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

Efficacité d'interception d'un décanteur lamellaire pour le traitement de la pollution pluviale particulaire selon le débit entrant

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RÉSUMÉ

La conception actuelle des bassins de retenue est basée sur la mise en œuvre d'un volume de stockage destiné à réduire la fréquence et le volume des rejets au milieu naturel. Le traitement des eaux pluviales est souvent très sommaire et l'amélioration des performances de traitement requiert l'installation au fil de l'eau de filtres ou de décanteurs lamellaires. Suivant le type de traitement considéré, les règles de conception des ouvrages et en particulier de détermination du débit nominal à traiter, ne semblent pas toujours fondées sur des critères de choix appropriés. Dans l'étude suivante, nous avons analysé l'efficacité d'interception d'un décanteur lamellaire, ainsi que les flux rejetés, selon différents épisodes pluvieux et pour différents critères de choix du débit à traiter. Six scénarios ont été choisis et appliqués à une surface imperméabilisée identique pour calculer le débit nominal. Pour une taille minimale de particules choisie, le nombre nécessaire de lamelles a été déterminé selon les scénarios envisagés. Parallèlement, des bassins de retenue ayant des volumes utiles équivalents à ceux des décanteurs ont été modélisés avec le modèle hydrologique SMUSI. La modélisation a permis de calculer le nombre de rejets, leur durée et les débits maximum rejetés. Des comparaisons avec les débits nominaux ont été effectuées. La taille des particules traitées lors des événements occasionnant des rejets a été calculée et comparée à la taille minimale des particules déterminées initialement.

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 very poor and is improved with mechanical equipment like filters or lamella particle separators. The general layout rules usually do 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 number of necessary 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.

KEYWORDS

Hydrologic modelling, lamella particle separator, stormwater tank design, stormwater treatment

1 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, 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) Therefore the layout of the particle separator is based on the sinking velocity and/or the desired particle size which should be treated. Then the resulting number of lamella plates is a function of the particle sinking velocity, the lamella size, the distance between the lamellas, their inclination as well as the inflow rate towards the treatment system. 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 design rules for the inflow which lead to efficient particle separators and not to oversized stormwater tanks.

The value of the inflow, together with the already mentioned variables, 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)

2 PARTICLE SEPARATION

2.1 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 micrometers, which charge the treatment plant as well as the receiving waters. (Ashley et al., 2004) (Chebbo, 1992 and 1995) (Kirchheim, 2005) (Sajet, 1994)

2.2 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.

2.3 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 and 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 degree 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 general 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 chamber where they remain for the rest of the storm event. Floatable sediments will be caught by a scum board at the end of the lamella system where they settle down after the rain event. (Figure 1)

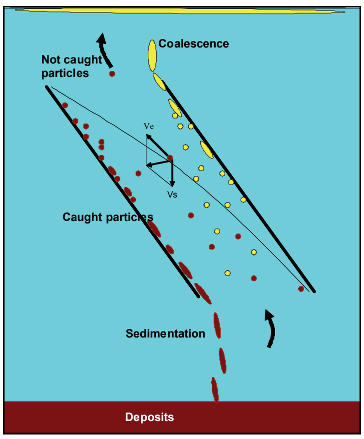

Figure 1. Gravimetric settlement of suspended solids.

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 micrometers. The sinking velocity v_s is calculated with the formula of Stokes (1) and is a function of the particle density ρ_p, the fluid density ρ_f, the particle diameter d, the gravity g and the kinematical viscosity η.

$$q_A < v_s = \frac{(\rho_p - \rho_f) \cdot g \cdot d^2}{18 \cdot \eta} \quad (1)$$

2.4 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 2)

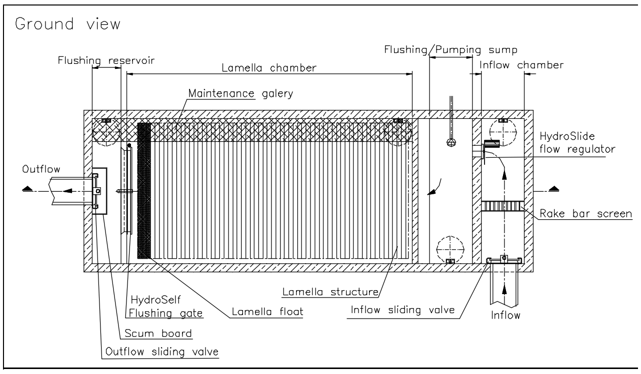

Figure 2. Functional diagram HydroM.E.S.I. Lamella separator, overview.

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.

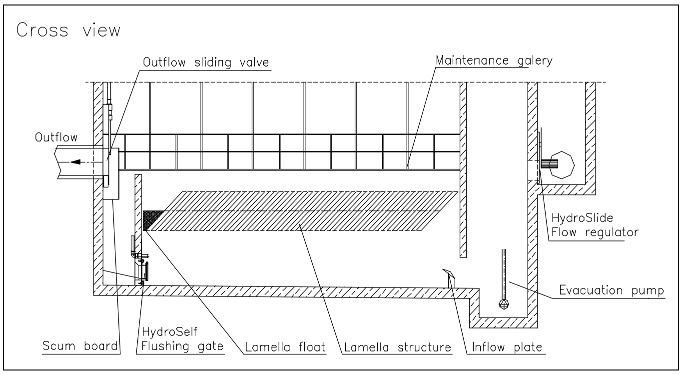

Figure 3. Functional diagram HydroM.E.S.I. Lamella separator, cross view.

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 degree working position. The water then runs through the lamellas and flows towards the outlet. Before it passes the scum board (catching of floatables) the flushing reservoir for the cleaning of the tank bottom is filled. (Figure 3)

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 also 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. The design of the inflow plate was analyzed as well as the creation of a homogenous inflow and distribution of the flow inside the lamella chamber. (Morin, 2002) In the year 2006 further numerical investigations were carried out in cooperation with the Laboratoire de Génie des Procédés et Environnement at the University of Bordeaux by applying a three-dimensional model on the particle separator. (Morin, 2006) (Morin et al., 2007) (Morin et al., 2008) (Morin et al., 2009)

3 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 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.

Scenario no.	**Precipitation load**	**Precipitation yield [l/(s*ha)]**	**Inflow [l/s]**
1	$r_{crit,1}$	7	35
2	$r_{crit,2}$	15	75
3	$r_{15;1}$	108.3	541.5
4	$r_{15;0.2}$	183.1	915.5
5	20 % $r_{15;0.1}$	43.08	215.4
6	20 % $r_{15;0.2}$	49.5	247.5

Table 1. Investigated scenarios (precipitation yield and inflow rate)

4 INVESTIGATIONS

4.1 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 ρ = 2300 kg/m³ and a diameter of d = 23 µm were chosen. Using equation (1) a sinking velocity of v_s = 1.03 m/h was calculated.

4.2 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 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 m³/s. The height of the lamellas H = 2.00 m and the width B = 3.08 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 f_c = 1.31. In the working position the lamellas show a declination α = 45 degree. The distance between the lamellas in vertical position is s = 9 cm.

The calculation of the quantity of lamellas, regarding the mentioned boundary condition, using equation (2) led to a number of 22. (Bourrier et al., 1995) Table 2 shows the results of the calculation for all scenarios.

$$N = \frac{Q}{H \cdot B \cdot f_C \cdot v_S \cdot (\frac{d}{H} + \cos\alpha)} + 1 \qquad (2)$$

Scenario no.	Inflow	No. of lamellas	Length of lamella field	Width of lamella field	L/W	Surface lamella field	Surface of lamellas	Reynolds no.
	[l/s]		[m]	[m]	[\]	[m²]	[m²]	[\]
1	35	22	3.3	3.34	0.98	11.04	177.53	155.21
2	75	45	5.37	3.34	1.61	17.95	363.13	158.74
3	541.5	313	29.49	3.34	8.82	98.51	2525.78	161.63
3	270.75	157	15.45	3.34	4.62	51.62	1266.93	161.63
4	915.5	529	48.93	3.34	14.65	163.44	4268.82	161.47
4	457.75	265	25.17	3.34	7.53	84.08	2138.44	161.47
4	228.87	133	13.29	3.34	3.97	44.4	1073.26	161.47
5	215.4	126	12.66	3.34	3.79	42.3	1016.77	160.48
6	247.5	144	14.28	3.34	4.27	47.71	1162.02	161.18

Table 2. Results of lamella field calculation

To ensure a homogenous 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. 3. 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.

4.3 Calculation of tank volume

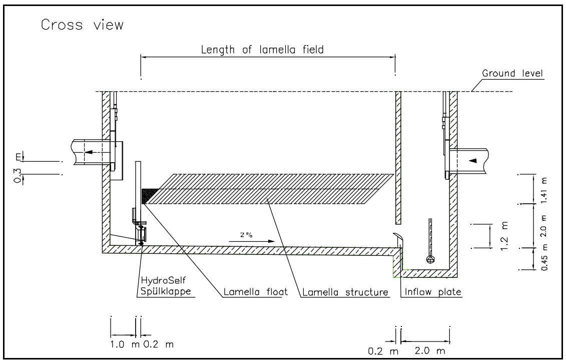

Figure 4. Standard tank design for HydroM.E.S.I. particle separator

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. In figure 4 a cross view of the tank design with the chosen dimensions is shown.

The volume of a stormwater tank consists of five sub-volumes. 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 m and 10.02 m. Table 3 shows the results of the volume calculation.

Scenario no.	Inflow [l/s]	Volume of stormwater tank [m³]
1	35	70.71
2	75	96.57
3	270.75	427.43
4	915.5	766.29
5	215.4	192.83
6	247.5	214.23

Table 3. Volume of stormwater tanks

4.4 Investigation of overflow behaviour

The stormwater tanks, as shown in figure 4, with the calculated volumes of table 3 were now investigated with the hydrological model SMUSI 4.0 to analyze the overflow behaviour of the different scenarios.

SMUSI is a distributed deterministic-hydrologic precipitation discharge and material transport model. It is developed for continuous long-term simulations. Beside flow it calculates concentrations of water constituents such as COB, BOD and filterable solids considered important for the evaluation of stormwater overflows on receiving waters, both in existing or planned systems. (Ostrowski, 1998)

To represent the different scenarios a model consisting of an urban catchment, a stormwater tank and a fictive treatment plant was set up. The urban catchment was defined via a totally sealed surface of 5 ha. This catchment was loaded with a representative rain series of SMUSI. This rain series was derived from several measured long term rain series. It includes their data and sums them up for a 9 month period. The chosen series had a mean annual rainfall of 775 mm according to the data of the Germany Weather Forecast (DWD) for the city of Darmstadt with 750 mm.

The chosen tank in the model SMUSI was a stormwater retaining tank in main systems to represent the shown stormwater tank in figure 4. This retaining tank is defined by the storage volume, the height and width of the overflow, the overflow coefficient and the regulated runoff by a throttle. It was chosen because it includes only one overflow structure as the stormwater tank in figure 4. Therefore it was easier to model and investigate the overflow events and their properties. It was not possible to model the drainage of the real tank via the pumps in SMUSI. The drainage of the tank after a rain event was carried out 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 filled tank when it should have been empty. To prevent this, the throttle runoff had been 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 l/s and 2 l/s. (Pfeffermann, 2009)

5 RESULTS

5.1 Number 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 5)

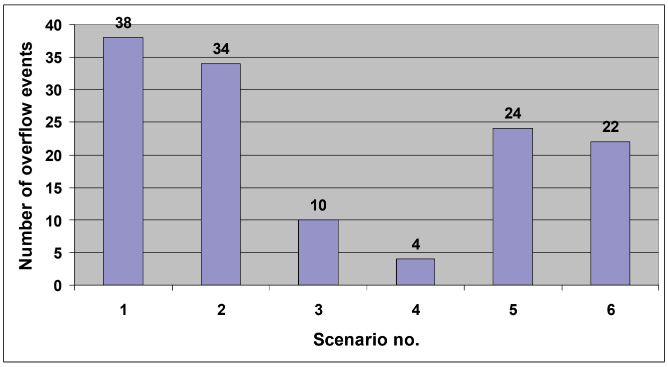

Figure 5. Number of overflow events.

5.2 Total duration of overflow events

Figure 6 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 5). 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.

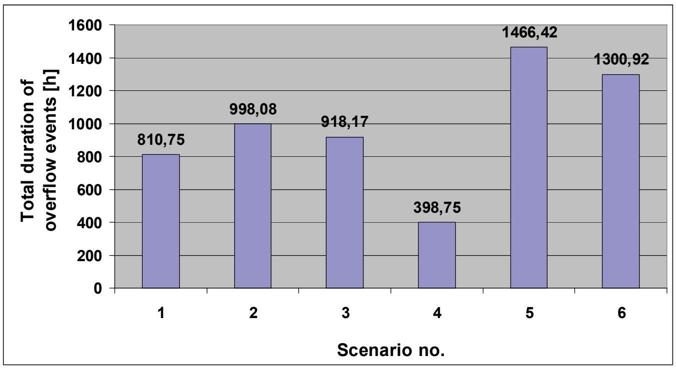

Figure 6. Total duration of overflow events.

5.3 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 7.

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.

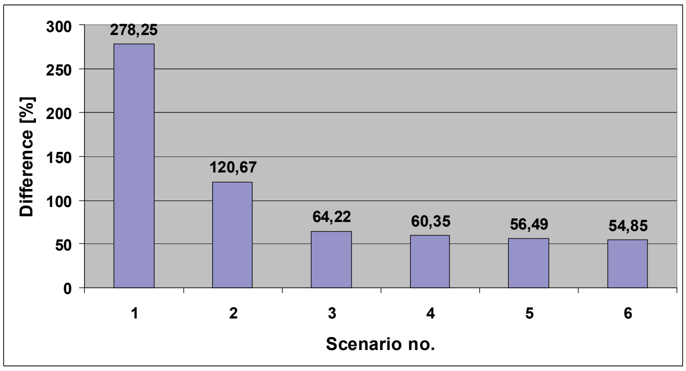

Figure 7. Mean differences of max. overflows compared to design inflow.

5.4 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 8)

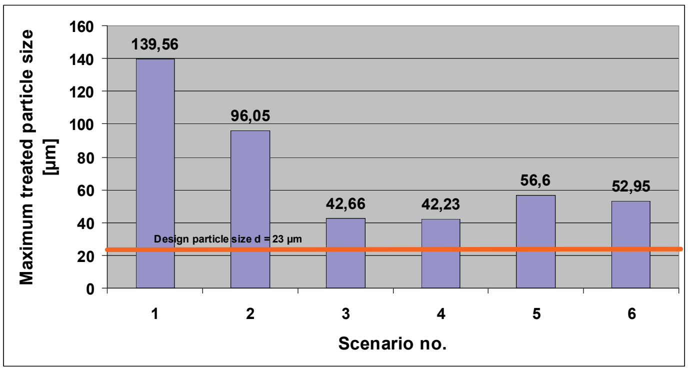

Figure 8. Maximum treated particle size.

Figure 8 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.

6 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 % r15;0.1 and 20 % r15;0.2 create competitive and hydraulic very effective stormwater tanks for the treatment of pollution loads bound to fine suspended particles.

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