Sewer solids separation by sedimentation – the problem of modeling, validation and transferability

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Abstract Sedimentation of sewer solids in tanks, ponds and similar devices is the most relevant process for the treatment of stormwater and combined sewer overflows in urban collecting systems. In the past a lot of research work was done to develop deterministic models for the description of this separation process. But these modern models are not commonly accepted in Germany until today. Water Authorities are sceptical with regard to model validation and transferability. Within this paper it is checked whether this scepticism is reasonable. A framework-proposal for the validation of mathematical models with zero or one dimensional spatial resolution for particle separation processes for stormwater and combined sewer overflow treatment is presented. This proposal was applied to publications of repute on sewer solids separation by sedimentation. The result was that none of the investigated models described in literature passed the validation entirely. There is an urgent need for future research in sewer solids sedimentation and remobilization!

Keywords Combined sewer overflow treatment; modeling; sedimentation; stormwater treatment; validation

Introduction
Sedimentation of sewer solids is the most relevant process to minimize the output of particles from Stormwater Outlets and Combined Sewer Overflows (CSO) to the receiving waters. Detailed research work shows, that depending on the design of facilities, not only sedimentation, but also its contrary, i.e. remobilization, occurs (e.g. Kutzner and Geiger, 2005). Due to the importance of sedimentation and remobilization a lot of studies were carried out worldwide. Their aim was to develop and to improve deterministic models in order to predict the performance of sedimentation by several devices (e.g. hydrodynamic separators or ponds). Nevertheless “many of the settlement and transport processes associated with sewage solids are still poorly understood” (Ashley et al., 2004).

These sedimentation models can be divided into two groups. One group is based on the technique of Computational Fluid Dynamics (CDF). Software tools are applied – consisting of a lot of mathematical sub-models – to describe in detail the flow patterns of water and solids (i.e. Schmitt et al., 2002). These models could be used to optimize the structural design but they are too laborious to be used for dimensioning every single facility or to be integrated into Quantity-Quality-Simulations (QQS). The other group consists of models which describe the movement of water or solids only in one spatial direction or without any spatial resolution. One can use these models to develop design procedures for the planning praxis or they can be incorporated into QQS. This requires that the relation between input and output parameters can be transferred to a new facility and that a range of values of model parameters is known. Until today German Water Authorities do not accept this new type of mathematical models and therefore these models mustn’t be applied for a water permit. For the simulation of the mass of
substances spilled by CSO treatment facilities only the effects of detention and flow split are taken into account. Sedimentation basins for CSO treatment are sized for a given maximum surface loading rate of 10 m/h with regard to the design rainfall intensity, which is normally 15 L/s ha. There exists only one exception for hydrodynamic separators (FluidSep) in the State of Baden-Württemberg, see Brombach and Weiß (1997).

The aim of this study was to examine whether this sceptical view to model transferability is reasonable. As there are no existing standards for validating and testing transferability of mathematical models a framework for this issue is developed. Afterwards this framework is adapted to the evaluation of models described in literature.

Methods

All models evaluated below are not totally mechanistic or white-box models (definition of model attributes, see Carstensen et al., 1997). That means they are not solely based on fundamental balances of energy, impulse and mass. They contain also phenomenological model parameters that have to be calibrated. Typically the authors use a certain part of their measurements for calibration and an independent second part for validation. Validation means that - by using input data from the second data set - measured and modeled values of output parameters are somehow similar. But there are a lot of different parameters and analyzing methods to prove similarity. It is nearly impossible to standardize a method for the validation due to the different parameters, combinations of processes and operation modes that are applied. The authors only provide a framework for the conduction of studies to develop validated mathematical models for separation processes (see Table 1).

The most important requirements for the development of a validated model are the following:

- Validation of a model for dimensioning facilities in practice is only possible by using data from monitoring at full-scale facilities under natural operation conditions (real world data). Studies by the means of down-scaled devices in the lab (physical, material models) are helpful to identify input parameters. But the conditions in stormwater and CSO treatment are too complex and dynamic for an entire simulation by a material model.
- Validation at full-scale facilities has to be based on measurements from numerous rain events. Model parameters have to show similar values when comparing different events.
- Validation has to be based on a relation between each input parameter and the output parameter of the mathematical model for the process(es). The relation must be independent from other processes and input parameters.
- The difference between measured and modeled values of output parameters must be quantified and not only presented by comparing the shape of graphs.

Results and discussion

It is impossible to explain in detail the application of all working steps and requirements shown in Table 1 to all evaluated mathematical models within this paper. Table 2 summarizes our findings. This table contains a short description of every model, shows whether the measurements were conducted under steady state conditions or whether event mean values or time series of data were used. Moreover values for model parameters are provided and if possible the efficiency predicted by these models is compared to the efficiency predicted by the Hazen-Model. The last column indicates which requirements of Table 1 are fulfilled and which are not. Whenever it was evident that very important requirements where not fulfilled, further requirements of Table 1 were not mentioned.
### Table 1: Working steps to develop and validate mathematical models to simulate separation processes in stormwater and CSO treatment

<table>
<thead>
<tr>
<th>Working steps</th>
<th>Experiments with physical, material models</th>
<th>Requirements/remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Identification of relevant input and output parameters</td>
<td>Literature study/observations and measurements on full-scale plants/pre-experiments at material models</td>
<td></td>
</tr>
<tr>
<td>2. Planning of experiments</td>
<td>It has to be guaranteed that effects of each single process are investigated separately.</td>
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<tr>
<td>3. Dimensional analysis / compliance with similarity laws</td>
<td>Dimensional analysis could reduce the number of input parameters to be investigated. Similarity laws have to be complied. If laws are competitive a reasonable decision has to be made for the more important one.</td>
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<tr>
<td>4. Realization of experiments under steady state conditions / otherwise additional investigation of mixing conditions</td>
<td>It is preferable to work under steady state conditions. If this is impossible and the effect of the process cannot be located in one point it is necessary to calibrate and validate a mixing model additionally because output parameters will always be effected by both mixing and separation process.</td>
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<tr>
<td>5. Variation of parameters</td>
<td>Each input parameter of the process is varied while the other input parameters remain constant. This could only be realized strictly under steady state conditions. If the influence of the input parameters on the output parameters could be described mathematically under (nearly) steady state conditions, then the relevance of dynamic effects has to be investigated later on.</td>
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<tr>
<td>6. Development of a mathematical model maximizing its mechanistic character</td>
<td>The number and the relevance of phenomenological model parameters have to be minimized. Parameter values for steady state conditions have to be calibrated and validated. The difference of output parameter values of experiment and model should be quantified in linear ratio to the measured values. Exponential or log-values can cover up differences.</td>
<td></td>
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<tr>
<td>7. Model validation under realistic conditions</td>
<td>The validation should be carried out under conditions which are as realistic as possible; this means simulation of rain events and process combinations similar to real conditions. It is necessary to validate each process model by itself. Therefore it is necessary to develop parameters for the effectiveness of single processes which could be computed using experimental data. An example is the efficiency of sedimentation for inline devices for CSO treatment developed by Hübn er and Geiger (1996) and Hübn er (1997).</td>
<td></td>
</tr>
<tr>
<td>8. Development of the measuring concept</td>
<td>A mathematical model cannot be developed only due to measurements on full-scale plants as it is nearly impossible to identify all relevant input parameters of a process by these measurements. But it is possible to adapt an existing model for another device when the combination of processes is similar to the actual one. The monitoring has to guarantee that all input parameters for the relevant processes and specific parameters for their effectiveness (working step 7) can be measured.</td>
<td></td>
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<tr>
<td>9. Validation of fundamental relations predicted by the mathematical model</td>
<td>Should be done on basis of effectiveness parameters which are specific for each process (see working step 7). For example, when the model predicts an exponential decrease of efficiency with increasing hydraulic loading but the measured data do not show any relation between these in- and output parameters the validation is negative.</td>
<td></td>
</tr>
<tr>
<td>10. Calibration / validation / transferability of model parameters</td>
<td>Should be done on basis of process specific effectiveness parameters (see working step 7). Validation for one facility has to be done by using data of events independent from calibration. A model is transferable if calibration/validation is possible for numerous plants and a confidence interval for parameters could be defined.</td>
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</table>

R. Kütner et al.
The basic theory of sedimentation was first developed by Hazen (1904) for rectangular sedimentation basins under steady state condition in the lab. His model describes the sedimentation efficiency as a linear function of the ratio of settling velocity to surface loading rate (first row of Table 2). This ratio is called “Hazen-Number”. The majority of the sedimentation models in Table 2 are based on this kind of relation, but the Hazen-Number is part of the exponent of an exponential term. Within some of the models sinking velocity is substituted by a model parameter.

Beforehand it has been pointed out that a model which shall be used to dimension treatment facilities in practice has to be validated by measurements at several full-scale facilities under natural operation mode. Due to this postulate the paper treats mainly this kind of validation. It was a disillusioning surprise that none of the models could be specified as “really validated”. As the remobilization process is much more complex compared to sedimentation process the degree of validation of remobilization models is much lower. Therefore remobilization models are only described in Table 2 but they are no more commented on in the text.

A very common and quite easy way to show a similarity between measured and predicted values is to plot the time series of concentration or loading in the outflow for both measured and computed data (see Figure 1). This comparison of plots does not comply with the requirement of validation (see Table 1) to use a relation between input and output parameters of the separation process model. Reasons are the following:

- Parameter of x-axis is time, but time is not an input parameter of the model.
- Concentration and load in the outflow are not only influenced by the sedimentation process but also by the mixing process. Every author uses some kind of model for the mixing process to compute a time series. However, no published study is known that validates a mixing model for the whole range of operation conditions of a full-scale plant for CSO or stormwater treatment.
- The output parameter of the most models is efficiency. But the shape of a modelled time-series-graph regarding to concentration in the outflow is similar to the measured one even when the efficiency of sedimentation is +5% in one time-step and −5% in the next one. This results from the fact that the shape of the graph is influenced by the time series of concentration in the inflow which is not an input parameter of the sedimentation model. If load is used for the comparison also the flow rates must additionally be taken into account.

Due to the problem of not knowing the mixing conditions in the facilities it seems to be nearly impossible to use time series data to quantify the difference between measured and modeled values. It seems to be better to use event mean values for calibration/validation.

Wong et al. (1999) calibrated the $kC^*$-model for event mean values of efficiency of a wetland for CSO treatment. They found out that the main treatment process of the wetland is sedimentation. The $kC^*$-model describes the efficiency as influenced by the ratio of a model parameter $k$ to the surface loading rate in an exponential term and the background concentration $C^*$ which is the minimum outflow concentration (Table 2) and which is not effected by the sedimentation process. Calibration and validation was not done by minimizing the difference of efficiencies but of log-values of loads in the outflow for fifteen events. For validation measured outflow mass was plotted against modeled mass in a double-log system of coordinates (Figure 2). In a follow up study Kutzner et al. (2004) tried to validate the model according to the requirements provided by Table 1 using measured data of Wong et al. As a first step they evaluated the relation between surface loading rate and efficiency. Therefore efficiency has to be defined independently of $C^*$. The definition could be seen at the y-axis of Figure 3. The continuous line shows...
Table 2 Description and evaluation of deterministic models for solids removal

<table>
<thead>
<tr>
<th>Literature</th>
<th>Temporal resolution (development/recommended application)</th>
<th>Mathematical model</th>
<th>Model Parameters/ratio of surface area</th>
<th>Validation material model (MM)/Full-scale plant (FSP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazen (1904)</td>
<td>Theoretical consideration for steady-state conditions</td>
<td>Sedimentation in rectangular basin: [ \eta_{TSS,sed} = 1 - \frac{X_{TSS,in}}{X_{TSS,in}} \begin{cases} 1 &amp; \text{for } \frac{h_0}{h} \leq 1 \ \frac{h}{h_0} &amp; \text{for } \frac{h_0}{h} &gt; 1 \end{cases} ]</td>
<td>No calibration for CSO or stormwater treatment facilities</td>
<td>No validation for CSO or stormwater treatment facilities</td>
</tr>
<tr>
<td>Hubner (1997): hydrodynamic separator (HS) Geiger et al. (1998): hydrodynamic separator and rectangular basin (RB)</td>
<td>Steady-state, no influence of dynamics existing/time series</td>
<td>Sedimentation in HS and RB: [ \eta_{TSS,sed} = 1 - 2 - \left(1 - \frac{q_A}{q_{A,HS}}\right)^{k_1} ]</td>
<td>( k_{1,HS} = 2.33, k_{2,HS} = 1.86/q_{A,HS} = 21% ) for L/W/H = 3:2:1 ( k_{1,HB} = 1.78, k_{2,HB} = 1.65/q_{A,HB} = 28% ) for L/W/H = 3:0.5:1 (Geiger et al., 2002) ( k_{1,HS} = 1.23, k_{1,HS} = 1.58/q_{A,HS} = 41% ) for ( H_{CS} = 0.1, D_{Ch} = 0.24, L_{Ch} = 1.3 ) ( k_{1,HB} = 0.87, k_{2,HB} = 1.85/q_{A,HB} = 57% ) for ( H_{CS} = 0.24, D_{Ch} = 0.24, L_{Ch} = 1.3 )</td>
<td>MM HS: no Froude-similarity for the whole range of ( v_t ), validation under realistic conditions only by time series MM RB: input parameters not complete, no validation under realistic conditions FSP HS: no relation between ( q_A ) and ( \eta_{TSS,sed} ) values of ( \eta_{TSS,sed} ) very low FSP RB: no monitoring</td>
</tr>
<tr>
<td>Luyckx et al. (2002)</td>
<td>Steady state/no recommendations</td>
<td>Sedimentation in HS: [ \eta_{TSS,sed} = 1 - e^{-k_1 h_t} ]</td>
<td>( k = 0.12/q_{A,HS} = 9% ) for ( H_{CS} = 0.1, D_{Ch} = 0.22 ) ( k = 0.72/q_{A,HS} = 52% ) for ( H_{CS} = 1; D_{Ch} = 0.22 )</td>
<td>MM: no similarity laws for particle movement, no validation under realistic conditions FSP: no monitoring</td>
</tr>
<tr>
<td>Brombach and Weß (1997).</td>
<td>Not published/long term average</td>
<td>Sedimentation in HS: diagram for [ \eta_{TSS,sed,1/4} = \frac{q_{A,HS}}{V_{in}} ]</td>
<td>diagram, no parameters ( q_{A,HS} = 33% ) for ( H_{CS} = 0.33, q_{A,HS} = 39% ) for ( H_{CS} = 1/4 ) all parameter values are integrated to the equation ( q_{A,HS} ) not computable because values for some special input parameters missing</td>
<td>MM: conducted, no documentation FSP: conducted, no documentation</td>
</tr>
<tr>
<td>Vaes et al. (1999)</td>
<td>steady state/time series</td>
<td>[ \eta_{TSS,sed} = \left(1 - e^{-0.20(1/H_{CS})^{1/3}(V_{in})^{1/2}}\right)^{1/3} ]</td>
<td></td>
<td>MM: (no access to literature source) FSP: only time series of loading used, no validation of relation between input parameters and efficiency of sedimentation model</td>
</tr>
</tbody>
</table>

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**Mathematical model**

- **Hazen-model to surface area this model**
- **No calibration for CSO or stormwater treatment facilities**
- **No validation for CSO or stormwater treatment facilities**

**Validation material model (MM)/Full-scale plant (FSP)**

- **MM HS: no Froude-similarity for the whole range of \( v_t \), validation under realistic conditions only by time series**
- **MM RB: input parameters not complete, no validation under realistic conditions**
- **FSP HS: no relation between \( q_A \) and \( \eta_{TSS,sed} \) values of \( \eta_{TSS,sed} \) very low**
- **FSP RB: no monitoring**

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<tbody>
<tr>
<td>Lessard and Beck (1991)</td>
<td>model adapted time series</td>
<td>k = 0 (Lessard et Beck without calibration)</td>
<td>FSP: only time series of loading used, no validation of relation between input parameters and efficiency of sedimentation (Zug et Gogien)</td>
</tr>
<tr>
<td>Zug and Gogien (2002)</td>
<td>sedimentation in RB:</td>
<td>v_sed = 0.56 cm/s</td>
<td>FSP: Wong et al., no relation between input parameters and efficiency of sedimentation/Fletcher et al. weak relationship, k varies during 5 experiments, highest value is double of lowest (see cell on the left)</td>
</tr>
<tr>
<td>Wong et al. (1998): wetland</td>
<td>wetland, event mean values/swales, steady state</td>
<td></td>
<td>only time series of output mass used, no validation of relation between input parameters and efficiency of sedimentation (Pettersson et Svensson)</td>
</tr>
<tr>
<td>Fletcher et al. (2000): swale</td>
<td>sedimentation in wetland and swale</td>
<td></td>
<td>MM: no validation of all relations between in- and output parameters, high deviation for validation using time series</td>
</tr>
<tr>
<td>EPA (1986), Pettersson and Svensson (1998)</td>
<td>no documentation/time series</td>
<td>because no validation was conducted no parameter values are cited</td>
<td>FSP: no monitoring</td>
</tr>
<tr>
<td>Geiger et al. (2002)</td>
<td>time series/time series</td>
<td>k_1 = 0.0013 dm^3/kgm</td>
<td>MM: no validation of all relations between in- and output parameters, high deviation for validation using time series</td>
</tr>
<tr>
<td>Frehmann (2003)</td>
<td>time series/time series</td>
<td>k_2 = 2 x 10^-11 N/m^2</td>
<td>FSP: no monitoring</td>
</tr>
</tbody>
</table>

Mathematical model:

Hazen-model to surface area

\[ B_{TSS, sed}(t) = X_{TSS}(t) \cdot (1 - k) \cdot v_s \cdot A \]

\[ k = 0 \] (Lessard et Beck without calibration)

\[ v_s = 0.56 \text{ cm/s} \]

Validation material model:

(Validation material model) MM/Full-scale plant (FSP)

Wong et al.: because of total failing of validation no parameter values are cited

FSP: Wong et al., no relation between input parameters and efficiency of sedimentation/Fletcher et al. weak relationship, k varies during 5 experiments, highest value is double of lowest (see cell on the left)

only time series of output mass used, no validation of relation between input parameters and efficiency of sedimentation (Pettersson et Svensson)

MM: no validation of all relations between input parameters and efficiency of sedimentation (Pettersson et Svensson)

Frehmann (2003) time series/time series sedimentation in inline retention sewer (IRS)

\[ B_{TSS, sed}(t) = X_{TSS}(t) \cdot (1 - h_{Wat}(t)) \cdot k_1 \cdot v_s \cdot \left( e^{\frac{k_2}{t}} \right) \]

\[ k, [\text{kg/m}^3 \text{d}] \]

\[ k, [\text{l/m}^2] \]

MM: predominant sed., TSS

MM, predom. rem., TSS

FSP A, one event, COD

FSP B, one event, COD

1.5 x 10^6

1115

5.1 x 10^6

860

5.0 x 10^10

2000

4.0 x 10^10

2500
Table 2 (continued)

<table>
<thead>
<tr>
<th>Literature</th>
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</thead>
<tbody>
<tr>
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</tr>
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<td>Validation material model</td>
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<tr>
<td>Hazen-model to surface area this model</td>
</tr>
<tr>
<td>(MM)/Full-scale plant (FSP)</td>
</tr>
<tr>
<td>Remobilization in IRS; B_{TSS,rem}(t) = X_{TSS}(t) \cdot A_{sed}(t) \cdot \tau(t) \cdot k_4 \cdot s^{1/3}</td>
</tr>
<tr>
<td>k_4 [kg/(m² d)]</td>
</tr>
<tr>
<td>k_3 [d/(kg m)]</td>
</tr>
<tr>
<td>model parameter values</td>
</tr>
<tr>
<td>comparing experiments with predominant sedimentation and predominant remobilization</td>
</tr>
<tr>
<td>FSP: only time series of concentration used for one event at each FSP, no validation of relation between input parameters and neither settled load nor remobilized load</td>
</tr>
</tbody>
</table>

**Note:**
- $D_{ch}$ = diameter of inlet channel; $H^*$ = dimensionless height; $A_{sed}$ = surface area of sediments; $B_{TSS,in}$ = solids load in the inflow; $B_{TSS,sed}$ = settled solids load; $B_{TSS,rem}$ = remobilized solids load; $B_{TSS,th}$ = solids load in the outflow via the throttle; $C^*$ = background concentration; $H$ = height; $h_{wat}$ = water level; $h_{sed}$ = sediment level; $k$ = model parameter; $Ha$ = Hazen-number; $L_{ch}$ = dimensionless undisturbed length of inlet channel; $Re$ = Reynolds-number; $L$ = length; $q_s$ = surface loading rate; $q_{s,ov}$ = surface loading rate regarding overflow; $q_{A,ov}$ = surface loading rate regarding overflow; $Q_{th}$ = throttle flow; $Q_{in}$ = inflow; $t$ = time; $v_s$ = settling velocity; $V_{sol}$ = volume of sediments; $W_{ch}$ = dimensionless width of rectangular basin; $\tau^*$ = dimensionless shear stress; $W$ = width; $X_{TSS}$ = concentration of solids; $Y_A$ = surface area for $\eta_{TSS,sed} = 50\%$ Hazen-model/surface area for $\eta_{TSS,rem} = 50\%$ this model; $\eta_{TSS,sed}$ = efficiency of sedimentation process; $\eta_{TSS,rem}$ = efficiency of quiescent settling; $\eta_{TSS,sed,quies}$ = accumulated efficiency of sedimentation and flow splitting; $\tau$ = shear stress
the relation predicted by the model. The dots are measured values. The dots do not show any relation between surface loading rate and efficiency. It seems that the surface loading rate is not the only parameter influencing the efficiency of sedimentation. Referring to Hazen’s model another five events were monitored at the wetland including the measurement of sinking velocity distribution. But it was even impossible to validate a relation between the event mean Hazen-Number and the efficiency of sedimentation (Kutzner et al., 2004). Kutzner and Geiger (2005) found out, that one problem in this wetland was the appearance of remobilization that makes modeling much more complicated.

Hübner (1997) fulfilled nearly all the requirements for the first section of mathematical model validation (see Table 1) with a material model. His mathematical model is described in Table 2 and shows the typical exponential influence of the Hazen-Number on the efficiency. He focused his research work on lab tests by the means of a material model of a hydrodynamic separator, but he also conducted field tests. Hydrodynamic separators are typically operated inline of the sewer system. Regarding the inline operation mode it is not trivial to define an efficiency of sedimentation independent from the effect of detention and flow splitting. The effect of flow splitting is that a defined proportion of the inflow load is directly released to the sewage treatment plant and therefore
it is not spilled. Hübner and Geiger (1996) elaborated a concept to calculate the efficiency of sedimentation under split flow conditions. However, during Hübner’s field tests the efficiency of sedimentation was very low, so that he could not validate the relation between hydraulic loading and efficiency (Figure 4). Hydraulic loading stands in a nearly linear relation to the surface loading rate at the investigated facility. Another problem was that the sinking velocity of particles was not measured.

For some of the studies with material models it was possible to validate a mathematical sedimentation process formula. This kind of validation is not sufficient to design full-scale facilities but it enables a reflection on the Hazen-Model. For a given example the mathematical models were used to compute the surface needed to reach a treatment efficiency of 50%. Then the same was done by using the Hazen-Model. For every example the computed area was much smaller for the Hazen-Model. The ratio of Hazen-Model-surface to other-model-surface ($\eta_A$) is between 9% and 57% (Table 2). This indicates that even for pre-dimensioning the use of Hazen-Model is critical because the performance seems to be clearly overestimated.

**Figure 3** Efficiency of TSS-removal versus event mean surface loading rate (Kutzner, 2005)

**Figure 4** Efficiency of TSS-removal versus surface loading rate (Hübner, 1997)
Conclusions

At present there exists no validated model to simulate sedimentation and remobilization of sewer solids in treatment facilities with acceptable reliability. The actual scepticism of authorities vis-à-vis advanced quality models is reasonable. Maybe there is a chance to validate this kind of models for hydrodynamic separators where the influence of remobilization is negligible.

Stormwater and CSO treatment is getting more and more important to protect receiving waters from pollutants. There is an urgent need for a better understanding of the sedimentation and separation processes. A promising approach seems to be the statistical analysis of a large number of effectiveness data from full-scale real-world plants without using complex parameters like settling velocity or Hazen-Number. First attempts for stormwater treatment can be found by www.bmpdatabase.org and for CSO treatment facilities in Kutzner et al. (2004).

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