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J. Schaffner, I. Mayer, H. Eckhardt, J. Steinhardt. Model based investigations on the pollution loads of stormwater treatment particle separators. Novatech 2013 - 8ème Conférence internationale sur les techniques et stratégies durables pour la gestion des eaux urbaines par temps de pluie / 8th International Conference on planning and technologies for sustainable management of Water in the City, Jun 2013, Lyon, France. <hal-03303552>

HAL Id: hal-03303552

<https://hal.science/hal-03303552v1>

Submitted on 28 Jul 2021

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Model based investigations on the pollution loads of stormwater treatment particle separators

Modélisation des flux de pollution des eaux pluviales dans les séparateurs de particules

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RÉSUMÉ

L'efficacité de traitement des ouvrages de décantation des eaux pluviales peut être augmentée de manière significative par l'adjonction d'équipements mécaniques comme des filtres placés en aval ou par la mise en place de lames dans l'ouvrage, tout en diminuant son volume (Fuchs et Mayer, 2009). Les directives allemandes pour l'aménagement de bassins de décantation des eaux pluviales ne prennent pas en considération la présence d'équipements comme les structures lamellaires.

La présente étude analyse les critères de conception et d'efficacité d'ouvrages de retenue et de décantation des eaux pluviales équipés de structures lamellaires. Pour cela, un modèle hydrologique déterministe des précipitations est utilisé pour analyser et évaluer l'efficacité et le comportement hydraulique des ouvrages de décantation des eaux pluviales, pour des séries de pluies sur une longue période. Plusieurs scénarios avec différentes modalités d'alimentation ont été conçus pour une aire imperméabilisée donnée.

Les premiers résultats de la présente étude ont conduit à une approche nouvelle pour dimensionner les ouvrages de décantation lamellaire des eaux pluviales en fonction des apports. (Schaffner et al., 2011) Des investigations complémentaires ont évalué la charge polluante annuelle des différents scénarios. En dernière analyse, la rentabilité économique des bassins de décantation des eaux pluviales, avec ou sans structures lamellaires pour séparer les particules, a été discutée.

ABSTRACT

The cleaning efficiency of stormwater sedimentation tanks can be increased significantly with mechanical equipment like downstream placed filters or implemented lamella plates whilst decreasing the required tank volume. (Fuchs and Mayer, 2009) The German guidelines for the layout of stormwater sedimentation tanks do not regard the implementation of mechanical equipment like lamella plates.

The present investigation analyses the design criteria and efficiency of stormwater treatment sedimentation tanks with implemented lamella separators. Therefore a hydrologic-deterministic precipitation runoff model is used to analyse and evaluate the hydraulic efficiency and the overflow behaviour of stormwater sedimentation tanks with implemented lamella plates on the basis of long term rain series. Several scenarios with different design inflows were created for a given catchment area.

The first results of the present investigation led to a new layout approach for stormwater sedimentation tanks with implemented lamella plates depending on the inflow. (Schaffner et al., 2011) Further investigations evaluated the annual pollution loads of the different scenarios to connected waters. In a final investigation the results were discussed regarding the economic or cost-effective installation of stormwater sedimentation tanks with or without a lamella particle separation system.

KEYWORDS

Annual pollution loads, Hydrologic modelling, Lamella particle separator, Stormwater treatment.

1 INTRODUCTION

Stormwater sedimentation tanks in separated sewer systems are used for the treatment of the inflow preceding its route to destinations such lakes, rivers or infiltration ponds. 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 preceding 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 irregular as it depends 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 surrounding it. 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. (Schaffner et al., 2011)

First investigations by Schaffner et al. (2011) analysed 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 calculate the effectively treated particle size and 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. (Schaffner et al., 2011)

In the following investigations the annual pollution loads to connected waters were calculated for the previously mentioned six scenarios. The general sedimentation by the tank volume was regarded as well as the sedimentation effect of the lamella field. The most effective scenario regarding sedimentation and pollution deposition was then compared with three conventionally designed stormwater treatment tanks without lamella separators based on German guidelines. A further comparison was then carried out regarding the costs of the conventional tanks against the lamella equipped design.

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; Saget, 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). The calculation of the effective footprint is based on the flow rate qA [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 $qA = 7.5$ m/h, tanks without for $qA = 10.0$ 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 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)

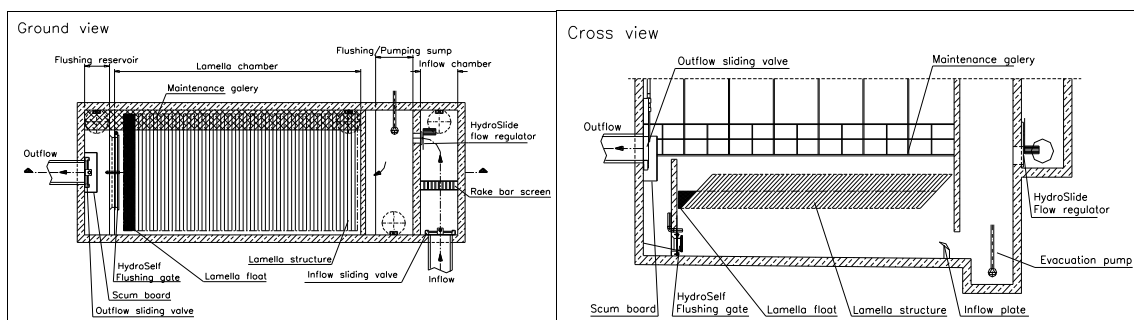


Figure 1. Functional diagram HydroM.E.S.I. lamella separator.

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 degree working position. The water then runs through the lamellas and flows towards the outlet. 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. After the lamellas the water flows into the flushing reservoir before it passes the scum board (catching of floatables) and leaves the tank. (Figure 1)

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 reaches the flushing sump. The flushing volume with the deposits is then pumped into the sewer system.

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. 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 .

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

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) using critical precipitation yields ($r_{crit,i}$), conservative approaches of engineering consultants (no. 3 and 4) using 1 and 5 year rain events with a duration of 15 min ($r_{15;1}$ and $r_{15;0.2}$) 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.

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

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

4 INVESTIGATION

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 $\rho = 2300$ kg/m³ and a diameter of $d = 23$ μ m 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 $Q = 0.035 \text{ m}^3/\text{s}$ with a surface load of $q = 1.0 \text{ m/h}$. 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 $f_c = 1.31$. In the working position the lamellas show a declination $\alpha = 45 \text{ degree}$. The distance between the lamellas in vertical position is $s = 9 \text{ cm}$.

$$N = \frac{Q}{H \cdot B \cdot f_c \cdot v_s \cdot \left(\frac{d}{H} + \cos\alpha\right)} + 1 \quad (2)$$

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.

Table 2. Results of lamella field calculation

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]	[-]	[m ²]	[m ²]	[-]
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

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

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 2 a cross view of the tank design with the chosen dimensions is shown.

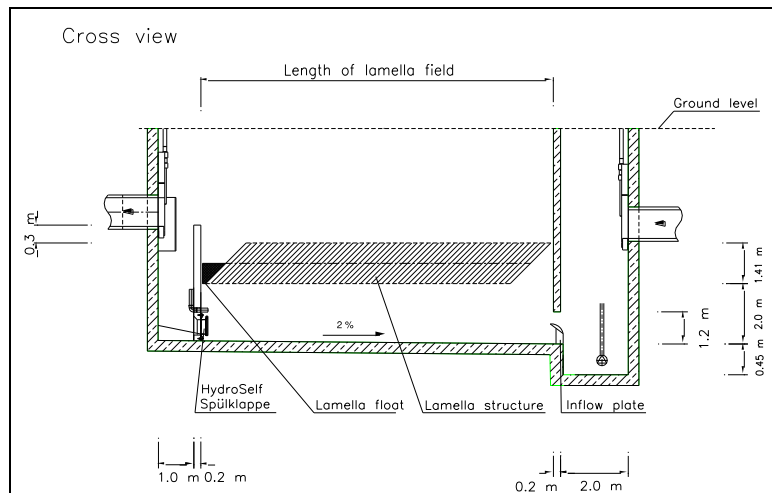


Figure 2. Standard tank design for HydroM.E.S.I. particle separator

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 (Bollich, 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 4 shows the results of the volume calculation.

4.4 OVERFLOW BEHAVIOUR

The stormwater tanks, as shown in figure 1, with the calculated volumes of table 4 were now investigated with the hydrological model SMUSI 4.0 to analyze the overflow behaviour and the pollutant loads 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 COD, 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.

4.5 POLLUTION LOADS IN THE DIFFERENT SCENARIOS

In previous investigations the number of overflow events, their duration, the maximum runoff values and effective treated particle sizes were modelled. (Schaffner et al., 2011) In the next step the annual pollution loads to the connected waters and the deposition rates of the different scenarios are calculated with the model SMUSI.

The pollution potentials of a total or partly sealed surface are defined in the model SMUSI by the suspended solids (SS), the biological (BOD₅) and chemical oxygen demand (COD), the total organic carbon (TOC), ammonium (NH₄) and phosphate (PO₄) with a value of kg/(ha*a). There are default values given in SMUSI but a research showed that they differ strongly compared to the results of investigations in the found literature. (ATV, 1992; Schäfer, 1999; Weyand, 1992) Due to their relevance only the results of the suspended solids, the BOD₅ and the CSO are regarded in the following investigations. (Table 3)

Table 3. Pollution potentials

Type of pollution	Average value [kg/(ha*a)]	Literature source
Suspended solids	870	Schäfer, 1999
COD	600	ATV – A 128
BOD5	135	Weyand, 1992

The model SMUSI calculates pollution loads to the connected waters by the incoming pollution load of the connected catchment during a rain event minus the detained pollution in the stormwater treatment tanks. Therefore it is necessary to define the pollution which is bound to particles or suspended solids to calculate the pollution load stored in the treatment tank. A literature research showed again marked differences to the default values of SMUSI. Therefore the average value of COD bound to suspended solids was chosen 87 % and 86 % for the BOD5. (Chebbo, 1992) The representation of the lamella system in the SMUSI model was defined by the sedimentation factor which was chosen to 80 % for the SS, the BOD5 and the COD based on the measurements of a particle separator in Lons Le Saunier, France. (Morin et. al, 2008)

5 RESULTS

5.1 Calculation of overflow loads

The annual pollution inflow loads to the stormwater tanks of the different scenarios caused by rain events, were constant with 3442 kg/a SS (suspended solids), 534 kg/a BOD5 (biological oxygen demand, 5 days) and 2374 kg/a COD (chemical oxygen demand). Due to the equal rain series and boundary condition for all scenarios the pollution concentration was also constant with 171 mg/l suspended solids, 27 mg/l BOD5 and 118 mg/l COD. The overflow loads and the deposition rate of the different stormwater tanks are shown in table 4.

Table 4. Overflow loads and deposition rates.

Scenario no. [-]	Tank volume [m ³]	Overflow load			Deposition rate		
		SS [kg/a]	BOD5	COD	SS [%]	BOD5	COD
1	82.91	443	69	305	87.13	87.08	87.15
2	108.64	421	65	291	87.77	87.83	87.74
3	456.84	197	31	136	94.28	94.19	94.27
4	830.06	112	17	77	96.75	96.82	96.76
5	204.41	342	53	236	90.06	90.07	90.06
6	225.70	312	49	216	90.94	90.82	90.90

The pollution load of the overflows of the three regarded parameters decreases naturally with an increasing tank volume. The same behaviour applies to the deposition rate. Due to the implemented lamella system the values of the deposition rates are generally high with 87 % for the smallest tank and 96 % for the largest one. The scenario no. 5 (S5) shows a deposition rate of 90 % which is already a very good value. To reach the maximum values of 94 or 96 % it is necessary to raise the tank volume by 200 or 400 %. This leads to a major increase in cost as shown in the following chapter. Therefore the results concerning the efficiency of the pollution deposition reveal that scenario 5 leads to very good results with a comparably small tank volume.

5.2 Comparison of S5 with stormwater treatment tanks

In this chapter the S5 will be compared with ordinary stormwater treatment tanks (STT) designed in accordance with governmental guidelines. (LfU, 2005) The first stormwater treatment tank (STT 1) was designed strictly according to the guidelines, the second (STT 2) had the same surface load as the already described scenario no. 5. The third tank (STT 3) also had the same surface load and design inflow as scenario no. 5. Table 5 shows the differences in detail:

Tabelle 5. Surface load and inflow definition for comparison

Type of tank	Surface load q [m/h]	Design inflow Qin [l/(s*ha)]
S5	1	20 % r15;01
STT 1:	10	Qcrit = 15
STT 2:	1	Qcrit = 15
STT 3:	1	20 % r15;01

The tank designs STT 1 – 3 were all modelled in the SMUSI model as described before for S5. The results were analysed for the number of overflows, their duration, total volume and annual pollution loads. Table 6 shows the hydraulic results of the modelling, the pollution loads and the deposition rate.

Table 6. Comparison S5 with guideline based stormwater tanks.

Type of tank	S5	STT1	STT2	STT3
Tank volume [m ³]	204.41	100.00	674.16	3341.80
Number of overflows [-]	24	34	4	1
Total overflow duration [h]	104.25	129.58	39.00	10.00
Total overflow volume [m ³]	9981	12607	3885	1288
Pollution load [kg/a]				
SS	342	2157	665	220
BOD	53	335	103	34
COD	236	1487	458	152
Deposition rate [%]				
SS	90.06	37.33	80.68	93.61
BOD	90.07	37.27	80.71	93.63
COD	90.06	37.36	80.71	93.60

The results show that for smallest tank by volume STT 1 the largest number of overflow events was registered and connected with that a long overflow duration and large volume. The annual pollution loads are six times higher than for the tank in S5. The deposition rate is the lowest in comparison with 37 %.

The tank SST 2 is three times bigger than S5 and has therefore only a small number of overflows, a short duration and a small overflow volume compared to scenario no. 5. But the annual pollution load is two times higher while the deposition rate is in the 80 % range.

The largest tank in this comparison is STT 3, which is 16 times larger than the volume in scenario no. 5. Nearly all rain events are stocked in this tank and only one overflow event occurs for the given rain series. Therefore the pollution loads are very small and the deposition rate can be given with 93 %. This is a good result but compared to the 90 % of S5 the good efficiency rate was bought with a lot a

storage volume.

S5 has a comparably small volume with a higher number of overflow events. The duration and the volume of the overflows are also high but regarding the annual pollution loads the cleaning efficiency is very high. The deposition rate of 90 % shows that a small tank with efficient treatment equipment can lead to very good cleaning results.

5.3 Cost calculation

A further comparison of the different tank designs was carried out by calculating the prices of the treatment tanks. The total price of the tank contains the price per volume and the mechanical equipment, in this case the lamella separator and the flushing system. (LFU, 2002; Sieker, 2005) Figure 3 shows that S5 is twice as expensive as STT 1 but compared to STT 2 (56 %) and STT 3 (16 %) the costs are relatively low.

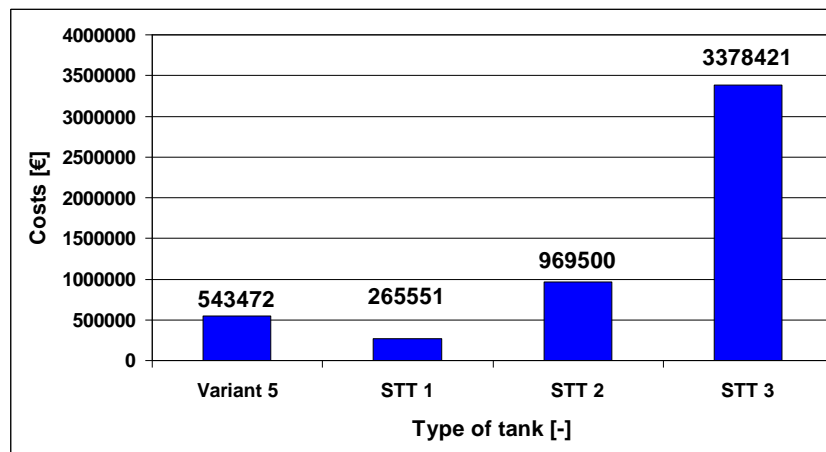


Figure 3. Comparison of costs.

The comparison of the four different tanks revealed that the design inflow of S5 leads to a small and cost effective stormwater treatment tank. A large number of rain events leads to overflows which are cleaned efficiently by the lamella system. Therefore a reduction of pollutant loads to the connected waters is achieved as well as a reduction of inflows to the treatment plant.

6 CONCLUSIONS

The evaluation of the first investigation results regarding the hydraulics for the different scenarios showed that the design approaches for the scenarios 5 and 6 lead to stormwater tanks with a good cleaning performance. Long overflow durations combined with comparably small differences between the maximum overflow rates and the original design inflow rates indicated that these tank designs were not overloaded. The small differences between the effective treated particle sizes at the maximum overflows and the initially chosen particle sizes in the scenarios 5 and 6 also indicated an effective stormwater treatment. (Schaffner et al., 2011)

The modelling results of the overflow loads and deposition rates showed that S5 has a high efficiency of 90 % due to the lamella system and its medium tank volume. To reach the maximum deposition rates of 94 – 96 % an increase of 200 – 400 in tank volume would be necessary. The comparison of S5 with stormwater treatment tanks designed by German standards (without lamella system) showed that an equal deposition rate to S5 could only be achieved with a 16 times larger tank volume. The following comparison of costs for the different tanks design revealed that the design inflow of S5 leads to a small and cost effective stormwater treatment tank.

The previous hydraulic investigations and the present analysis of the pollution loads and deposition rates showed that it is possible to design appropriately sized and cost effective stormwater tanks in contrast to federal design standards. The use of treatment equipment like lamella plates increases the treatment efficiency and reduces the necessary volume as well as the hydraulic and pollution impacts

to connected waters.

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