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A field experiment to evaluate the cleaning performance of sewer flushing on non-uniform sediment deposits

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ABSTRACT

The results of a field experiment to evaluate the scouring effect of a single flush operation in a compound-section sewer channel in Paris, France, are presented in this paper. Full monitoring of the experiment allowed identifying flush-related transport/deposition key processes playing a role on the evolution of the deposited sediments. Overall, the flush was able to scour sediments accumulated over the channel invert up to a significant distance from the gate. The analysis of the results revealed that the flush had a different impact on the various sediments present in the bed mixtures, with most of the eroded volume including sediment particles smaller than the median grain size.

1. Introduction

Sediment settling and accumulation are the cause of worrisome hydraulic and environmental problems in combined sewer systems. Negative impacts range from the reduction of sewer flow transport capacity to the increase of pollution associated with the discharge through overflow devices of sediments re-suspended from the channel invert during storm flow events.

During the last decades, flushing has been recognized as a cost-effective technique for the removal of sediments deposited in sewer channels. Such a technique consists of generating artificial flushing waves able to scour sediments accumulated over the channel invert and to transport them downstream through sections that endow sufficient self-cleaning conditions. Recently, experimental and numerical researches have been carried out to investigate the cleaning performance of different flushing devices for both storm water and combined sewer channels (Bertrand-Krajewski et al., 2003; Guo et al., 2004; Bong et al., 2015).

Results from field experiments have shown different impact of flushing depending on the geometry of the sewer (e.g. type of cross-section and longitudinal slope of the invert), on the hydraulic characteristics of flushing devices (e.g. initial water head and stored volume available for the flush), and on the properties of accumulated deposits (e.g. type and size of sediments, organic matter content, degree of consolidation, etc.). Based on the results of an early analysis carried out in a combined circular sewer with relatively flat invert, Ristenpart (1998) has shown that flushes generated by a valve gate holding an initial water head of 0.8 m were able to provide erosional effects up to about 90 m in the downstream channel. Lorenzen et al. (1996) explored the impact of flushes characterized by high initial water head in a large compound sewer in Hannover (Germany). They reported significant erosional effects on the deposits (prevalently composed by fine sandy sediments) over a distance of about 600 m downstream of the gate. Experiments involving larger sediments were carried out by Dettmar and Staufer (2005) in a circular combined sewer channel with trunks of variable diameter and slope. Results of the experiments revealed that the shear stresses generated by the flushes were able to erode sediments up to a distance of nearly 300 m downstream of the gate. In addition, the effects of flushes on coarse sands deposited on the bottom of a circular sewer were observed by Dettmar et al. (2002) who highlighted the occurrence of erosion also in sewer sections upstream of the gate. More recently, Creaco and Bertrand-Krajewski (2007, 2009) evaluated the cleaning performance (in

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terms of removed volume of sediments) of thousands consecutive flushes on relatively fine sediments accumulated in a large oval-shaped sewer channel in Lyon (France). Results of the experiments highlighted that nearby 200 m channel length downstream of the gate was subject to erosion. It was also highlighted that invert irregularities played a key role in affecting transport and re-deposition processes during the flushes.

Side to field experiments, laboratory tests using scaled physical models of flushing devices were also carried out by Guo et al. (2004) and by Campisano et al. (2004) in order to investigate the scouring effects determined by flushes of variable water head on deposits of prefixed thickness and uniform sediment size. Other laboratory tests (Campisano et al., 2008; Todeschini et al., 2008) have further explored the flushing erosional effect on sediment mixtures with cohesive behaviour.

Moreover, data from both field and laboratory flushing experiments have been compared with numerical models proposed by various researchers. Early works have focussed on the hydraulics of the flushing process with the main aim to identify relationships between induced shear stress and sediment scouring capacity of the flush (e.g. Staufer et al., 2007). More recent studies include coupling 1-D unsteady flow modelling with sediment transport equations for a detailed simulation of erosion and transport phenomena associated with flushing (Creaco and Bertrand-Krajewski, 2009; Shirazi et al., 2014). Also, results of model simulations have been used to develop compact charts/relationships for flush design in combined/stormwater sewers based on hydraulic and sediment-related parameters (Campisano et al., 2007).

The major part of the previous works have analysed the sensitivity of the flush “cleaning” performance to the flush hydraulic parameters and to the sewer geometrical characteristics. However, so far very limited attention has been addressed to the impact that sediment characteristics may have on the flush removal process, i.e. the way type and size of the deposited sediments affect the transport processes associated with the flush. The laboratory flush tests have been usually developed under simplified conditions by using sediments of almost uniform characteristics, thus precluding the analysis of flush differential effects on sediments of non-uniform size. In contrast, a number of studies have pointed out that sewer sediment characteristics are highly variable (Crabtree, 1989; Ashley et al., 2004) and that solid transport in combined sewers may show patterns typical of sediment mixtures (Verbanck et al., 1994; Ashley and Verbanck, 1996; Ota et al., 1999).

Although the review of the scientific literature highlights that much work has been carried out in the past, sediment transport mechanisms/modalities associated with the rapidly varied flow conditions occurring during sewer flushing are still far from being fully clarified. Actually, an important gap concerns the lack of experimental observations of flush erosional effects on the modification of the sediment deposit texture and composition. Understanding selective erosional/depositional effects of the flush on non-uniform sediment beds may enable an improved evaluation of the flush removal efficiency in sewers.

In order to contribute to increase the comprehension of the described processes, a field campaign of experiments was recently launched in Paris within the framework of a larger project supported by the municipality and aiming at exploring the potential of implementation of flushing techniques in the parisian combined sewer network. A trunk of a large combined sewer prone to sediment deposition was selected as pilot channel for the experiments. An existing gate device already installed into the channel was re-arranged for flushing purposes. The channel was equipped with sets of measurement devices in order to monitor flow and sediment-related processes during a full-scale flush experiment. This paper reports in detail the results of the experiment with a focus on the evolution of the bed sediment deposits induced by the flush. The analysis allowed to identify erosional and depositional processes occurred in the channel, as well as to evaluate the flush removal effects on deposited sediments of different size. The results of the analysis may contribute to the improvement of knowledge for the assessment of the performance of flushing in sewer systems.

2. Materials and methods

2.1. Study site

Paris municipality (*Ville de Paris*) spends annually hundred thousands €/km to clean out combined sewers from accumulated sediments. The need to reduce costs as well as risks for health and safety of sewer operating personnel (by limiting direct entrance into the network) has motivated recently the municipality to explore the potentiality of flushing techniques in cleaning sewer channels (Alzabadi, 2010).

A large combined sewer (*Collecteur des Coteaux*) belonging to the sewer sub-network of the 11th arrondissement of Paris city was selected by the municipality to conduct the experimental campaign. The sewer conveys an average dry-weather flow of about 0.35 m^3/s. The scouring effects of a single flush have been investigated over a 1.1 km long channel trunk of the selected sewer. The sewer trunk is characterized by a compound cross-section with central cunette and side-walkways (see Fig. 1). The figure shows the elevation profile of the channel, highlighting a weighted average longitudinal invert slope of about 0.09%. The upstream portion of the channel trunk shows several invert irregularities with the presence of sections in counter-slope. The channel receives combined sewer flows from four minor tributary inlets located at sections S_{+170}, S_{+650}, S_{+850}, and S_{+920}, being the first one the most relevant in terms of expected inflow and contribution of sediments to the trunk. At the downstream end of the channel a diversion structure allows to convey the flow to a chamber for trapping transported sediments.

An electrically-driven sector gate with sharp crested weir (Fig. 2) is placed at S_0, about 50 m downstream of the beginning of the studied channel trunk. The gate, which has been originally conceived with the aim to control combined sewer overflows during storm events, allows for in-line storing conveyed flows in the upstream channel stretch (several hundred meters long stretch with average slope of about 0.15%) and in additional upstream branches with an estimated volume of store in the order of 8000 m^3. Due to its potential to produce high water-head flushes, the control gate was adopted for the purpose of this project and thus re-arranged accordingly to the experimental setup.

2.2. Experimental setup and data collection

Five sections of the analysed channel trunk were selected and equipped with a set of measuring devices to monitor both flow and sediment transport parameters during the experiment. Monitoring sections were located upstream (S_{-50}, S_{-5}) and downstream (S_{+5}, S_{+50}, S_{+100}) of the gate.

Flow rate was measured with an accuracy of ±1% by a beam-pulsed Doppler device (Sontek IQ Plus™) installed on the sewer invert at each of the five identified sections (see Fig. 3). The device is an area/velocity sampler, i.e. the flow rate is indirectly obtained by simultaneous measurement of water level and flow velocity. Each monitoring section was equipped with an ultrasound probe installed on the top of the channel. Such probes enabled redundancy in water level measurements and allowed improved analysis of the flush release process. The used type of ultrasound sensor has a sampling resolution of 4 mm at full-scale water level of 3 m.

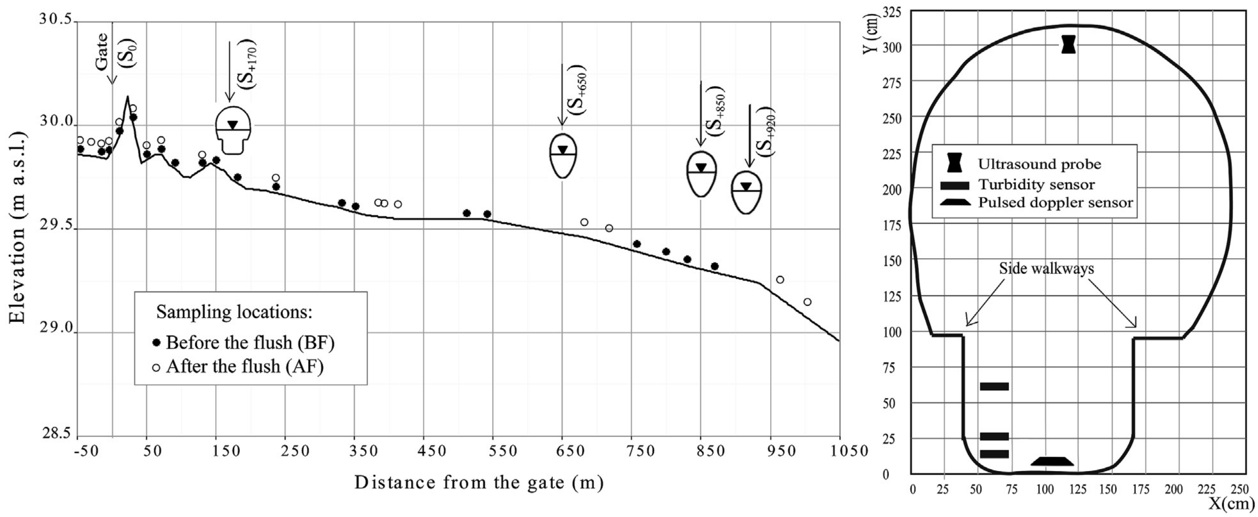

Fig. 1. Selected pilot channel: left) longitudinal profile of the examined stretch; right) channel cross-section.

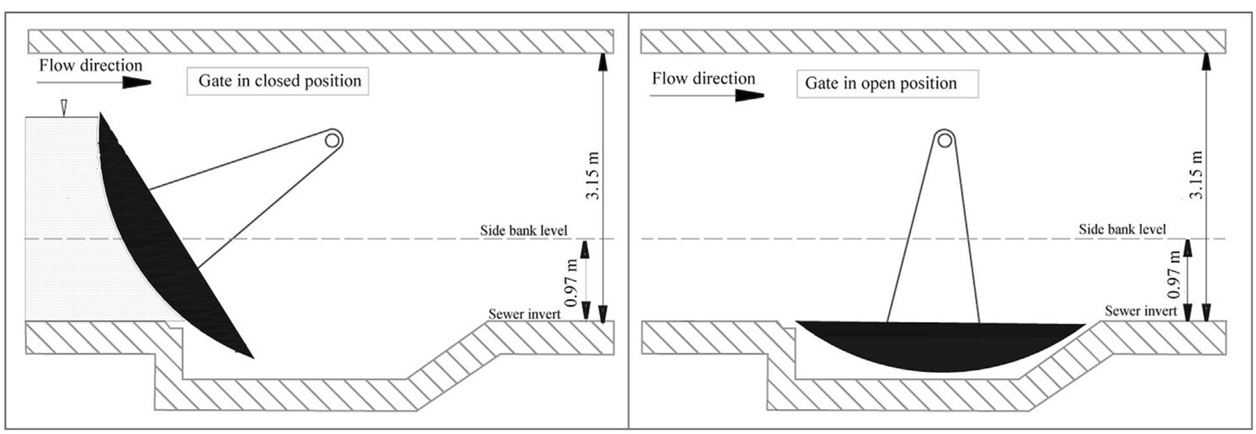

Fig. 2. Sketch of the gate installed into Collecteur Des Coteaux and used for the flush experiment.

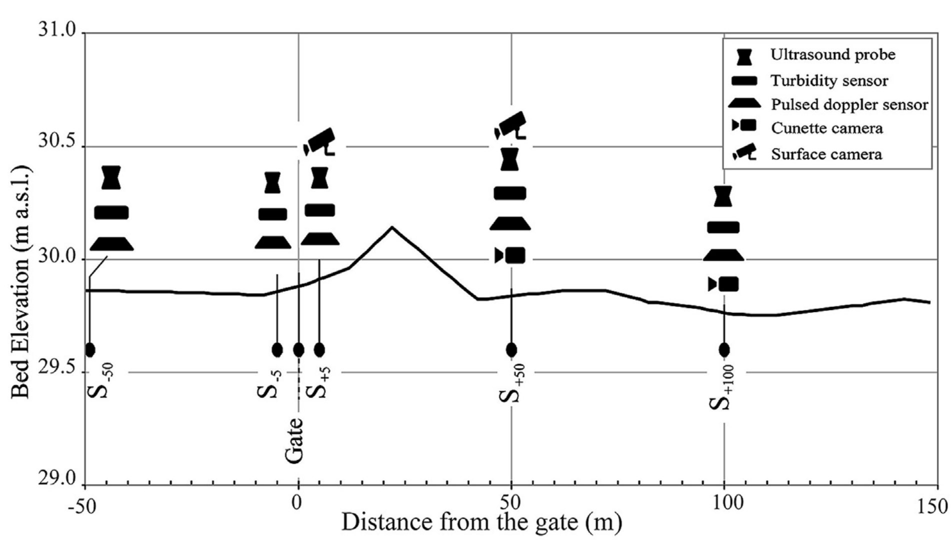

Fig. 3. Monitored sections with installed measurement equipment.

Measurements provided by another water level ultrasound probe at section S_{+1050} were also used. This probe is part of a permanent station installed by the municipality for network monitoring and provides water level records on every 150 s (on average). During the flush test, measurements obtained by this station supplied relevant information about flow characteristics at the channel outlet.

Flow turbidity during the experiment was monitored at the five sections by using optical sensors adapted for urban wastewater monitoring applications. Measurement range of these sensors was 0–4000 NTU (Nephelometric Turbidity Units, $\theta = 90°$) with maximum error of 5% of the reading. A set of three sensors was installed at each section at elevations of 15, 25, and 65 cm above the channel invert (hereafter, indicated as sensors T15, T25, and T65, respectively). All the sensors were calibrated using the same tuning procedure (Anderson, 2004) to allow successive consistent comparison of recorded data (Shahsavari et al., 2016).

In order to observe the solid transport during the flush directly, two video cameras were installed in the channel trunk at sections S_{+50} and S_{+100}. The two cameras were placed inside glass boxes encased in the left-side bank of the channel in order minimise disturbance to the flow. In absence of direct measurement of bed-load transport and sediment concentration in the flow during the flush, both turbidity measurements and images from the two video-cameras contributed to interpretation of the main sediment transport/deposition processes occurring during the experiment. Moreover, two additional video-cameras (equipped with proper light) were fasten to the top of the channel at sections S_{+5} and S_{+50} to visualize the surface flow and survey the gate opening process during the flush test.

As bed deposits are concerned, a radar/sonar technique was applied to evaluate the height and the volume of the deposits throughout the channel. The deposits in the cunette were scanned throughout the length of the trunk before and after the flush. Bed-scanning was carried out using an average spatial longitudinal step of 3.5 m. The radar system allowed obtaining the bed elevation in correspondence to the axe of the cunette, while the sonar provided information about the transversal distribution of the deposits. Coupling radar/sonar outputs enabled the estimation of sediment volumes accumulated on the channel invert before and after the flush.

The whole experiment was carried out during five consecutive days in the period July 7th–11th, 2014. Main developed activities are outlined in Table 1.

The flush consisted of two phases. First, the gate was closed (the weir crest level was raised up to about 2.4 m above the channel invert elevation) in order to store the flow upstream of the device. The stored water mainly included the intercepted dry-weather flow. Most likely, additional minor contribution to the flow came from residual wet-weather flows associated to relatively low-intensity precipitations occurred in the days before the experiment. The storing phase was completed in a few hours when the water level behind the gate achieved its maximum value of 2.15 m (measured at section S_{-5}). Then, the gate was quickly opened in order to release the flush.

The flow measurements during the flush were recorded at a high sampling frequency (acquisition time smaller than 0.1 s). Average values over a 10 s time interval were calculated and used for successive elaborations. Similarly, water level measurements by ultrasound probes were acquired on every 15 s. Selected time intervals allowed a good compromise between the total number of observations to elaborate and the minimum accuracy to capture correctly the main hydrodynamic processes during the whole flush duration. Consistently with flow measurements, turbidity data were recorded using a 10 s sampling time interval.

Table 1
Detail of the activities developed for the field measurement campaign.

Date [d/m/y]	Experimental activity
07-08/july/2014	Collection of bed samples before the flush
09/july/2014	Setup of experimental equipment
10/july/2014	Execution of the flush test and data acquisition
11/july/2014	Collection of bed samples after the flush

In order to analyse the evolution of the bed sediment characteristics determined by the flush, two sampling campaigns were carried out in the days before and after the flush experiment, respectively. Preliminary information obtained during a survey along the channel which preceded the sampling campaigns allowed to recognize differences in the size of the bed sediments accumulated throughout the trunk. Overall, a rather evident transition from finer to coarser sediment mixtures was observed at almost half of the total trunk length (close to S_{+500}), in proximity to a major change in the slope of the channel. Accordingly, two different methods were adopted to collect sediments upstream and downstream of S_{+500} during the sampling campaign. In particular, upstream of S_{+500}, sediment cores were extracted from the deposits by using a small boring device to limit in-bed intrusion. More simply, for the segment downstream of S_{+500}, samples were collected by means of a small shovel in order to reduce sample disturbance as much as possible.

In total, 37 samples were collected before (BF) and after (AF) the flush throughout the trunk. Full and empty dots in Fig. 1 show the channel locations from which samples were extracted BF and AF, respectively. General aims for the selection of sampling sections were i) to get distributed information about sediments along the whole channel and ii) to select as much as possible the same sections BF and AF in order to allow successive consistent comparison of the results. Overall, samples were extracted from 20 and from 17 sections BF and AF, respectively. Fig. 1 shows that 9 of the selected sections BF and AF coincided, while for the remaining sections overlap was not achieved due to the lack of deposits AF. All 20 core samples collected from the initial bed deposits, as well as the 17 cores extracted from the bed AF were transported to the laboratory by means of hygienic protection kits for successive off-line analyses.

2.3. Data preparation

Pre-processing of both turbidity measurements and data related to sediment samples was required for the analysis of the results.

As already found by other researchers (Ristenpart, 1998; De Sutter et al., 2009), the analysis of turbidity records during the flush revealed highly fluctuating values of turbidity for all the installed sensors. Collected raw data were affected by the presence of records lying out of the range of measurement. In addition, some inconsistencies were found within the data, e.g. missing records and readings out of the limit of detection of the sensor (Shahsavari et al., 2016). Identification of such inconsistencies enabled their preliminary elimination from the dataset. Finally, cleaned data was averaged over 1-min time steps in order to identify turbidity trends during the flush.

Data preparation involved also the treatment of sediment samples collected from the bed. Preliminary procedures for sample analysis consisted of extracting sediment cores and separate granular sediments from eventual untypical gross solids (mainly for samples collected in the downstream channel sections). Procedures for sample analysis consisted of drying extracted cores in oven at 105 °C for 24 h. Subsequently, standard protocols were applied to obtain the specific weight and the porosity of the sediment, as well as the grain-size distribution and the organic matter (OM) content for each sample. The analysis showed the specific weight of the sediments to range between 2220 and 2532 kg/m^3 depending on the sampling sections. The porosity was observed to slightly vary between 0.40 and 0.42. With respect to the sediment size analysis, the cumulative weight frequency of grain sizes was calculated for each sample by using laser diffraction (for particles smaller than 1 mm with accuracy of 1 μm) and sieve-based analysis (for particles larger than 1 mm with accuracy of 0.01 g). Finally, statistical parameters (*i.e.* geometrical mean, skewness, characteristic particle sizes) were calculated for each sample.

The organic matter content of the samples was determined in order to get indication about the attitude of the deposits in exhibiting potential cohesive behaviour. This analysis allowed also to recognize variations of OM content in the deposits due to the flush. The ORSTOM oxidation protocol (ORSTOM, 1993) was used to evaluate the OM fraction (*i.e.* organic carbon) for all the samples. Specifically, a prefixed volume of hydrogen peroxide was added to 20 g of sediments belonging to fractions with size less than 2 mm. Then, the samples were re-dried at 105 °C and re-weighted for final evaluation of the destroyed OM.

3. Results

3.1. Analysis of the flush through the observation of the videos

Surface cameras allowed monitoring the gate opening (camera at S_{+5}) as well as the flow release process during the whole experiment. As already observed during previous experiments (Campisano et al., 2004), an up-going negative wave associated with the emptying/release process developed upstream of the gate. Conversely, the cameras installed in the banks enabled the observation of flow and sediment-related processes occurring under the water surface with specific reference to the bed-water interface. The analysis of the videos from these cameras showed the sediment wash-off process due to the transit of the flush at sections S_{+50} and S_{+100}. High turbulence and secondary flows visibly affected the behaviour of the sediments within the flow column (see Fig. 4), mainly at the beginning of the flush. A few minutes after the flow peak, well defined sediment transport modalities were observed, with distinguished bedload and suspended load transport patterns at S_{+50}. Conversely, suspension was identified as the prevalent mode of transport at S_{+100}. Sanitary solids such as papers and fine miscellaneous sewage litter were also observed to be transported in the water column during the experiment. During the flow receding phase, the flush erosional effects visibly tended to decrease. As expected, during this phase, the transport involved mainly the fine and medium sediment sizes, while the flow was not able to scour large grain sizes anymore, thus leading to the partial re-establishment of bed deposits.

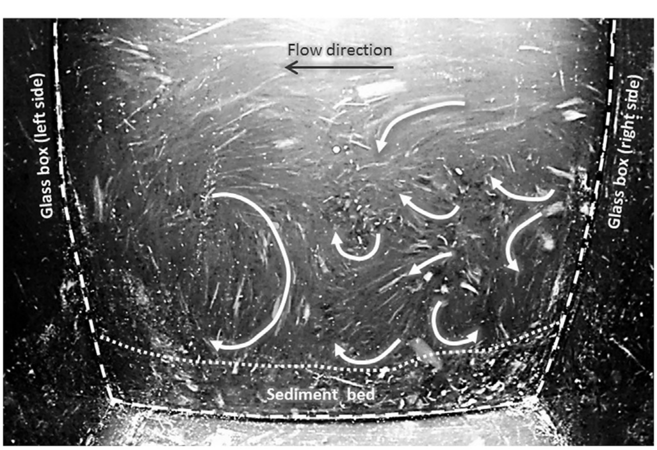

Fig. 4. Video from the camera installed at S_{+50}. Turbulence and secondary flows in the water column are highlighted in the captured frame.

3.2. Flow and turbidity patterns during the flush

Results concerning flow parameters (*i.e.* water level and flow discharge) and turbidity measurements collected during the flush are summarized in Fig. 5 for all the monitored sections.

The figure shows the sudden increase in flow discharge at the different sections after the beginning of the flush release phase. A peak flow value up to 3.9 m^3/s was registered at sections S_{-5} and S_{+5} close to the gate. Accordingly, water levels upstream of the gate (S_{-5}) were observed to decrease rapidly from 2.15 m to about 1.5 m (in about 1 min after the gate opening); conversely, water levels downstream of the gate increased rapidly from an initial value of about 0.5 m (dry-weather flow) to about 1.5 m due to the surge front propagation. The graphs show also that the flow discharge progressively receded to achieve a value close to 1.4 m^3/s in less than 1 h since the beginning of the flush. Unfortunately, due to a malfunctioning of the flow measurement device, flow discharge data was not recorded at S_{+100}. A similar concern regarded also section S_{+50} where the flow was not recorded for a relatively long period including the peak time. Besides, Fig. 5 points out the global effect of the flush on the turbidity variation at the monitored sections. Results show that, the rising limb of the flow discharge (up to the flow peak value) was accompanied, at least for sensors T15 and T25, by a sudden increase in turbidity for almost all the sections. Also, the figure shows that the turbidity varied significantly through the water column. Overall, measurements indicate that a significant part of the sediment would have been transported near the bed, with peak values of turbidity up to about 8000 NTU for T15. However, information was not complete since the sensor at S_{+5} did not record any data during the flush. Conversely, lower values of turbidity were recorded by sensors T25 and T65. Unexpectedly, a peak value for sensor T65 was achieved at S_{+100} (about 4500 NTU) after almost 45 min since the start of the experiment. Later, the analysis of the video clip captured by the camera at S_{+100} helped explaining this turbidity peak with the temporary blockage of sanitary paper in front of the turbidity sensor. Overall, as fluctuation of turbidity is concerned, preliminary evaluation of the standard deviation provided values of 1565, 680, and 183 NTU for sensors T15, T25 and T65, respectively, thus showing major variability for the sensors near the bed.

3.3. Flush effect on the evolution of the sediment deposits

Results from radar/sonar scanner output are summarized in Fig. 6. The figure shows that much of the initial sediments BF were accumulated upstream of S_{+500}. Average and maximum thickness of the deposit in this segment were about 5.6 and 31.5 cm, respectively. In contrast, the segment downstream of S_{+500} exhibited an initial average height of the deposits of about 1.2 cm with a maximum of 17.9 cm. The different spatial distribution of the deposits BF reveals the influence of the local channel longitudinal slope (average 0.07% and 0.1% for the segments upstream and downstream of S_{+500}, respectively) on the sediment erosional/depositional attitude of the different channel sections. Also, Fig. 6 shows that the irregularities of channel invert locally impact the sediment transport, causing sediment accumulation due to the reduced sewer self-cleansing capacity. Accumulation in the channel also occurs close to the lateral inlets due to sediments supplied by such inlets.

The impact of the flush on the initial deposits was different along the channel. Globally, the comparison of bed profiles BF and

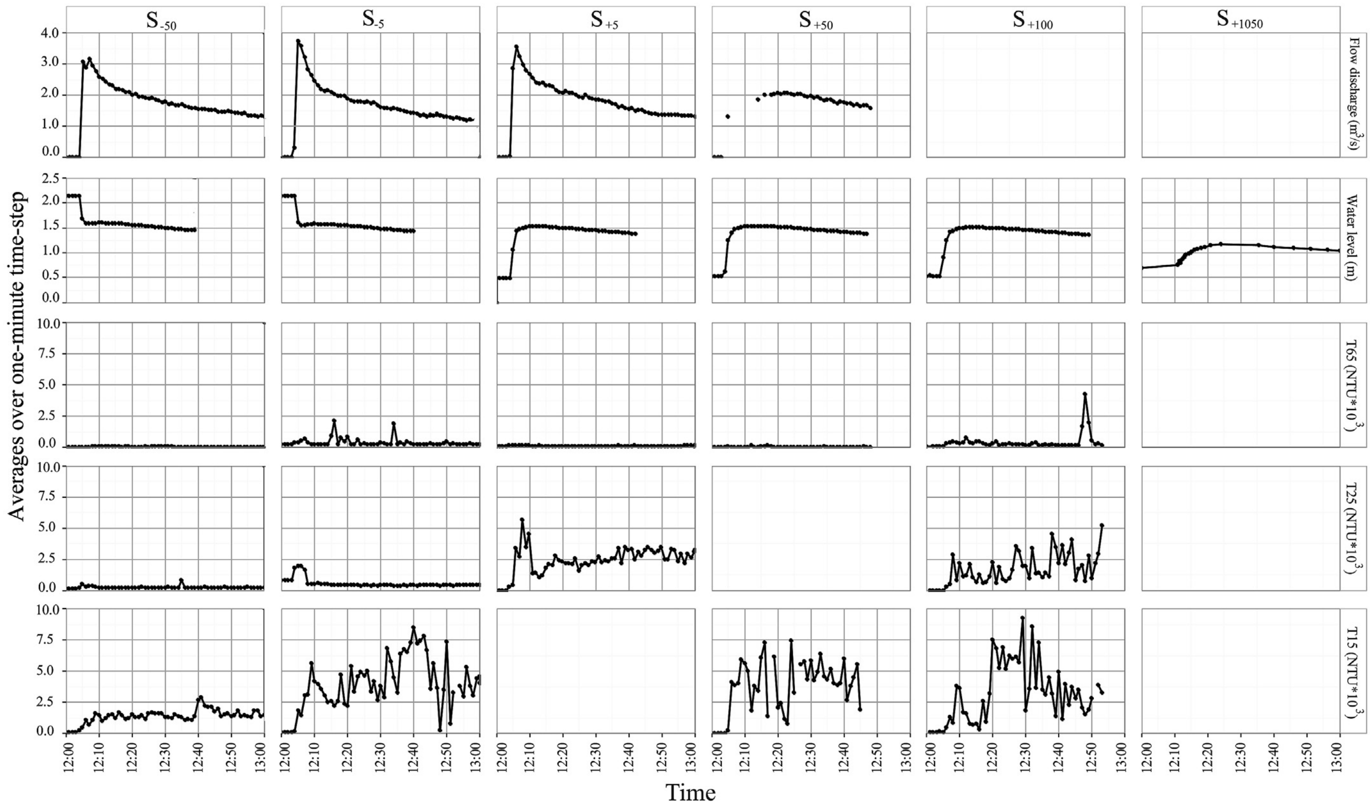

Fig. 5. Flow and turbidity parameters during the flush at the five monitoring sections. Values are averaged using a 1-min time step.

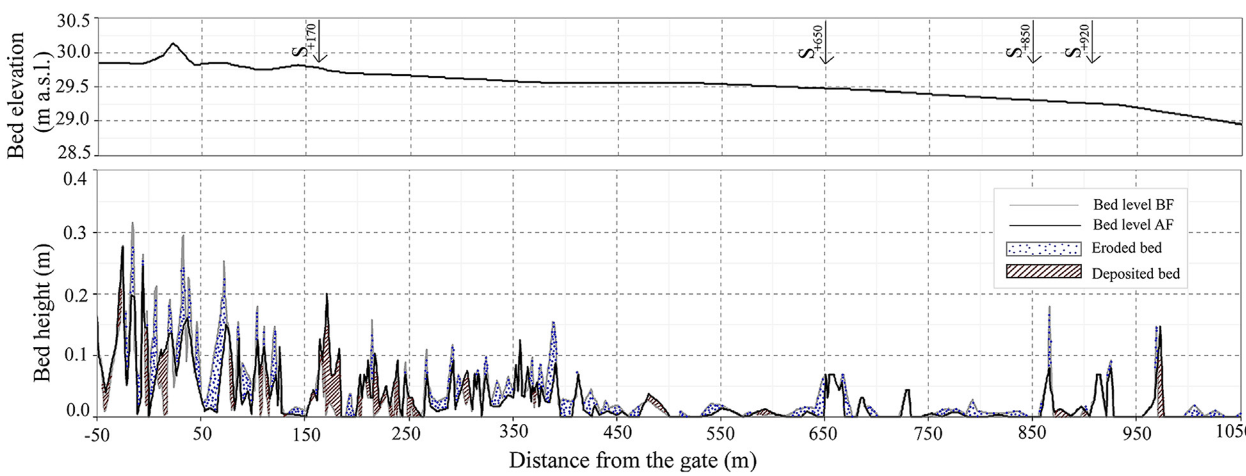

Fig. 6. Sediment bed profiles in the channel BF and AF from radar/sonar analysis.

AF highlights the occurrence of (significant) erosion up to S_{+850}, thus providing indications on the maximum channel length (distance from the gate) that was affected by the flush. Erosion was prevalently concentrated between S_0 and S_{+120}, though limited deposition occurred between S_{+10} and S_{+20} due to the local negative slope of the channel. Erosion was also observed (even if to a minor extent) downstream of section S_{+250}. Conversely, deposition occurred in the channel portion between S_{+120} and S_{+250}.

The volumetric analysis of the deposits BF and AF provided an estimation of the cleaning performance. The comparison of radar/sonar output data showed a significant reduction of the deposits in the channel. Overall, the total sediment volume accumulated in the whole channel trunk downstream of the gate (from S_0 to S_{+1050}) decreased (of 5.4 m^3) from 27.2 m^3 to 21.8 m^3. Fig. 6 shows that the sediment removed from S_0 to S_{+850} summed up to about 5.3 m^3, thus providing a flush cleaning performance of 21.4% sediment reduction (the initial sediment in this segment was about 25 m^3).

3.4. Impact of the flush on the bed sediment mixtures

The grain size analysis of the samples extracted by the channel bed pointed out the presence of heterogeneous sediments with large variety of grain sizes. The textural analysis of the deposits BF revealed a ‘pluri-modal’ frequency distribution of sediment sizes

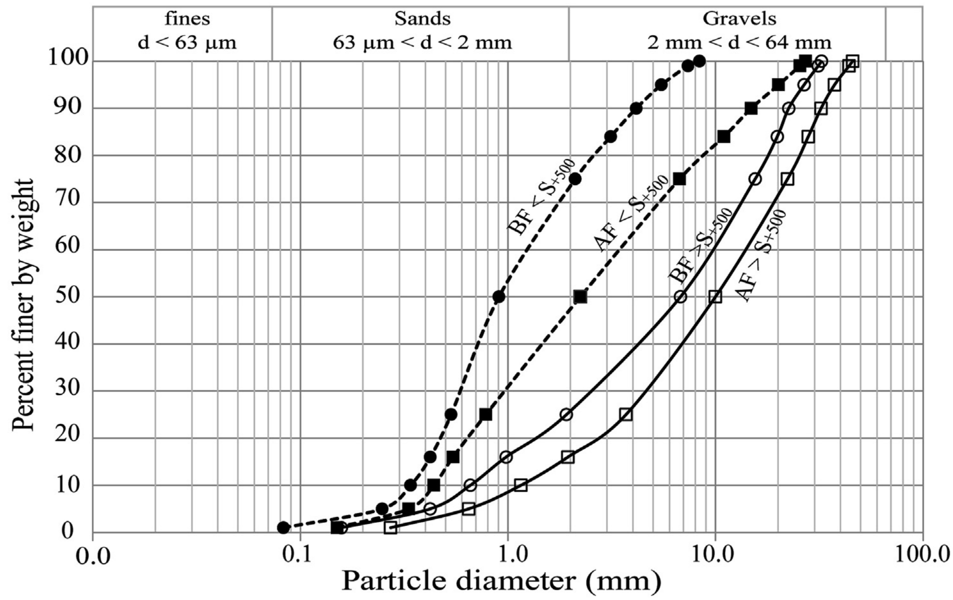

Fig. 7. "Average" grain size distributions relative to segments upstream and downstream of S_{+500} BF and AF.

for most of the samples (dominant mode diameters 0.8, 1.6, 2.5, 4.2 and 8.0 mm), thus indicating potential for sediment transport selectivity by the flush (*i.e.* erosion/transport of selected grain sizes within the mixture) (Vanoni, 2006; Garcìa, 2008).

Results presented in Fig. 7 show the effects of the flush on the various sediment fractions composing the deposits. The figure reports the "average" grain size distributions relative to all the samples extracted from the channel segments upstream and downstream of S_{+500}, respectively. The distributions representing the initial bed composition (BF) show that - excluding very fine particles (smaller than d_1) - grain sizes ranged between 0.08 and 8.5 mm ($d_{50} = 0.90$ mm, $d_{90} = 4.15$ mm) upstream of S_{+500} (see BF < S_{+500}) and between 0.17 and 34.9 mm ($d_{50} = 6.78$ mm, $d_{90} = 22.51$ mm) downstream of S_{+500} (see BF > S_{+500}). The plotted distributions analytically confirm qualitative information acquired during the preliminary sewer survey. In particular, Fig. 7 shows that about 73% of the sediment composing the bed upstream of S_{+500} was initially made by sand-sized particles (63 μm - 2 mm) while the gravel-sized particle fraction (2–64 mm) was nearby 26%. Conversely, the initial bed downstream of S_{+500} was in large part composed by gravel-sized particles (close to 74%) with a minor fraction of sand (25%). The fine fraction (sediments smaller than 63 μm) was less than 1% all over the channel trunk.

The comparison of cumulated volumes of deposits BF and AF shown in Fig. 8 highlights the different impact that the flush had on the non-uniform sediment mixtures forming the mobile bed in the

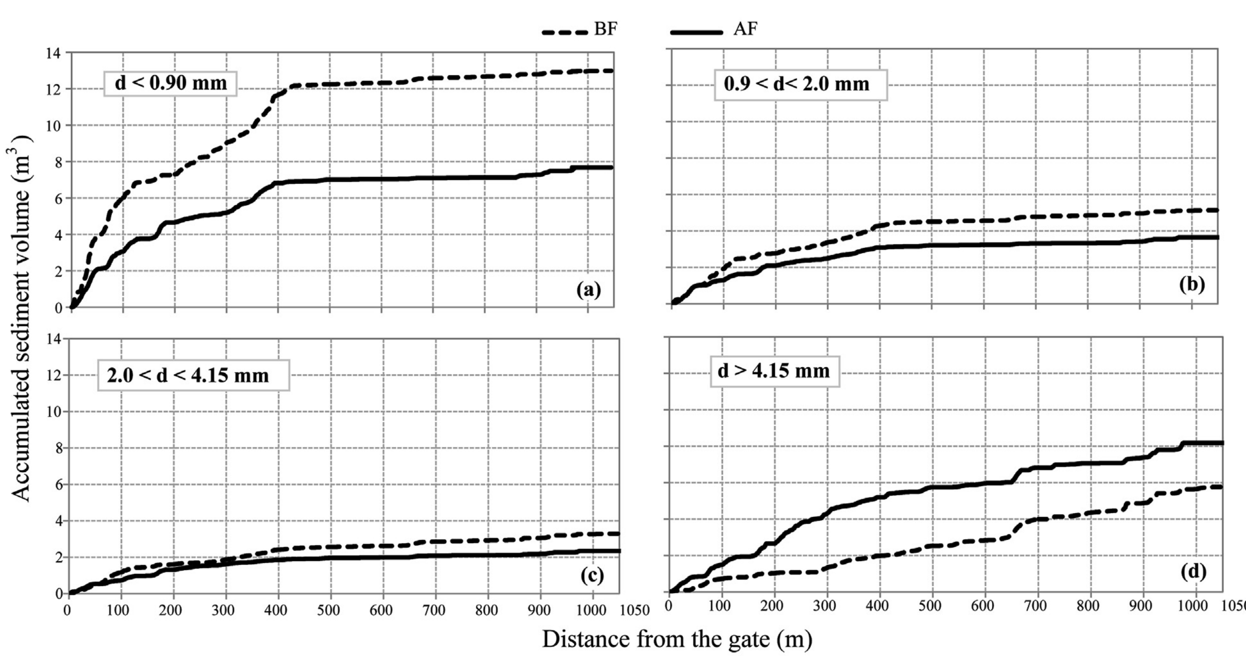

Fig. 8. Cumulative fractional volumes of sediments BF and AF downstream of the gate.

channel. Plotted results are referred to four fractions ($d < d_{50}$; $d_{50} < d < d_{sand}$; $d_{sand} < d < d_{90}$; and $d > d_{90}$ with $d_{sand} = 2$ mm being the limit of sand size) selected on the basis of average characteristics (d_{50} and d_{90}) of the deposits BF < S_{+500}. Overall, the plotted graphs reveal the non-uniformity of flush erosion effects for the different fractions (Fig. 8a-b-c). As expected, the figure points out that the major part of the sediment eroded by the flush was finer than d_{50} (Fig. 8a). Smaller contributes to erosion were associated with fractions $d_{50} < d < d_{90}$ (Fig. 8b–c). Conversely, an increase in the volume of sediments coarser than d_{90} occurred prevalently in the first 300 m long segment downstream of the gate (Fig. 8d), thus revealing deposition of coarser sediments remobilized from upstream sections by the flush.

The different impact of the flush on the various sizes of the mixture altered the bed texture in a significant way. Fig. 7 shows an evident right-shift of the distribution AF < S_{+500} as compared to the analogous curve BF < S_{+500}, thus revealing sediment bed coarsening for all the characteristic grain sizes in the upstream part of the trunk. Similar sediment coarsening effects were observed also downstream of S_{+500}. Coarsening effects were quantified by the change of the average skewness *Sk* for all the grain size distributions:

$$Sk = \frac{\log\left(\frac{d_g}{d_{50}}\right)}{\log\sigma_g} \tag{1}$$

where $d_g = \sqrt{d_{16}.d_{84}}$ is the geometric mean size and $\sigma_g = \sqrt{d_{84}/d_{16}}$ is the geometric standard deviation of each sample (Inman, 1952).

A summary of the results is presented in Table 2. The table shows the skewness to increase from 0.20 (BF) to 0.27 (AF) and from −0.29 (BF) to −0.23 (AF) for the segments upstream and downstream of S_{+500}, respectively, thus providing a shift of the asymmetry of the distributions toward the large particle sizes.

Globally, Fig. 7 highlights that, due to the flush experiment, the percentages of sand-sized particles in the bed deposits decreased from 73% to 47% and from 25% to 16% upstream and downstream of S_{+500}, respectively; correspondingly, gravel-sized fractions increased from 26% to 52% and from 74% to 83% upstream and downstream of S_{+500}, respectively.

Details concerning the textural modifications of the bed as induced by the flush are presented in Fig. 9 separately for selected characteristic grain sizes (d_5, d_{10}, d_{16}, d_{50}, d_{84}, d_{90}, d_{95}). The grain diameter for each characteristic size BF and AF is shown in the left and right sides of the figure for the channel segments upstream and downstream of S_{+500}, respectively. The figure confirms the effect of bed coarsening determined by the flush. For example, the figure shows that the d_{90} at S_{+70} (second to last graph in the left side of the figure) increased from 3.4 mm to about 19.4 mm after the flush. As expected, such an effect is much more evident for the large grain sizes (>d_{50}) than for the fine ones (<d_{50}). In fact, the calculated Mean Absolute Percentage Error (MAPE) of the samples BF and AF

Table 2
Sediment grain size characteristics BF and AF upstream and downstream of S_{+500}.

	BF<S_{+500}	BF>S_{+500}	AF<S_{+500}	AF>S_{+500}
d_{50}	0.90	6.78	2.23	9.99
d_{90}	4.15	22.51	14.86	32.24
Sk	0.20	−0.29	0.27	−0.23

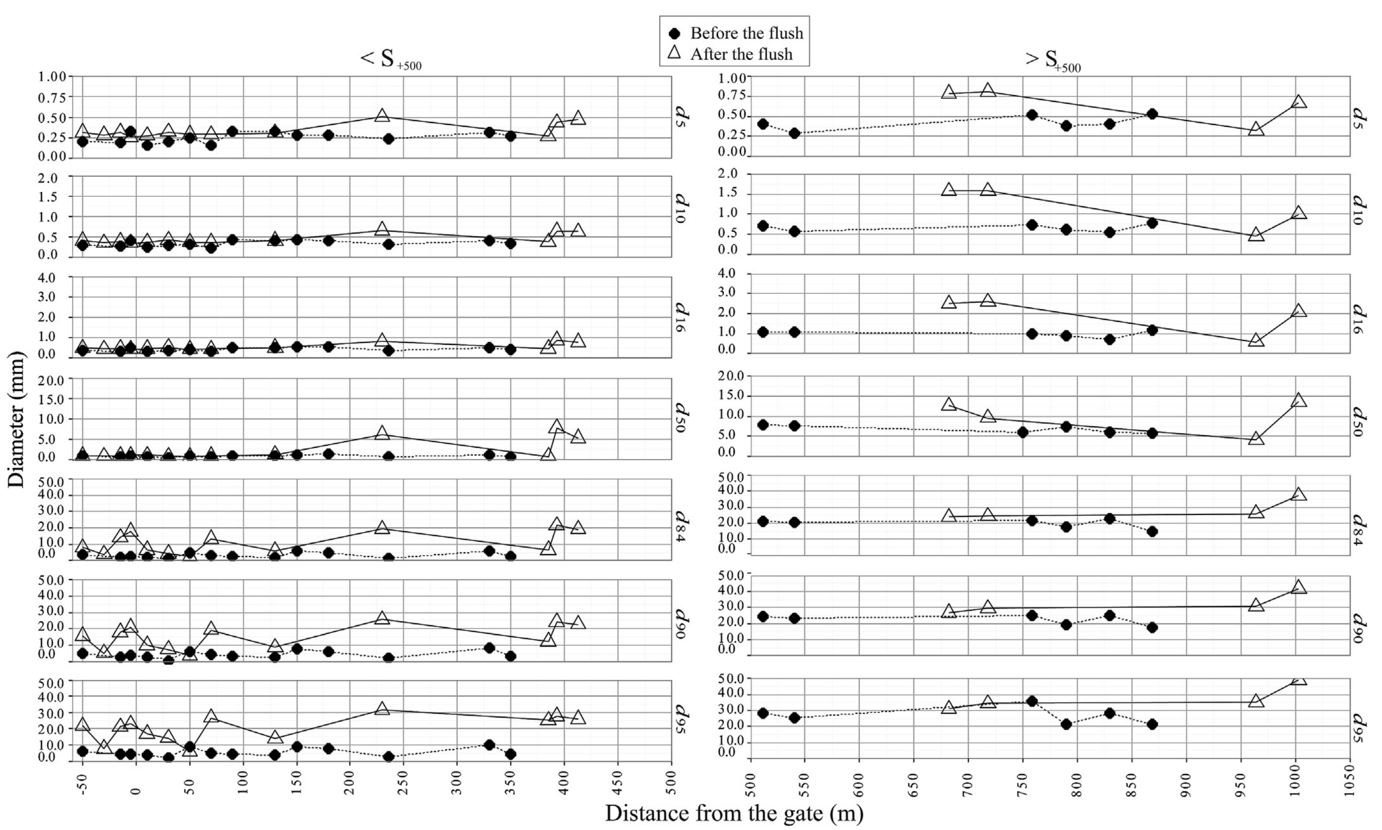

Fig. 9. Evolution of the sediment bed composition after the flush. Circles and triangles represent samples BF and AF, respectively. Left and right side graphs are relative to samples upstream and downstream of S_{+500}.

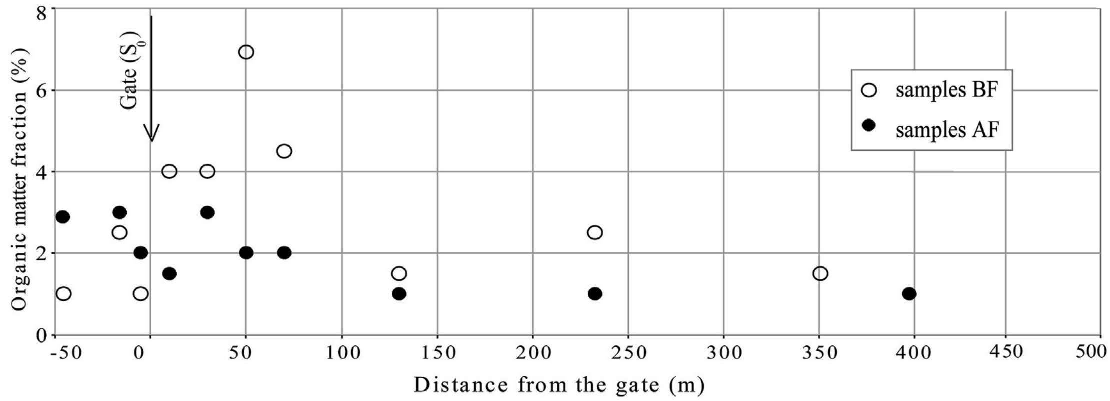

Fig. 10. Organic matter content in samples extracted from the segment upstream of S_{+500}, BF and AF.

showed deviations of 34.0% and 305.9% for particles smaller and larger than d_{50}, respectively.

3.5. Variation of organic matter content due to the flush

Fig. 10 shows part of the results (upstream of S_{+500}) concerning the analysis of the organic matter content in the bed sediments BF and AF.

Organic fraction contained in all the extracted samples did not exceed 7% in weight (average content was 2.9%) before the flush experiment. This average amount decreased down to about 2% after the flush. According to Crabtree (1989) such result would allow classifying sewer sediments in the Collecteur des Coteaux as class A sediment type (granular sediments with weak organic content). A relatively minor OM content after the flush was found in the sediment samples extracted from the sections close to the gate. Based on the results presented in Fig. 8a, such sections were also affected by the largest removal of fine sediments due to the flush; this result is in agreement with findings by Michelbach (1995) who highlighted that the organic matter is highly related to the presence of fine sediments in the bed mixture. Interestingly, Fig. 10 also confirms that the organic matter content AF tends to decrease as the distance from the gate increases, in agreement with the observed decrease in fine sediments along the channel.

4. Discussion

Beyond the effects of the geometry and operation of the used gate device, the flush release can be hydraulically assimilated to a "dam-break" process characterized by an initial sharp increase in the flow and by a relatively slow decreasing phase after the achievement of the flow peak.

The generated flow hydrograph and associated shear stresses highly depend on the water head and on the stored volume upstream of the gate at the time of the beginning of the flush release phase. The initial water level is the most crucial parameter affecting the magnitude of the shear stress generated by the flush, as it is a measure of the initial energy held by the water behind the gate. Dettmar and Staufer (2005) have shown that such a parameter mostly affects the maximum distance from the gate that could be impacted by flush erosion, thus providing insight on the potentially "cleanable" channel length. Differently, the stored volume available for the flush allows sustaining the shear stresses during time, thus having a key role on the duration of the erosional process, and consequently on the amount of sediment removed during the whole flush (Campisano et al., 2007). Combination of flow data presented in Fig. 5 allowed calculating the average shear stress $\tau = \gamma RJ$ (γ is the water specific weight, R is the hydraulic radius, and J is the energy line slope) generated by the flush during the experiment throughout the pilot channel. The average peak shear stress achieved in proximity to the gate (at S_{+5}) was close to $\tau_{peak} = 10.3$ N/m^2. Dissipation processes associated with the flush propagation did not reduce significantly the shear stress, which was observed to assume values at the peak larger than 9.5 N/m^2 also in the downstream part of the channel.

The large stored water volume released by the gate during the flush allowed sustaining the flush with shear stress values after the flow peak always larger than 2.8 N/m^2 in the whole channel for more than 1 h. Based on Shields' theory (Shields, 1936), such a shear stress value would be able to remobilize grains with maximum size around 4.0 mm. Notably, this is consistent with the results presented in Fig. 8 that show prevalent erosion and transport of fine/medium sediment sizes and stability of coarse sediments in the deposits during the flush. More in detail, Fig. 8 shows that more than two thirds of the total eroded sediments were smaller than the d_{50} of the segment upstream of S_{+500} BF (0.90 mm), thus confirming the high non-uniformity of sediment transport determined by the flush in the channel. This result suggests that any evaluations of the sediment transport due to the flush which would rely on the use of single sediment sizes (e.g. the median sediment size) would lead to a simplistic interpretation of the process as it would not allow to take into account the transport selectivity attitude of sediment mixtures.

Although the flush conserved erosive shear stress up to a long distance from the gate, most of the eroded sediment was remobilized from the segment between the gate location and S_{+500}. Conversely, downstream of this section the flush did not determine a significant modification of the bed, mainly due to the presence of coarser sediments forming the deposits. Furthermore, as observed during the preliminary survey, deposits close to the downstream end of the channel were also characterized by gross solids of various nature (e.g. residuals of construction, pieces of asphalt, etc.) and by elements originating from sewer maintenance (e.g. bolts, nuts, spikes, etc.). Much of these solids were observed to overlay granular sediments in the bed, thus potentially triggering bed armouring effects during the flush. Based on these results, sediment transport in this final segment was probably occurring mainly as wash-load without relevant exchange of sediments at the water-bed interface.

The comparison of bed profiles BF and AF presented in Fig. 6 shows that the flush determined sediment erosion also upstream of the flushing gate, affecting the bed up to a relatively long distance from the device. This result confirms previous findings by Ristenpart (1998) and Dettmar et al. (2002), that have reported erosional capacity of the up-going sunk wave generated by the flush up to tenths meters behind the gate. As a peculiarity of the considered sewer, due to the steeper invert slope of upstream stretch, the calculated shear stress behind the gate locally achieved values close to 5.5 N/m^2, thus potentially determining effects of remobilization and transport of relatively large sediments. The occurrence of such effects is supported by the results of Fig. 8d that show an increase in the volume of sediments larger than d_{90} in the pilot channel AF.

Globally, erosion upstream of the gate may have had a role on the global performance of the flush. In fact, although the overall volume of sediments removed downstream of S_0 was relatively high (about 5.4 m^3), such a volume was the result of a balance between fine outgoing material (about 7.8 m^3 smaller than 4.15 mm) and more coarse incoming material (about 2.4 m^3 larger than 4.15 mm) which ended re-depositing in the channel, most likely in the first 300 m downstream of the gate. Such an hypothesis would find confirmation from Fig. 9 that shows sediments at sections between S_{+100} and S_{+300} to be subject to major coarsening after the flush.

Although the used equipment was one of the strength points of the experiment, unavailability of direct sediment discharge measurements during the flush was identified as one important limitation of the study. However, combined use of turbidity records and radar/sonar output, and analysis of video clips extracted by the video-cameras installed in the channel bank allowed basic interpretation of the main sediment transport processes occurred during the flush. For example, the intermittent transport of sanitary litter observed in the video-clips at S_{+50} and S_{+100} as well as the incidental dislodgement of bed sediment packages and their entrainment into the flow provided potential explanation of fluctuations in the turbidity records.

A final aspect deserving discussion concerns the adopted experimental conditions for the flush. As the normal functionality of the sewer system was conserved during the period of the experiments, the normal flow (dry-weather flow and eventual flow from runoff) may have contributed to sediment erosion and transport in the channel between BF and AF sampling phases, thus leading, in principle, to overestimate the sediment removal performance of the flush. However, considering that the total period needed to develop the experiment was relatively short, contribution to sediment transport of this flow may be assumed as negligible, being eventually limited to very fine fractions only. In addition, it has to be stressed that the presence of dry weather flow at the beginning of the flush (although due to lateral inlets only) in the channel downstream of the gate may have played a role in reducing the erosive effect of the flush wave over the deposits, thus potentially leading to underestimate the flush cleaning performance. Overall, it is believed that such considerations may be valid suggestions to improve protocols for future flush monitoring tests planned by the municipality.

5. Conclusions

Main conclusions drawn from the analysis of the results of the flush experiment include the following points:

- Due to the high initial energy of the flush, erosional effects were observed in the channel bed up to about 850 m downstream of the gate section. The large water volume available for the flush assured sufficient shear stress values to erode sediments for almost the whole flush duration;
- The non-uniform size of the sediments forming the deposits had a significant role on the flush cleaning performance in the channel; about 2/3 of the sediment flushed out of the channel was composed of particles smaller than the initial d_{50}, thus revealing the flush attitude to prevalently select fine/medium particles for sediment transport; in contrast, fractions larger than the initial d_{90}, were not significantly affected by erosion downstream of the gate;
- Overall, the flushing cleaning performance was relatively high with about 21.4% of the total deposits washed-off with a single flush. However, the cleaning performance was negatively affected by the deposition of incoming sediments which were most likely remobilized from upstream the gate section;
- Sediment coarsening was observed almost over the whole channel bed after the flush mainly due to the removal of fine-medium fractions from the initial bed mixture;
- The results have demonstrated complex water-sediment dynamics to occur during sewer flushing, and have highlighted the role of non-uniform sediments in affecting the overall cleaning performance of the flush;
- The obtained results open perspectives for improved modelling of flushing in sewers, with specific reference to the setup and calibration of numerical models for sediment transport with non-uniform sediments. It is believed that the use of improved models will help the identification of strategies for the appropriate scheduling of flushing operations in sewers.

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