Erosion characteristics of raw sewage: investigations for a pumping station in northern Germany under energy efficient pump control

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ABSTRACT

Flow controlled sewage pumping stations offer high potential for energy savings. But along with a reduced flow velocity, flow-controlled pumping increases the risk of deposits formation. This work presents an experimental procedure to assess the erosion behaviour of municipal wastewater as a basis for solid transport characterization considering an energy efficient pump control. Raw sewage, sampled at the inflow channel to a pumping station in the city of Rostock (northern Germany), has been investigated under dry weather inflow conditions by means of a self-constructed laboratory-scale erosion measurement. Received data have been processed into critical bed shear stress points (for incipient erosion and total resuspension) and into erosion rates. Both bed shear stress points increase with the settling duration, from initially 0.016 N/m² (incipient erosion) and 0.2 N/m² (total resuspension) after 20 minutes settling, to respectively 0.14 N/m² and 1 N/m² after 3 days settling. With a reduced flow rate within the energy efficient control, the pump pauses decrease, from 64 min (regular control with higher flow rate) down to 20 min. Thus, both respective bed shear stress points are below the bed shear stress level of the energy saving control (0.2 N/m²), and a resuspension of the settled particles is guaranteed.

Key words | critical bed shear stress, energy efficiency, erosion rate, resuspension, wastewater

INTRODUCTION

The operation of wastewater facilities depends almost entirely on pumping processes, powered by electricity. Especially in flat and sparsely populated areas, wastewater-pumping stations for pressurized sewage transport take a large share of operation cost. Application of appropriate pump control offers a high energy savings potential for those facilities. Usually, pumping stations are, operated in a two-point control mode where pumps switch on and off at defined water levels. In shut-on mode, the pump works with maximum design flow, which is in most cases higher than required. The related high flow velocity leads to high friction losses and unnecessarily high consumption of electricity.

The use of an electronic speed control solves this drawback of a two-point control. Within a case study at University of Rostock, an urban-influenced pumping station (PS) has been equipped with frequency pump controllers operated by an energy saving pumping strategy. The intention was to operate sewage pumps under an attempt to reduce consumption of energy as far as possible and to ensure safe system operation. The applied rule-based pump control aims at a reduction of friction losses by adapting flow to inflow conditions (Knubbe et al. 2014).

The recommended flow velocities for safe operation may often be underrun (0.6 to 1.2 m/s for self-cleaning effects at least once per day, according to DIN EN 16932-2:2018). Therefore, operators are confronted with finding a balance between attempted energy reduction and the safe operation of wastewater pressure pipes. In its worst case, blockage of a pipe entails costly repair works.

Safe operation depends on transport conditions inside the pipe, whereby flow velocity and bed shear stress are significantly responsible. Within the switch-off sequence (zero flow rate), particles settle inside the pipe. A previous homogeneous particle distribution over pipe cross-section changes to an increasing concentration from top to bottom. If bed shear stress in switch-on sequence is below a critical limit (low flow rate), deposited particles only resuspend partially. In nominal condition, at design flow rate, bed
shear stress is usually above the critical limit. However, for speed-controlled systems, this limit must be known to avoid harmful sedimentation.

The objective of this article is to define effects of energy saving pumping operation (low flow rate) on solids erosion behaviour within a pressure pipe system. The effect of a reduced flow rate on the safe transport of wastewater is not identified. To assess the transport conditions during the energy saving operation, this article pursues the following procedure:

- investigation of erosion behaviour of a typical, pure sewage dominated wastewater at the inflow side of a PS with a laboratory device (reaction chamber);
- determination of critical bed shear stress points after different settling periods: (i) critical bed shear stress ($\tau_{\text{crit}}$), to define the beginning of an erosion event and (ii) a minimum required bed shear stress ($\tau_{\text{req}}$) that relates to particle transport without sedimentation effects;
- evaluation of the erosion behaviour by calculating the erosion rate.

**Literature review**

A large number of experimental designs for the assessment of erosion characteristics have been presented in the past. These designs split into in-situ and laboratory designs. In situ designs are application dependent, e.g. modified for channel flow systems (Hoef 2015). Original in-situ devices have been presented by Paterson (1989) (cohesive strength meter). Laboratory devices can be split into: (i) reaction chambers, as used in this work and (ii) flumes. The reaction chambers largely originate from Schünemann & Kühl (1991). In adaption to their EROMES-system, various designs have been developed specific for each targeted application, e.g. a laboratory design by Seco et al. (2014), but also in-situ devices, as EROSIMESS by Liem et al. (1997). An overview of different in-situ devices is given by Tolhurst et al. (2000a), and a comparison between in-situ and laboratory design by Tolhurst et al. (2000b), Widdows et al. (2007) and Hoef (2015).

**METHODS**

**Study site**

The investigated PS is located in northern Germany in the city of Rostock. PS Rostock-Schmarl receives untreated domestic, industrial and commercial wastewater from approximately 40,000 inhabitants by a separate sewerage system of 80 km length. Additional surface runoff from main roads discharges to the PS, while roof runoff discharges into a storm water system. Four pumps, each with a power of 55 kW, raise the wastewater to the central treatment plant in two cast iron pipelines (DN 600, each of 4,100 m length). Within the case study, two pumps were equipped with an energy saving pump control mode over the period of 1 year. The energy savings were achieved by reducing the flow with frequency controllers during nominal conditions (dry weather inflow) to an energy optimum. However, the reduction to an energy optimum results in reduced flow velocities and bed shear stresses.

To assess the erosion behaviour of the transported raw sewage of PS Rostock-Schmarl, samples were collected at the inflow channel (DN 1,200) to the pumping well with a ladle during dry weather inflow. In total six samples, each with a volume of 25 l, were collected during the case study. Due to the mechanical treatment at the inflow, in the form of a rake with a wide-space bar opening (20 mm), coarse material was removed from the samples before processing.

**Experimental design for erosion measurement**

The presented experimental design is based on the work of Lange (2013) and Hoef (2015), both of which reference their constructions to Liem et al. (1997). The applied device for measuring erosion events (see Figure 1), consists of the following components:

- polyvinyl chloride (PVC) cylinder (diameter = 125 mm) as erosion chamber;
- PVC fixed flange (diameter = 125 mm) as mounting fixture for the PVC cylinder;
- PVC blind flange (diameter = 125 mm) as bottom component;
- six PVC baffles for axial direction of flow conditions;
- speed controlled stirrer motor (Heidolph RZR 2,102) and a pitched blade propeller for applying bed shear stress;
- extinction sensor (Semitec Dynamic Extinction Probe) for continuous erosion measurement.

The transparent PVC cylinder ($V = 6.14 \text{l}$) is fixed to a revolving metal frame rack, which ensures stability during the stirring process. The stirrer motor is fixed above the PVC cylinder on the metal frame rack as well. Motor speed can be adjusted up to a maximum of 2,000 rpm and is controlled by defined sequences using MatLab. The...
blade propeller is located 5 cm above the bottom. Six PVC baffles are attached to the PVC cylinder, which are constructed in two pieces (beam and baffle) to allow for adjustment of flow conditions.

The erosion of the sediments was measured continuously with an extinction sensor (Semitec Dynamic Extinction Probe). The extinction itself is defined as the negative logarithmic ratio between emerged and entered radiation. Thus, the erosion was measured as a light attenuation. The sensor is fixed vertically to the PVC cylinder and is located equal to propeller height. So, the extinction laser measures vertically, near to the sediment bed. Sensor and motor data have been logged in a time interval of 3 seconds.

**Stirrer motor calibration**

The device cannot directly measure shear stress (N/m²). Hence, values of shear stress are derived from applied motor speed (rpm). For this, experiments of Shields (1936) (erosion of defined sand particle sizes) serve as the basis to relate present shear stress to applied motor speed. Within a mathematical approximation of Shields’s experiments from Schröder & Zanke (2003), critical bed shear stress \( \tau_c \) (N/m²) is calculated for each grain size \( d_m \) (mm) eroded by a specific Shields bed shear stress \( \tau_{c,\text{shields}} \) (N/m²), the density of applied sand \( \rho_S \) (kg/m³), fluid density \( \rho \) (kg/m³), and gravitational acceleration \( g \) (m/s²), see Equation (1):

\[
\tau_c = \frac{\tau_{c,\text{shields}} \cdot (\rho_S - \rho) \cdot g \cdot d_m}{C_1}
\] (1)

The calibration process itself was conducted by four observers and 11 different sand particle classes \( d_m \) between 0.1 and 8 mm). After filling and complete settling of each individual class in the erosion cylinder, stirrer speed was increased stepwise. The erosion of each class was then detected from each observer when 10% of the settled sediment bed eroded. The critical bed shear stress \( \tau_c \) for the erosion of each class was calculated applying the approximation of Schröder & Zanke (2003) (Equation (1)). The respective stirrer speed noted at 10% erosion then marks the calculated critical bed shear stress \( \tau_c \). Equation (2) shows the resulting calibration function.

\[
\tau(\text{rpm}) = 8 \cdot 10^{-6} \text{ rpm}^{1.96}
\] (2)

**Experimental procedure**

Each experiment starts by filling the erosion cylinder with homogeneous raw sewage \( V = 6 \text{ l} \) from PS Rostock-Schmarl. The subsequent settling sequence ends after one of the following periods: 20 min, 1 h, 4 h, 7 h, 14 h, 17 h, 24 h or 72 h. Once settling is completed, the erosion sequence with the stirrer motor starts at 20 rpm (0.003 N/m²), increasing every 60 seconds by 10 rpm (0.0007 N/m²) and ends at 400 rpm (1 N/m²) automatically. In parallel, the extinction sensor measures continuously the light attenuation, caused by the eroded particles in the fluid section. It is assumed that the light attenuation is lowest at the beginning of each experiment, varies by a certain amount within each bed shear stress level and increases with each level up to a maximum value.

**Determination of erosion data**

The erosion behaviour of transported wastewater inside the pipe is described by three parameters: (i) the critical bed shear stress at beginning of erosion, described by \( \tau_{\text{crit}} \) (N/m²); (ii) erosion rate \( a \) (kg/(m s)) describing the dynamic of an erosion event per pipe length; (iii) bed shear stress value when all particles are completely resuspended, described by \( \tau_{100} \) (N/m²).
Determination of the critical and complete resuspension bed shear stress

The most common applied methods to identify critical bed shear stress points ($\tau_{\text{crit}}$) have been presented by Amos & Gibson (1994) (erosion events from dredge material) and Amos et al. (1997) as well as Amos et al. (2004) (erosion from river delta and tidal flats sediments). Following these methods, the course of measured erosion is expressed by either two power functions (Amos & Gibson 1994) or as a linear and a logarithmic function (Amos et al. 2004). $\tau_{\text{crit}}$ is then defined as the point of intersection of the respective function set. Here, the latter method of Amos & Gibson (1994) was chosen, due to smaller standard deviations for the reproduction of the erosion results $\tau_{\text{crit}}$ and $\tau_{100}$.

The continuous extinction measurement provides information about the influence of any bed shear stress value to resulting erosion behaviour. So not only $\tau_{\text{crit}}$ can be calculated, but also $\tau_{100}$ by the same method. Similar to assessing $\tau_{\text{crit}}$, $\tau_{100}$ is the result of the point of intersection of the equal function set, only shifted to the right on the measured extinction curve. Errors from the continuous extinction measurement were removed by Chauvenet’s criterion.

As an example, Figure 2 shows the results for assessing $\tau_{\text{crit}}$ and $\tau_{100}$ for an erosion experiment after 4 h settling. If the left and right plot are joined, the measured extinction forms an s-curve, where four power functions were fitted. Following the respective functional expression, the points of intersection were calculated as 139.3 rpm and 224.3 rpm. $\tau_{\text{crit}}$ and $\tau_{100}$ are now calculated by the help of Equation (2) as 0.128 N/m² and 0.325 N/m².

Determination of the erosion rate

In order to calculate the erosion rate $a$ (for the activation of sediments) (kg/(m s)), the particle concentration profile must be derived from the measured extinction curve for each procedure. This curve can be idealized in the form of a sigmoid function (Equation (3)), where the upper limit ($e_{\text{max}}$) marks the maximum light attenuation (all particles are resuspended) and the lower limit ($e_{\text{min}}$) the minimum light attenuation (certain proportion of particles settled), see Figure 3. The function itself can easily be adjusted using the least squares method with fitting parameters $c$ (-) and $p$ (s).

$$f(\text{rpm}) = \frac{e_{\text{max}} - e_{\text{min}}}{1 + c \cdot e^{-\frac{p}{\text{rpm}}}} + e_{\text{min}}$$  \hspace{1cm} (3)

When all particles are resuspended, the particle concentration inside the fluid is equal to the initial particle concentration of the raw sewage sample. Thus, the total suspended solids (TSS) profile of the erosion experiment can be displayed, if the initial TSS (kg/m³) of the raw sewage sample is known. The initial TSS of the six collected samples was determined as 0.28, 0.33, 0.3, 0.3, 0.29 and 0.18 kg/m³.

The erosion of the sediments is then described by Equation (4),

$$a(\tau) = d \cdot (\tau - \tau_{\text{crit}})$$  \hspace{1cm} (4)

with $d$ (s), the erosion parameter, which indicates the strength of an erosion event, $\tau$ (N/m²) the current bed shear stress value and $\tau_{\text{crit}}$ (N/m²) the critical bed shear stress after a specific settling duration. The value of $a$ itself is obtained by solving the optimization problem in Equation...
(5). Here, \( d \) and additionally \( \tau_{\text{crit}} \) are obtained by fitting \( a \) to the measured erosion of particles inside the erosion cylinder \( e_a \) (kg/(m s)).

\[
\min_d \sum_{i=1}^{n} e_{a,i} - a_i \cdot w_i
\]  

(5) where \( n \) is the number of applied bed shear stress intervals (\( n = 39 \)), \( e_{a,i} \) the measured erosion rate at the interval \( i \), \( w_i \) (kg) the particle mass on the bottom of the cylinder at the interval \( i \) (calculated as difference from the TSS concentration profile multiplied by cylinder volume). \( e_a \) itself is derived from the TSS difference by Equation (6),

\[
e_a = \frac{TSS_i - TSS_{i-1}}{\Delta t} \cdot A_s
\]

(6) where \( \Delta t \) is the time difference of the bed shear stress increase interval (\( \Delta t = 60 \) s) and \( A_s \) is the surface area of erosion (m²).

**RESULTS AND DISCUSSION**

**Critical and complete resuspension bed shear stress**

To ensure safe transport under energy efficient control, the methods to determine bed shear stress points must be reliable. Since two different methods were used to determine \( \tau_{\text{crit}} \) (power function set and erosion rate), reliability can be tested. If the results of both methods differ significantly, at least one of the methods is not applicable. If the results are similar, then the power function set is applied to determine \( \tau_{100} \) as well. The results are illustrated in Figure 4. The boxplot on the left shows the bed shear stress values of the critical parameters, depending on used method and settling duration. The \( \tau_{\text{crit}} \) values of both methods are in a similar region. The mean-difference plot on the right shows the difference for each determined bed shear stress inside the pipe under energy efficient control, regular control, full flow and parallel pumping (left plot) and mean-difference plot of power function and erosion rate method (right plot).
shear stress point in relation to the average of both methods. There is a maximum difference of 0.0928 N/m² (60 min settling) and an average of 0.01964 N/m² between both methods. The positive mean average shows that \( \tau_{\text{crit}} \) is tending to slightly lower values when the erosion rate is applied. Next to this, only one point is located outside the confidence interval. Based on these facts, both methods are considered as applicable.

Figure 4 on the left also shows the average \( \tau_{\text{crit}} \) and \( \tau_{100} \). A large \( \tau_{\text{crit}} \) or \( \tau_{100} \) value is the result of a long settling period with both settling (TSS increase) and consolidation effects (cohesion/compaction/biological solidification).

Table 1 shows the maximum, mean and minimum shear stress values and standard deviation determined by the experimental procedure. Here, \( \sigma \) indicates the deviation of the critical parameter of the different sewage samples. Both critical parameters increase with settling duration. Especially after 20 and 60 min settling, a strong increase of \( \tau_{\text{crit}} \) was detected (\( \tau_{\text{crit}} \) from 0.02 N/m² at 20 min to 0.146 N/m² at 240 min). \( \tau_{100} \) increases after 20, 240 and 1,440 minutes strongly (from 0.2 N/m² at 20 min to 0.4 N/m² at 240 min up to 0.6 N/m² at 1,440 min and 1 N/m² after 3 d settling). The TSS increase of sediments up to a settling duration of 240 min seems to have a decisive influence on \( \tau_{\text{crit}} \) and \( \tau_{100} \). This increase seems completed after 420 min settling. From 420 min up to 1,440 min, \( \tau_{100} \) remains at a level of \( \approx 0.6 \) N/m², and \( \tau_{\text{crit}} \) remains constant also (0.13 to 0.146 N/m²). Progressive settling (TSS increase) is negligible after 420 min and does not yield further increase of \( \tau_{\text{crit}} \) and \( \tau_{100} \). Subsequent effects responsible for further increase of \( \tau_{\text{crit}} \) and \( \tau_{100} \) are slower processes: cohesion, compaction, biological solidification. These consolidation processes become effective after 420 min, where \( \tau_{100} \) increases up to 1 N/m². \( \tau_{\text{crit}} \) is still small since even lighter and smaller particles settle on the surface of the sediment bed, which can therefore be eroded even more easily. This was also recognized by Banasiak et al. (2005) (‘first foul flush’, p. 5228). In summary, the TSS increase is the first effect that increases \( \tau_{\text{crit}} \) and \( \tau_{100} \) and occurs in the first 4 hours of the settling process. Cohesive interaction (particle–particle, particle–surface), gravitation (compressing in lower sediment layer) and biogenic changes of the sediment (conversion of organics by bacteria) work decisively slower and appear to be the main effects after 4 hours settling.

Both shear stress points decide on the energy saving intentions of PS Rostock-Schmarl. If the operational bed shear stress is smaller than \( \tau_{\text{crit}} \) and \( \tau_{100} \), the pump control needs adjustments to guarantee a resuspension of the settled particles after a pump pause. Within the energy saving control, the flow rate and flow velocity decrease, from 90.3 l/s and 0.32 m/s in regular control, down to 75.3 l/s and 0.27 m/s respectively. The bed shear stress inside the pipe \( \tau_{\text{pipe}} \) (N/m²) is then calculated as 0.2 N/m² (while 0.3 N/m² in regular control, see Figure 4), based on the fluid density \( \rho \) (kg/m³), the flow velocity \( v \) (m/s) and the friction factor \( \lambda \) (calculated after the Colebrook–White equation), with Equation (7).

\[
\tau_{\text{pipe}} = \frac{\rho}{2} \cdot \frac{v^2 \lambda}{4}
\]

With a reduced flow rate, the pump pauses decrease as well. The average pump pause reduces from \( \approx 64 \) min (regular control with higher flow rate) down to \( \approx 20 \) min. As \( \tau_{\text{crit}} \) and \( \tau_{100} \) for 20 min settling are below the bed shear stress level of the energy saving pumping mode, a resuspension of the settled particles after the pump pauses is guaranteed, as well as a complete transport.

Larger pump pauses should be kept below 4 h. Especially at night (0:00 to 6:00), with low inflow rates, the pump pauses increase. In regular control mode, these pauses last on average 2.5 h. These could be reduced by the energy efficient control down to 40 min, so the bed shear stress of 0.2 N/m² is still higher than the respective \( \tau_{\text{crit}} \) value. However, a total resuspension is not reached by the energy efficient control. To tackle this problem, pumps should start-up to maximum power, in the case of PS Rostock-Schmarl with a flow of 137 l/s and a flow velocity of 0.5 m/s (respectively 0.6 N/m² bed shear stress, see Figure 4), before regulating the flow rate down to the energy saving flow. The deposited sediments by pump pauses over 7 h are only resuspended by parallel pumping.

<table>
<thead>
<tr>
<th>Settling duration</th>
<th>( \tau_{\text{crit}} ) (N/m²)</th>
<th>( \tau_{100} ) (N/m²)</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(min)</td>
<td>20</td>
<td>60</td>
<td>240</td>
</tr>
<tr>
<td>max</td>
<td>0.03</td>
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<td>0.16</td>
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<tr>
<td>mean</td>
<td>0.02</td>
<td>0.08</td>
<td>0.146</td>
</tr>
<tr>
<td>min</td>
<td>0.01</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>max</td>
<td>0.22</td>
<td>0.42</td>
<td>0.46</td>
</tr>
<tr>
<td>mean</td>
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</tr>
<tr>
<td>min</td>
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<td>0.35</td>
<td>0.52</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>0.01</td>
<td>0.03</td>
<td>0.07</td>
</tr>
</tbody>
</table>
with a bed shear stress of 1.4 N/m² (respectively 212 l/s flow and 0.75 m/s flow velocity).

Erosion rate

In contrast to the single value of \( \tau_{\text{crit}} \) or \( \tau_{100} \), the erosion rate \( a(\tau) \), as a mathematical function, serves as a continuous description of an erosion event and contains information about its dynamics inside the pipe. The erosion rate in literature is always applied to a non-limited sediment bed (e.g. De Sutter et al. 2000; Banasiak et al. 2005; Seco et al. 2014), see Equation (4). Therefore, all erosion rates found in literature permanently increase with the bed shear stress. However, since the mathematical approximation of the erosion rate by Equation (4) neglects the available sediment bed (non-limited sediment bed), it is expected that for a limited sediment bed, the actual eroded mass per time will be higher after longer settling durations than for shorter durations. This limitation is therefore defined as the available particle mass at the bottom, settled within the respective settling duration.

By solving Equation (5), the erosion rate \( a(\tau) \) from Equation (4) is fitted to the measured erosion rate \( e_a \) from Equation (6) by multiplication with the available (limited) sediment bed on the bottom of the erosion cylinder \( (w) \). Here, additionally \( \tau_{\text{crit}} \) is received. The resulting erosion rates \( e_a \) and \( a(\tau, w) \) inside the erosion cylinder (limited sediment bed), as well as \( a(\tau) \) for a non-limited sediment bed (Equation (4)), are shown in Figure 5 (one erosion rate as an example for each settling duration). Additionally, bed shear stress values for different control strategies as well as \( \tau_{\text{crit}} \) and \( \tau_{100} \) values are illustrated.

With increasing bed shear stress inside the cylinder, more particles resuspend in the same time interval, until the erosion collapses at its peak (see Figure 5, left plot). The raw sewage represents a mixture of particles with different size. So, each peak shows the critical bed shear stress for the dominating particle fraction of the raw sewage. The peak is always located at the inflection point of the sigmoid function (Equation (2)). After the collapse, the erosion decreases and tends slowly to zero.

Comparing the curves with each other, it becomes clear that with an increased settling period, the function changes significantly. While the maximum erosion is initially located at 0.05 N/m² (for 20 min settling), the peaks shift towards larger bed shear stresses with increasing settling duration (up to 0.33 N/m² for 3 d settling). Here, the increase in erosion resistance of the sediment bed becomes visible as the peaks shift to the right. It is the result of the already mentioned TSS increase as well as effects of cohesion, gravitation and biological solidification. The different heights of the peaks can be related to the TSS increase as well. Since the erosion rate is linked to the available particle mass \( w \) on the cylinder bottom, the peak height

![Figure 5](https://iwaponline.com/wst/article-pdf/78/9/1997/513764/wst078091997.pdf)
increases with the settling duration. The highest peak was measured for 1,440 min settling (1.8 g/(m s)). It represents an unconsolidated state with a high particle mass on the bottom. This, in turn, explains the smaller peak after 5 d settling (1.3 g/(m s)), where cohesion, gravitation and biological solidification have already contributed to the further increased mass on the bottom. Next to the lower peak, the larger spread of the 3 d curve can be explained by this as well. The structure of the sediment bed has changed. Previously easily erodible particles are now released from the bottom slowly.

The energy efficient control of PS Rostock-Schmarl is not influenced by these effects, since the average settling durations between the pump pauses were reduced to \( \approx 20 \) min (formerly 64 min in regular control). The bed shear stress for the reduced flow rate is above the 20 min \( \tau_{\text{crit}} \) and equal to the \( \tau_{\text{100}} \) value. The erosion rate inside the pipe is then in the range of 0.04 to 0.08 kg/(m s). For settling durations \( > 20 \) min, \( \tau_{\text{100}} \) is not reached. Hence, after larger pump pauses, the bed shear stress inside the pipe must be increased (start-up regular flow at 0.5 N/m\(^2\)), which ensures a higher and faster remobilization of the more resistant sediment bed.

Figure 5 on the right shows the erosion rates \( a(\tau) \) for a non-limited sediment bed. The erosion rate increases in each case with bed shear stress. But at equal bed shear stress, \( a(\tau) \) is smaller the longer the previous settling duration lasts. Especially the erosion rate for settling durations of 3 days is, above a bed shear stress of 0.2 N/m\(^2\), significantly lower than others. For a bed shear stress of 0.2 N/m\(^2\) (energy efficient control), the erosion decreases from 15 g/(m s) after 20 min settling to 2 g/(m s) after 3 d settling by a factor of 7.5. This is due to an increased erosion resistance of the sediment bed, because of consolidation effects (cohesive interaction, compressing and biogenic changes). It shows the rapidly changing erosion characteristics of raw sewage and the need to reduce pumping pauses to a minimum.

The idea of a non-limited sediment bed, as illustrated in Figure 5 (right plot), is incompatible with the erosion processes inside a pressure pipe. Due to the switch on/off regulation of pumping stations, particles inside the pipe settle and resuspend alternately. The on/off regulation is regardless of the control mode. Thus, the sediment bed increases once in the switch-off sequences until a certain proportion of particles has been settled and decreases once in the switch-on sequences until the sediment bed is empty. When the sediment bed is empty, the erosion rate is zero, regardless of the bed shear strength. So the erosion process inside the pipe is more similar to the process inside the erosion cylinder (see Figure 5, left plot).

If the erosion rates \( a(\tau) \) from Figure 5 (right plot) are now set as functions of the bed shear stress inside the pipe \( \tau_{\text{pipe}} \) and the limited sediment bed on the pipe bottom \( w_{\text{pipe}} \) (kg), \( a(\tau_{\text{pipe}}, w_{\text{pipe}}) \) represents real-life conditions inside the pressure pipe. The sediment bed on the pipe bottom \( w_{\text{pipe}} \) was calculated similar to \( w \) (particle mass on cylinder bottom), assuming a TSS of 0.5 kg/m\(^3\) (see ‘Methods’ section). Figure 6 illustrates the calculated erosion rates \( a(\tau_{\text{pipe}}, w_{\text{pipe}}) \) over the complete pipe length \( l_{\text{pipe}} = 4,100 \) m of PS Rostock-Schmarl after different settling durations of four different control modes in the pump’s run-up phases: rule-based, modified rule-based, full power and parallel pumping. The run-up phases represent real values measured.

Each pump start is followed by an erosion of the formerly settled sediments, if \( \tau_{\text{crit}} \) is reached. The course of the erosion itself is similar to the erosion cylinder. The erosion is zero if the sediment bed is empty, and also if the flow decreases before the sediment bed is completely resuspended. In usual energy efficient control, pumps run up to the operation bed shear stress of 0.2 N/m\(^2\) without a high-power run-up, see Figure 6 top left plot. The settled particles in a previous pump pause of 20 min (25.14 kg respectively) are then completely resuspended within 28.7 s. But in the case of larger pump pauses (e.g. at night, repairs, damages) the sediments are only resuspended partially. Adding a high-power run-up (up to 0.6 N/m\(^2\)) to the rule-based control enables complete resuspension of settled sediments from pump pauses up to 7 h (top right plot). Deposits from 7 h settling are removed within \( \approx 35 \) s (respectively 96 kg in sum). With settling sequences \( \geq 24 \) h, full flow or parallel pumping is recommended. In parallel pumping control (1.4 N/m\(^3\)), a settled particle mass of 225.7 kg (3 d settling) is completely resuspended after 75 s.

The results showing that a safe sewage transport and an energy efficient control are not mutually exclusive. Due to the high erosion rates of the raw sewage, deposited sediments are resuspended fast (mostly <30 s). A safe transport can always be guaranteed by adding a high-power run-up to the pump control, especially in energy efficient controlled PS. In the case of PS Rostock-Schmarl the maximum pump pause duration is 40 min (night) under nominal inflow conditions. A pump run-up to full flow for 60 s followed by energy saving flow strikes a good balance between the energy saving intentions and a safe sewage transport.
Comparison with literature data

Erosion data from different investigations are mostly hard to compare, due to several reasons: sediments with different settling/consolidation times (minutes to years), different types of sediment (organic, cohesive, natural material), testing with different methods (cylinder, flume, ex-situ, in-situ). The critical values for incipient erosion of the raw sewage from PS Rostock-Schmarl is in the range of 0.01 to 0.146 N/m². The closest values were found in Banasiak et al. (2005), with \( \tau_{\text{crit}} \) values of 0.2 to 1 N/m² for deposited sewer sediment determined by a flume test, and in Ristenpart (1995), with \( \tau_{\text{crit}} \) values of 0.44 to 1.02 N/m² by field tests under dry weather flow. As both tests were performed with already existing deposits, this might be the main reason for the differences.

Although test conditions differ greatly, the results from Ristenpart (1995) and Dette et al. (1996), regarding the complete resuspension \( \tau_{100} \), are relatively similar. The critical values for a complete resuspension of the raw sewage from PS Rostock-Schmarl is in the range of 0.2 to 1 N/m². Ristenpart (1995) have come to a range of 0.04 to 0.67 N/m² by a field test under dry weather inflow. Dette et al. (1996) determined a value of 0.6 N/m², by field test in a combined sewerage system. Comparative literature data regarding the erosion rate are also hardly available: the erosion rate is determined either for different grain classes (e.g. Wilcock & McArdell 1996) or for different material (highly organically loaded like Seco et al. (2014), admixtures of sediments like De Sutter et al. (2000)). However, relatively comparable test conditions are provided by Banasiak et al. (2005). With up to 2.5 g/(m s) at 1 N/m² bed shear stress, and up to 10 g/(m s) at 2 N/m² bed shear stress, the erosion rate is significantly smaller compared to the presented results. Depending on the settling duration, the erosion fluctuates at 1 N/m² between 8.6 g/(m s) (for long settling periods) and 40 g/(m s) (for settling periods <4 h), and at 2 N/m² between 18 g/(m s) and 86 g/(m s) (see Figure 5).
Decisively for the differences is the tested material. A general statement on the erosion properties of a wastewater, in the form of recommended values, is therefore hardly feasible.

CONCLUSIONS

The presented experimental procedure and its subsequent calculation methods allow a precise determination of erosion data for raw sewage (critical bed shear stress points, erosion rates). The published data are exemplary for a separate sewerage system in an urban region. This contributes to a more precise characterization of raw sewage and helps to further understand sewage and sediment transport processes in urban drainage systems. Today's tools to challenge increasing urbanization, energy optimization or storm water management, are often numerical simulations. The provision of precise data enables a more accurate calibration of urban water models and finally more sustainable solutions to be designed.

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