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Impact of surface condition and roughness on sediment formation: an experimental sewer system operated with real wastewater

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ABSTRACT

Regular sewer cleaning in North Rhine-Westphalia (Germany) generates annual costs of around 50 million Euros. This leads to the question of whether and to what extent sewer cleaning is necessary. To determine the effect of roughness, sewer surface condition and discharge, experiments with real wastewater were performed, using a sewer test track with acrylic glass tubes (DN 300) prepared with abrasive paper and nature stone tiles at the wastewater treatment plant (WWTP) Bochum-Ölbachtal (Ruhrverband, Germany). A logarithmic relationship between deposit height and time was found to lead to maximum deposit heights of 5 to 60 mm. Surface structure analysis by texture measuring indicated that deposits within the first 28 days after cleaning are highly influenced by the surface condition of the sewer and not necessarily by roughness. Furthermore, under dry weather conditions deposit heights are nearly stable after this time, indicating the limiting effect of sewer cleaning. Deposit formation amounted to 1.75–1.80 mm/d at a roughness of $k_s = 0.10$ mm (fine but catchy microstructure) and 0–0.1 mm/d at k_s 1.25 mm (wavy microstructure) at steady state and transient discharge within the first 28 days after sewer cleaning.

Key words | deposit formation, roughness, sewer sediments, surface condition

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INTRODUCTION

Sedimentation of solids in sewer systems is seen as a critical factor because of its potential consequences of restricting the hydraulic efficiency, odour emissions from sewer systems and increased maintenance costs. For this reason, there are legal regulations or recommendations in many countries for the design of sewer systems, which aim to ensure a deposit-free state. To achieve a deposit-free state, a minimum velocity or slope is required. In practice, however, sewers that have been planned and constructed in compliance with these regulations may still have deposits (DWA A-110 2012).

This is due to the very complex process of deposit formation, which depends not only on flow or slope, but also on a number of different parameters (e.g. water depth, solids concentration, consistency and density of the solids, flow properties like density and viscosity, and sewer characteristics like size, shape and roughness) (Sousa *et al.* 2009). According to Dettmar & Staufer (2006), deposits result mainly from hydraulic (e.g. low dry weather flow or rainfall), material (e.g. large and heavy solids), structural (e.g. surface quantity) and operating (e.g. discharge barriers) conditions. Because of these numerous factors, the attempt to identify sewer sections tending to deposition based solely on their hydraulic characteristics (bed slope, flow rates, shear stress) and calculations would reflect reality inadequately (Stein *et al.* 2006).

In the past, many attempts were made to find parameters that could serve as an indicator of whether the probability of deposit formation within sewer sections is high. For example, investigations by Bachoc (1992), who studied the influence of bed slope on deposit formation at various combined wastewater networks in France, revealed that 95% of the identified deposits were found in sewers with a slope of less than 10 ‰, whereas 62% of the sewers with a slope of less than 1 ‰ were free of deposits. This shows that, contrary to previous approaches, the bed slope is unsuitable as a sole criterion to identify critical areas (Staufer 2009). Corresponding to Ashley *et al.* (2005), it's rarely possible to predict at which time and place solids will settle exactly. This is due to the large

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spatial and temporal variability of solid entries, flow conditions and operating conditions. This applies to the forecast of both the amount and the composition of the deposits. Because of fluctuations in discharge caused by rainfall in sewers, sediments with very different characteristics can form deposits in the same place at different times (Saul *et al.* 2003).

Through texture analysis, this study therefore aims to determine the influence of sewer surface condition on the rate of deposit formation.

MATERIAL AND METHODS

Experimental setup

Experiments were performed on a sewer test track at the wastewater treatment plant (WWTP) Bochum-Ölbachtal (Ruhrverband, Germany). The inflow to the WWTP is a combined sewer system with a mean dry weather flow of $41,000 \pm 2,500\ m^3/d$. The highest measured storm water flow was $170,000\ m^3/d$. Typical mean COD_{tot} concentrations were $435 \pm 85\ g/m^3$ (dry weather flow), and under storm water conditions $100\ g/m^3$.

The experimental setup consisted of three parallel acrylic glass tubes with a length of 10 m and a diameter of 300 mm (Figure 1). Openings in the crown of the pipe allowed samples and measurements to be taken at any location of the pipe.

In order to obtain results as representative as possible, the experiments were conducted with real wastewater. Wastewater substitutes often resulted in unrepresentative predictions, especially where the biochemical properties are of importance (Banasiak & Tait 2008). Here, the wastewater was taken directly from the inlet channel of the WWTP Bochum-Ölbachtal. It was transported by a self-priming centrifugal pump (type 'Abwasser Star 6″' with a free passage of 76 mm, HEIDE-Pumpen GmbH, Germany)

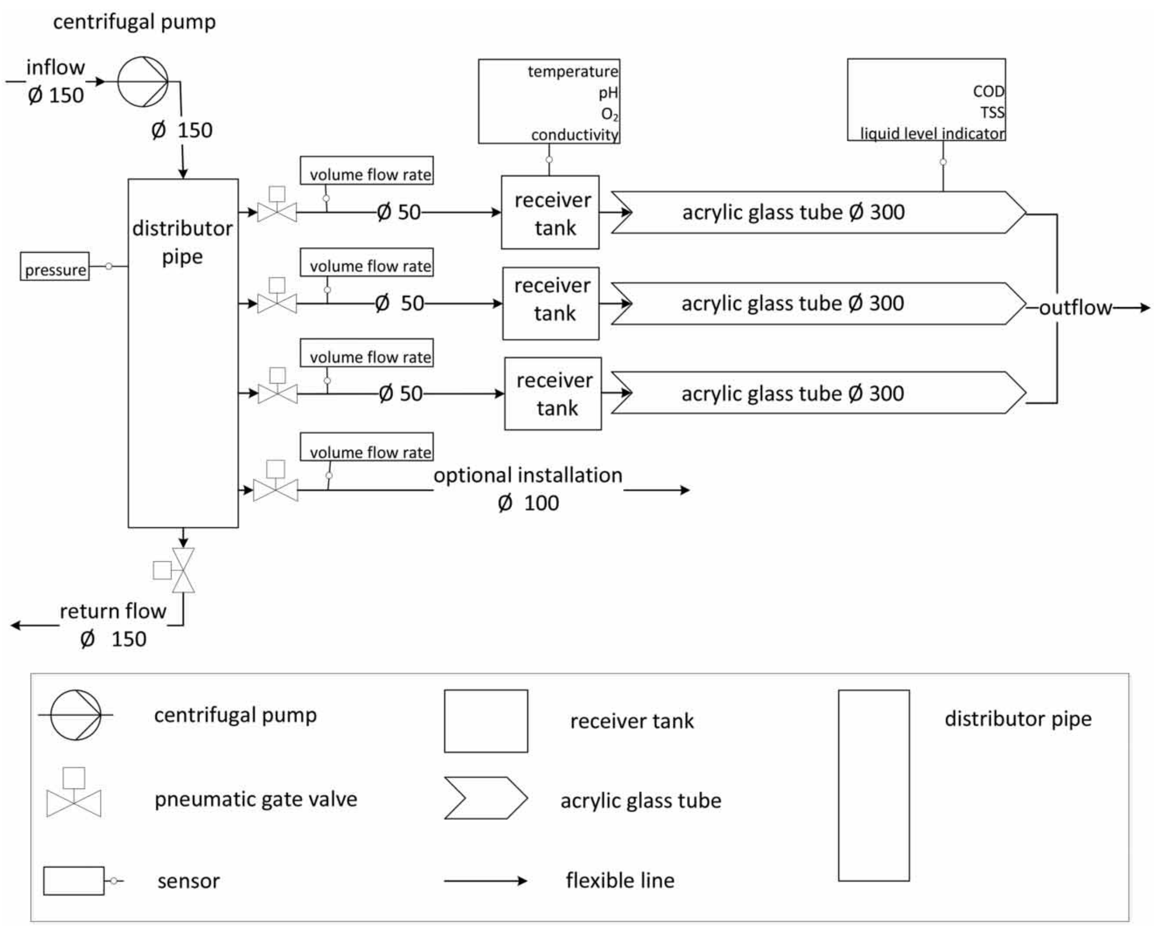


Figure 1 | Schematic drawing of the sewer test section (Lange & Wichern 2013).

into a distributor pipe. From there it passed through flexible tubes to the individual test pipes. The discharge was controlled by the combination of pneumatic valves (DOMINO-Schieber, GEFA Processtechnik GmbH, Germany) and magnetic inductive flow meters (type Promag 50 W, Endress + Hauser Promag, Germany). The maximum achievable flow rate was 35 L/s.

The cross braces of the substructure were freely adjustable in height, so the slope was variable in the range of −10 to +20 ‰. For maximum accuracy, geodesists specifically arranged a geodetic levelling of the pilot plant.

Abrasive papers were glued to two of the acrylic glass pipes as indicated by Banasiak *et al.* (2005). This method proved to be a good way to vary the roughness of the pipe and to realize values of roughness comparable to concrete pipes. Additionally, one pipe had nature stone tiles fixed in it with mortar. Each tile had a dimension of 22 × 22 × 4 mm with 1 to 5 mm gaps.

Operating conditions

Before the start of a test series, the pipes were cleaned to model situations directly after sewer cleaning. For the experimental duration of the test series (28 days), there was constant discharge flowing through the pipes. The discharge was interrupted only for daily maintenance and execution of the measurement of the deposition heights. The different experimental settings are listed in Table 1.

Data collection and analysis

Deposit heights were recorded manually with a digital sliding caliper at 40 points per pipe daily. To ensure that measurements were always carried out at the exact same positions, the digital sliding caliper was mounted on a substructure, which could accurately be placed at the openings of the pipes. Blank values of 40 measurement points were determined at the beginning of a test series, before inflow of sewage into the test pipes started. By forming the difference of blank value $h_{E,i}$ and measured value $h_{F,i}$ (from the top of the deposition) the deposit height h_i was determined (Equation (1)).

$$\mathrm{h_i = h_{E,i} - h_{F,i}\,(mm)} \qquad (1)$$

Deposit heights were compared and discussed using results from the middle part of the pipe (from meter 2 to 6). Measurements from the inlet and outlet of the pipe were left out to avoid the influence of turbulence on results.

Table 1 | Summary of the different experimental startup settings.

Number of trials	Slope *I* (‰)	Roughness k_s (mm)	Discharge *Q* (L/s)
1	1	0.100	2
8	1	0.400	2
3	1	0.635	2
2	1	1.25	2
1	1	0.400	1–4 (~2)[a]
1	1	0.635	1–4 (~2)[a]
1	1	1.25	1–4 (~2)[a]

[a]Daily fluctuations.

Statistical analysis

Statistical evaluation was performed with Origin Pro 2015G (OriginLab Corporation, USA) Version b9.2.214. The trendlines generated were chosen such that a best possible r-square (≥0.9) was achieved. In addition, the lines converge and the Chi-tolerance level of $1 \cdot 10^{-9}$ was met.

Surface quantity (roughness)

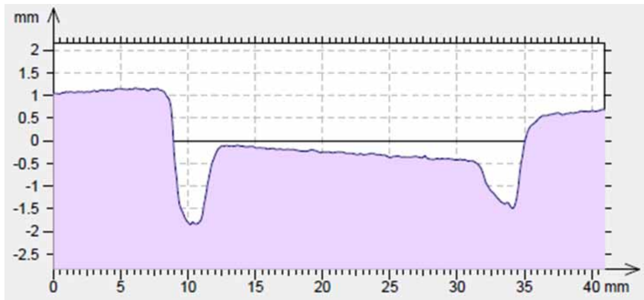
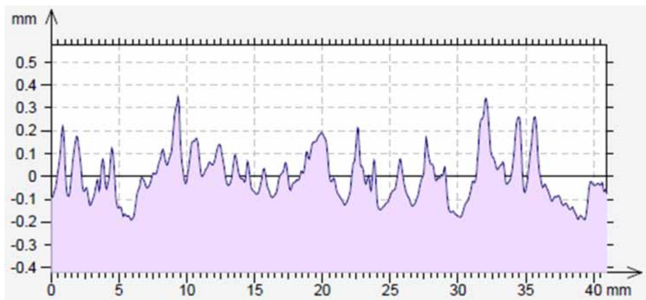
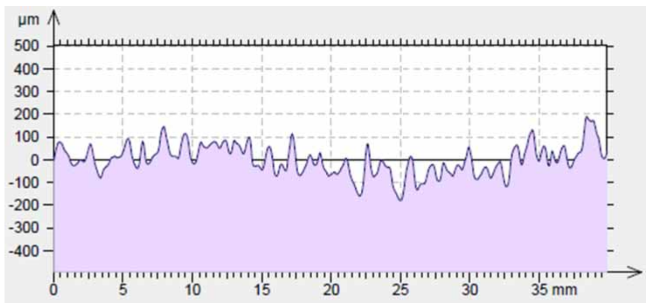
According to DWA-A 110 (2012), it is important to know the equivalent sand or natural roughness of the inner wall of a pipe. This measurement of roughness is set in advance, based usually on experimental data, but also possibly by a true estimate or determination through company's experience.

Here, sewer surface properties were identified with a texture-measuring device (TopoCAM, GFM GmbH, Germany). The texture meter is based on the principle of scattered light projection. The measurement field volume was 40 × 30 mm^2, the specified height resolution was 6 microns and the lateral resolution 53 microns. The measurement data were converted on a PC with the software MountainsMap® form (Digital Surf, France) Vision 6.2.6845 in a two-dimensional slice.

The sand roughness (ks (mm)) of the abrasive paper was calculated by means of a grading curve according to mesh. This describes the number of meshes of a screen per inch (25.4 mm). The larger the P-number, the finer the grain size. A rough estimate applies to the grain size: grain size in mm = 25.4/P. The sand roughness of the natural stone tiles was 1.25 mm compared with the optical and calculated results of the sandpapers. It was obvious during initial evaluation of the surface conditions that the natural stone tile having a joint structure in its roughness was significantly different from the other materials (Table 2).

In addition, the arithmetic average roughness R_a was added, which is the arithmetic average of the magnitudes of the roughness profile ordinates within the sampling length. It represents the mean deviation of the profile from the mean line. The roughness cannot distinguish between peaks and ridges, or recognize different profile shapes. Since its definition is based on a strong averaging, the values deviate only slightly and are highly reproducible.

Table 2 | Experimental surface properties of abrasive paper and stone tiles

Material/Sand roughness	Surface property
Natural stone tiles $k_S = 1.25$ mm $R_a = 0.52$ mm	
Abrasive paper P = 40 $k_S = 0.635$ mm $R_a = 0.15$ mm	
Abrasive paper P = 60 $k_S = 0.400$ mm $R_a = 0.072$ mm	
Abrasive paper P = 240 $k_S = 0.100$ mm $R_a = 0.040$ mm	

RESULTS AND DISCUSSION

In the following, the results of the sewer material analysis and sewer deposit formation are shown.

Roughness and surface condition

Surface properties of the different materials are presented in Table 2. Initial surface condition of the natural stone tile differed significantly from the other materials.

In accordance with DIN 4760 (1982), surfaces are described by the deviation from an ideal form. A deviation of second order is described as a wavy structure, while the fourth order is characterized by a roughness with scores or scales (Figure 2). The sandpaper is classified according to a fourth order roughness, whereas the natural stone tile can be characterized as second order. This allows for fibre particles at the beginning of the experiments to attach to sandpaper and to settle, as these can easily become wedged in existing grooves. Meanwhile, the natural stone tile offers no detention for fibre deposits due to the smoother wavy surface structure.

To verify the comparability of the experimental materials against real sewer system materials, additional measurements with the texture-measuring device were executed (Table 3). Here, similar structures were observed – i.e. a used concrete pipe has a smooth surface just like the used stone tile. The main roughness is generated by a wavy structure. The surface structure of a vitrified clay pipe is similar to abrasive paper. The surface structure is rougher but flatter than the concrete pipe and the stone tiles.

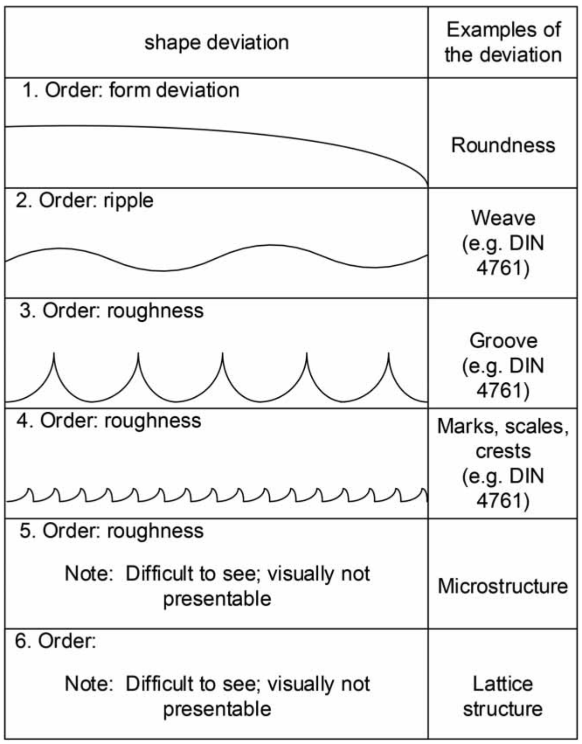


Figure 2 | Schematic drawing classification system for structural variations after DIN 4760 (1982).

Deposit formation in the sewer system at constant flow

Figure 3 shows the development of the average deposit heights for different values of roughness. A logarithmic regression curve fits well to the measured points in Figure 3.

Roughness with third and fourth order (representing $k_s = 0.100–0.635$ mm) is especially critical for an initial strong deposit formation. It can be seen that in the first 10 days after the start, these materials resulted in a deposit height of 10 to 40 mm. At the very close and rough structure of third and fourth order, fibrous materials stick quickly and permanently – similar to hook-and-loop tape.

Because of the strong mean variation, the R^2 values in tubes with a k_s of 0.100 to 0.635 mm are between 0.3 and 0.5. Scattering of the data points may be attributed to the daily change in wastewater composition. Statistical analyses were used to verify if the correlation between the parameters was not incidental. After a normal distribution test, Pearson tests were conducted and the results indicated that all tests correlated significantly ($\rho_k = 0.62–0.66$, $p = 0$).

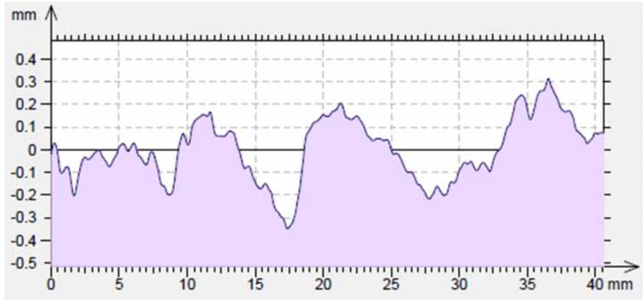
A complete non-attachment of deposits on the surface structure of the natural stone tile was observed. An increase in test duration led to biofilm growth, as described in literature. This changed the surface properties in all tubes. For this reason, also in the natural stone tile, a deposit formation was recognized later. Nevertheless, attachment was much lower compared with sandpaper, because initial deposit formation was prevented.

In addition, results of statistical analyses are shown in Figure 4. To determine the boxplots, the last eight readings of each test series of experiments were used to exclude the initial fluctuations. These rates of deposit growth correlated with the corresponding pipe roughness. An increase in pipe roughness resulted in a reduction of deposit growth rate (Figure 4). The growth rate was about 1.80 mm/d at a roughness of $R_a = 0.04$ mm and near to 0 mm/d at R_a 0.52 mm within 28 days. Characteristics of the trend line can be reproduced with a logarithmic function.

Deposit formation in the sewer system at transient flow

Based on the results so far, with a constant discharge, a daily transition from 1.0 to 4.0 L/s was investigated (average

Table 3 | Surface properties of two typical sewer system materials used in Germany

Concrete pipe used for more than 20 years $k_S = 1.00$ mm $R_a = 0.30$ mm	
Vitrified clay pipe $k_S = 0.60$ mm $R_a = 0.15$ mm	

Concrete can be compared with the natural stone tile; in contrast, the vitrified clay pipe fits a sandpaper.

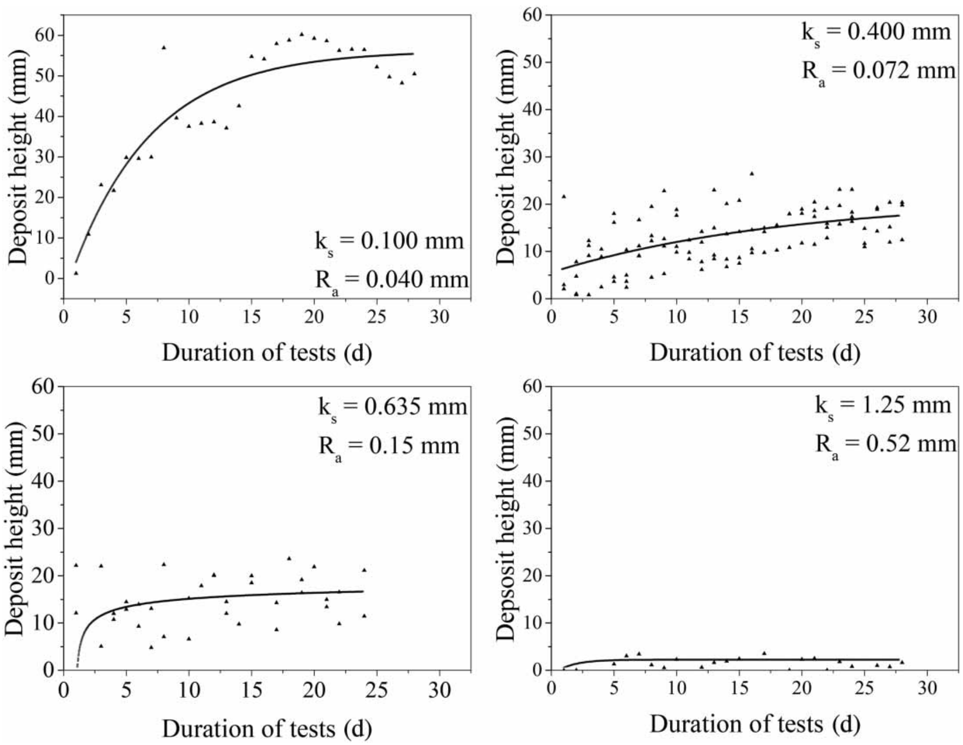


Figure 3 | Development of the average deposit height at different values of roughness. Duration of test 28 days, slope 1 ‰, discharge 2 L/s. With increased roughness, the deposit height decreases from up to 60 mm ($k_s = 0.100$ mm) to about 4 mm ($k_s = 1.25$ mm). Logarithmic trend lines have been added.

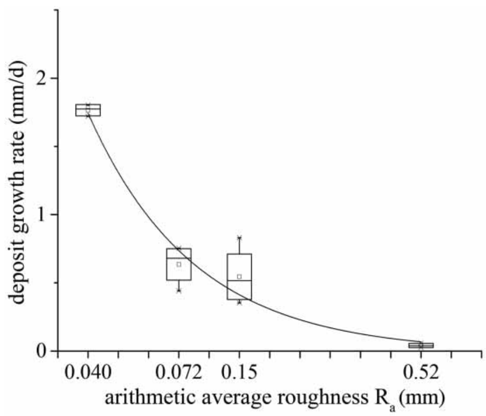


Figure 4 | Increase of deposit heights as a function of the arithmetic average roughness R_a. After calculating the boxplots, an asymptotic function was added using the mean values of each roughness ($R^2 = 0.95$).

discharge of 2.0 L/s). For this, three settings were tested (Figure 5). The deposit rates and the calculated asymptotic function ($R^2 = 0.95$ to 1) are also illustrated in Figure 5. Significantly increased deposition heights in the two test tubes 0.400 and 0.635 mm can be explained by the increased solids being transported. Larger particles couldn't be remobilized in times of low flow rates, which made total deposit height increase. Deposition heights with a roughness of $k_S = 0.400$ mm were approximately twice as high (14.8/30.3 mm) compared with steady state conditions. For the roughness 0.635 and 1.25 mm, the deposition height on average was 50% higher ($k_S = 0.635$ mm 13.2/22.2 mm, $k_S = 1.25$ mm 1.4/2.1 mm).

Dividing deposit heights in Figure 5 by the corresponding duration of tests resulted in an approximate linear function (Figure 6). Accordingly, the increase in deposits in the relevant series with a slope of $I_S = 1.0$ ‰ and a roughness of $R_a = 0.072$ mm was approximately 1.75 mm/d, while in the pipe with a roughness of $R_a = 0.52$ mm the growth rate was about 0.100 mm/d.

According to Walski *et al.* (2009), it is important to know whether solids are completely immersed in water or only partially. In the latter case, an increase in flow rate led to better solids transportation. Our own investigations showed that the structure of the particles has a significant impact on deposits. With a serrated structure and materials with $k_s = 0.400$ and 0.635 mm, mainly fibrous materials (toilet paper and towels) remained at the surface. This behaviour could be detected in both steady state and transient discharge. If this initial deposition can be prevented, only small deposits can be found (see $k_S = 1.25$ mm) even after long-term tests.

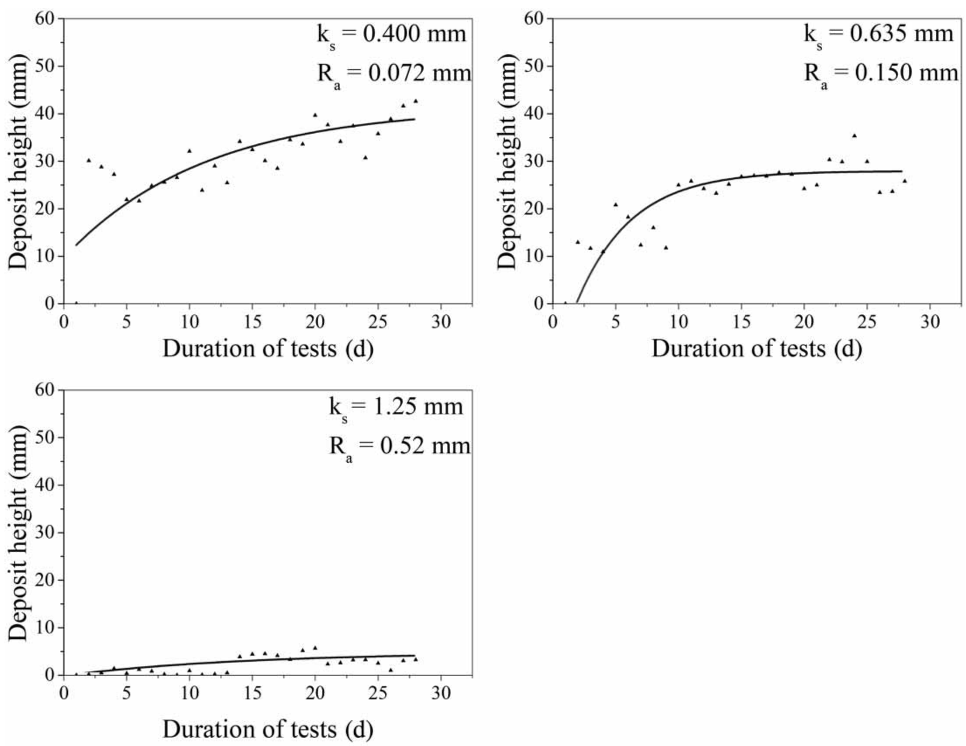


Figure 5 | Development of the average deposit heights at transient flow (mean value 2 L/s). Duration of test 28 days, slope 1 ‰. Equal to a constant discharge after 28 days, a maximum deposit height of about 42 mm ($k_s = 0.400$ mm) to about 3 mm ($k_s = 1.25$ mm) was determined. The calculated trend lines are asymptotic functions ($R^2 = 0.95$ to 1).

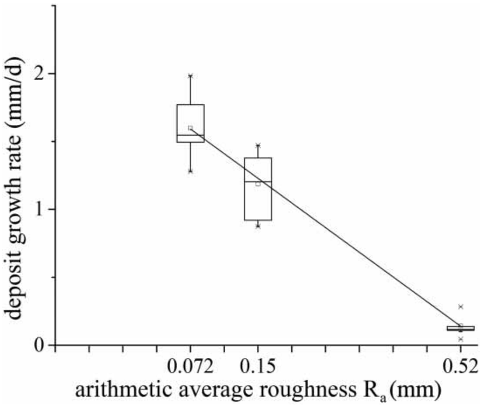


Figure 6 | Increase in deposit growth rate as a function of the arithmetic average roughness R_a. After calculating the boxplots, a linear function was added using the mean values of each roughness ($R^2 = 1.0$). The same trend as under steady state conditions was observed. With increased roughness the deposit growth rate decreased from 1.75 mm/d to 0.100 mm/d.

As described in Lange & Wichern (2013), deposit sedimentation altered the surface condition of the pipes and led to increased sedimentation of inorganic particles, such as sand. This resulted finally in flatter growth curves, as shown in Figures 4 and 6.

CONCLUSIONS

Sediments in sewers can cause different problems, like sewer blockage or corrosion. To prevent these problems, in Germany sewers are often cleaned at intervals of up to two years or less (Birkner *et al.* 2003). A broad knowledge of sewer dynamics would help to optimize sewer cleaning strategies and also reduce associated costs. The different developments of deposits were investigated in sewer test pipes with a diameter of 300 mm using raw sewage from the inlet channel of the WWTP Bochum-Ölbachtal (Ruhrverband, Germany). The focus of the research was set on the initial sewer surface structure and different roughness ($k_s = 0.10$–1.25 mm) as well as on constant and transient discharge.

At comparatively high initial equivalent sand roughness, the lowest deposit amounts were observed in the test tubes. The main influence for deposit formation within the test-run period of 28 days was not due to roughness, but rather, surface structure of the pipes. A texture analysis showed that a typical saw-tooth structure has an increasing impact on deposit formation. This effect could, however, not be observed for the wavy structure of the natural stone tile, which had high equivalent sand roughness. Furthermore, under dry weather conditions, deposit heights are nearly stable after 28 days, indicating the limiting effect of sewer cleaning on deposit heights.

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