Small sedimentation devices and tanks: Comparability and TSS63 annual efficiency

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Sammendrag

Småskala sedimentasjonsenheter og -bassenger; sammenlignbarhet og TSS63 årlig effektivitet. Artikkelen presenterer en metode for å utlede kalibrerte sedimentasjonskurver for en liten sedimentasjonstank, eller et sedimentasjonsanlegg, basert på resultater fra hydrauliske tester av et sediment med kjent synkehastighetsfordeling, for eksempel i tråd med den tyske DIBt-testprosedyren. På den ene siden kan slike kurver brukes til å sammenligne ulike sedimentasjonssystemer. På den andre siden gjør kurvene det mulig å beregne den samlede årlige renseeffekten for meget finkornet suspendert stoff i det aktuelle sedimentasjonssystemet, slik det blant annet kreves i den nye tyske retningslinjen DWA-A 102. Dette kan gjennomføres enten ved en representativ langtidssimulering av det undersøkte anlegget, eller ved bruk av en forenklet beregningsmetode.

Summary

A procedure is presented for deriving calibrated sedimentation curves for a small sedimentation tank or device from the results of hydraulic tests for a sediment with a known setting velocity distribution, for instance following the German DIBt test procedure. On the one hand, these curves can be used for mutual comparison of such sedimentation systems. On the other hand, using these curves, it is possible to determine the overall annual removal efficiency for very fine suspended solids for the sedimentation system under investigation, which is required e.g. by the new German DWA-A 102 guideline. This can be done either by means of an exemplary long-term simulation for the device under investigation or also with a simplified procedure.

Introduction

For treatment of storm water of small catchment areas prior to discharge into water bodies of moderate sensitivity, frequently decentralised sedimentation structures are used. Such devices are usually small, in the size of a common manhole or somewhat larger, and can be classified as:

- Simple settling chambers, basins or tanks, optionally elongated or with internal baffles to achieve directional flow or for deposit protection
- Lamella separators with plate or honeycomb elements to reduce the vertical settling distance
- Vortex separators: structures through which flow is vortex-like and in which, in addition to gravity, centrifugal force and / or secondary currents near the bottom may favour sediment separation

Such prefabricated systems, suitable for small to medium catchment sizes of typically, say, less than 1 hectare, come from several suppliers. Larger settling tanks or lamella units are oftenly constructed individually, but may still fall in the device class investigated here.

Small low-tech sedimentation devices usually are filled with water permanently. However, it will increase the overall efficiency if the structure is emptied automatically, e.g. after every rain. For an even better removal of pollutants, units with integrated filter elements are also available. Due to absorption processes, these may have some efficiency also for dissolved pollutants. Such filter units are not considered in this study. Not considered, either, are combined sewer overflow structures.

The dimensioning of small sedimentation plants calls for criteria which ensure a sufficiently high degree of protection of the receiving waters. The DWA Code of Practice (Arbeitsblatt) DWA-A 102-2 [4], issued in December 2020, introduces some concepts which may also be useful in countries or situations where a strict application of this new guideline is not required. The idea thus shall be briefly introduced:

- Use of the parameter TSS63 (total suspended solids with grain diameter D < 63 µm, in German labeled AFS63, see [1]) as target parameter since it is known from recent research that many pollutants, including e.g. heavy metals, attach mainly to those fine sediment fractions
- Characterisation of the degree of pollution of the runoff by a catchment area categorisation by its land use which in turn defines typical TSS63 washoff loads in kg/(ha a), e.g. 530 kg/(ha a) for medium-polluted Cat. II surfaces such as roads with medium traffic
- Emission-based approach, generally allowing for a maximum annual pollutant discharge load into the river which is equal to the washoff load of the least-polluted catchment category I (280 kg/(ha a))
- In a physically consistent way, any treatment unit must consequently prove a sufficiently high total annual TSS63 removal efficiency (or, alternatively, a sufficiently low emitted annual TSS63 load directly) in order to comply with this load criterion.

A detailed general procedure how to obtain the current TSS63 removal efficiency is not described in A 102-2. Some simplified efficiency curves for settling basins are shown in the guideline, however these are not applicable for the settling units described here. Anyhow, calculation of the total efficiency should generally account for all crucial effects, namely, e.g., the annual precipitation pattern as well as the effect of storage inside of structures which are emptied to a treatment plant after each rain event.

The present paper keeps close to the German publication (Weiß, G. (2021) and makes a methodological proposal for this. Furthermore, it also shows a method to compare different sedimentation devices with each other and with classical settling basins. For this purpose, the sedimentation process is described in detail. The sediment is not defined by a grain size but directly by its settling velocity distribution. For this purpose, a calculation curve of settling velocity distribution is derived for the target parameter TSS63, in order to infer from measured efficiencies for a model sediment those for TSS63. Finally, the total annual removal efficiency can be determined by a long-time simulation or, in a simplified yet coarse way, by applying some defined rainfall events.

Material and Methods

Fractioned sedimentation in steady flow

Let the inflow Q be constant first. If sedimentation in the earth's gravity field is the decisive process, the steady-state sedimentation efficiency essentially depends only on the dimensionless ratio q_A/v_s of the surficial loading $q_A = Q/A$ in the basin (where A is the idealised plan view water surface (length times width) of an open settling basin or the projected lamella surface of a lamella settler) and the sediment settling velocity v_s. A formula that takes up this relationship is the sedimentation formula according to Fair-Geyer [5] for the design of sedimentation basins:

$$\eta = 1 - \left(1 + \frac{1}{n} \cdot \frac{v_s}{q_A}\right)^{-n} \quad (1)$$

where n (dimensionless) is a plant-specific factor that can vary between 1 (poor settling conditions, e.g. short-circuit flows in the basin) and 5 (very good conditions). For an ideal settling plant, η approaches infinity. The efficiency equals 1 for low values of q_A/v_s and drops asymptotically to zero for very large q_A/v_s.

Natural sediments and also the mentioned model sediments cannot be characterised by a single value for the settling velocity v_s, as required in Eq. (1), but by a distribution of this quantity. Therefore, the sediment is divided into a number m of non-overlapping grain fractions i with a characteristic mass fraction α_i of the sample ($\Sigma\alpha_i = 1$) and a mean settling velocity $v_{s,i}$ for each. The steady-state sedimentation efficiency h_{sed} for the sediment under investigation can then be obtained by evaluating Eq. (1) fraction by fraction:

$$\eta_{sed} = \sum_{i=1}^{m}\left[\alpha_i \cdot \left(1 - \left(1 + \frac{1}{n} \cdot \frac{v_{s,i}}{q_A}\right)^{-n}\right)\right] \quad (2)$$

Settling velocity distribution for TSS63

For TSS63, a settling velocity distribution for calculation purposes has been published in [11]. It is compiled in Figure 1 compared with the range of TSS (total suspended solids) measurements from stormwater runoff of separation systems given e.g. in [2], [6], [7],[8]. The distribution of settling velocity is scattered over several decades. This is caused by the inhomo-

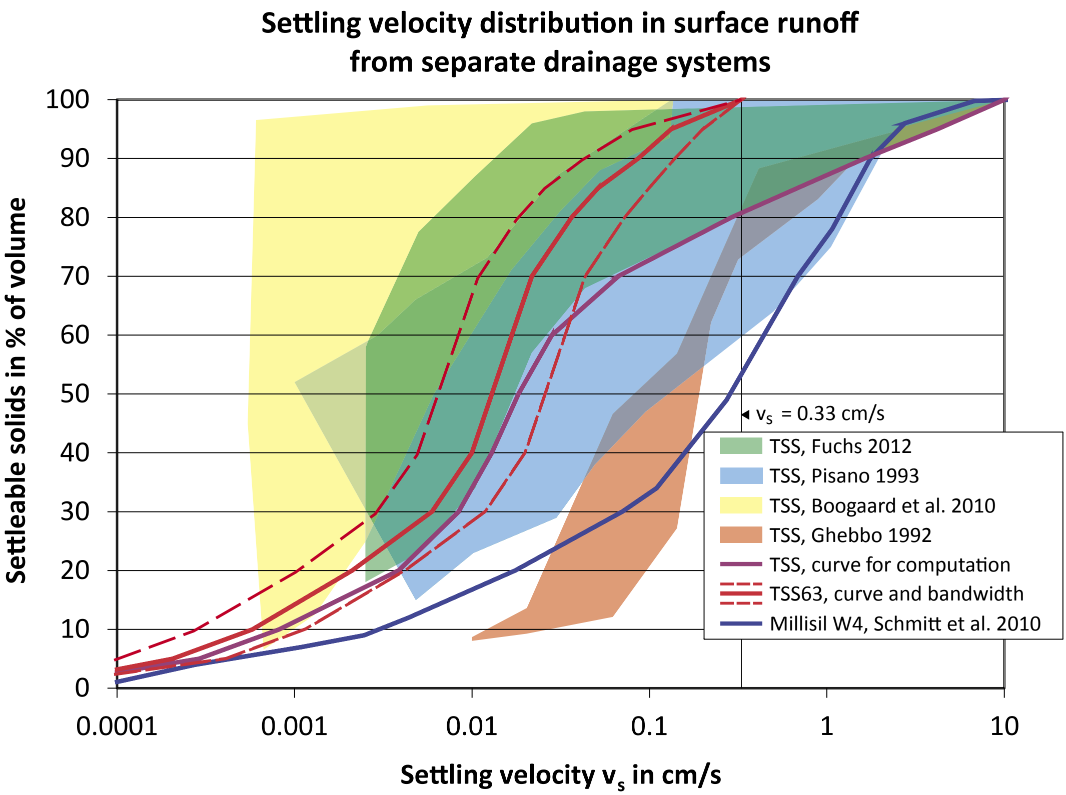


Figure 1. Distribution of the settling velocity for the test sediment Millisil W4 as well as for TSS and TSS63 according to [10].

geneity of the sediment, by the sampling and evaluation methodology (use of a settling column or subsample withdrawal at different times from a defined depth from a sample container) as well as by the influence of possible spontaneous flocculation. At present, there are no reliable data on a closer correlation of the settling velocity distribution to certain catchment characteristics, nor is there yet a standardised analytical procedure for the determination of TSS63 [1]. Figure 1 also shows a bandwidth of the TSS63 curve. For this purpose, the settling velocities of the fractions were arbitrarily halved or doubled while retaining the highest settling velocity of 0.33 cm/s.

For model sediments, it is possible to calculate the settling velocity distribution from a grain size distribution using the known density ρ_s by the well-known Stokes formula or a similar approach from literature. This is skipped here for brevity. Alternatively, the settling velocity distribution can also be experimentally determined in a settling column. For the quartz powder Millisil W4 used in the German standardized DIBt test procedure according to [3], the distribution of the settling velocity is also shown in Figure 2. It is clear that Millisil W4 approximately describes the best-settling TSS grain fractions only, i.e. on average it can be removed much easier by sedimentation than TSS and even easier than TSS63.

Calibration of device sedimentation efficiency curves by sedimentation tests

For the description of a certain sedimentation system or device by means of Eq. (2), the decisive parameter is the area A for the calculation of the surficial loading which is effective for settling and which is hidden in the surficial loading q_A. A is generally not equal to the plan view base area A_{Ground} of the device, but is influenced by internal structures and by the flow

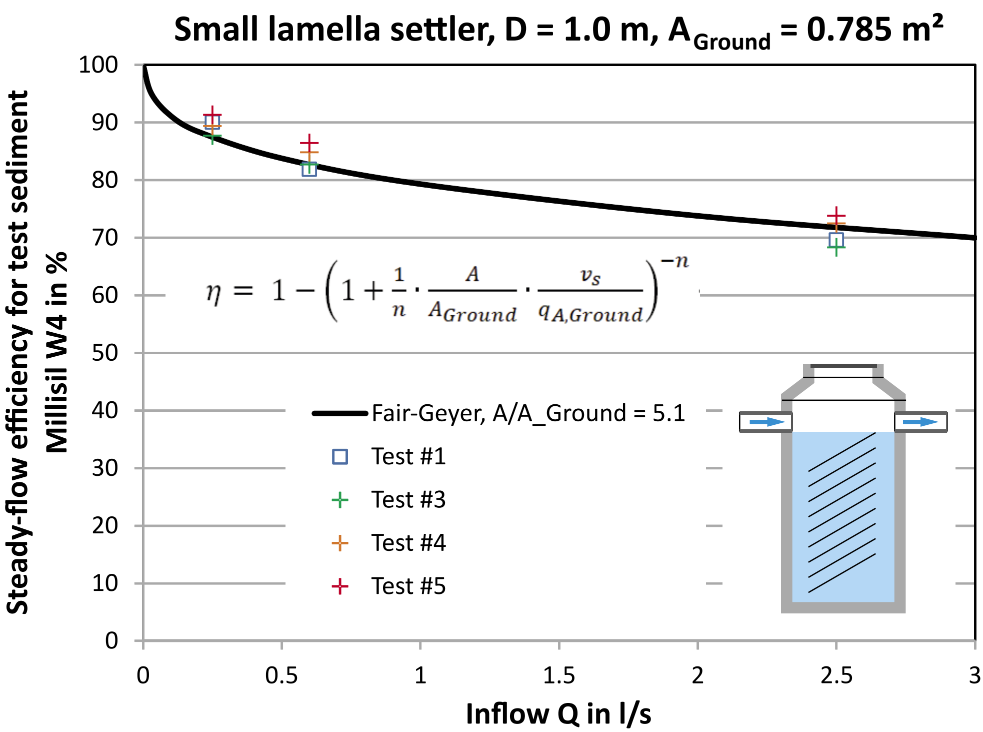


Figure 2. Calibration of the factor A/A_{Ground} for a small lamella settler on the results of a test following the DIBt procedure.

pattern in the sedimentation plant with detachment zones, etc. In lamella separators, A can correlate with the projection area A_{proj} of the lamellae, but not necessarily. With vortex separators, the additional effect of secondary flows, centrifugal force and depot shielding occasionally results in a value for A that is significantly larger than the base area A_{Ground} of the unit.

To separate the influence of the size of the unit and that of these secondary effects, the factor A/A_{Ground} is introduced as a free, calibratable parameter. The surface loading q_A is calculated with the reciprocal value A_{Ground}/A as

$$q_A = \frac{Q}{A_{Ground}} \cdot \frac{A_{Ground}}{A} \qquad (3)$$

For a known distribution of v_s, e.g. for a model sediment, one can determine the steady-flow efficiency h for different given inflows Q with Eq. (2) and (3) and represent it in a graph as $\eta = f(Q)$. If A/A_{Ground} is varied, the curve thus obtained is distorted in the Q direction.

In the past years, testing methods especially for filter devices for treatment of rain runoff have been developed. In Germany, a method according to the Deutsches Institut für Bautechnik (DIBt) [3] is standardized. In the UK, a Code of Practice by British Water applies while in the US, a protocol by the New Jersey Corporation for Advanced Technology (NJCAT) is applicable; for both see [12]. In short, in each of these procedures, a device is tested experimentally by charging it with several different yet constant inflows over a specified time of several hours and by applying defined loads of a specified model sediment with known grain size or settling velocity distribution, determining individual steady-flow removal efficiencies for the model sediment. Frequently, also pure sedimentation devices are tested according to this protocol.

If, for the sedimentation plant under investigation, results of such steady-flow tests in the hydraulic laboratory are available, these can be plotted in the same diagram as Figure 3. The variation of the factor A/A_{Ground} which is specific for the device allows the adjustment of the calculated curve $\eta = f(Q)$ to the measured data and thus a calibration of this key figure (Fig. 3). Because of the usually considerable scatter of such measurement data, a visual adjustment is sufficient.

It is decisive that the calibrated value for A/A_{Ground} can also be inserted as a constant in Eqs. (1) and (2):

$$\eta = 1 - \left(1 + \frac{1}{n} \cdot \frac{A}{A_{Ground}} \cdot \frac{v_S}{q_{A,Ground}}\right)^{-n}$$

$$\text{with} \quad q_{A,Ground} = \frac{Q}{A_{Ground}} \qquad (4)$$

$$\eta_{sed} = \sum_{i=1}^{m} \left[\alpha_i \cdot \left(1 - \left(1 + \frac{1}{n} \cdot \frac{A}{A_{Ground}} \cdot \frac{v_{s,i}}{q_{A,Ground}}\right)^{-n}\right)\right] \qquad (5)$$

Eq. (4) applies to any sediment with a known settling velocity v_s and is a universally valid dimensionless sedimentation curve for the investigated sedimentation device. Eq. (5) extends Eq. (4) again to arbitrary v_s distributions. If one chooses the TSS63 settling velocity distribution, a steady-flow efficiency curve $\eta_{TSS63} = f(Q)$ can be calculated for the respective plant by means of a renewed fractional calculation using Eq. (5).

Results

Comparison of different sedimentation devices

With the aid of Eq. (4), different sedimentation devices, each with its own calibrated value for A/A_{Ground}, can now be compared with each other by selecting the ratio $q_{A,Ground}/v_s$ as the abscissa value. In Figure 4, a small lamella settler in a DN 1000 manhole where $A/A_{Ground} = 5.1$ was derived by the cited method is compared with a classic stormwater settling tank with permanent water filling, if the entire base area A_{Ground} is assumed to have a sedimentation effect, i.e. $A/A_{Ground} = 1$. In reality, due to detachment zones and non-parallel flow through the settling tank, A/A_{Ground} is likely to be significantly smaller than 1, so the curve that would then be valid would still be below the one given. These curves are still valid for any sediment.

The effective settling area A of the lamella settler is significantly larger than the base area

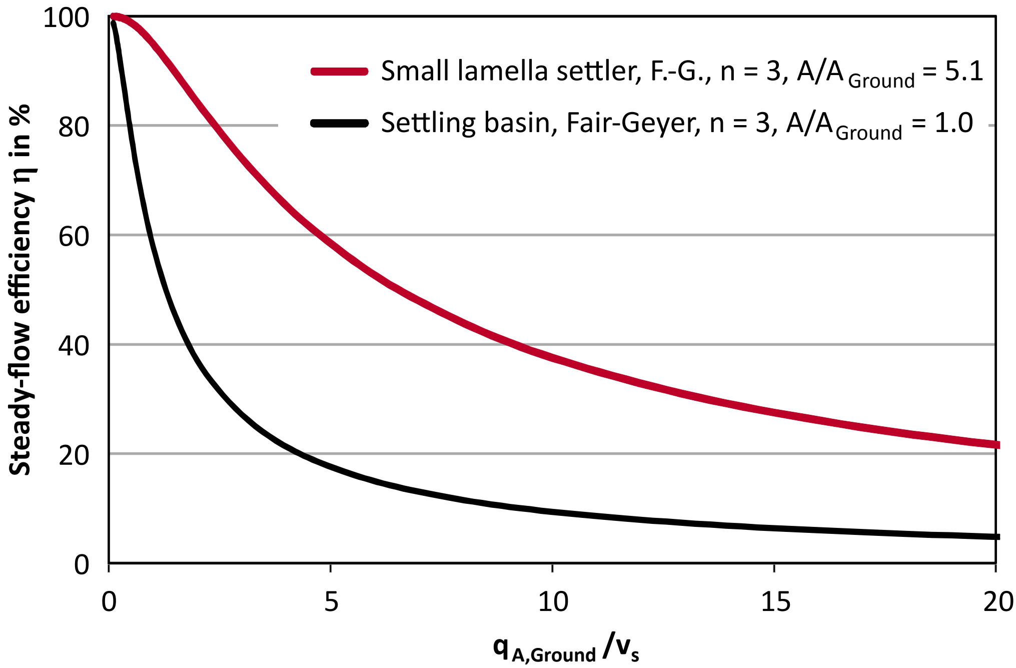


Figure 3. Calibrated sedimentation curve $\eta = f(q_{A,Ground}/v_s)$ *for a small lamella settler in comparison to a classic stormwater settling tank with permanent water filling, valid for any sediment of given settling velocity* v_s.

of the chamber (DN 1000, A_{Ground} = 0.785 m²) due to the installed cross-flow lamellas with the calibrated value A/A_{Ground} = 5.1. The chamber thus has a more favourable separation behaviour in relation to the size of the structure than a classic settling basin. The projection area of the lamellas, on the other hand, measures A_{proj} = 5.75 m², which would result in A_{proj}/A_{Ground} = 7.32. The calculated effective settling area A is therefore also smaller, anyhow, than the installed lamella projection area A_{projj}. Obviously, the flow through the lamellas is not completely uniform in this system, either.

A comparison of different commercial sedimentation devices is also possible on this basis by plotting their calibrated sedimentation curves in Figure 3. The larger A/A_{Ground}, the more effective is the plant for the same footprint. However, such a comparison is not made in this methodological paper. There are some secondary factors included in A/A_{Ground} due to the process. In addition to the lamellae and the flow guidance, this is above all the fact that not only the sedimentation process is decisive, but also the fate of the sediment that has already settled, e.g. by possible resuspension or by sticking to or sliding down off the lamellae. With compact vortex separators, there can be an additional sedimentative effect due to the centrifugal flow, which can make such devices relatively effective, especially if the sediment deposit is additionally shielded by internal bafflework.

With calibrated value A/A_{Ground}, small decentralised sedimentation devices can also be more justifiably classified wherever a direct design surficial load q_A is asked for, e.g. in former German guidelines. The calculation of q_A, e.g. for a small lamella separator, then need not based on the installed projection area A_{proj}, but on the calibrated value A determined in this way. This avoids the otherwise necessary (and actually unfounded) assumption that the installed settling surface is fully effective and has an optimal flow. The method, moreover, can also be used for vortex separators and other devices without a defined settling surface.

Steady-flow efficiency for TSS63

Through the described calibration and conversion, curves of the steady-state sedimentation efficiency $\eta_{sed} = f(Q)$ can be given for TSS63 and other sediments for the sedimentation device investigated, even if no own laboratory tests were carried out for the sediment in question.

For TSS63, only moderate steady-flow settling efficiencies result (cf. Figure 4): With a rainfall intensity of q_{krit} = 15 l/(s·ha) and 0.1 ha of connected impervious area, the inflow is Q_{krit} = 1.5 l/s. The surface loading is then q_A = 1.35 m/h, and the steady-flow efficiency for TSS63 (mean curve) is approximately η_{sed} = 35 %. The applied bandwidth of TSS63 is of course also reflected in a considerable variation of the efficiency, here approx. 24 - 46 %. It can also be seen from Figure 4 that the steady-flow efficiency for the model sediment Millisil W4, as it can be measured in hydraulic tests, exceeds that for TSS63 by far and the results of such tests can therefore only be transferred to a limited extent.

Calculation of the annual total efficiency

If the total annual removal efficiency η_{ges} for TSS63 is sought, as in the German DWA-A 102-2 guideline, this will differ fundamentally from the steady-flow efficiency η_{sed} considered so far. It results as a consequence of the annual precipitation pattern with rainfall inflow varying with time and dry periods. The determination can be carried out with a long-term simulation or, in a simplified way, with a determined number of rains with defined duration and inflows.

Direct long-term simulation**:** Here, the inflow hydrograph Q(t) from the catchment to the sedimentation plant is calculated and a quasi-steady behaviour (as if there were a constant flow) is postulated, cf. also [10]. The settling velocity distribution of the sediment as well as

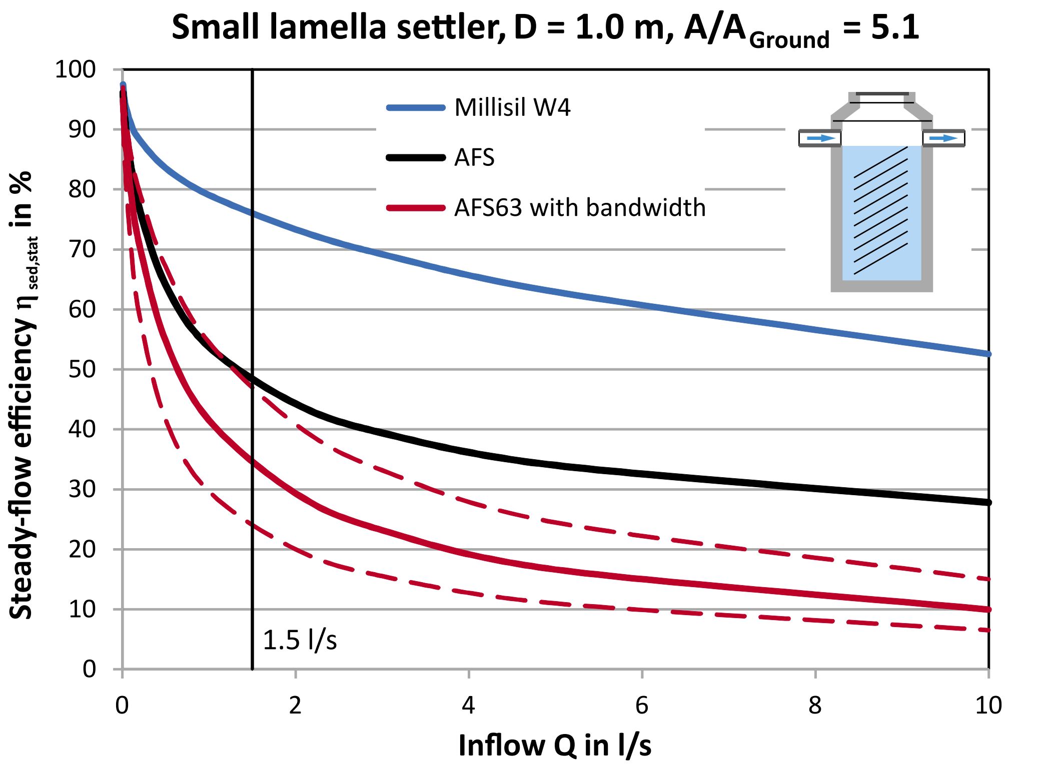


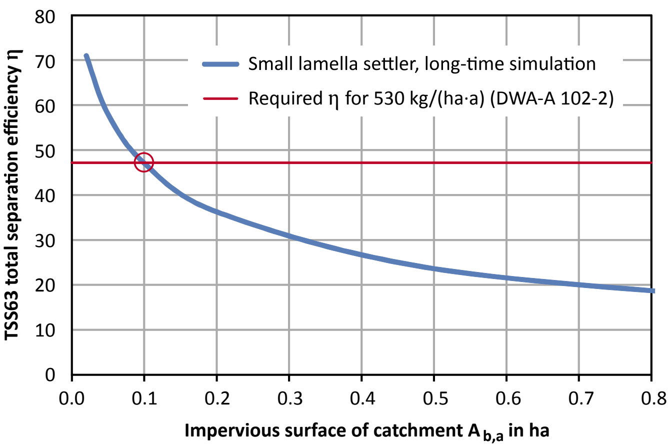
Figure 4. Calibrated steady-flow sedimentation curves η = f(Q) for the lamella settler for sediments with different settling velocity distributions.

its concentration in the rainfall runoff are known, e.g. by assuming either a simply constant inflow concentration or – somewhat more elaborated – a concentration dependent on the rain intensity. Details must be skipped here for brevity. Using curves as in Figure 4, statements can be made about any sediment. The current TSS63 efficiency η(t) is obtained, followed by the effluent concentration C(t), and then, by integration over the simulation period, the total effluent load and finally also the sought TSS63 annual efficiency η_{ges} can be determined. Of course, this procedure is also suitable for plants which are emptied after storm events e.g. by pumps, if this emptying process is modelled appropriately. This takes also into account the storage effect which may be considerable.

Commercial decentralised systems should get by without a project-specific detailed design by the consultant. A simulation where a site-specific rainfall series for each project is necessary would be far too time-consuming. A simplification is possible by defining an „unfavourable" rain series as valid for everywhere within a certain larger region (such as the German Mühldorf rain series mentioned below) or by defining local rain series valid e.g. for larger cities. In this case, a manufacturer can carry out or commission a few „master" simulation runs for his product using this rainfall series, valid for different sizes of the impervious area $A_{E,b}$ in ha. The result is the annual efficiency $\eta_{ges} = f(A_{E,b})$ that can be achieved with the sedimentation system. Since η_{ges} is not concentration-dependent, so the assumed specific washoff load in kg/(ha a) from the surface area is irrelevant for the determination of this correlation, only for the final evaluation.

An example is shown in Figure 5. A long-term simulation with a commercially available hydrological model comprised only one catchment area and one lamella settler, simulated as a basin with the throttle discharge zero. The overflow hydrograph then corresponds approximately to the inflow hydrograph and was evaluated by postprocessing. For the sediment concentration, a rainfall-intensity-dependent approach was taken. The area was a category II area (medium pollution level). The basic TSS63 concentration C_0 in mg/l was therefore chosen in such a way that the corresponding TSS63 washoff rate of 530 kg/(ha·a) (the typical A 102-2 calculation value for a Cat. II area) was achieved. According to A 102-2, a TSS63 discharge load of 280 kg/(ha-a) is permissible. With a connected impervious area of $A_{b,a}$ = 0.1 ha, this target is narrowly missed in Figure 5.

<u>Three representative storms</u>**:** In the already mentioned DIBt standard test method, a treatment device is charged with three different yet



Results of long-time simulation		4838158 time steps		
Small lamella settler		With permanent water level		
Basic data:		(KOSIM input data)		
Impervious surface of catchment		0.100	ha	
Projected plate surface of lamella settler		4	m²	
Duration of simulation		46	Jahr(e)	
Mean inflow TSS63 concentration		61.3	mg/l	
Mean inflow TSS63 concentration for a TSS63 washoff rate of		*61.4* / *530*	*mg/l* / *kg/(ha·a)*	
Results of simulation	*TSS63 conc. in mg/l*	Volume in m³	TSS63 load in kg	
Inflow to sedimentation device	*105,7*	23043.2	2435.8	
Upstream emergency overflow				
Outflow	*56,0*	23043.2	1289.3	
		Volume in m³/a	TSS63 load in kg/a	TSS63 washoff in kg/(ha·a)
Inflow to sedimentation device		500.9	53,0	**529.5**
Upstream emergency overflow				
Outflow		500.9	28,0	**280.3**
		Criterion according to A 102 MISSED		
Total TSS63 removal efficiency				
Computed total annual TSS63 efficiency			**47.1%**	
Minimum required value according to DWA-A 102-2			**47.2%**	

Figure 5. TSS63 annual efficiency as a function of the connected impervious area (results of the long-term simulation, mean curve for TSS63). According to A 102, an area of just under 0.1 ha can be connected to the lamella settler shaft if a Cat. II surface with a specific washoff rate of 530 kg/(ha-a) is assumed.

*Table 1. Simplified dimensioning of a settling unit UFT-*FluidSettle *using three distinct storm events.*

Sedimentation device: Small lamella settler DN 1000		Project name	Demonstration project
Dimensioning according to DWA-A 102-2		Project number	25-12345
Determination of total TSS63 removal efficiency (simplified method)			

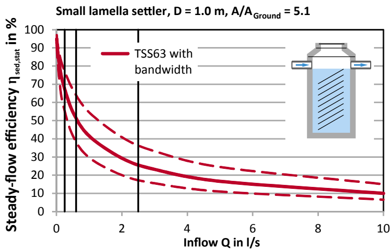
Project data and required efficiency

Impervious surface $A_{b,a}$	0.10	ha	
Annual TSS63 washoff load of this surface	530	kg/(ha·a)	
Permissible spilled TSS63 load (DWA-A 102-2)	280	kg/(ha·a)	
Required minimum total efficiency η	47.2	%	
Computed mean total efficiency η for „medium“ TSS63	**54.8**	**%**	Criterion according to A 102 FULFILLED

Data of sedimentation device

Used formula for description of sedimentation process Fair-Geyer		
Fair-Geyer parameter n	3	(dim.-less)
Settling-effective surface of device A_{proj}, calibrated from model tests	4.0	m²

TSS63 removal efficiency of this device



		Rain intensities according to DIBt test protocol			
Rain intensity q		2.5	6	25	l/(s·ha)
Inflow Q		**0.25**	**0.6**	**2.5**	**l/s**
Surficial loading q_A		0.23	0.54	2.25	m/h
Steady-flow sedimentation efficiency $\eta_{sed,stat}$ for this inflow	TSS63 max	76.9	63.9	36.5	%
	TSS63 medium	67.0	51.0	25.8	%
	TSS63 min	54.5	37.8	17.3	%
Share of annual inflow TSS63 load		50.0	33.3	16.7	**%**
Weighted total TSS63 efficiency	TSS63 max	**65,8**	**%**		
	TSS63 medium	**54,8**			
	TSS63 min	**42,7**			

constant inflows. The basic idea is that these three idealized test storms should represent an one-year rainfall pattern, albeit in a rough and simplified manner, see [9]. The test storm intensities were originally derived from a 36-year long-term rainfall series of a rain gauge in Mühldorf am Inn in Upper Bavaria, which was found as the less favourable rainfall series by a hydrological investigation. Three classes of rainfall intensity were determined with mean values of 2.5, 6.0 and 25 l/(s·ha). Time durations were found to be in a ratio of 8 : 3.3 : 0.8, each representing 1/3 of the mean annual rainfall volume. Furthermore, a sediment load distribution of 3:2:1 was assumed. Thus, the test sediment concentrations are dependent on the test storm intensity, where a dilution effect takes place. Finally, the DIBt test carries out a flushing trial with a very strong rainfall intensity.

A simplified method to obtain the total TSS63 removal efficiency (instead of a long-term simulation) could be to mathematically reproduce the DIBt sedimentation test procedure when the settling performance of the device under examination is known. Rather than the Millisil test sediment, directly TSS63 with its settling velocity distribution according to Figure 1 is used. The three steady-state inflows are derived from the DIBt rainfall intensities times the impervious catchment area. Then, for each inflow, a partial steady-flow TSS63 efficiency is taken from a graph like Figure 4. The total load of sediment is not included in the calculation of the total annual efficiency, but the partial efficiencies must be weight-averaged by the 3:2:1 load ratio. The method directly takes into account the differences between TSS63 and the significantly better settling Millisil test sediment. The mentioned flushing test cannot be taken into account because Eq. (5) does not account for sediment remobilisation by erosion. However, since most of the annual runoff occurs at small to medium flows, this neglect seems justifiable. The procedure is shown in Table 1.

For the same input data, the simplified method yields a total TSS63 removal efficiency of a similar order of magnitude as the direct simulation, but of course no exact agreement. The deviations may be due to the different rainfall series (the simulation used a storm series of the same station, but more years with more frequent heavy rainfall) and also due to the simplified approach itself. In this example, the simplified method yields a higher efficiency

(54.8 %) than the simulation (47.1 %), so it is not on the safe side. Of course, there is also a strong sensitivity to the sediment properties; here, the A 102 requirements would be met for the "coarse" and "medium" TSS63 curves, but not for the "fine" one. Overall, however, the simplified procedure for determining the annual efficiency could be proposed for use with the same degree of abstraction as the DIBt test because of the same basic idea of representation of the annual rainfall series.

Conclusions

If a sedimentation formula with a free parameter is used, it is possible to calibrate this parameter on steady-flow test results by means of fractional sedimentation with a known settling velocity distribution of the test sediment. With the characteristic sedimentation curve of the tested sedimentation system obtained in this way, it is possible to determine the annual TSS63 removal efficiency, as required by the German DWA-A 102-2 Code of Practice, either by a single direct long-term simulation or by applying three distinctive rain events of well-defined intensity, duration and inflow sediment concentration. In both cases, the sedimentation system can be dimensioned for each project in a simple manner and without an elaborate verification procedure. The basic approach can be used or adapted also where the German guideline formally need not be applied and thus it may be interesting also e.g. for the Scandinavian countries.

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