Characterisation of sediments during transport of solids in circular sewer pipes

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ABSTRACT

This research is focused in the monitoring of sediments in circular sewer pipes with different diameters at a flume facility fed with urban wastewater. For this purpose, sediment physical and chemical characteristics, and sediment mobility were recorded. The Structure from Motion photogrammetric technique was used for the measurement of sediment bed evolution. In addition, sediment properties were determined in order to study the cohesiveness of the bed deposits. In particular, the chemical oxygen demand and the oxygen uptake rate of the sediment samples were analysed after different accumulation periods on the pipe inverts, resulting in a relation between these parameters and the mobility processes of solids.

Key words | combined sewer, flume test, photogrammetry, sediment transport, sewer sediments

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INTRODUCTION

The accumulation of sediments in combined sewers is a significant problem in urban sanitary systems. The erosion and resuspension of these solids during rainfall events is one of the most important sources of pollution, causing environmental impacts in the case of combined sewer overflow (CSO) events or wet weather flow discharges at wastewater treatment plants (WWTPs) (Suárez & Puertas 2005). In combined systems, a relevant fraction of the sediments are organic and cohesive solids and their release to the aquatic media is linked with dissolved oxygen depletion and other sediment-attached pollutants (Rushforth *et al.* 2003).

The characterisation of sediments has been reported in multiple studies during the past decades. Some examples are the works of Crabtree (1989), Verbanck (1990), Chebbo & Bachoc (1992) and Ashley *et al.* (2004). The influence of the age of sewer sediments in solid properties and biological activity was first introduced by Ristenpart (1995). Furthermore, the analysis of oxygen consumption parameters was considered by Vollertsen & Hvitved-Jacobsen (2000) to assess the sediment biological processes and, from that, to estimate the bed resistance. More recent works were focused on the bed strength variances depending on the consolidation time and the aeration conditions (Tait *et al.* 2003; Banasiak *et al.* 2005; Schellart *et al.* 2005; Seco *et al.* 2014). In those studies, it was concluded that the deposit strength is affected by the microbiological activity due to the organic matter and the oxygen content.

Sediment characteristics are linked with the suspended or bed load transport rates in sewers (Ashley *et al.* 2004). Traditional sediment transport models are based on river sand equations while other parameters, such as cohesiveness, are not considered (Bertrand-Krajewski 2006). Laboratory and field work have been reported to validate sediment transport formulas in sewers but only physical properties of the sediments have been included in the proposed models (Skipworth *et al.* 1999; De Sutter *et al.* 2003). The presence of organic particles has been also studied in some laboratory campaigns, from which it was concluded that bed shear stress and, consequently, the sediment transport rate are affected by small organic fractions (Rushforth *et al.* 2003; Banasiak & Verhoeven 2008).

The management of sewer sediments is still an important issue in urban areas with significant associated costs of maintenance. In combined sewers, upstream secondary pipes (diameters < 400 mm) are supposed to contribute in

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the solid production due to the particle sedimentation favoured by the dry-weather flow conditions (Rammal *et al.* 2017). To better understand the transport processes of cohesive sediments in sewers, the age of the sediments and the temporal evolution of their physicochemical properties have to be included in the models. The objective in the present research is to assess how these issues affect the sediment erosion. For that, an experimental campaign was performed in two circular commercial pipes at a flume test facility fed with real wastewater.

MATERIAL AND METHODS

Experimental flume and test procedure

The experimental flume was built at the pretreatment facility of the WWTP of A Coruña (Spain). It presents a length of 10 m, a width of 0.8 m and a variable slope in the range of 0% to 2%. The purpose of this facility is to test different cross-sections (mainly sewer pipes and open channels) with real wastewater under controlled laboratory conditions. For this research, two conventional circular PVC pipes with outer diameters of 315 and 400 mm and a length of 7.5 m were placed over the flume metallic bench (Figure 1). A pumping supply system introduces urban wastewater taken after the mechanic racks (3 mm aperture) placed upstream of the grit chamber of the WWTP to the inlet chamber of the flume. This chamber connects with each pipe through a triangular weir. An automatic tailgate is placed at the end of the flume to fix downstream boundary conditions. Also, the flume is equipped with hydraulic and wastewater load sensors. More detailed information about the facility can be found in Regueiro-Picallo *et al.* (2017).

A long-term accumulation test was designed to study the evolution of the deposited mass and the sediment properties during 20 days. For this purpose, constant hydraulic conditions were established: flow rate (Q) of 4.1 L/s, slope of 0.1% and downstream boundary condition of 85 mm (22.5% and 28.4% filling ratio in 315 and 400 mm pipes respectively). Following previous studies at the same facility (Regueiro-Picallo *et al.* 2017), sediment deposits appeared with mean flow velocities of about 0.24 m/s in a circular 315 mm pipe. Furthermore, a constant accumulation rate was recorded up to 7–11 days. After this accumulation period, a quasi-constant sediment bed height was observed. In the present study, the resulting velocities were 0.26 and 0.22 m/s for the 315 and 400 mm pipes respectively in order to allow sediment bed accumulation.

A series of three sediment accumulation–erosion tests were conducted to force sediment resuspension and erosion after 3, 7 and 20 days of accretion period in both pipes. The main objective of these tests was determining the effect of the consolidation period of the sediments on their erodibility. A similar analysis was performed by Tait *et al.* (2003), Schellart *et al.* (2005) and Seco *et al.* (2014), who simulated different sediment dry-weather periods in order to measure the sediment resistance with an erosion meter.

The first erosion test was performed on the last day of the long-term accumulation experiment. Two more accumulation tests were completed trying to reproduce the same initial sediment height conditions; hence hydraulic conditions were modified during the deposition phase. As a result, lower velocities were set to increase the accumulation rate in both pipes in order to fix the same initial conditions. Before each test starting, bed deposits and sediment characteristics were recorded. Then, the erosion discharge was fixed for 30 min (similar to Rushforth *et al.* 2003) while wastewater loads were monitored upstream and downstream of both pipes. Afterwards, flow rate was suddenly stopped and the final bed deposits were measured.

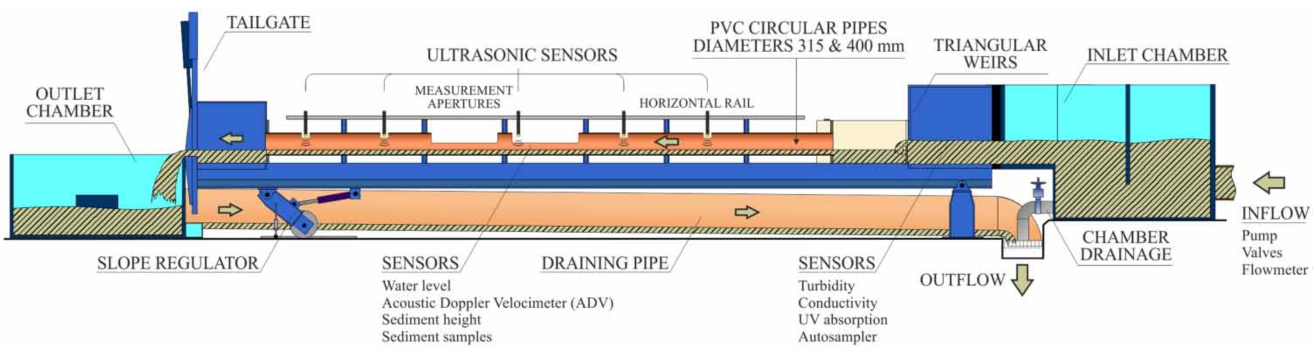

Figure 1 | Schematic drawing of the flume test facility.

Determination of sediment deposits

Two main apertures of 70 cm were opened in the middle of each pipe for measuring sediment deposits and collecting sediment samples. Bed deposits were almost daily recorded in the same aperture in order to compare the evolution of the accumulated solids. For this purpose, the wastewater supply system was halted and both pipes were carefully drained avoiding the bed structure erosion using the automatic tailgate.

The accumulated solids were measured using the Structure from Motion (SFM) photogrammetric technique. This non-intrusive method allows obtaining a 3D reconstruction model of the bottom of each pipe from a series of random images taken around the aperture with a convectional camera (Figure 2). Free licence software VisualSFM (Wu *et al.* 2011; Wu 2013) and MeshLab were used to perform the point reconstruction and the surface mesh respectively. The main advantage of this low-cost methodology is that it allows measuring of both cross-sectional and longitudinal profiles with a high spatial resolution (0.1 mm roughly). Therefore, the accumulated volume of sediments was obtained from the difference between the bed deposit surface mesh and the theoretical geometry of each pipe. In order to obtain accurate measurements with this methodology, an overlap of the images and a high contrast between vertexes are required. Also, at least four known coordinate points are necessary to transform the model into a known coordinate system. A similar SFM procedure was used by Detert *et al.* (2016) in order to perform the ortho-rectification of images and rendering of a river course.

Determination of sediment properties

The sediment characteristics were recorded during the long-term accumulation and before starting each erosion test. For that purpose, the physicochemical properties were studied for each sample. Total solids (TS), volatile solids (VS) and the density were analysed following the standard methods (APHA *et al.* 1998), while particle size distribution was performed according to ISO 13320:2009 (ISO 2009). Furthermore, the chemical oxygen demand (COD) and the oxygen uptake rate (OUR) were selected to analyse sediment chemical parameters. The COD shows an absolute value of the sample pollution while the OUR indicates the relationship with the readily biodegradable organic matter of the sediment.

Following McGregor *et al.* (1993), the COD values from sewer sediment samples were obtained with three different sampling preparation methodologies. These techniques consisted of blending, stirring and mixing the sample with distilled water at different revolutions (Table 1). McGregor *et al.* (1993) suggest that different pollutant fractions are obtained from these three sample preparations. The total sediment COD load is obtained from the blending procedure (COD Type I) while COD from the readily erodible fraction is determined by the stirring and mixing preparations (COD Type II and III, respectively).

After the sample preparation, the dilution was centrifuged at 2,000 g for 30 min to separate the liquid–solid phases, similar to the standard of leaching of granular waste materials and sludges, UNE-EN 12457-2:2002 (AENOR 2002). In the case of sewer sediments, solid particles are more disaggregated than waste and sludges, so the agitation time to perform the sample preparation can be smaller. Finally, the COD determination was carried out for the supernatant following the standard procedure (APHA *et al.* 1998).

OxiTop® respirometers (Weilheim, Germany) were used in order to measure the sediment OUR during the first days of the sample biodegradation. The OUR values were obtained from the oxygen consumption rate after 48 hours

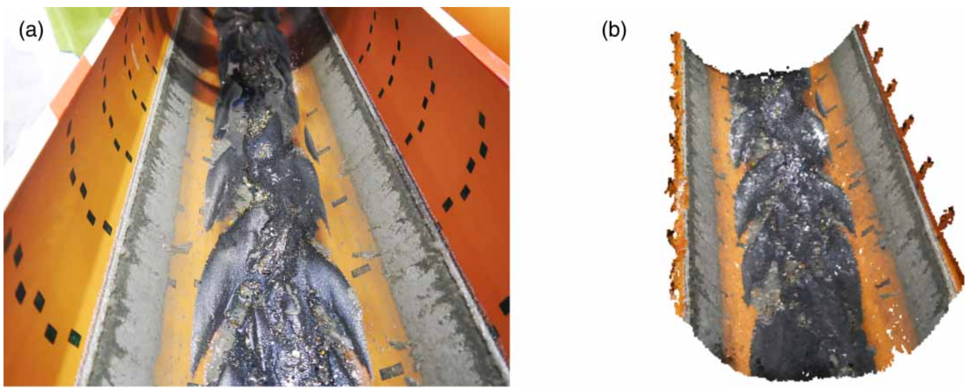

Figure 2 | Example of a picture of the accumulated sediments in the pipe contour (a) and view of the 3D reconstructed model (b) of the 315 mm diameter pipe.

Table 1 | Sample preparation methodologies for COD analysis based on McGregor *et al.* (1993) studies

COD code	Method	Apparatus	Dilution factor	Agitation time	Revolutions
COD Type I	Blending	Blender	1/3 during blending and distilled water addition up to 1/10	5 minutes	>5,000 rpm
COD Type II	Stirring	Magnetic stirrer	1/10	2 hours	900 rpm
COD Type III	Mixing	Mechanical mixer	1/10	2 hours	55 rpm

(Sadaka *et al.* 2006). As other studies suggested, this parameter is connected with the strength of the bed deposits (Vollertsen & Hvitved-Jacobsen 2000; Seco 2014). In this study, the objective of measuring the chemical properties from sediment samples was to consider the strength and cohesiveness of the bed deposits.

RESULTS AND DISCUSSION

Long-term accumulation

Constant hydraulic conditions were established and recorded during the 20-days accumulation test. However, wastewater loads presented daily patterns due to the WWTP operating conditions (Regueiro-Picallo *et al.* 2017). Therefore, wastewater was continuously monitored with different probes at the inlet chamber, which were calibrated with an automatic autosampler, resulting in average total suspended solids (TSS) and COD concentrations of 224 ± 65 mg/L and 414 ± 80 mgO_2/L respectively. As a result, the settling of particles was forced by the inlet sediment discharge together with the insufficient velocities in both the 315 and 400 mm pipes. A quasi-linear growth of the sediment mass was obtained after processing the images with the SFM technique for the first 6 days of the long-term deposition test (Figure 3(a)). The resulting accumulation rates were 0.377 and 0.447 kg/(m day) for the 315 and 400 mm pipes respectively (3.10 and 3.16 mm/day expressed in sediment heights). These values are similar to those obtained by Regueiro-Picallo *et al.* (2017), 1.4–3.8 mm/day, and Lange & Wichern (2013), 2.85 mm/day, in a 300 mm inner diameter pipe.

Two types of sediments were easily identified in the contour of both pipes (Figure 3(b)). The growth of a dark granular and cohesive sediment was observed at the bottom while fine slimes were attached to the pipe-walls and developed from the maximum water level to the invert of the pipe. Following Crabtree (1989) classification, bed deposits are identified as Type A/C and wall biofilms as Type D sediments.

Three sediment samples were manually collected during the long-term accumulation test. The samples were taken after 3, 6 and 20 days from the beginning of the experiment. In order to obtain representative results, all of them were sampled in the same aperture but from a different location, so the sediment properties were kept undisturbed.

The physicochemical average values for the 315 and 400 mm pipes are presented in Table 2, since slight differences were found between both geometries. No temporal-trends were apparently found after analysing the set of samples; only the OUR values show a clear decrease in time, which indicates the loss of the sediment biological activity. In comparison with sewer sediment values reported in the literature over past decades, similar physicochemical results were obtained. Nevertheless, smaller values for VS of biofilms were observed presumably due to small grained

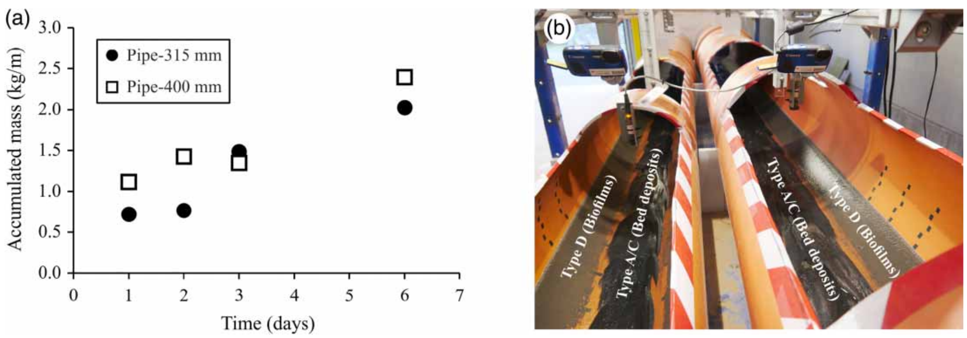

Figure 3 | Accumulated sediment mass during the first 6 days of the long-term accumulation test (a) and appearance of two types of sediments in 315 and 400 mm pipes (b).

Table 2 | Time-evolution of bed deposits (Type A/C) and wall biofilms (Type D) physicochemical properties for 3, 6 and 20 days in the long-term accumulation test and comparison with average values in previous studies

	Type A/C				Type D			
Parameter	Day 3	Day 6	Day 20	References[1),2),3)]	Day 3	Day 6	Day 20	References[1)]
Density (kg/m3)	1,461	1,546	1,477	1,544	1,183	1,112	1,186	1,210
Total solids (%)	52.9	59.4	56.6	58.7	30.9	24.6	28.2	25.8
Volatile solids (%)	12.1	8.7	11.3	14.4	19.1	17.7	14.7	61
Mean grain size (μm)	125	146	138	63–2,000	40	39	42	63–2,000
COD Type I (g/kg)[a]	4.6	3.5	4.0	69.8	–	–	–	193
COD Type II (g/kg)[a]	1.5	1.1	2.7	–	17.9	32.2	14.8	–
COD Type III (g/kg)[a]	1.8	1.2	1.9	–	17.9	29.2	12.1	–
OUR (g/(kg day))[a]	13.3	9.8	5.9	6.5[b]	48.2	39.6	16.0	20.6[b]

Average values: [1)]Crabtree (1989); [2)]Ristenpart (1995); [3)]Ashley *et al.* (2004).
[a]g/kg and g/(kg day) dry solids.
[b]calculated from 5-day biochemical oxygen demand values.

particles stuck to the biofilm close to the water surface level and, in addition, higher differences were obtained for COD values in both Type A/C and Type D sediments. The amount of wall biofilm samples was insufficient to analyse the COD Type I. Furthermore, a good agreement was observed between the VS and the COD Type I values for the Type A/C sediments due to the fact that both parameters quantify the presence of organic matter in the samples.

Different COD values were recorded depending on the sampling preparation technique. The COD Type I method presents higher values than COD Types II and III in all the Type A/C samples because of the sample preparation procedure. The high-speed blending procedure of COD Type I method disaggregates sediments and releases attached pollutants, so total sediment COD load can be determined. The readily erodible fraction determined by COD Type II and III estimates the pollution that could be released to the wastewater if the shear stress conditions were increased. In order to obtain this COD fraction, lower stirring frequencies are defined in the sampling preparation processes.

The obtained results agree with McGregor *et al.* (1993) and Ashley *et al.* (2004) studies showing that different COD polluting fractions are obtained according to the selected preparation method. An average percentage of readily erodible fraction of 42% from the total sediment load was resulted from Type A/C sediments, while percentages of 25% and 57% were reported for Type A and Type C sediments respectively by Ashley *et al.* (2004). Thus, between a quarter and a half of the pollutants attached to the sewer sediments are susceptible to being quickly released into the combined sewage during rain episodes or even during daily peaks in dry-weather conditions. Additionally, a continuous pollutant exchange over the sediment surface should be considered due to sorption and diffusion processes (Ashley *et al.* 2004).

Erosion tests

Three erosion tests were performed under similar inlet conditions ($Q = 11.6 \pm 0.5$ L/s and $TSS = 323 \pm 64$ mg/L) but with different sediment accumulation periods of 3, 7 and 20 days. In order to calculate the eroded mass of sediments, the volume of eroded solids was determined using the SFM technique as the difference between initial and final bed deposits. The initial sediment height was set to 7.3 ± 3.9 mm and 14.3 ± 2.0 mm in the 315 and 400 mm pipe respectively.

Although the tests were performed with similar flow discharges and initial bed heights, the total amount of eroded mass decreases as the sediment consolidation time increases (Figure 4(a)). The averaged physicochemical properties of the bed deposits determined at the beginning of the erosion tests in both pipes are plotted in Figure 4(b). A reduction of COD, VS/TS and OUR values was also recorded for longer accumulation periods. These results suggest that the bed strength and erodibility are affected by the biological activity of the sediment, as stated previously by Tait *et al.* (2003) and Seco *et al.* (2014). A higher cohesiveness of the bed deposits is expected in long-term deposition because of the decrease of the organic content concentration and the sample degradation. Therefore, 'fresh' sediment conditions were more susceptible to being eroded.

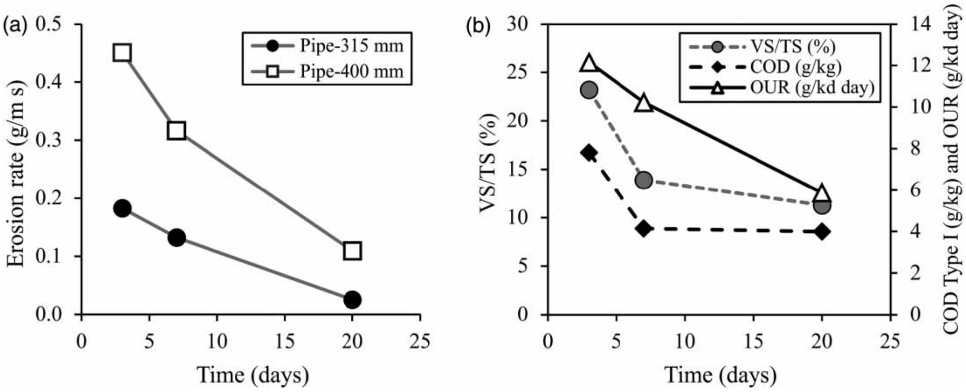

Figure 4 | Variation of the erosion rate (a) and the physicochemical properties of initial bed deposits (b) for different consolidation period tests.

Comparing the mass erosion rate in both geometries, the highest values were observed in the 400 mm pipe due mainly to the fact that the deposited mass was also higher. Nevertheless, the ratio between the eroded and accumulated mass was 85%, 18% and 11% for the 315 mm pipe and 50%, 23% and 9% for the 400 mm pipe after 3, 7 and 20 days of consolidation periods respectively. Therefore, these results suggest that the transport capacity of the sewer pipes is influenced by its geometry and also the consolidation period of the sediments.

Differences between initial and final sediment distributions in bed deposits were recorded during the erosion tests. Ripples and dune formations were developed after each experiment in the 400 mm pipe (Figure 5(a)–5(c)) while an unclear bed form distribution (similar to flat bed) was found in the 315 mm pipe, mainly due to the smaller initial sediment surface width (<100 mm). During the erosion tests, Froude number F was 0.51 and 0.44 in the 315 and 400 mm pipes respectively, where $F = U/(gA/T)^{0.5}$, U is mean velocity (m/s), g is gravity acceleration (m/s^2), A

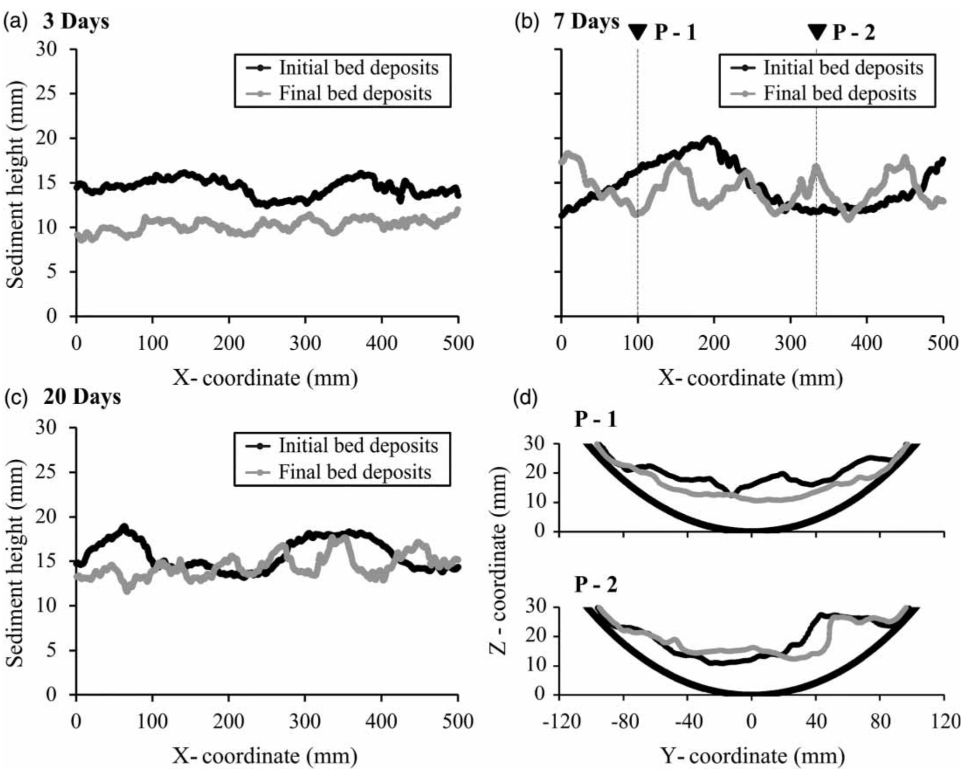

Figure 5 | Initial and final bed deposit formations for different consolidation times of 3 (a), 7 (b) and 20 days (c) and two cross-sectional profiles during the sediment deposition test of 7 days (d) in 400 mm pipe.

is flow area (m^2) and T is water surface width (m). Bed form heights of 2, 6 and 3 mm and wave lengths of 56, 83 and 72 mm were measured in the 400 mm pipe for the erosion tests with sediment consolidation periods of 3, 7 and 20 days respectively.

Bed formations are responsible for a fraction of the total bed shear stress. The shear stress partitioning is composed of the grain shear stress and the shear stress induced by bed forms (Banasiak & Tait 2008). Thus, the SFM technique is presented as a procedure to be able to calculate bed form shear stress from the sediment surface information. This methodology improves other non-intrusive methods such as punctual measures or cross-sectional profiles. In these techniques, the average eroded mass might be overestimated or underestimated depending on the selected locations (Figure 5(d)) while complex bed deposit distributions could be studied with a 3D reconstruction.

CONCLUSIONS

A series of accumulation and erosion tests were performed in two circular PVC pipes (315 and 400 mm outer diameters) with different hydraulic conditions in a flume test facility fed with urban wastewater. In addition, accumulated bed deposits were measured and sediment samples were collected from the pipe inverts, distinguishing between granular cohesive bed deposits and slime wall biofilms. The photogrammetric SFM methodology was utilised to calculate the accumulated mass under the sediment surface while physicochemical parameters were analysed from manual samples.

The evolution of sediment physicochemical characteristics was studied with three sampling campaigns after 3, 6 and 20 days from the beginning of the long-term accumulation test. No significant sediment property differences were recorded between the 315 mm and 400 mm pipes. An evident daily pattern was only observed in the OUR values, decreasing from the 'fresh' sediments after a few days to less biodegradable samples at the end of the accumulation period. Furthermore, most of the parameters were found to be in the same range as in studies of the past decades. However, lower values were reported for the total sediment COD. Different COD analyses were performed following three sample protocols in order to obtain the total and the readily erodible pollutant fractions of sewer sediments. It was concluded that between 25% and 50% of the pollutants attached to the bed deposits could be released due to higher shear stress conditions.

Erosion tests were performed with the same hydraulic and initial sediment height conditions in order to study the influence of three different sediment consolidation periods (3, 7 and 20 days) in the bed erosion processes. A lower erosion rate was found as the sediment consolidation time was increased. The decrease of the eroded mass matched with lower values of the chemical (COD and OUR) and organic matter properties of the initial bed deposit samples while the rest of the initial physical parameters were undisturbed. Therefore, a higher bed strength and cohesiveness might be expected as the accumulation period increases. The erosion rate was higher in the 400 mm pipe due to the higher amount of sediments deposited in each pipe at the beginning of the experiments. Despite that, similar trends were obtained in both geometries.

Ripple and dune formations were observed after the increase of the flow rate in the 400 mm pipe tests. These bed forms were obtained from longitudinal profiles with the SFM technique. The main advantage of this methodology is the information provided about the sediment surface, allowing an accurate determination of the bed deposit volumes and the bed shear stress partitioning compared with punctual and cross-sectional measurements.

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