

## Monitoring accumulation sediment characteristics in full scale sewer physical model with urban wastewater

Manuel Regueiro-Picallo, Juan Naves, Jose Anta, Joaquín Suárez and Jerónimo Puertas

### ABSTRACT

A series of experiments were carried out with real wastewater in a pilot flume located at A Coruña wastewater treatment plant (WWTP) (Spain). A full scale model was developed to test a circular (300 mm inner diameter) and an equivalent area egg-shaped plastic pipe under controlled experimental conditions (pipe slope 2–5‰, averaged discharge  $Q = 4$  L/s). Velocity profiles and sediment accumulation in the pipe invert was daily measured. Within the 7–11 days, the average sediment accumulation rate found in the circular pipe was between 1.4 and 3.8 mm/d. The sediment height depended on the input wastewater sediment distribution and organic content. The egg-shaped pipe presented no sediment deposit for the same downstream boundary conditions, although biofilms were attached to the walls of both pipes. Besides, wastewater quality was monitored continuously and sediment composition was studied at the end of experiments. Two types of sediment were recorded: a granular bed deposit ( $\rho = 1,460$  kg/m<sup>3</sup>,  $d_{50} = 202$   $\mu$ m) and wall biofilms ( $\rho = 1,190$  kg/m<sup>3</sup>,  $d_{50} = 76$   $\mu$ m).

**Key words** | combined sewer, deposition, flume test, sediment accumulation, sewer dynamics, sewer sediments

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### INTRODUCTION

One of the major problems of combined sewer systems is the accumulation of sediments. Bed deposits inside conduits are produced especially during dry weather flow conditions caused by insufficient velocities or after heavy rain episodes. A consequence of accumulation in sewers is the loss of capacity to transport solids in conduits, because the height of bed deposits causes a decrease of the effective flow area and increases the hydraulic resistance. The organic content of sediment deposits also can produce gases (methane and hydrogen sulfide) and odours that are unhealthy for breathing (Ashley *et al.* 2004). Furthermore, the erosion and transport of sewer sediments caused by overflows during rainfalls is an important source of pollution leading to an impact in the environment, as combined sewer overflows or a surcharge at wastewater treatment plants (WWTPs) (Suárez & Puertas

2005). In order to prevent all previous problems it becomes necessary to clean sewer systems regularly, producing important costs of maintenance (Lange & Wichern 2013).

To approach the knowledge of sediment accumulation and transport processes in sewers, main investigations were focused in measurements in real sewers or studies of sewer hydraulics in full scale models. Uncertainties in flow rates and concentration of solids measurements are the main disadvantage of studying sediment transport in real sewers (Bertrand-Krajewski *et al.* 2003). To control this source of uncertainty, different laboratory experiments were performed on test flumes under controlled conditions. These full scale models often replace wastewater and sediments with non-cohesive granular materials (Ota & Nalluri 2003). Surrogate sediments with cohesive properties were also used to study erosion and sediment transport but without presence of organic matter, biofilms or gross solids (Tait *et al.* 1998; Banasiak *et al.* 2005). However, both non-cohesive granular particles and artificial sediment mixtures show unrepresentative behaviour of real sewer deposits.

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Few investigations were found that matched real wastewater under controlled laboratory conditions with the aim of calculating sediment accumulation and transport rates in sewers (Rushforth *et al.* 2003; Lange & Wichern 2013).

The aim of this study was to study the daily evolution of bed deposits in combined sewer pipelines under controlled conditions with real urban wastewater. For this purpose, a series of tests were carried out in a flume test facility located at A Coruña WWTP (600,000 inhabitants). As part of the experimental procedure, it was necessary to control sewer hydraulics and determine wastewater characteristics. At the same time, sediment heights were monitored with different techniques in order to calculate sedimentation growing rates.

## MATERIAL AND METHODS

### Flume test facility

The flume test facility was equipped with two different pipe geometries. A conventional circular PVC pipe with an inner diameter of 300 mm was compared with an egg-shaped cross section pipe. Both pipelines were made of plastic with a length of 8 m. The egg-shaped geometry was developed from a concatenation of arcs. For that, the top and bottom radius ( $R$  and  $r$ , respectively) and the total height ( $H$ ) were defined. Both cross section pipes should keep an equivalent area so that results could be comparable. Therefore, egg-shaped cross section presented a total height of  $H = 385$  mm, a top radius of  $R = 110$  mm (220 mm width) and a bottom radius of  $r = 55$  mm (Regueiro-Picallo *et al.* 2016).

Both pipelines were placed over a metallic bench, with variable slope ranging from 0 to 2%. Wastewater was pumped with a submersible sludge pump (ABS JS44 with

a free passage of  $50 \times 40$  mm) from post-sieving system of the WWTP (3 mm aperture) towards a head tank placed before the entrance into the pipes in order to avoid turbulences and to spill excess flow. To control the inflow, a set of valves and an ultrasonic flowmeter were set up in the pump system pipeline. Wastewater was directed into the pipelines through two triangular weirs, so the discharge was the same in each pipe and it could be monitored by an ultrasonic water level sensor before the weirs. Besides, a total of five windows were opened at the top of both pipes to measure water depth also with ultrasonic sensors. In addition, two main apertures of 90 cm long were set in the middle of each pipe as control sections for measuring deposit heights and velocity profiles. At the end of the bench, a receiver tank was placed with a tailgate that could be automatically controlled to set downstream boundary conditions for both pipes (Figure 1). More detailed information about the developed flume can be consulted in Suárez *et al.* (2015).

A Nortek Vectrino© Acoustic Doppler Velocimeter was used to record 3D flow velocities. Centerline velocity profiles were measured at a distance of 4 m from the inlet chamber of each pipe, using one of the main apertures of the control section. Velocity data were measured with a vertical resolution of 5 mm and 2.5 mm for positions close to the pipe invert and with a sampling frequency of 25 Hz during 120 s, to ensure that the turbulence intensity was within 5% of its measured long-term average. All velocity data were de-spiked using the phase-space thresholding method of Goring & Nikora (2002) as suggested by Cea *et al.* (2007).

As part of the wastewater characterization, total suspended solids (TSS) and total dissolved solids were monitored and correlated from the records of turbidity (SOLITAX) and conductivity (LANGE 3798-S) probes, respectively. In addition, wastewater chemical oxygen demand (COD) was correlated with an organic matter

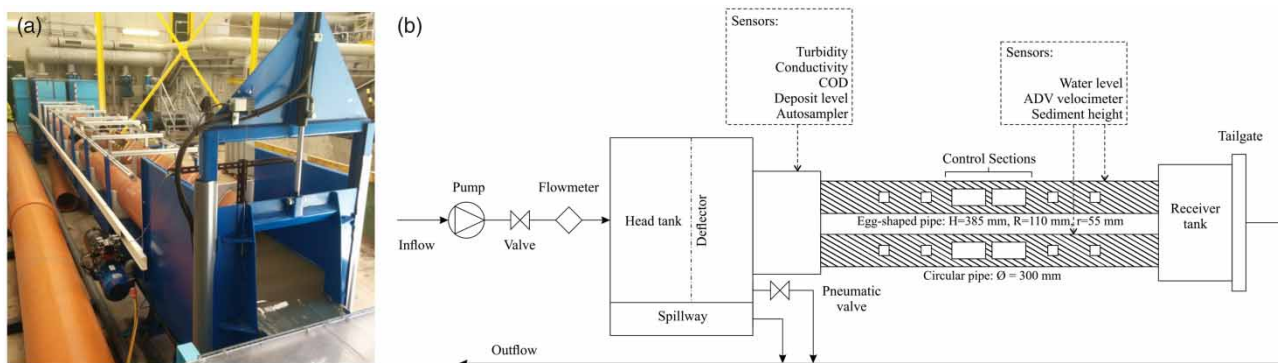


Figure 1 | General view (a) and scheme (b) of the flume test facility.

(UVAS) probe (results not shown here). An automatic sampler placed at the head tank was utilized to collect a sample every 6 h in order to fit the best linear calibration of these probes. Manual grab samples at the head tank and the receiver tank were taken to complete the sediment and wastewater characterization.

### Experimental procedure

A series of tests were conducted in order to study the evolution and characteristics of bed solids and the efficiency of circular and egg-shaped pipes. For this purpose, a constant discharge was established during several days with different slope and water depth conditions. Two slope values were set at 2‰ and 5‰. In addition, two different downstream boundary conditions were analyzed. On the one hand, tailgate was completely open so a free discharge was generated at the end of the pipes (critical depth). On the other hand, a water depth of 100 mm was established in the receiver tank with a fixed opening value of the tailgate. In two experiments (Nos. 4 and 7) with fixed downstream water depth condition, a small submersible pump was installed in the head tank to resuspend particles. This forced recirculation introduces largest particles into the pipes, avoiding their long-term accumulation in the head tank. All test conditions were summarized in Table 1.

For each test, sediment bed heights were daily measured. As part of the procedure, it was necessary emptying both pipes in a controlled way without affecting the sediment bed structure. Two different methods were set to record the deposit height. An imaging technique was utilized in order to measure several sediment profiles at the main apertures of both pipes and, at same time, the ultrasonic sensors recorded the sediment height along both pipes.

The imaging technique consisted in a camera recording the height of the bed deposits, which were pointed by a laser sheet (Figure 2(a)). An image bilinear transformation was applied to transform camera pictures to real world coordinates (Raffel *et al.* 2007). The difference between the image with sediments and the pipe cross section geometry allowed calculating the accumulated area of solids (Figure 2(b)). A total of six profiles, three per aperture 15 cm separated, were recorded in each pipe with a wheeled structure. This kind of automatic and non-intrusive technique improves the measurement accuracy of the sediment profile regarding manual methods (Bertrand-Krajewski & Gibello 2008). This imaging technique was previously tested over a flat surface with a trapezoid-shaped object as an artificial sediment bed in order to evaluate the uncertainties. In a similar laser scanning methodology within egg-shaped sewers (400/600 mm), Stanic *et al.* (2014) showed that the main sources of uncertainties are the accuracy of the cameras, the alignment of the lasers and the distance in the measuring setup. A complete set of misalignments of the trapezoid-shaped object and the world-camera calibration sheet were recorded to evaluate the uncertainties. With this methodology, an overall error of a 2% of the area of the trapezoid was estimated.

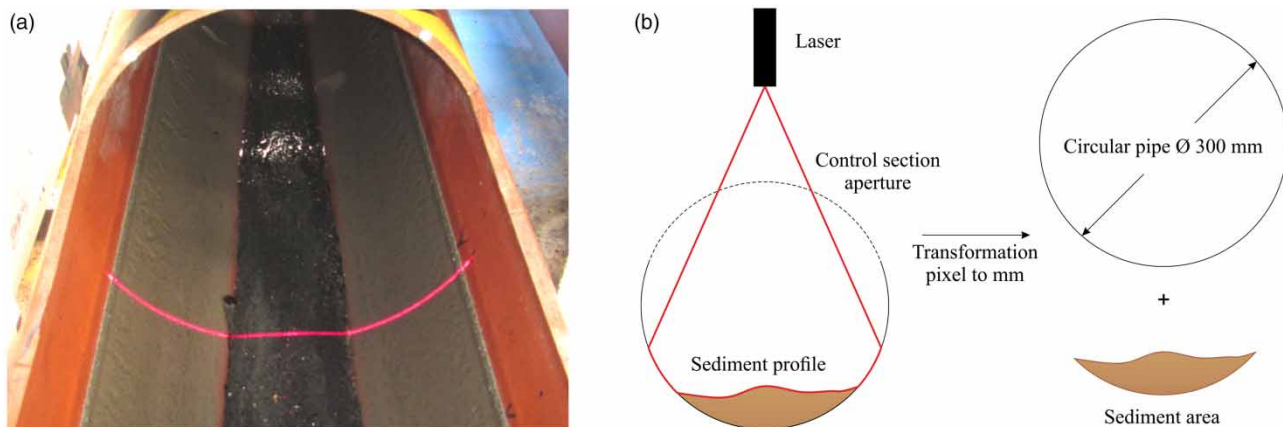
Sediment height was also monitored with ultrasonic sensors in the five opened windows while images were taken. The resolution of sensors was 0.13 mm and the deviation of the ultrasonic beam was 4.6°. Therefore, measurements were dismissed when sediment heights were less than 2 mm in circular and 8 mm in egg-shaped pipe.

At the end of each test, two different types of solids were sampled from the pipes. A coarser mixture of granular and cohesive bed material was observed at the bottom while

**Table 1** | Summary of test conditions: discharge (L/s), slope (m/m), downstream boundary condition, water depth (mm), average mean velocity (m/s) and head tank mixing

Test no.	Discharge (L/s)	Slope (m/m)	Downstream B.C.	Water depth (mm)		Mean velocity (m/s)		Recirc. head tank
				Egg-shaped	Circular	Egg-shaped	Circular	
1	3.5	0.5	Critical depth	70	42	0.49	0.58	No
2	3.0	0.5	WD = 100 mm	81	78	0.34	0.21	No
3	3.9	0.5	WD = 100 mm	87	84	0.41	0.24	No
4	3.9	0.5	WD = 100 mm	86	84	0.41	0.24	Yes
5	4.3	0.2	Critical depth	84	51	0.47	0.54	No
6	4.6	0.2	WD = 100 mm	100	95	0.39	0.24	No
7	4.5	0.2	WD = 100 mm	99	95	0.39	0.24	Yes

(\*) WD = water depth.



**Figure 2** | Raw image of laser pointing sediment profile (a) and calculation of sediment area with numerical subroutine (b).

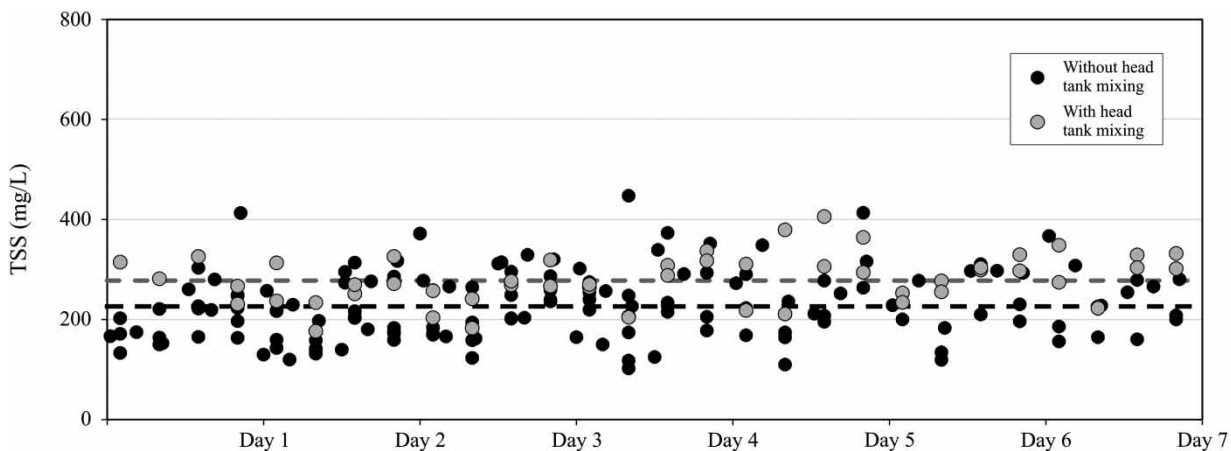
fine grained and organic slimes were stuck to the pipe walls. Particle size distribution of both types of sediments was obtained with a wet-sieved analysis following the [ISO 2591:1988](#). In addition, it was calculated the amount of total solids (TS), the moisture content (W), the percentage of volatile (VS) and the density of each type of solid following [APHA \(1995\)](#) methods. In order to obtain the COD, it was followed [McGregor et al. \(1996\)](#) stirring method for preparing the sediment sample.

## RESULTS AND DISCUSSION

### Wastewater characterization

For all experiments, flowrates varied between 3 and 4.6 L/s in both pipes, remaining almost constant during each test. The concentrations of TSS presented a smooth daily pattern,

with a mean value ( $\pm$ standard deviation) of  $240 \pm 67$  mg/L. Most of the suspended solids fractions were organic matter with an average VSS/TSS ratio of 87%. The variation of solids concentrations was caused by wastewater daily variability. The influence of rainy periods in TSS loads was almost negligible. Although more sediments are released into the WWTP after heavy rainfalls, sediment loads at the pilot flume were largely constant during rainy events due to the large capacity of A Coruña WWTP and the fact that the source of wastewater to the experimental facility is placed after the post-sieving system. Besides daily patterns, the main relevant sediment input variation was connected with the forced agitation of wastewater in the inlet chamber of the flume. As stated in the previous section, in test Nos. 4 and 7, a recirculation pump was operated to increase mixing and reduce the sedimentation of the particles in the head tank. [Figure 3](#) shows the weekly variation of the TSS upstream of the pipes for all the experiments. A slightly



**Figure 3** | Weekly variation of TSS input to the experimental facility.

higher concentration of TSS was recorded in the experiments when the mixing pump is working, with an averaged value ( $\pm$ standard deviation) of  $278 \pm 49$  mg/L. When the recirculation pump was not operated, the determined TSS were  $226 \pm 62$  mg/L.

Figure 4(a) shows the particle size distribution and the volatile and fixed fractions of the sediments fed to the experiments with and without the recirculation pump in the head tank. The activation of the mixing pump changed the sediment composition and distribution. A more uniform distribution of the particles available for transport and sedimentation in the pipes was found if mixing was enhanced, meanwhile, mean sediment size decreased from  $d_{50} = 616 \mu\text{m}$  to  $d_{50} = 270 \mu\text{m}$  (Figure 4(b)). Because of this recirculation in test Nos. 4 and 7, the resuspended solids presented a higher fixed fraction (roughly 80% in mass) with a mean size of  $254 \mu\text{m}$ . In the tests without head tank mixing, the organic fraction showed a higher contribution (70% in mass) with a mean diameter of  $526 \mu\text{m}$ . These differences in the sediment availability, composition and distribution have affected to sedimentation processes in the pipes as will be shown following.

### Accumulation of sediments in pipes

No bed deposits were recorded under critical depth downstream conditions for slopes of 2‰ and 5‰ (test Nos. 1 and 5) in both pipes. Bed deposits were only measured in circular pipe in experiments with fixed downstream water depth conditions. For the analysed hydraulic conditions, no sediment accumulation was recorded in the egg-shaped cross section pipe. The appearance of bed deposits was similar for all experiments; a granular-cohesive sediment

mixture was formed because of the insufficient velocity of granular particles and the high presence of organic substances. Although fibrous materials may have allowed sands and organic solids to settle (Lange & Wichern 2013), a low content of fibers was observed due to the fact that sieving treatment removes a high amount from the wastewater used in the tests.

An organic slime was attached to pipe walls during the development of the test in both circular and egg-shaped conduits (Figure 5(a)–5(b)). The growth of biofilms was observed from water surface to the bottom, getting an indistinguishable interface between the two types of sediments in some cases. Thickness of biofilm in both pipes' walls has depended on test's duration, though composition and structure of wall sediment were similar at the end of all experiments.

Particle size ranges associated with the circular pipe bed deposits and wall slimes are presented in Figure 5(c). Following Crabtree (1989), sewer sediment classification system, the bed deposits can be classified mainly as Type A sediment, composed of a mixture of fine-medium sand. The organic content of the samples ranged from 7% to 12%, indicating the presence of some cohesive sediment. The mean particle size of bed deposits matched with highest inorganic sediment fraction in Figure 4(b). Besides, small differences in the particle size (mean  $\pm$  standard deviation) of bed deposits were found between experiments with the recirculation pump mixing in head tank ( $240 \pm 28 \mu\text{m}$ ) and without mixing ( $177 \pm 32 \mu\text{m}$ ). The pipe-wall biofilm are considered as Crabtree's Type D sediments. The biofilm is composed mainly of silt particles with some fine sand due to fat adhesion. The organic content of the samples is not very high, ranging from 11 to 18%, and the mean size is about  $76 \mu\text{m}$ .

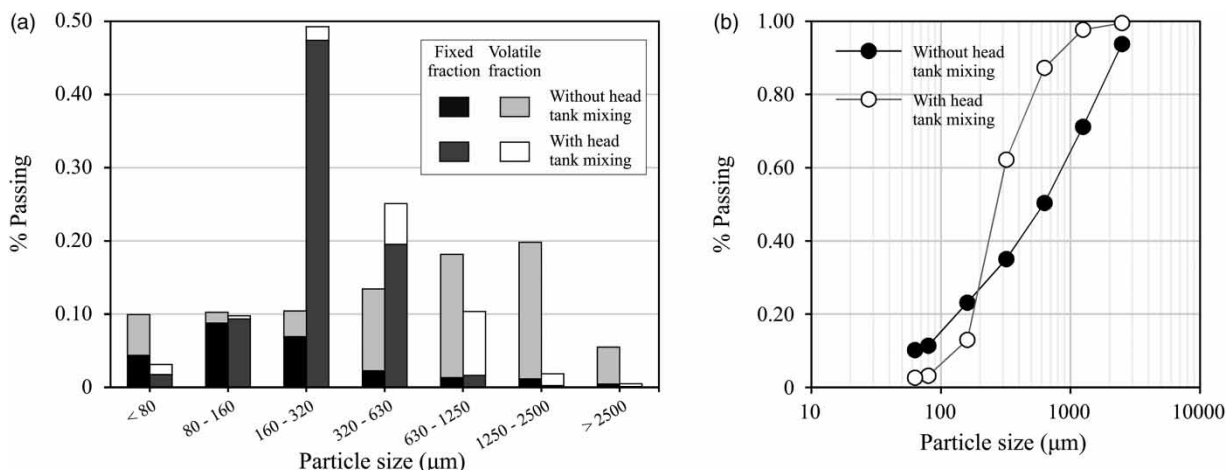
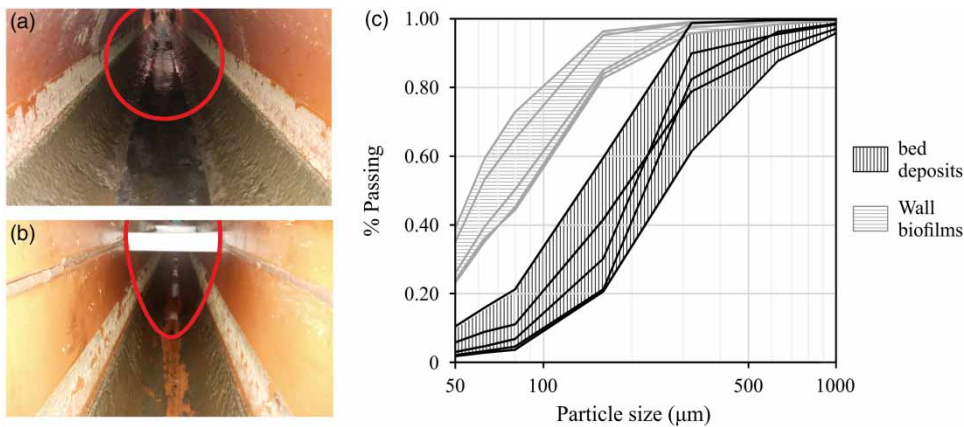


Figure 4 | Fixed and volatile fraction (a) and particle size distribution (b) of input sediments in tests with and without recirculation in head tank.





**Figure 5** | Appearance of the sewer sediments after 1 week in the circular (a) and the egg-shaped (b) pipes and particle size distributions of bed deposits and wall slimes in circular pipe tests.

Table 2 summarizes the characteristics of the bed deposits and sediment biofilms in the circular pipe experiments. Bottom deposits were composed by particles with higher density and particle size, while wall slimes show higher moisture content. The sediment bulk density, moisture and organic content of the in-pipe deposits are in the range of Type A and Type C sediments of Crabtree's classification. The organic wall slime density and moisture are also in the range of the Crabtree's values. Smaller mean values were found for the organic content of biofilms and for the COD of bed deposits and biofilms in comparison with the reported values at the literature.

### Evolution of bed deposits

The height of bed deposits has been daily measured with the imaging technique at central apertures and with ultrasonic

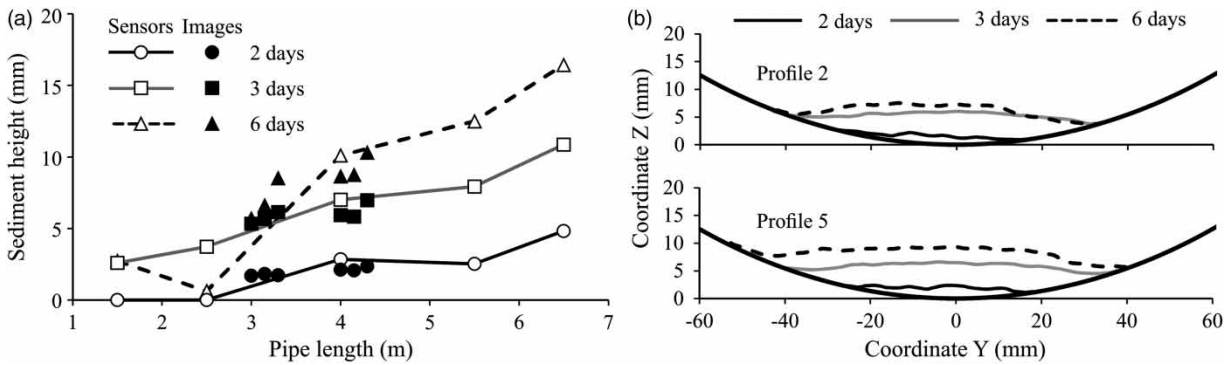
sensors along pipelines. Similar results were obtained between the central ultrasonic sensor (4 m from the pipe inlet) and the average height of the profiles recorded with the cameras for all experiments. As an example, Figure 6(a) shows the concordance of both measurements for several days in test No. 2. Small differences were identified mainly because of two sources of errors. On the one hand, some ultrasonic measurements were affected by the interference of the beam shape geometry due to the irregular surface of bed deposits. On the other hand, profiles recorded with cameras could be distorted by small variations in the image calibration or wheeled structure positioning.

One of the main advantages of the imaging technique was the accuracy to record sediment profiles, so the bed deposit area was easily calculated (Figure 6(b)). The average accumulation rate was determined from the measured bed deposits and sediment heights at the middle section of the

**Table 2** | Characteristics of bed deposits and wall biofilms for all experiments and comparison of mean values with previous studies: sediment density ( $\text{kg/m}^3$ ), moisture content (%), organic content [VS/TS] (%), COD (g/kg) and mean particle size ( $\mu\text{m}$ )

Sample	Sediment density ( $\text{kg/m}^3$ )	Moisture content (%)	Organic content (%)	COD (g/kg)	$d_{50}$ ( $\mu\text{m}$ )
<b>Bed deposits</b>					
Mean $\pm$ std. dev. values	1,460 $\pm$ 98	44 $\pm$ 7.3	13 $\pm$ 6.9	4 $\pm$ 3.0	202 $\pm$ 44
Crabtree (1989) (Type A)	1,720	27	7	23	63–2,000
Crabtree (1989) (Type C)	1,170	63	50	76	<200
Ristenpart (1995) (*)	1,510	30	9	55	–
Chebbo et al. (2001)	–	–	17	430	<400
<b>Biofilms</b>					
Mean $\pm$ std. dev. values	1,190 $\pm$ 29	70 $\pm$ 4.3	13 $\pm$ 2.6	17 $\pm$ 10.2	76 $\pm$ 13
Crabtree (1989) (Type D)	1,210	74	61	193	63–2,000
Chebbo et al. (2001)	–	–	71	1,400	–

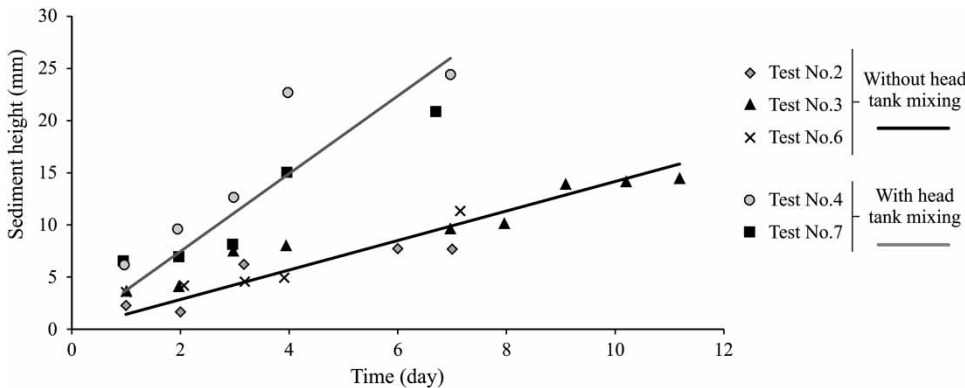
(\*) Middle age values.



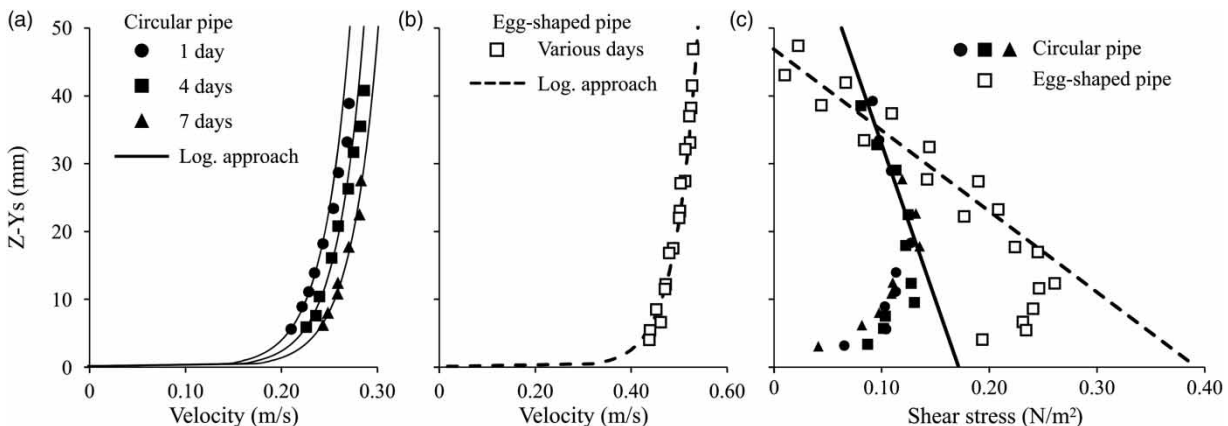
**Figure 6** | Sediment heights over the pipe length recorded with images and acoustic sensors (a) and evolution of sediment profiles in two different cross sections of the circular pipe (b) for test No. 2.

circular pipe (from 2.5 to 5.5 m). Figure 7 represents the amount of sediment deposits in the circular pipe in all the tests. The evolution of bed deposits was linear within the duration of each experiment (7–11 days). However, growth rates were affected by the recirculation of wastewater in head tank.

A mean growth rate of 3.8 mm/d was measured for test Nos. 4 and 7 with head tank mixing, while a rate of 1.4 mm/d for test Nos. 2, 3 and 6. The measured growth rates are similar to those found by Lange & Wichern (2013) for similar experiments with real wastewater conducted in 300 mm acrylic pipe with 1‰ slope. These authors reported a mean



**Figure 7** | Measured sediment height in the circular pipe (range from 2.5 to 5.5 m) during all tests (marked with different symbols).



**Figure 8** | Evolution of centerline velocity profiles for circular (a) and egg-shaped pipe (b) and Reynolds shear stress ( $-\rho\overline{u'w'}$ ) (c) in test No. 6.

value of the daily change of bed deposits of 2.85 mm, with sporadic daily variations related with dry weather – wet weather flow variability. The higher sediment accumulation rate reported in tests with recirculation in the head tank are attributable to different particle size and composition, as it was mentioned in previous sections, and with higher sediment discharge. The mean sediment discharge was 1.2 and 0.9 g/s for experiments with and without head tank mixing, respectively.

Sediment growth in the in-pipe bed is also connected with the sewer hydrodynamics. As an example, Figure 8 shows the vertical centerline mean velocity and Reynolds shear stress profile evolution over the sediment bed height ( $Y_s$ ) for both circular and egg-shaped cross section pipes in test No. 6. Due to the growth of bed deposits, a slight increase of the velocity profiles on the circular pipe was produced (Figure 8(a)). In the egg-shaped cross section, the measured velocity profiles were similar during all the duration of the experiment as no sediment was deposited in the pipe invert (Figure 8(b)).

Although circular pipe flow were accelerated as bed deposit height increased, the centerline Reynolds shear stress remained quasi-constant during the experiments, presenting a constant value of  $0.170 \text{ N/m}^2$  near the bed in test No. 6 (Figure 8(c)). As the shear stress is not influenced by the sediment accumulation within the duration of the tests, a constant accumulation ratio can be expected. Higher mean velocity (0.39 vs 0.24 m/s) and centerline Reynolds shear stress ( $0.400 \text{ N/m}^2$ ) values avoid the formation of bed deposits in the egg-shaped pipe.

## CONCLUSIONS

A test flume facility was developed with the purpose of studying sewers hydraulics under controlled conditions with real wastewater from a WWTP. A circular plastic pipe with a diameter of 300 mm was compared with an equivalent area egg-shaped cross section. Bed deposits were only measured in the circular pipe for certain downstream conditions, while no-accumulation was recorded in the egg-shaped pipe. The deposited bottom solids showed higher density and particle size values, while wall biofilms introduced more moisture and organic content.

Bed deposits were daily measured to calculate their evolution. Depending on the particle size and the input sediment discharge, sediment growth rate range between 1.4 and 3.8 mm/d within the duration of the experiments (7–11 days). As the height of the deposit increased in circular pipe,

slightly higher centerline velocity profiles were recorded but Reynolds shear stress remained nearly constant. Comparing the two different cross section pipes, egg-shaped pipe showed higher mean velocities and shear stress than circular conduit under the same fixed downstream water depth conditions. The experiments performed confirm that under low flow conditions egg-shaped cross section pipes present better self-cleaning conditions. As the sediment re-suspension and erosion of bed deposits in sewers during wet weather conditions is one of the main source of pollution associated with CSO events, the egg-shaped pipes can also be considered an efficient way of CSO mass reduction to receiving media.

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