Inflow based investigations on the efficiency of a lamella particle separator for the treatment of stormwater runoffs

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ABSTRACT

The present design of stormwater tanks is based on the creation of storage volume to retain stormwater and the prevention or reduction of stormwater overflows. The treatment of stormwater is often improved with mechanical equipment. The general layout rules do usually not include the appropriate choice of design inflow related to the chosen treatment equipment. In the following investigations it was the task to analyze the hydraulic efficiency and the overflow behaviour of a lamella particle separator inside a stormwater tank under different design approaches regarding the chosen design inflow. Therefore six scenarios with different precipitation yield approaches were chosen and applied to a given constant sized catchment to calculate the design inflows. For a given minimum particle size, the necessary number of lamellas were determined for the scenarios and standard stormwater tanks were dimensioned. These stormwater tanks were modelled in the hydrologic model SMUSI to investigate the overflow behaviour of the different tank sizes. The number of overflow events, their duration and maximum flow rates were the results of the modelling. Comparisons to the design inflows were carried out. The treated particles sizes at the overflow events were determined reversible and compared to the original chosen minimum particle sizes.

Key words | hydrologic modelling, lamella particle separator, stormwater tank design, stormwater treatment

INTRODUCTION

Stormwater tanks in combined sewer systems are usually provided to reduce peak flows to treatment plants by retaining the water in their storage volume and releasing it constantly in even amounts back into the system. Overflows are regulated by laws and should be avoided, if possible, to secure the connected waters. In separated sewer systems stormwater sedimentation tanks are used for the treatment of the inflow before proceeding it to lakes, rivers or infiltration ponds. The effectiveness of these stormwater sedimentation tanks and their high constructional costs are questioned quite often by operators, engineers and scientists (ATV 1992; Kirchheim 2005).

To improve the effectiveness of stormwater sedimentation tanks different kinds of treatment equipment can be installed. For example, the implementation of particle separators using parallel lamella plates increases the effective sedimentation area in existing tanks and therefore the stormwater treatment efficiency. For new planned constructions the footprint, the volume and the costs of a stormwater tank can be reduced by including lamella plates (Steinhardt GmbH 2008).

The efficiency or performance of a particle separator is defined by the smallest particle diameter able to be settled between the lamella plates. This particle diameter depends on the density of the suspended solids and their sinking velocity (Morin et al. 2008).

The inflow rate to the particle separator is usually unsteady over the time depending on the characteristics of the rain event. A separator design based only on maximum inflows would lead to very large and expensive stormwater tanks. Mean inflow values or lower rates for small rain events can lead to inexpensive but mostly overloaded tanks. In Germany there are no federal rules or design guidelines for particle separators. Therefore it is necessary to
define a design rule for the inflow which leads to efficient particle separators and not to oversized stormwater tanks.

The value of the inflow, together with the already mentioned ones, then leads to a lamella field which is responsible for the volume of the resulting stormwater tank. To optimize the efficiency of the particle separator it is necessary to treat as much small rain events as possible. Therefore a comparable small tank volume is needed where the stormwater will flow through the lamellas to the overflow before being proceeded to connected waters. It is not the target to create large and expensive settlement tanks with low efficiency. In contrast to these demands heavy rainfalls with large inflows should not exceed the capacity of the particle separator to a large extend (Pfeffermann 2009).

In the following investigations it was the task to analyze the hydraulic efficiency and the overflow behaviour of a stormwater particle separator under different design approaches regarding the chosen inflow. Therefore six scenarios with different precipitation yield approaches were chosen and applied to a given constant sized catchment to calculate the design inflows. For a given minimum particle size, the necessary number of lamellas were determined for the scenarios and standard stormwater tanks were dimensioned. The number of the mean and maximum overflows were modelled by using a hydrological model and compared against the initial chosen inflows to define the efficiency of the treatment system. A reversible calculation of the smallest treatable particle size at peak and mean overflows and a comparison of the original design particle size allowed statements of the treatment efficiency of the different inflow approaches. In the end an evaluation of all results will lead the way to a smart design rule regarding the choice of the inflow to the particle separator (Pfeffermann 2009).

**PARTICLE SEPARATION**

**Pollution of storm water runoffs**

Urban stormwater runoffs can pollute the environment in different degrees caused by the alternating and combined effects of pollution concentration, hydraulic stress, duration of runoff, number of storm events and their duration. Fine particles smaller 100 μm diameter dominate the suspended phase and represent between 66 and 85% of the total mass with mean diameters ranging from 25 to 44 μm. Since the nineties many investigations have proven that the main part of stormwater pollution is bound to small suspended solid particles. Approximately 80% of the COD and BOD5 are bound to solid particles with a diameter smaller than 100 μm, which charge the treatment plant as well as the receiving waters (Chebbo 1992; Saget 1994; Chebbo et al. 1995; Ashley et al. 2004; Kirchheim 2005).

**Design of stormwater sedimentation tanks**

Stormwater sedimentation tanks are used for the treatment of the described stormwater runoffs before entering connected waters like lakes, rivers or infiltration ponds. They can be distinguished into tanks with a permanent impoundage and without. In Germany their design is based on the regulations ATV A – 128 (1992) and ATV A – 166 (1999). The calculation of the effective footprint is based on the flow rate $q_A$ (m/h), which describes the ratio of the inflow to the footprint/sedimentation area of the stormwater tank. Stormwater sedimentation tanks with a permanent impoundage should be designed for a flow rate of $q_A = 7.5$ m/h, tanks without for $q_A = 10.0$ m/h. These flow rates usually are not suitable to settle fine particles in stormwater runoffs as described before. To improve the efficiency of stormwater sedimentation tanks or reduce the demand of space a field of parallel lamella plates can be installed to reduce the flow rate in the tank to values below 1 m/h. This practice is used successfully for the removal of sludge in sewage treatment plants for many years.

**Stormwater treatment – Gravimetric settlement**

The treatment of stormwater to remove floating and suspended solids as well as heavy metals and germs or toxins can generally be divided into filtration and sedimentation. Fine bar screens and sieves are widely known systems but their efficiency is limited due to their mechanics. Vortex separators are used for the sedimentation of gross solids and were the subject of many investigations (Anoh et al. 2002; Faram & Harwood 2002; Okamoto et al. 2002).

The later investigated HydroM.E.S.I. (‘Matières en Suspension Intercepteur’) particle separator is a lamella based treatment system for the separation of particular pollutants from storm water runoffs before they enter connected waters or infiltration areas (Steinhardt GmbH 2008). The stormwater is cleaned by the gravimetric separation and settling of solids in a counter flow system. The inflow is divided into smaller parts when passing the arrangement of several parallel lamellas which are inclined in a 45°
angle. Therefore the upward velocity of the stormwater between the lamellas is reduced and a laminar flow is generated.

Suspended particles having, due to their density, a higher settlement velocity than the upward flow velocity will be caught on the lamellas. There they will settle down and form clusters of sediments. When these clusters overcome the resistance of the lamellas and the flow velocity they run down to the bottom of the lamella tank. Floatables will be caught by a scum board at the outflow end of the lamella (Figure 1).

Usually the size of particles to be treated is very small and a common particle size for the layout of the HydroM.E.S.I. is a diameter of 30 μm. The sinking velocity \( v_s \) is calculated with the formula of Stokes (1) and is a function of the particle density \( \rho_p \), the fluid density \( \rho_f \), the particle diameter \( d \), the gravity \( g \) and the dynamic viscosity \( \eta \).

\[
q_A < v_s = \frac{(\rho_p - \rho_f) \cdot g \cdot d^2}{18 \cdot \eta}
\]

(1)

**Functional description of the particle separator**

The particle separator system HydroM.E.S.I. consists of the inflow chamber, the pumping and flushing sump, the inflow shield, the lamella chamber, the flushing reservoir and the scum board at the outlet (Figure 1).

After or during rain events the runoff enters the pumping and flushing sump before it flows across the inflow shield into the sedimentation chamber. The inflow shield guides and distributes the flow under the lamellas and
creates an area from where the already settled particles will not be lifted again.

In an empty tank the lamellas are in vertical position; with the rising water level the float attached to the first lamella rises and lifts the lamellas to the 45° working position. The water then runs through the lamellas and flows towards the outlet. Before it passes the scum board the flushing reservoir for the cleaning of the tank bottom is filled (Figure 1).

The design of the particle separator is strongly depending on the size, the density and the therefore resulting sinking velocity of the suspended solids to be treated. The number of lamellas, necessary to create the low flow velocity, is a function of the inflow quantity, the size of the lamellas and their interspaces.

After the rain event, when the inflow to the lamella system has stopped, the tank is drained by the pump into the sewer system. The lamellas fall into vertical position which causes the wet solids attached to the lamella surface to slide down and fall to the bottom. When the stormwater tank is completely empty the flushing gate is opened. Using the water volume of the flushing reservoir the tank bottom is cleaned by a highly turbulent wave. The inflow shield which consists of a flexible bottom part is opened by the flush wave before the wave is reaching the flushing sump. The flushing volume with the deposits is then pumped into the sewer system.

To improve the performance of the lamella system two-dimensional investigations were carried out in the year 2002 (Morin 2002). In the year 2006 further numerical investigations were carried out in cooperation with the University of Bordeaux by applying a three-dimensional model on the particle separator (Morin 2006; Morin et al. 2007, 2008, 2009).

**DEFINITION OF INVESTIGATED SCENARIOS**

The main target of the available investigation was to find a design rule for the layout of the particle separator together with the necessary volume of the stormwater tank regarding the precipitation yield and the flow rate. Therefore six scenarios with different precipitation yields were chosen to investigate the efficiency of the resulting stormwater treatment. The scenarios are a mixture of official tank design rules (no. 1 and 2), conservative approaches of engineering consultants (no. 3 and 4) and practical layouts resulting from the Steinhardt company experience in stormwater treatment (no. 5 and 6). To achieve comparable results, the size of the catchment connected to the stormwater tank was kept constant with \( A = 5 \text{ ha} \). The rain data for the precipitation yield was taken from the Kostra Atlas for the area of Darmstadt, Germany, the hometown of the author (German Meteorological Service 2005). Table 1 shows the chosen precipitation yield together with the resulting design inflow to the particle separator.

### INVESTIGATIONS

**Sinking velocity of investigated particles**

The sinking velocity of the particles suspended in the stormwater is a major parameter for the layout of the particle separator. According to this value the number of necessary lamellas is calculated to create the desired laminar flow which allows the settlement of the particles. In the presented investigation uniform particles with a density \( \rho = 2,300 \text{ kg/m}^3 \) and a diameter of \( d = 25 \text{ µm} \) were chosen. Using Equation (1) a sinking velocity of \( v_s = 1.03 \text{ m/h} \) was calculated.

### Calculation of lamella number

The next step in the investigations was the calculation of the number of lamellas for the particle separator. This calculation will be carried out for scenario no. 1 as an example.

The inflow to the particle separator in scenario no. 1 is assumed to be constant with \( Q = 0.035 \text{ m}^3/\text{s} \). The height of the lamellas \( H = 2.00 \text{ m} \) and the width \( B = 3.08 \text{ m} \) was chosen due to the fact that these dimensions are standard values in many practical applications. The lamellas have a trapezoid surface with a stretching factor \( fc = 1.31 \). In the working position the lamellas show a declination \( \alpha = 45° \). The distance between the lamellas in vertical position is \( s = 9 \text{ cm} \).

The calculation of the quantity of lamellas, regarding the mentioned boundary condition, using Equation (2) led to a

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**Table 1 | Investigated scenarios (precipitation yield and inflow rate)**

<table>
<thead>
<tr>
<th>Scenario no.</th>
<th>Precipitation load</th>
<th>Precipitation yield [L/(s*ha)]</th>
<th>Inflow [L/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( r_{crit,1} )</td>
<td>7</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>( r_{crit,2} )</td>
<td>15</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>( r_{15,1} )</td>
<td>108.3</td>
<td>541.5</td>
</tr>
<tr>
<td>4</td>
<td>( r_{15,0.2} )</td>
<td>183.1</td>
<td>915.5</td>
</tr>
<tr>
<td>5</td>
<td>20% ( r_{15,0.1} )</td>
<td>43.08</td>
<td>215.4</td>
</tr>
<tr>
<td>6</td>
<td>20% ( r_{15,0.2} )</td>
<td>49.5</td>
<td>247.5</td>
</tr>
</tbody>
</table>
number of 22 (Bourrier et al. 1993). Table 2 shows the results of the calculation for all scenarios.

\[ N = \frac{Q}{H \cdot B \cdot f_o \cdot v_s \cdot (\sqrt{g} + \cos \alpha)} + 1 \]  

(2)

To ensure a homogeneous flow distribution inside the lamella field the ration of \( L/W \) should not exceed the value of 5. The calculations for scenario no. 3 and no. 4 showed that this rule was violated. To overcome this problem a lamella field with 2 lanes of lamellas was created in case of scenario no. 5. Each lamella lane treats half of the original inflow and shows a good \( L/W \) ratio. In case of scenario 4 three lamella lanes were created to treat a third of the original inflow in each one.

**Calculation of tank volume**

Before using the model SMUSI to investigate the overflow behaviour of the particle treatment system in the different scenarios, the volume of the stormwater tanks resulting out of the calculations in Table 2 had to be calculated.

The volume of a stormwater tank consists of five sub-volumes (Figure 1). First the flushing and pumping sump, then the entrance to the lamella chamber, the lamella chamber itself, the volume over the weir and the flushing reservoir. The overflow height above the weir was calculated using the Poleni equation for non-free overflows (Bollrich 1993). The width of the stormwater tanks was constant for all scenarios with \( w = 3.34 \) m, except for the two- and three lane systems in scenarios no. 3 and 4. Here the width was 6.68 and 10.02 m. Table 2 shows the results of the volume calculation.

<table>
<thead>
<tr>
<th>Scenario no.</th>
<th>Inflow (L/s)</th>
<th>No. of lamellas</th>
<th>Length of lamella field (m)</th>
<th>Width of lamella field (m)</th>
<th>( L/W )</th>
<th>Surface lamella field (m²)</th>
<th>Surface of lamellas (m²)</th>
<th>Reynolds no. (v)</th>
<th>Volume of stormwater tank (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>22</td>
<td>3.3</td>
<td>3.34</td>
<td>0.98</td>
<td>11.04</td>
<td>177.53</td>
<td>155.21</td>
<td>70.71</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>45</td>
<td>5.37</td>
<td>3.34</td>
<td>1.61</td>
<td>17.95</td>
<td>363.13</td>
<td>158.74</td>
<td>96.57</td>
</tr>
<tr>
<td>3</td>
<td>541.5</td>
<td>313</td>
<td>29.49</td>
<td>3.34</td>
<td>8.82</td>
<td>98.51</td>
<td>2,525.78</td>
<td>161.63</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>270.75</td>
<td>157</td>
<td>15.45</td>
<td>3.34</td>
<td>4.62</td>
<td>51.62</td>
<td>1,266.93</td>
<td>161.63</td>
<td>427.43</td>
</tr>
<tr>
<td>5</td>
<td>915.5</td>
<td>529</td>
<td>48.93</td>
<td>3.34</td>
<td>14.65</td>
<td>163.44</td>
<td>4,268.82</td>
<td>161.47</td>
<td>–</td>
</tr>
<tr>
<td>6</td>
<td>457.75</td>
<td>265</td>
<td>25.17</td>
<td>3.34</td>
<td>7.53</td>
<td>84.08</td>
<td>2,138.44</td>
<td>161.47</td>
<td>–</td>
</tr>
<tr>
<td>1</td>
<td>228.87</td>
<td>133</td>
<td>13.29</td>
<td>3.34</td>
<td>3.97</td>
<td>44.4</td>
<td>1,073.26</td>
<td>161.47</td>
<td>766.29</td>
</tr>
<tr>
<td>2</td>
<td>215.4</td>
<td>126</td>
<td>12.66</td>
<td>3.34</td>
<td>3.79</td>
<td>42.3</td>
<td>1,016.77</td>
<td>160.48</td>
<td>192.83</td>
</tr>
<tr>
<td>3</td>
<td>247.5</td>
<td>144</td>
<td>14.28</td>
<td>3.34</td>
<td>4.27</td>
<td>47.71</td>
<td>1,162.02</td>
<td>161.18</td>
<td>214.23</td>
</tr>
</tbody>
</table>
by setting the runoff throttle to a very low value. The determination of the exact value had to be chosen very carefully. On the one side it had to be low so that not too much water was lost via the throttle during the rain event instead of going over the overflow weir. But a too small throttle runoff lead to problems when two rain events followed each other fast and the second runoff went into a still fully stored tank when it should have been empty. To prevent this the throttle runoff had to be chosen high enough to drain the stormwater tank quickly enough before the next rain event started. Depending on the investigated scenario the throttle runoff was calculated iteratively and was changing between 1.5 and 2 L/s (Pfeffermann 2009).

RESULTS

Number of overflow events – total duration of overflow events

The first results of the modelling with SMUSI were the number of overflow events when the catchment was loaded with the chosen rain series. As expected, the scenarios with the smallest tank volume (no. 1 and 2) had the largest number of overflows while the larger tanks volumes (no. 5 and 6) captured the small rain events without an overflow. For these scenarios only the large rain events led to an overflow and therefore to a working particle separator (Figure 2).

Figure 2 also shows the total duration of overflow events for the different scenarios. The tanks in scenario 1–3 show an equal behaviour, while scenario 4 has the shortest overflow time due to its small number of overflow events (Figure 2). Scenario numbers 5 and 6 have the longest overflow times which means that the particle separator was working longer then for the other scenarios. This might lead to the conclusion that for these inflow and volume approaches efficiently working particle separators were designed.

Difference of maximum overflows compared to design inflow

The maximum overflow of each single rain event was now compared to the initially chosen design inflow (Table 1). The mean difference over all rain events for each scenario is displayed in Figure 3.

Again the scenarios with the smallest tank volume showed the largest deviation. The smallest difference of the maximum overflows compared to the design flow can be encountered in the scenarios no. 5 and 6 which shows that these design approaches lead to an effective treatment of the inflow.

Difference of treated particles at maximum overflows compared to design inflow

The following investigation took the total maximum overflow event of each modelled scenario for a reversible calculation of the treated particle size. Using Equation (2) for a given maximum overflow rate and a fixed number of lamellas (Table 2) the effective particle sinking velocity was calculated for each scenario. With Equation (1) the effective treated particle size at the maximum overflow was determined (Figure 4).

Figure 4 shows that the smaller tank volumes have the largest difference between the effective treated particle size
and the originally design particle size. The high tank volumes possess the smallest deviation. Scenario no. 5 and 6 have significant smaller volumes than no. 3 and 4 but their difference to the design particle size is only slightly bigger. Therefore again it is shown that these design approaches have a good efficiency while having smaller tank volumes.

**CONCLUSIONS**

The evaluation of the investigation results for the different scenarios show that the design approaches for the scenarios 5 and 6 lead to stormwater tanks with a mean volume which will be inexpensive compared to the large tank volumes of scenarios 3 and 4. The number and the total duration of the modelled overflow events show a good cleaning performance for the scenarios 5 and 6. Long overflow durations combined with comparable small differences between the maximum overflow rates and the original design inflow rates indicate that these tank designs are not overloaded like in scenario 1 and 2 and work efficiently. The differences between the effective treated particle sizes at the maximum overflows and the initially chosen particle sizes in the scenarios 5 and 6 are also on the smaller side and not much higher than for the larger and much more expensive tanks. These results lead to the conclusion that the design approaches of 20% $r_{15,0,1}$ and 20% $r_{15,0,2}$ create competitive and hydraulic very effective stormwater tanks for the treatment of pollution loads bound to fine suspended particles.

**REFERENCES**


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