on the road surface. Although Sun et al. (2015) state that a first flush in their study area was not common based on strict definitions, the data of Bach et al. (2010) and Barjenbruch et al. (2016) support the first flush effect. Since the flow rates and thus the surface loadings of the system are often quite high during these periods, the removal efficiencies will then be particularly low.
(d) An uneven flow distribution. It is likely that flow velocities through different channels of the plate pack are not constant. In that case even large particles can pass through the system due to high local flow rates. Since measurement of the flow distribution was not possible, this effect cannot be assessed in detail. Further work will include flow modeling, which might give more insight into the hydraulic conditions inside the system.

So far there are not enough data available to distinguish between the impacts of each effect. For a rough estimate the separation size for settling processes according to Stokes' law was calculated for two different types of particles, sand (particle density = 2.5 $g/cm^3$) and organic matter (particle density = 1.5 $g/cm^3$), that were assumed to be spherical. The results are given in Figure 8 as a function of surface loading of our system. In addition, the residence time for water in the system as well as the flow conditions of the laboratory and field tests is illustrated. Accordingly, the separation size will be 50 μm for sand and 85 μm for organic matter at a surface loading of 5 $m^3/(m^2 h)$, while the numbers are 32 μm and 54 μm, respectively, at a surface

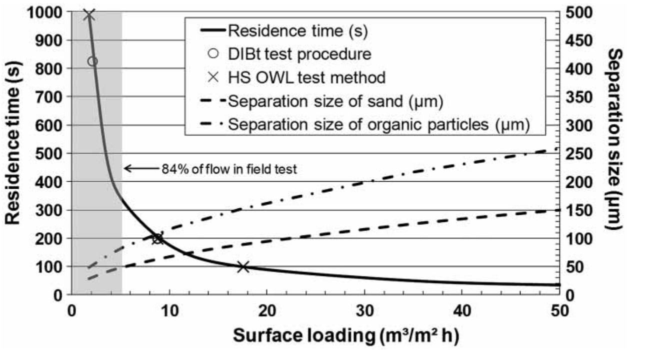


**Figure 8** | Residence time and separation size of two different materials as a function of surface loading of the lamella system (filling volume = 198 L).

loading of 2 $m^3/(m^2\,h)$. Particles larger than the separation size are not completely removed by settling under ideal conditions, but at least in part. When assuming a particle size distribution with a median of 63 µm and an organic fraction of 35%, better removal than observed in the field study should be expected. Therefore it is concluded that both the shape of the particles, the first flush effect and possibly an uneven flow distribution also contribute to the low removal efficiencies observed in the field.

With respect to the test methods it can be stated that the flow rates seem to represent the range encountered in the field: the DIBt method corresponds to surface loadings between 0.9 and 8.8 $m^3/(m^2\,h)$, while the HS-OWL test even covers the range between 1.8 and 18 $m^3/(m^2\,h)$ and thus more than 90% of the water flow rates through the system (Figure 7).

However, it is strongly suggested to modify the test methods in such a way that the test material better represents the particles in runoff regarding size and composition. The DIBt test could be adjusted by using a second material with lower density besides Millisil and by reducing the influent concentration to realistic values. The HS-OWL method could be modified by using a larger fraction of both mineral and organic fine solids. Furthermore the first flush effect could be accounted for by conducting the high flow rate test with a higher influent concentration. The goal should be to obtain a better predictability of the systems' performance in the field based on laboratory test results.

## CONCLUSIONS

1. The decentralised lamella system developed has shown good hydraulic properties. The bypass that limits the flow rate through the system to 3 L/s was activated only seldom during the field study.
2. The laboratory test results for particle removal were similar or better than those of commercial systems of the same size according to both test methods applied. However, the TSS removal efficiency in the field was considerably lower.
3. Among possible explanations for this discrepancy the hydraulic conditions may play a certain role, but it is likely that parameters such as size, shape and density of the particles are more important. In addition the first flush effect or an uneven flow distribution inside the plate pack can reduce the TSS removal efficiency. More studies particularly under field conditions are needed to clarify this puzzle.
4. The laboratory test methods need to be adjusted in order to better represent the practical circumstances and to provide more realistic results. This applies first of all to the type and concentrations of the test material. Meanwhile the hydraulic conditions seem to be similar to those encountered in the field.

## ACKNOWLEDGEMENTS

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