Sedimentation dynamics in combined sewer systems

R.-L. Lange and M. Wichern

ABSTRACT

Sediments in combined sewers may negatively affect the performance of sewer systems and significantly promote the formation of hydrogen sulfide. To prevent this, German sewer systems are cleaned regularly but at high costs. In order to optimize the cleaning intervals, this study investigates how deposits build up and change over a defined period under constant conditions. The experiments were performed using real wastewater at a pilot plant consisting of three 10 m long acrylic glass pipes with a diameter of 300 mm, a slope of $I = 1‰$, a discharge of $Q = 2$ L/s and a roughness of $k_S =$ 0.4 mm. Within the first 30 d, a slow increase of the deposit height (averaged over the pipe length) of 0.75 mm/d was observed. The deposits did not build up continuously, but in between times also decreased due to erosion. The daily changes in deposit amounts occurred partly as a function of the rainfall conditions and could go beyond the average growth many times. Within a day, the deposit height (averaged over pipe length) changed by up to 20 mm, at single measuring points even up to 100 mm. After about 50 d under constant test conditions, the deposit height came to a state of equilibrium between sedimentation and erosion.

Key words | deposit growth rate, erosion, sewer cleaning, sewer sediments

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INTRODUCTION

In industrialized nations, the drainage of urban areas is normally brought about by sewer systems that collect the accumulated wastewater as well as rain water and lead it to treatment plants. In addition large amounts of solids are washed into the sewer pipes. These usually originate from wastewater or in the case of rainfall from surfaces (roofs, roads, etc.) (Ashley *et al.* 2004). In addition solids are transported into sewers by wind and by external water, which enters through leaking pipes or faulty discharges (Gebhard 2009).

If the shear stress is no longer sufficient to transport the solids contained in the discharge, they gravitate to the bottom and settle there (Ristenpart 1995). This occurs especially after heavy rain or during times of low dry-weather flow, for example at night times. To prevent problems caused by sediments, sewer systems are cleaned regularly. In North Rhine-Westphalia, where sewer cleaning is necessary when the deposit height reaches 15% of the pipe diameter (MURL 1995), most of the sewer systems are cleaned at intervals of 2 years or less. Given an absolute length of the sewer systems of about 90,000 km, this causes costs of 50 million euros per annum (Orth *et al.* 2009). The adjustment of regular cleaning intervals to the actual demand is very important for a cost-effective cleaning strategy. This requires extensive knowledge of deposition characteristics of individual sewer sections. The actual deposit amount is usually unknown, so it is assumed that deposits increase steadily with time. Different measurements taken in real sewer systems proved that this assumption is not valid (Dette *et al.* 1996; Lange *et al.* 2010). The deposit heights at the observed locations varied enormously.

Since measurements of flow rates or concentrations of solids in real sewers are subject to very high uncertainties even under careful execution (Bertrand-Krajewski *et al.* 2003; Biggs *et al.* 2005), pilot experiments were performed on a test channel. The aim of these experiments was to determine the rate of deposit formation and to prove whether or how quickly a state of equilibrium is reached. The realization of investigations in a sewer test section allowed the processes in sewers to be studied under largely controlled conditions and with less effort compared with measurements in real sewer systems.

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MATERIAL AND METHODS

The experimental setup consisted of three acrylic glass pipes (Figure 1) with a length of 10 m and a diameter of 300 mm. In order to guarantee access to any place within the pipes, several windows were cut into the pipe. The slope was variable in the range of −10 to +20‰.

In the past several different laboratory tests for sedimentation and erosion behavior in a variety of scales were conducted (Ota & Nalluri 2003; Tait *et al.* 2003; Campisano *et al.* 2004). However, these studies were executed almost exclusively using replacement fluids and sediments. The use of substitutes leads to unrepresentative results compared with the behavior of real channel deposits, especially when biochemical properties are of importance (Banasiak & Tait 2008). For this reason, the experiments were operated with raw sewage taken directly from the inlet channel to the Ölbachtal wastewater treatment plant (WWTP) (Bochum, Germany) run by the Ruhrverband.

A self-priming centrifugal pump (type Abwasser Star 6″ with a free passage of 76 mm, Heide-Pumpen GmbH, Germany) transported the sewage into a distributor pipe. One of the outlets served to maintain constant pressure in the distributor pipe and to divert excess water into the channel. The remaining four exits were used to feed the test pipes. A pipe with a diameter of 100 mm could be optionally connected to either of the three test pipes to carry out erosion tests. The flow control was brought about by a combination of pneumatic slides (DOMINO-Schieber, GEFA Processtechnik GmbH, Germany) and magnetic inductive flowmeters, type Promag 50W (Endress+Hauser, Germany). To avoid excessive turbulences at the entrance of the test pipes, the wastewater was first directed into a receiver tank.

Acrylic glass pipes have an extremely smooth surface. To get a roughness comparable to stoneware and concrete pipes, similarly to Banasiak *et al.* (2005), abrasive paper was glued into the acrylic glass pipes. This method proved to be a simple and convenient way to vary the roughness of the pipes. The experiments were carried out with a grain corresponding to a pipe roughness of $k_S = 0.4$ mm. The slope was $I = 1$‰, and the discharge $Q = 2$ L/s.

As part of the experimental procedure different wastewater parameters, e.g. total suspended solids (TSS), chemical oxygen demand (COD), oxygen, pH value and conductivity, were recorded using on-line measurement techniques. At the center of this study was the daily measurement of deposit heights with a digital sliding caliper.

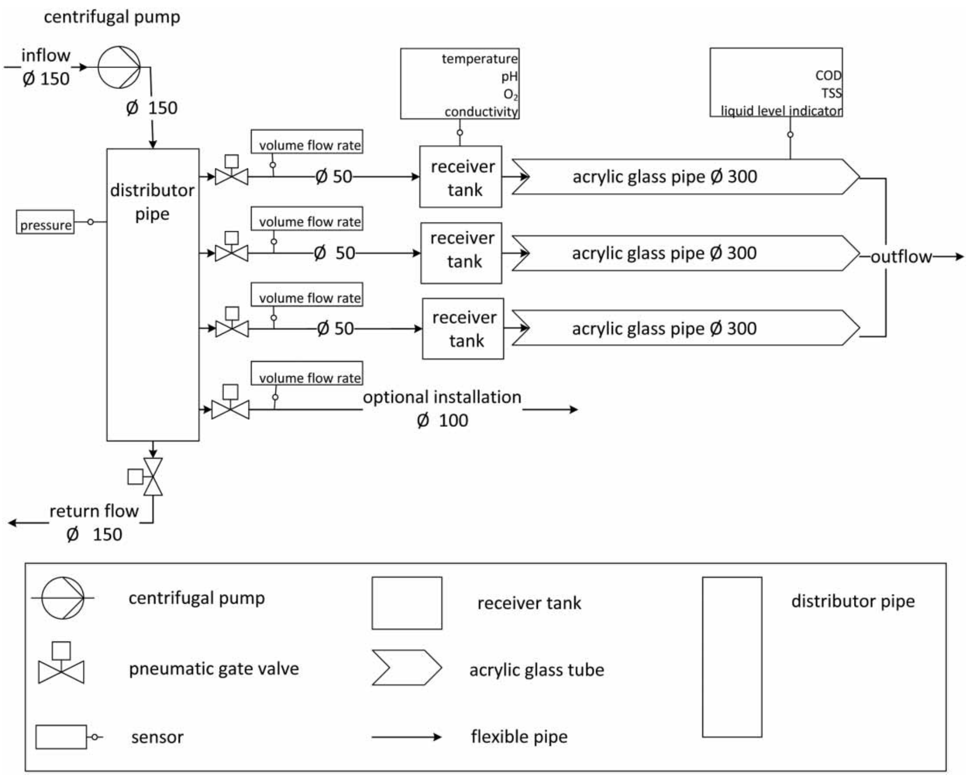

Figure 1 | Schematic drawing of the sewer test section (diameter values in mm).

For each test pipe, deposit heights were measured at 40 certain spots. Usually deposits do not have a flat surface. So occasional very high or very low levels of deposition were measured in the middle of the cross-sections and referred to an entire pipe section. Calculation of the deposit amount for every second one of the 40 measured deposit heights led to a divergence of the calculated deposit amount in the entire test pipe of 1%. This suggests that an increase in the number of measurement points means no significant increase in accuracy with respect to average deposit height or the entire deposit amount.

The deposit heights were generally lower in the rear pipe section than in the front and middle areas. This is due to the fact that the water at the end of the pipe exited freely, so that the flow was accelerated in the rear region of the pipe. To take this effect into consideration, as well as possible turbulences at the entry, the focus of the data analysis in this study was on the middle pipe section (2–6 m). In this section largely constant flow conditions prevailed.

RESULTS AND DISCUSSION

The formation of deposits

The formation of deposits during the test series was always very similar. Right from the beginning selective deposit heights of up to 100 mm could already be observed. Responsible for these deposits were fibrous materials (mainly hygiene products), which remained adhering to the (because of the abrasive paper) rough pipe wall. Since these fibers have a large contact area with the flow and are thus washed away easily, the deposit profile was exposed to large fluctuations during the first test days. After 4–7 d especially in the tidal zone a biofilm developed, which covered the sand grains of the abrasive paper. As a result, fewer fibers could be observed, which hooked onto the abrasive paper. The relatively bulky fibers allowed other minerals (fine to coarse sand, occasionally small stones) and organic solids (food waste, leaves, etc.), to settle in their slipstream. With time, gaps between the individual deposits were filled and a largely homogeneous deposit profile developed. Figure 2 shows various stages of deposit formation.

The evolution of individual deposits towards a largely homogeneous deposit profile is shown in Figure 3. After a week, the individual deposit heights are very inhomogeneous over the flow length and vary between 0 and 30 mm (in the meantime also higher values up to 100 mm are measured). The longer the deposition time, the smoother the deposit profile, since most of the gaps between the initial selective deposits are filled after this period.

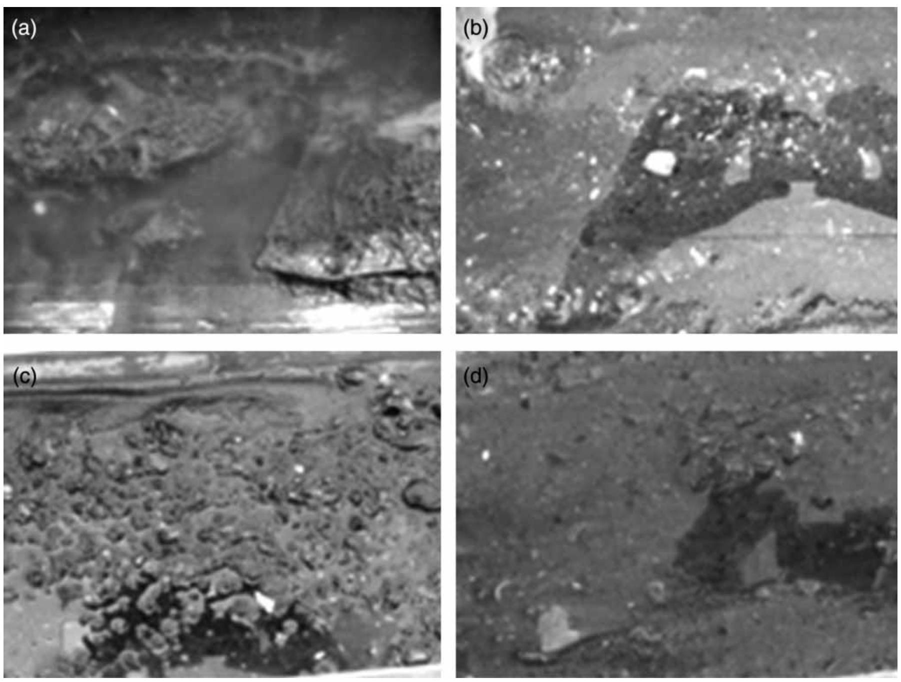

Figure 2 | Appearance of the deposits after (a) 1 week, (b) 1 month (c) 3 months and (d) 5 months ($Q = 2$ L/s, $I = 1‰$, $k_S = 0.4$ mm). The photos show the same pipe section.

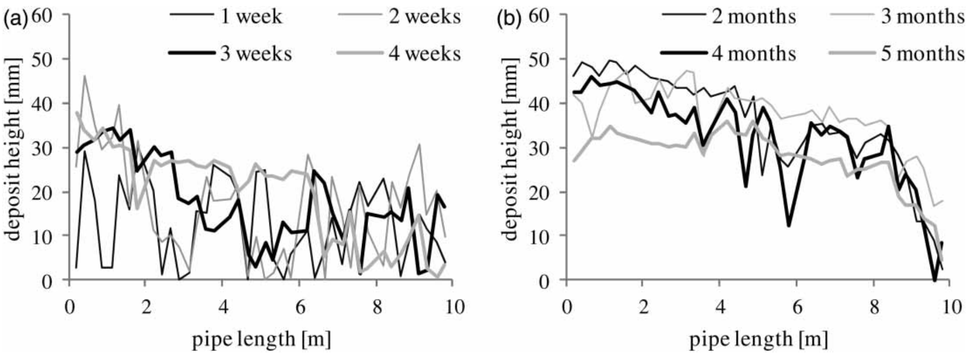

Figure 3 | Deposit heights over the pipe length after different test durations.

Growth and erosion of sediments

At the beginning of each test series, the deposits increased. The average growth within the first 30 d was around 0.75 mm/d (Figure 4). If the sediments were to continuously grow at this rate, sewer cleaning would be necessary very often. But both the broad distribution of the data in Figure 4 and the fact that in Figure 3 the deposit heights after 5 months were lower than after 3 months make clear that the increase does not take a continuous course, but that phases of sedimentation and erosion alternate. The mean value of the daily change in the average deposit levels (relative to observed pipe section) was 2.85 mm with sporadic significantly higher values of up to 20 mm/d. In rare cases even changes in deposit height of up to 100 mm/d were possible. In spite of largely constant flow conditions in the test pipes, solids not only settled but also were eroded. This is largely caused by two factors, which are described below.

Behind large conglomerates of fibrous materials wastewater swelled until the water pressure was great enough to keep these conglomerates moving through the test pipes at slow speeds of around 0.01–0.1 m/s. Here, existing sediments were partially eroded and transported away by the turbulent flow surrounding the solid ball. This effect cannot be accurately quantified, but is by no means negligible.

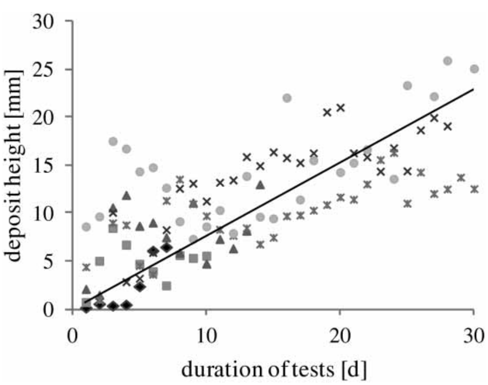

Figure 4 | Amount of deposits in the test pipe (range from 2 to 6 m) during the first 30 d of several test series (marked with different symbols) with unvaried test conditions.

More important than the cleaning effect of these spontaneously generated solid bales is the influence of variations in the concentrations of solids in the fed wastewater. The dry weather flow was, apart from the usual daily fluctuations, of largely constant quality. It was different, however, during rainfall. Then the solids concentrations in the wastewater flow were subject to strong fluctuations. Depending on various effects (e.g. rainfall duration or intensity, dry weather period, flow time) the solids concentration in the combined wastewater discharge can exceed values significantly above or below the dry weather flow concentrations (Ashley *et al.* 2004; Rutsch *et al.* 2005). Strong fluctuations of the water flow and suspended solids concentrations result in a constant interaction between sedimentation and erosion of solids in sewers (Banasiak *et al.* 2005).

Especially during heavy rainfalls large quantities of solids were released into the inlet channel of the Ölbachtal WWTP. The extraction of wastewater for the test pipes took place near the channel bottom in order to ensure that the pilot plant could be supplied with low dry-weather runoff, too. Since the concentration of solids in a flow cross-section increases from top to bottom, the amount of solids, which was transported into the test pipes, increased in times of heavy rainfall. The transport capacity of the wastewater flows in the test pipes was exceeded, which led to an increased deposit formation. After a rainfall the solids concentration came down to normal again. So the transport capacity of the discharge was no longer exhausted and an erosion of the previously formed deposits took place.

The influence of rainfall and of the inflow to the WWTP on the test results becomes obvious in Figure 5. During the increase in deposit heights in the first 70 d rainfall occurred regularly and deposit amounts were subject to relatively large daily fluctuations. In dry periods between day 70 and 90 and between day 110 and 150, however, a largely constant decline in deposits was seen.

The influence of rainfall on deposition dynamics is also illustrated in Figure 6. The biggest changes in the average deposit levels from one day to the next occurred during the first few days after rainfall. At times, they reached values of more than 20 mm/d, which corresponds approximately to the total increase in deposits in the test pipe within the first 30 d. The longer a period of constantly dry or wet weather, the lower the fluctuations of the deposit heights. This suggests that, with continued unchanged flow conditions, a state of equilibrium is reached, at which the deposit amounts in a sewer section vary, as described by Ristenpart (1995), at a characteristic deposit amount.

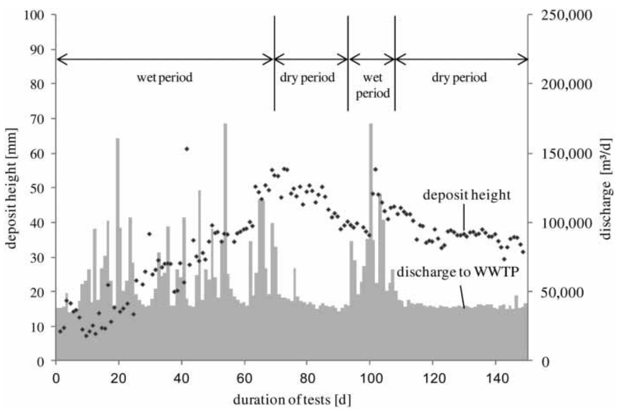

Figure 5 | Average deposit height in the test pipe during the test period (150 d) and daily wastewater flows to the WWTP. Significant increases in deposit levels are associated with rainfall-induced inflow peaks. In dry periods the amount of sediments in the test pipe decreased.

Attainment of a state of equilibrium

The state of equilibrium was defined as a situation where sedimentation and erosion occur varyingly and come to a long-term balance. If the deposit height at the state of equilibrium is below a critical value, intervals for sewer cleaning can be relatively large. So knowledge about the characteristic deposit heights of sewer sections helps to reduce the costs of sewer cleaning, which are currently around €0.5/(m·a). Looking at the longest experiment series of 150 d duration, for long periods of dry weather, an average deposit amount in the test pipe of 35 mm is observed (Figure 5). This value was exceeded for a longer period for the first time after approximately 50 d. This suggests that for this test series it took approximately 50 d until a state of equilibrium was established. Because of the dependence on rainfall, it was not possible to fully verify in the course of the previous experiments whether such a state of equilibrium sets in automatically and how long it takes until it is achieved. Further long-term testing is required.

CONCLUSION

Studies on sedimentation dynamics in sewer test pipes with a diameter of 300 mm showed that under the set conditions deposits arise within a few days. The average growth within the first 30 d of approximately 0.75 mm/d was not

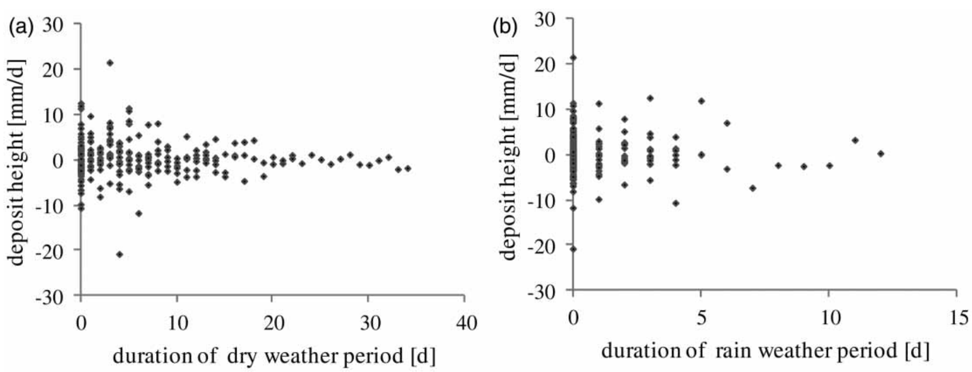

Figure 6 | Daily change of the average deposit height in the test pipe as a function of the duration of dry and rain weather period. The largest fluctuations occurred within a few days after a rainfall.

continuous, because of a constant change of sedimentation and erosion. The most relevant factor for the dynamics of deposition were weather-related changes in the solids concentrations of the raw sewage. The continuous change between sedimentation and erosion led to the fact that after a longer period a state of equilibrium occurred, where erosion and sedimentation arrived largely at a state of balance.

In regard to optimizing sewer cleaning intervals using the results of this study, it is necessary to achieve broad knowledge of the typical deposition characteristics of each sewer section. Practical criteria for the choice of cleaning intervals are the deposit growth rate and the typical deposit height of a sewer section. Deposit formation usually occurs within a short time (several hours or days up to a few weeks). But as long as a state of equilibrium below a critical value (e.g. 15% of the pipe diameter) is reached, there is no need to clean the sewers at regular intervals of 2 years or less. In many municipalities this would immensely reduce the costs of sewer cleaning. If the characteristic deposit height is above the critical value, cleaning intervals have to be the smaller, the higher the deposit growth rates. To specify this statement, further research is necessary.

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