Bed Evolution under One-Episode Flushing in a Truck Sewer in Paris, France

Gashin Shahsavari, Gilles Arnaud-Fassetta, Roberto Bertilotti, Alberto Campisano, Fabien Riou

***Abstract*—**Sewer deposits have been identified as a major cause of dysfunctions in combined sewer systems regarding sewer management, which induces different negative consequents resulting in poor hydraulic conveyance, environmental damages as well as worker's health. In order to overcome the problematics of sedimentation, flushing has been considered as the most operative and cost-effective way to minimize the sediments impacts and prevent such challenges. Flushing, by prompting turbulent wave effects, can modify the bed form depending on the hydraulic properties and geometrical characteristics of the conduit. So far, the dynamics of the bed-load during high-flow events in combined sewer systems as a complex environment is not well understood, mostly due to lack of measuring devices capable to work in the "hostile" in combined sewer system correctly. In this regards, a one-episode flushing issue from an opening gate valve with weir function was carried out in a trunk sewer in Paris to understand its cleansing efficiency on the sediments (thickness: 0-30 cm). During more than 1h of flushing within 5 m distance in downstream of this flushing device, a maximum flowrate and a maximum level of water have been recorded at 5 m in downstream of the gate as 4.1 m3/s and 2.1 m respectively. This paper is aimed to evaluate the efficiency of this type of gate for around 1.1 km (from the point -50 m to +1050 m in downstream from the gate) by (i) determining bed grain-size distribution and sediments evolution through the sewer channel, as well as their organic matter content, and (ii) identifying sections that exhibit more changes in their texture after the flush. For the first one, two series of sampling were taken from the sewer length and then analyzed in laboratory, one before flushing and second after, at same points among the sewer channel. Hence, a non-intrusive sampling instrument has undertaken to extract the sediments smaller than the fine gravels. The comparison between sediments texture after the flush operation and the initial state, revealed the most modified zones by the flush effect, regarding the sewer invert slope and hydraulic parameters in the zone up to 400 m from the gate. At this distance, despite the increase of sediment grain-size rages, D_{50} (median grain-size) varies between 0.6 mm and 1.1 mm compared to 0.8 mm and 10 mm before and after flushing, respectively. Overall, regarding the sewer channel invert slope, results indicate that grains smaller than sands (< 2 mm) are more transported to downstream along about 400 m from the gate: in average 69% before against 38% after the flush with more dispersion of grain-sizes distributions. Furthermore, high effect of the channel bed irregularities on the bed material evolution has been observed after the flush.

***Keywords*—**Bed-material load evolution, combined sewer systems, flushing efficiency, sediment transport.

Gashin Shahsavari, PhD student, and Gilles Arnaud-Fassetta, Advisor, are with the PRODIG Laboratory (UMR 8586), Paris Diderot University, Rue Albert Einstein - 75013 Paris, France; e-mail: gashin.shahsavari@gmail.com, gilles.arnaud-fassetta@univ-paris-diderot.fr).

Alberto Campisano, Associate Professor, is with the Department of Civil Engineering and Architecture, University of Catania, Viale A. doria, 6, 95125 Catania, Italy (e-mail: acampisa@dica.unict.it).

Roberto Bertilotti, Co-advisor, and Fabien Riou, Engineer, are with the PROLOG Engineering consulting, 3-5 Rue de Metz -75010 Paris, France.

I. Introduction

MANY urban drainage networks in Europe are combined which can convey domestic wastewater, rainfall and also water used for cleaning streets and gutters. Due to complex geometric characteristics of sewer conduits, self-cleaning of combined sewers is not always guaranteed within hydraulic conditions occurring during both dry and wet weather [1]. In order to overcome the significant problems associated with accumulated in-sewer deposits (*e.g.* the degradation of the hydraulic capacity and the increase of surcharge risks during storm flows, sediment removal from networks becomes essential [2]. This can be hydraulically pursued by producing artificial high flows able to flush sediments from the invert of sewer channel. In the point of view of network managers, automated flushing techniques are considered as a cost-effective and practicable way to reduce the accumulation of sediments as they are a healthier way to proceed for sewer workers [3], [4]. Flushing, by prompting turbulent wave effects, produced high bed shear stresses that modify the sediment bed profile and properties. Description of sediment movement and knowledge of mechanisms through a flush with in real sewer studies with high resolution in spatial and temporal observations is not completely known, basically because of complexity of the processes and conditions that may vary among different sewers [5], [6]. The need for high values of critical shear stress in order to start erosion of in-sewer deposits in combined systems can be explained by bed formation and consolidation also due to the potential presence of significant amounts of organic solids that increase resistance to erodiblity [7].

Since more than two decades, many types of flush devices have been investigated in terms of both their hydraulic performance and their capability of sediment removal [4], [8]–[12]. Experimental and numerical investigations have been carried out under laboratory controlled conditions [10], [13]–[15] and in real sites [4], [16], [17] in order to understand the cleansing effectiveness of various flushing devices and to obtain data for the development and calibration of predictive numerical models [4], [13], [18], [19]. These studies point out a number of key parameters which play an important role to ensure a satisfactory performance of flushing operation. Based on *in-situ* observations, it was estimated that a flush event may decrease by 1-30% the total deposits with high impact on resuspension of sediments accumulated over the pipe invert [17]. Research conducted by other authors [5], pointed out that even though flushing practice is an economic way to control sedimentation, total cleansing of long sewer reaches may not be feasible in combined sewers. Specifically, many researchers assume that the flush removal efficiency is normally limited to a distance close to the gate [5], [20].

Recently, special attention is paid to the flushing performance of sewer control gates, as an additional objective with respect to their function to control flows and increase the sewer online retention. Such gates are commonly activated by wastewater storage so that to use them for flushing purposes is an ecological and economic way for scouring conduits without using external water supply by off-line tanks [15], [21], [22]. The gate stores wastewater within the sewer during dry-weather conditions and then, its quick automatic opening induces a rapid discharge of the stored flow in the downstream reach with the generation of the flush. The main objectives of the previously developed experimental researches were to examine the flushing efficiency by investigating the shear stress generated over the downstream mobile sediment bed. The results from experiments show that scouring effects of the flushing wave may be particularly effective in large sewers due to the high volume of water stored behind the gate previous to the flush event. However, the flush was not always able to wash off particles with diameters higher that fine gravel in combined sewers [15]. Besides, the presence of organic matters and the modification of their rheological properties through the time, may significantly modify the processes of sediment transport in the sewer due to the cohesion bonding effect that is developed between particles [8], [9]; this effect also varies with sediment bed depth. Moreover erosion resistance change also during time due to physical and biological activities [10], [11].

Much of the existing studies basically focused on the bed height evolution as the consequence of flushing in combined sewer systems [1], [5], [23]. Oppositely, little research has been carried out about the modifications of the grain-size distribution and organic content of the deposited sediments due to the sewer flush.

From many years, The Paris Municipality (*Ville de Paris*) tries to improve the sewer scour processes of cleaning in the combined sewer network by testing the hydrodynamic effects of the mechanical equipment of flushing. In this perspective, The Sewer Network section of the Paris city, in 2014, realized a set of complete experimentation in order to evaluate the scouring effect a sector gate throughout a man-entry trunk sewer (collector). The collector of *Des Coteaux*, with a largest diameter of 2.40 m and 3.20 m of height, consists of a cunette-shaped channel to discharge the dry-weather water. The observations were effectuated over about 1km by the mean of five measurement sections along the flushing line on the sediments which are naturally accumulated on the channel invert potentially 0-30 cm per year.

In this study bed modifications after a single flush event are investigated by a set of experiments carried out in a combined trunk sewer of Paris, France. The flush was generated by an existing gate which is placed upstream of a high deposition reach of the sewer. The reach was equipped with a high-resolution monitoring system which was customized in order to measure water levels and flow rates in different sections of the sewer channel, together with a video camera system for direct observation of flushing effects over the sediment bed.

This paper aims at (i) presenting the preliminary results of the evaluation of the spatial and temporal evolution of the sediment bed within the complex sewer channel after the flush has occurred, and (ii) exploring the areas where the flow provided a higher interaction with the bed in terms of scouring effects. Emphasis is put on comparing the sediment bed changes in terms of spatial grain-size distribution and organic fraction with reference to the initial bed conditions.

II. Flushing Procedure

A. Site Description

The experimental field is an 1100 m long combined sewer reach of a man-entry size trunk sewer called *Des Coteaux* in the center of Paris (11th). The mean bed slope of longitudinal channel axis is about 0.8 ‰. The compound section is cunette-shaped section with two lateral banks in both sides of the channel for worker's mobility (Fig. 1). This trunk sewer is dealt with an estimated yearly sediment accretion maximum height of about 20-30 cm per annum. Specific topography of the study sewer channel is illustrated in Fig. 2. The sector gate valve has been designed and implemented to control the overflow in flood cases. It is driven by hydraulic jacks to adjust the weir head, which can reach up to 2.37 m when it is fully closed.

A single flushing experiment was conducted in the combined sewer which took place in more than 1h since the gate-opening up to the time that flow rate began to be stable at about 1 m.s^{-1}.

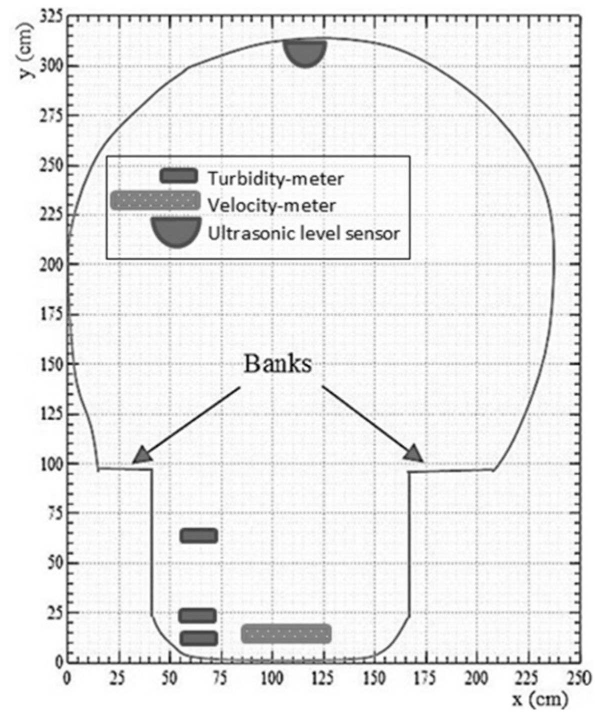

Fig. 1 Sewer Section Details and Measurement Equipment Position

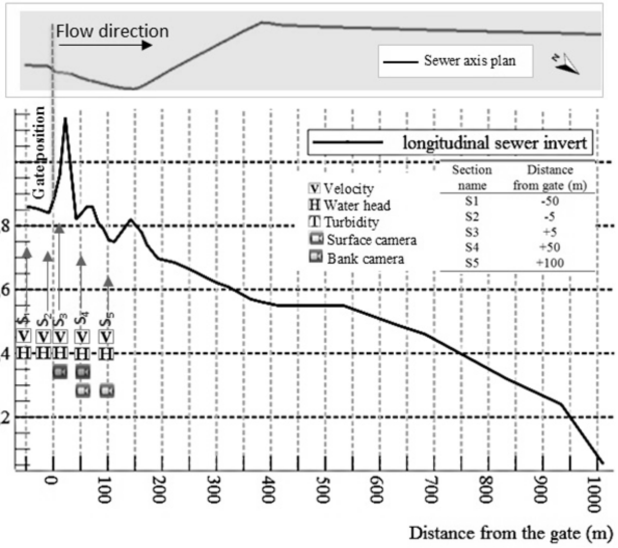

Fig. 2 Profile and plan view of sewer channel axis and implemented measurement tools

During the flush the speed rate for the gate opening was recorded at about 4.5 cm.s^{-1}. The flushing procedure involves a dry-weather storage phase and a successive flush releasing phase. During the flush, flow measurement (flowrate and water height) and sediment transport measurements (turbidity) took place.

B. Data Collections

Bed height and profile measurement in sewers is a difficult task; methods to develop more applicable and more resistant and accurate measuring devices in sewers have been attempted [22]. Despite difficulties, a complex experimental setup was implemented in the field reach to allow accurate data collection regarding the sediment entrainment due to the flush. Data acquisition was carried out in three set of times: before, during, and after that the flushing event occurred. Table I summarizes the campaign duration and details of measurement.

TABLE I
DURATION OF THE MEASUREMENT CAMPAIGN

Date [d/m/y]	experimentations
07/07/2014	Sample collection before the flush (part I)
08/07/2014	Sample collection before the flush (part II)
09/07/2014	Measuring setup installation
10/07/2014	Flush procedure and data collection
11/07/2014	Sample collection after the flush

C. Experiments during the Flush Event

A set of measurement devices has been installed in the trunk channel in order to remotely monitor the flow and the sediment parameters continuously during the flush. Figs. 1 and 2 illustrate the general arrangement of the in-site apparatus in five observation sections along the sewer channel reach. The measuring devices were installed by trying not modifying the initial bed and not disturbing the sediment transport during the flush. Hydraulic parameters such as flow velocity and flowrate were sampled by a beam pulsed Doppler, SonTek IQ Plus™, to obtain continuous and high-accuracy data with the interval of 10s. The advantage of this device is to obtain 3D velocity components with its four velocity beams. Water level measurements were taken on every 15s using an Ultrasonic sensor installed on the celling of the channel. Moreover, a high precision and chemical resistant apparatuses were used for turbidity and velocity measurements. In particular, turbidity was sampled on every 10s during the flow by using optical turbidimeters with measuring range up to 10,000 NTU. Three turbidity sensors were installed at three various levels within the channel: 15, 25, and 65 cm above the invert.

In order to observe directly how the bed material dynamics and the sediment behavior are affected by the flush, two boxes were equipped with video cameras. These cameras were installed in the channel bank at sections S_{+50} and S_{+100}. Two other video cameras were installed at S_{+5} and S_{+50} on the celling of the channel to visualize surface flow and opening displacements of the gate.

D. Experiments Before and After the Flush

To assess the flush consequences on the deposits, the sediment grain-size distribution and the sediment organic matter content were considered and compared in space and time (before and after the flush). In fact, most of flow behavior aspects (hydraulic, geomorphologic and ecological) are closely linked to the bed-material characteristics such as grain-size distribution [24]. Two series of tests were conducted to evaluate and determine these sediment characteristics:

1. Before the flush in 8 sampling sections of the first 180 m of the sewer reach, for two mineral and organic bed layers of deposits. The 8 sections were selected according to the presence of sediments on the channel invert before the flush event. Because of the delicate nature of organic matter's layer, high attention was paid during sampling to extract with minimum disturbance fine materials deposits contain the organic portion at the bed surface. Thus, a manual device was applied for sampling sediment bed at various depths, basically consisting of vertically taking a carrot out of deposits.
2. Before and after the flush, along the sewer channel axis (by considering total depth of the sediment as a sample for that section). Fig. 3 shows sampling sections of this second test set. The planned activity was to take samples with interval of 20 m; however, after the flush, areas of deposition before the flush were washed off while other previously clean areas were covered by sediments after the flush event. Then, totally 20 points and 17 points were sampled through the sewer channel between S_{-50} m and S_{+1010} m before and after the flush, respectively. Moreover only 9 samples were taken from common sections for proper comparison before and after the flushing event. In addition two more samples at S_{+350} m (S_{+385} m after the flush) and S_{+710} m (S_{+750} m after the flush), were considered for the comparative analysis. The sampler device used for the first test, where sediment diameters were enough small, is used also in this test for the

distance before S_{+400}. Because the device function is limited to extract the sediments with a diameter that not exceed more than 35 mm. Deposits with coarser fractions were collected with a manual sampler.

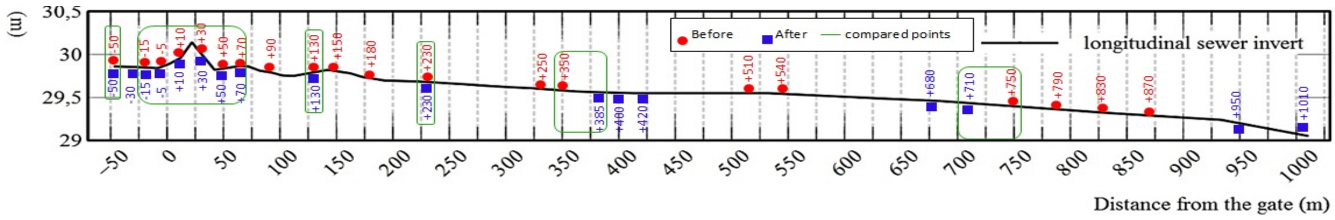

Fig. 3 Sampled points before and after the flush event along the sewer invert

The sediment sample quantities were different because of the availability of the deposits which was variable along the bed profile. To determine granulometric curves and organic fraction of in-sewer deposits, all sediment samples were collected, secured and immediately transported to the PRODIG laboratory in hygienic kits. Samples were treated in less than 24h after the collection by drying them in the oven at temperature of 105°C during 24h.

Dried samples were split in two parts: the first for the grain-size distribution analysis and the second for evaluation of the organic matter content. For the grain-size distribution analysis, samples were separated: grains with diameters more than 1 mm were weighted and sieved with AFNOR standard sizes. Fine grain fractions (<1 mm) were treated by laser diffraction technique (*Coulter LS300*). Coarse grains with irregular shape were assumed to be spherical in their smallest diameter. Results from both techniques contributed to build the curve of the cumulative weight of the mass whose size is smaller than the mesh size. Then, granulometric curves were used to evaluate sedimentary indexes such as D_{50} (median) and sorting index.

As the analysis of the organic matter fraction is concerned, oxidation method by using hydrogen peroxide (H_2O_2) digestion was applied following ORSTOM protocol [25]. For this purpose, a defined volume of hydrogen peroxide was added to 20 g of grains finer than 2 mm. After the complete reaction, the sample was dried in 105°C and re-weighted. The difference in the weight was calculated in percentage.

III. Results and Discussion

A. Hydraulic and Turbidity Variation during the Flush

Flush variables are measured in the five observation sections that are illustrated in Figs. 4 (a)-(e). Some data are missing due to malfunctioning of the measurement device (see for example the flow rate at S_{+100} and S_{+50}). Higher fluctuations of monitored variables during the initial phase of the flush release were observed due to the surge front development and advancing along the sewer channel. The figure firstly shows flow rate to decrease down rapidly within a short time. For example in S_{-5}, flow rate drop down to its half in about 9 min. As the data shows, maximum flowrate (4.1 m3.s^{-1}) is recorded just upstream the gate S_{-5} (Section II) after 40s after that the gate started to open. The maximum velocity observed in this section was 1.9 m.s^{-1}. This, agrees with one of the conclusions outlined by [9]. The mean local average shear stress at S_{-5} was then estimated to about 4.5 N.m^{-2} based on the classic relation for uniform flow. This value is in the range of the critical shear stress for the beginning of the erosion to expect a cleaning performance [15]. With regard to the turbidity raw data averaged on every 1 min in this section, at the first half an hour, a huge quantity of sediments was observed to be re-suspended and to be transported along the sewer. According to the turbidity measurement at 15 cm from the bottom we can observe an average of about 3700 NTU (Nephelometric Turbidity Unit) and a peak of about 6600 NTU. As in this section the initial height of deposits was close to zero before flushing, these high turbidity values can be explained by the transport of sediments deposited in the closer upstream sections after erosion and resuspension due to the shear stress produced by the flush in the vicinity of the gate [26].

It is clear that the amount and rate of sediment that can be carried out by the flush are observed by the turbidity data in three levels. According to the turbidity data, captors recorded sharp gradient of turbidity in the water column. As expected, higher values of the turbidity were observed by the captor situated close to the channel invert for all sections during the flush. High difference of this parameter at the position of 15 cm and both other positions in the sections could prove the large bed load transport during the flush.

Overall differences between turbidity variations in S_{-50} in upstream of the gate, shows that flush influenced this section but not as high as the sections downstream the gate. The high concentration in upstream section is then produced near the gate localization, which shows the influence of the flow propagation toward upstream due to the weir function by stirring the bed materials. Unfortunately, in S_{+5}, the turbidity sensor in the lowest level was not working maybe due to conveyance of the huge amount of stocked-sediment behind the gate by the water stocking procedure. But from the two sensors in upper positions, high values of the concentration at the very near bed level could be figures out.

In S_{+50}, the both upper sensors registered very low data in contrast with that in the lower level which shows the high transport of bed-material load near the bed. Comparing S_{+50} with the section in 50 m further in downstream, noticeable difference in turbidity values signifying sediment entrainment is found going up again despite the flow decreasing through downstream. This may be derived from the presence of fine particles between after S_{+50}, which induce the increasing of the turbidity in particular toward the inner region of the flow. Fig. **5** shows the difference between the fluid turbidity in both last sections (S_{+50} and S_{+100}) taken from the cameras installed in the lateral bank. The snapshots present the instance of the flush wave entrance which mobilizes the bed material load.

In addition, the form of the longitudinal bed slope, available energy, grain interactions could be the factors which induce resuspension of the bed by increasing the driving force [27]. According to the videos recorded from both bank cameras implemented in S_{+50} and S_{+100}, the turbulent front wave entrance to the observation section is visible. A snapshot taken at the first instance of the entrance of these two the sections is shown in Fig. 5. At S_{+50}, according to the video, particles are coarser which passed through the observation section whereas at the second one an abrupt increase of the concentration wastewater as the high-density 'cloud'. This is related to the "first foul flush" phenomenon as happens at the first stage of the storm event. Flush's boundary shear and wave propagation is impacted by the suspended solids transported by the flow and also the bed load transport at the bottom and wall friction of the bed materials. Furthermore, the height of the bed and the water depth alter the effective shear stress and the turbulent velocities. That's why the flow misses gradually its energy and the transport capacity [2].

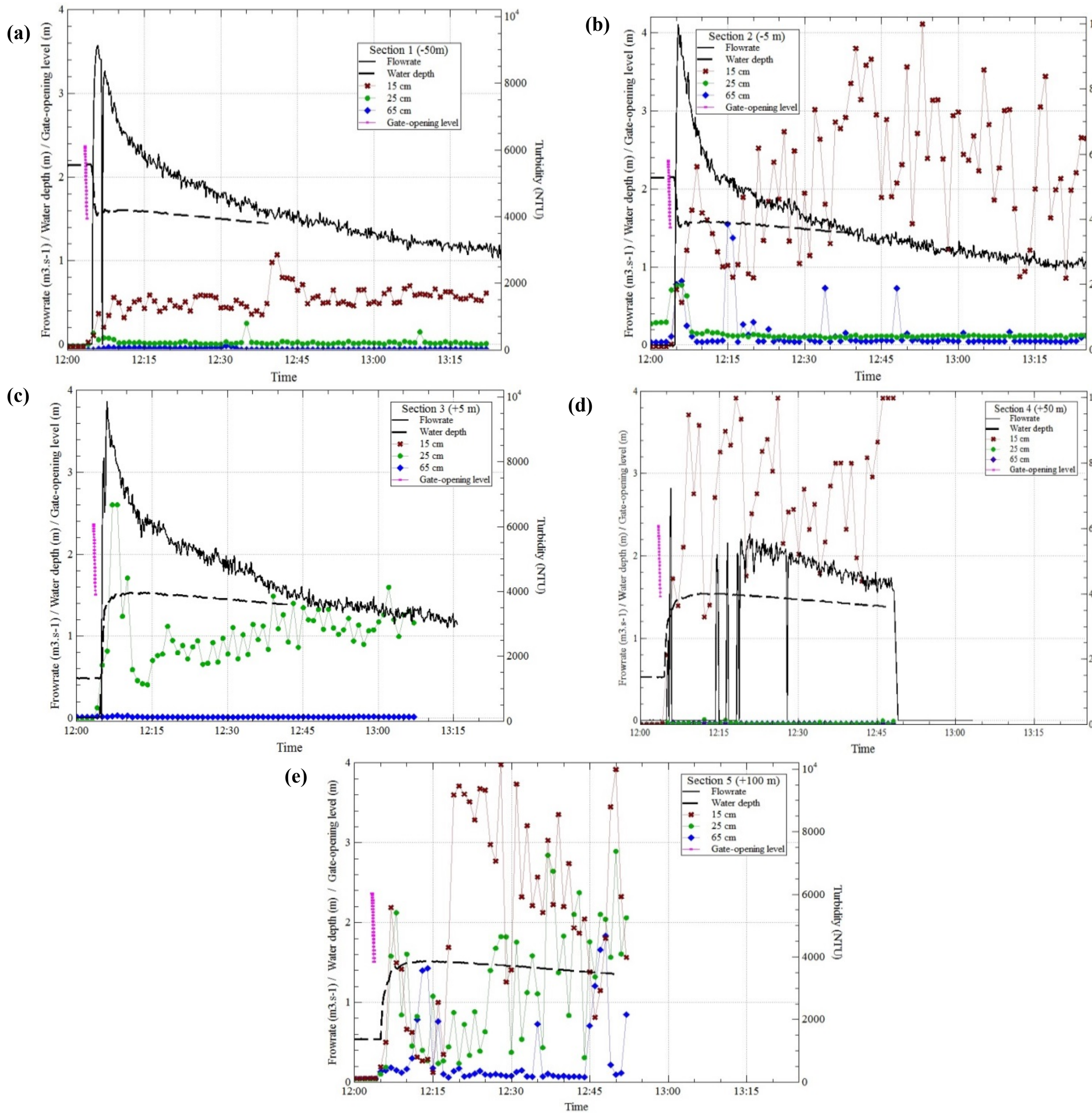

Fig. 4 Sampled variables during the flush in five observation sections

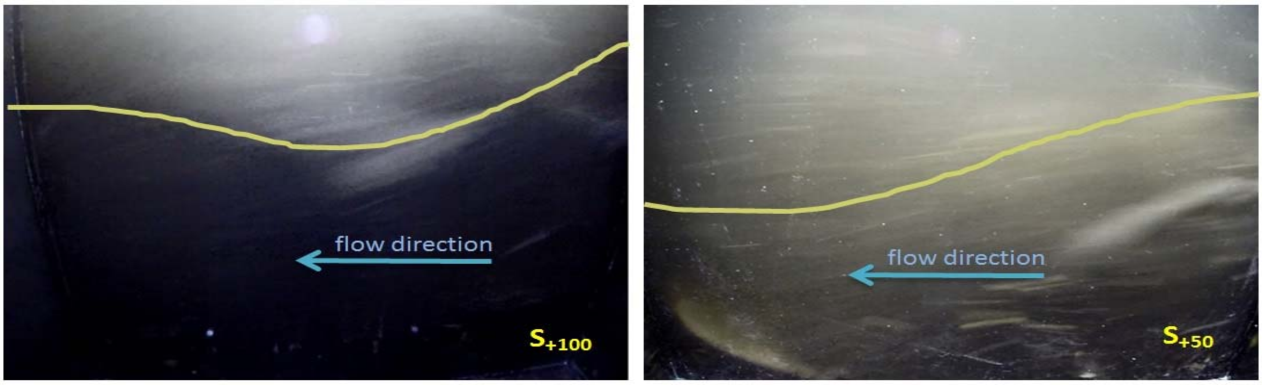

Fig. 5 Snapshots of initial wave passing from observation sections S_{+50} and S_{+100} (The limits indicate wastewater and initial concentrated wave of the flush)

B. *Bed-Materials Modification in Space and Time*

1. Variation of Organic Matter Content

Laboratory analysis of the first test provided quantification of organic content in both the upper and the lower layers of the deposits, which is been presented in Fig. 6. The results are in agreement with previous studies, *i.e.* the higher percentage of organic matters was generally found at the top of the bed that overlay the mineral sediments on the bottom [28]–[31]. For example, compared to other experimental works [28], the so-called "A" and "C" layers correspond to the coarse mineral and fine organic layers, respectively. The results of the present study are generally in agreement with the vertical quantification of organic matter in deposit profile regarding the organic fraction percentage. However, the organic fraction in upper layer of deposit's profile was not as high as found by reference [28] showing the sediment material transported by the channel to be prevalently not cohesive. Furthermore, as the second part of the experiments, the amount of organic fraction obtained from the samples between S_{-50} and S_{+400} before and after the flush, was quantified and compared. Results are summarized in Fig. 7. The figure also shows the spatial and temporal evolution of the median diameter (D_{50}) associated to each sample. The content of the organic fraction is shown to decrease after the flush over almost all the reach downstream the gate position, with the exception of section S_{+30} where an increase was observed. This opposite behavior is attributed to the reduced shear stress due to the invert counter-slope and to the existing sewer inverts irregularities and will require future specific analysis.

Detailed results of organic content at the various sections before and after the flush are presented in Table II. The table shows a reduced quantity which is been impacted by the flush over the entire sewer reach, although surface and depth sediments are poor on organic matter compare to the results of [28]. In fact, the amount of accumulated organic matter highly depends on many factors as sewer conduit size and roughness, flow condition as well as range of the sediment characteristics [32].

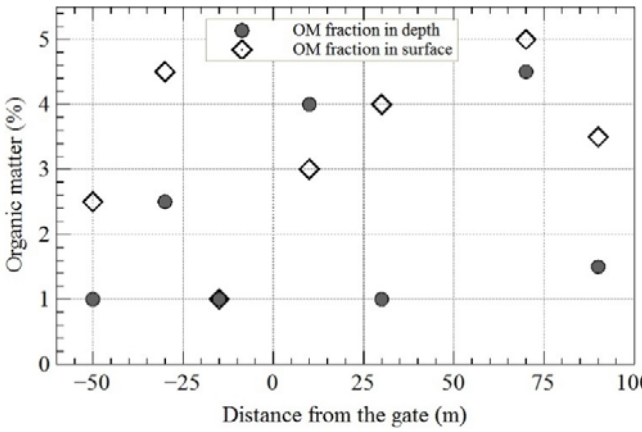

Fig. 6 Organic proportion vertical layers of settled bed

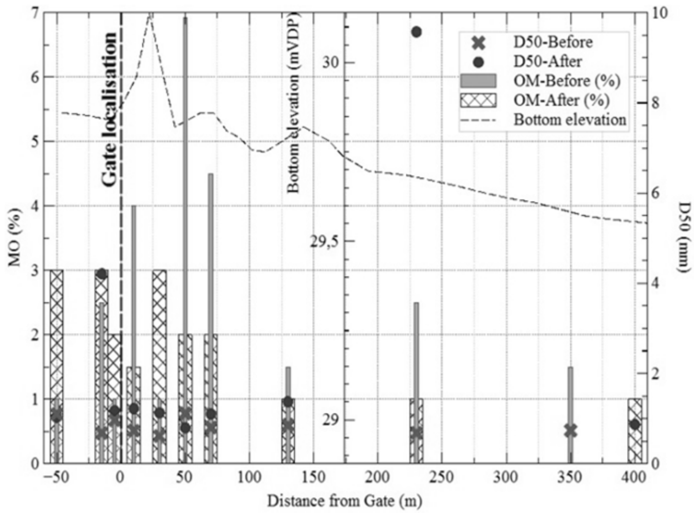

Fig. 7 Organic fraction and associated median of samples before and after the flush event

2. Grain-Size Distribution

Two series of in-sewer samples were analyzed at the laboratory to consider their grain-size distribution before and after the flush. Judging from the results and observations, a large sediment heterogeneity and diversity was observed during the analysis at the laboratory, in terms of diameter and shapes as well as the nature. Results presented in Table II confirm that the sediment all along the sewer is basically sand of various sizes with a portion of cobbles with higher size.

More detailed analysis from all samples taken before the flush have shown two distinct grain-size distribution patterns corresponding to both areas between S_{-50} and S_{+400} and between S_{+400} and the channel end. The first area is dominated by more fine grains with averaged values D_{50} = 1.0 mm; beyond S_{+400} the deposits are coarser with averaged D_{50} = 23.6 mm.

Results of bed sample are analyzed and illustrated in Fig. 8, which expresses the percentage by weight falling within each size class computed for all samples from bed materials over the first 450 m of the sewer section.

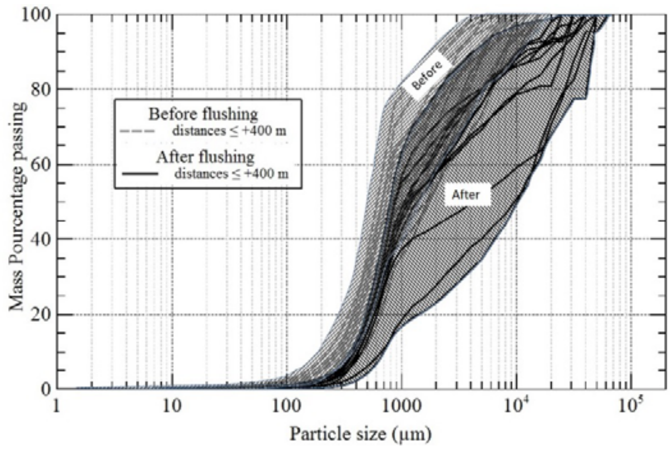

Fig. 8 Grain-size distribution of samples between -50 and +400 m taken before and after flushing

As expected, after the flush, diameter distributions are more dispersed with average D_{50} equal to 2.1 and 18.0 mm for the two previous areas, respectively.

Data shows that, compared to sandy portion, the percentage of cobbles-diameters increases in the upstream section and decreases in the downstream sections due to the flush sorting effects. Based on curves in the figure, grains with diameter smaller than 0.9 mm show a good sorting particularly at upper reach of the sewer channel both before and after the flush event, but in overall, sample ranges spin up to large diameters of the solids. Before the flush, whole samples present poor to very poor sorting. Sample sorting indexes indicates the fluctuations in kinetic energy or flow velocity of the flow in which particles are deposed. The sediments after the flush contained more chaotic mixture of different gains which is expressed in the sorting index of the samples.

Compared to the results of other studies, this study shows an overall larger range of diameters confirming how the variability of the sewer solids may vary locally due to several factors such as the sewer network geometry and catchment size, the type of materials entering the sewer, the mesh size of the sewer entrance, etc. [32].

TABLE II
SUMMARIZED CHARACTERISTICS OF THE SAMPLES COLLECTED BEFORE AND AFTER FLUSHING ALONG THE SEWER CHANNEL

Distances (m)	D_{50} (mm)		Organic fraction (%)	
	Before	After	Before	After
-50	1.1	1.0	1.0	3.0
-30	-	1.1	-	0.5
-15	0.7	4.2	2.5	3.0
-5	1.0	1.2	1.0	2.0
+10	0.7	1.2	2.0	1.5
+30	0.6	1.1	4.0	3.0
+50	1.1	0.8	1.0	2.0
+70	0.8	1.1	6.9	2.0
+90	1.0	-	4.5	-
+130	0.9	1.4	1.5	1.0
+150	2.1	-	5.0	-
+180	1.7	-	2.1	-
+230	0.7	9.6	2.5	1.0
+330	1.6	-	1.5	-
+350	0.7	-	1.5	-
+385	-	0.9	-	1.0
+400	-	10.2	-	0.0
+420	-	10.1	-	1.0
+510	23.3	-	1.0	-
+540	24.3	-	3.0	-
+680	-	28.1	-	1.5
+710	-	26.6	-	0.5
+750	23.7	-	1.5	-
+790	21.8	-	2.0	-
+830	21.7	-	1.5	-
+870	26.5	-	0.3	-
+950	-	5.1	-	0.5
+1010	-	28.2	-	0.3

By classifying sediment diameters of the samples in AFNOR standard (mm), details of four fraction ranges, show that the bed material composition ranges from silts to cobbles (*i.e.* mainly gravels). Fine particles with diameters smaller than sand (2 mm) are mainly flushed away after the flush event.

Based on the data, general textural analysis of the collected samples from upper reach (< S_{+400}) represents “sandy very fine gravel” or “very fine gravelly coarse sand” and beyond this distance sediments are in coarse gravel category. After the flush, the texture in upper and lower reach is mainly modified to sandy coarse/very fine gravel and very coarse gravel, respectively. Besides, by more analyzing the data, it is appeared that mobility of the grains under this flush is mainly limited to the grains smaller than 1.25 mm (smaller than coarse sands), which explains the selectivity of the flow due to its available energy. Sands (63 µm-2 mm) are appeared to be the main fraction of the present in the deposits composition in particular over the distance before +400 m with an average of 74% whereas after the flush this value is 54%.

Comparing two time-episodes, quantities of grains with ranges > 2 mm, are increased after the flush over the sewer reach. Other compositions are relatively diminished along the channel to half of their amount which means that the flush had a scouring effect on the grains sized almost smaller than 2 mm. Over the first 450 m of the sewer reach, average percentage value of these bed-materials size is 69.4% before the flush comparing to 38% after the flush. In contrast, the quantity of greater than 2 mm sizes is increased about 20% after the flush.

Sections with complete removal of sediments and areas with sedimentation magnitude after the flush are highlighted. Based on preliminary analyzed data, most areas where sedimentation is occurred after the flush are with negative slope. This is confirmed grace to the video cameras installed at the banks. As shows a snapshot of the camera in Fig. 9, an immediately sediment build is observed just after 1 minute after the first wave passing from the observation section situated in S_{+50} where the bottom invert is negative whilst the other camera located on a positive slope at S_{+100}, did not show any sediment bed-up along the whole flow.

Fig. 9 Snapshot from video camera situated on a negative slope invert at 50 m from the gate after one minute since the flush beginning

Despite the small distance from the gate, location with the presence of irregularities are prone to build-up the deposits. Moreover, regarding the grain size distribution, the sediments deposited are mostly sand or fine gravels, which are left by the flow.

Although flushing efficiency is the result of the main parameters such dam-height, storage length, storage volume and bottom slope in gate downstream as well as in storage section [10], [15], [20], [33]. Hence, bottom slope variability has shown a considerable effect on the grain-size distribution and organic fraction in specially before flushing where they accumulated under dry weather condition. Reciprocally, the bed-material characteristics impact also the flushing efficiency, depending on their prehistory of being scoured and level of their consolidation.

In-site observations of the gross sediments at the site found mostly at the distance more than +400 m from the gate show that the sediments are generally the solids that are from the constructions or street asphalt debris. This is may be due to the altered gullies who plays an important role on the solid particle size distribution [2]. In the last 200 m, gross solids contain those from the pipe repairing such as large metal nuts and bolts. In addition their large distance from the gate, due to the high density of these solids, their transport is less probable [34]. Moreover deposit structures were observed different in different areas along the sewer reach. For example as deposits were found to be paved. These sediments showed a tendency to be '*armoured'* bed structure which takes place in gravel-bed. Therefore in addition to the hydraulic and complex geometrical properties and characteristics of the particle such as density, the structure of the bed is important in removal effectiveness of the flush.

The high difference of concentration between the level above the bed invert at 15cm and two other levels at 25 and 65 cm from the bottom is evident. This means that during the flush a great part of the bed materials is eroded and transported just near the bed. That's why flush could be a mean to improve the water quality in sewer network [35].

It has to be stressed that sediment consideration from 50 m at the upstream of the gate while the upstream end extends to a long distance. Due to the large distance influence of the in-line storage during the experimentation, it is probable that sediments are remobilized beyond this distance. Besides, the occurrence of an adverse during the night after the flush should be taken in account while second set of sample collecting was done the day after. According to recorded data from *Mont-Souris* weather station, the accumulated amount of 40.8 mm in 48h with maximum intensity of 12.4 $mm.h^{-1}$ [36]. Unfortunately, it is possible that the adverse has brought grits and debris into the sewer section and left its effects on the flush efficiency.

As summary, erosive effects of flushing depend significantly on geometrical properties of the sewer conduit (*e.g.* bottom slope), as well as hydraulic performance of the flush. In fact, the response of the sediments to flush characteristics varies different sewers regarding to their geometrical properties. Moreover sediment characteristics, in particular their size, shape and density and their position along the sewer is important; due to their characteristics, they show different mode of transport and response to the flow energy during the flush. In-sewer sediments are predominantly containing the sand ranges and based on their characteristics, this particle fraction are subjected to the main erosion under the flush.

Many authors outlined that a single intensive flush is less effective than repetitive and less intensive flushes (for example [13]). However a single flush, could considerably modify sediments composition and structures depending on the characteristics of the flow as well as the sewer conduit's geometry. Moreover, large range of bed materials with high heterogeneity is varied in different sections of the studied reach.

IV. Conclusion and Perspective

This article deals with preliminary results of the influence of an individual flush in a real big-size trunk sewer on effectiveness of in-sewer sediment removal. Considering grain-size distribution and organic fraction along the sewer reach in space and in time, used weir function gate's flush may impacts the bed over an appreciable distance. But regarding the geometry of the trunk sewer, it cannot ensure the high performance of sediment removal. This study has shown that unique flush by such gate could degrade mainly the particles smaller than sand diameters (D < 2 mm). The parameter that may considerably impact the sediment transport mechanism during the flush realized in such big combined sewer with high heterogeneity in bed materials is the bottom slope. Higher slopes entrain more bed materials during the flush despite of the distance from the gate.

Dam-beak wave effects of the flush have induced the quantitative and qualitative modifications throughout the bed deposits in the sewer. During the flush, solids in suspension and as the bed material degrade reciprocally the wave propagations of the flow. Maximum bed-erosion was occurred in the sections with the bed more positive slope.

Decreasing of the organic fraction which contains a high quantity of pollution, optimizing such gates could be effective in the point view of the managers to minimize the sedimentation's problems.

Even though this type of gate, by just one flush did not manifest a high efficiency distance for a flushing away deposits, but it may reduce the amount of such pollution over a long distance by using repetitive flushes before the storm event as concluded also by [30]. This could help the wastewater treatment plant's function while storm events and surcharging to avoid high load of pollution. These results and the additional experiments data are expected to be used for next step of the study to develop a model to simulate the flush in order to better understand the transport mechanism of the sediments during this event. The simulation work is in progress. The aim is to focus on the prediction of particle behavior bed evolution in such unsteady turbulent flow by taking account of geometrical parameters and then understanding the efficiency of flushing by considering two key mechanisms for in-sewer sediments: bottom shear stress variations along the bed as well as organic substances as a responsible for shear resistance.

ACKNOWLEDGMENTS

The authors express their gratitude to Paris Municipality "Ville de Paris" for funding data as well as Mr. Jean-François Ferrandez for his support during the project. Authors are also grateful to the Campus France and the Kurdish institute of Paris for their funding partnership. Special appreciation is given to the PRODIG geography-physic laboratory.

REFERENCES

[1] G. Chebbo, D. Laplace, A. Bachoc, Y. Sanchez, and B. Le Guennec, 'Technical solutions envisaged in managing solids in combined sewer networks', *Water Sci. Technol.*, vol. 33, no. 9, pp. 237–244, 1996.
[2] R. M. Ashley, J. L. Bertrand-Krajewski, T. Hvitved-Jacobsen, and M. A. Verbanck, *Solids in sewers - Characteristics, effects and control of sewer solids and associated pollutants*. 2005.
[3] W. C. Pisano, G. L. Aronson, C. S. Queiroz, F. C. Blanc, and J. C. O. Shaughnessy, 'Dry-weather deposition and flushing for combined sewer', 1979.
[4] J. L. Bertrand-Krajewski, A. Campisano, E. Creaco, and C. Modica, 'Experimental analysis of the hydrass flushing gate and field validation of flush propagation modelling.', *Water Sci. Technol.*, vol. 51, no. 2, pp. 129–37, Jan. 2005.
[5] E. Ristenpart, 'Solids transport by flushing of combined sewers', *Water Sci. Technol.*, vol. 37, no. 1, pp. 171–178, 1998.
[6] E. Ristenpart, 'Sediment properties and their changes in a sewer', *Water Sci. Technol.*, vol. 31, no. 7, pp. 77–83, 1995.
[7] Y. L. Lau and I. G. Droppo, 'Influence of antecedent conditions on critical shear stress of bed sediments', *Water Res.*, vol. 34, no. 2, pp. 663–667, 2000.
[8] R. H. S. M. Shirazi, R. Bouteligier, P. Willems, and J. Berlamont, 'Preliminary results of investigating proper location of flushing tanks in combined sewer networks for optimum effect', in *11th international Conference on Urban Drainage*, 2008, pp. 1–9.
[9] A. Campisano and C. Modica, 'Flow velocities and shear stresses during flushing operations in sewer collectors.', *Water Sci. Technol.*, vol. 47, no. 4, pp. 123–8, Jan. 2003.
[10] A. Campisano, E. Creaco, and C. Modica, 'Dimensionless approach for the design of flushing gates in sewer channels', *J. Hydraul. Eng.*, vol. 133, no. 8, pp. 964–972, 2007.
[11] A. Campisano, E. Creaco, and C. Modica, 'Laboratory investigation on the effects of flushes on cohesive sediment beds', *Urban Water J.*, vol. 5, no. 1, pp. 3–14, Mar. 2008.
[12] C. H. J. Bong, T. L. Lau, and A. Ab Ghani, 'Hydraulics characteristics of tipping sediment flushing gate.', *Water Sci. Technol.*, vol. 68, no. 11, pp. 2397–406, Jan. 2013.
[13] A. Campisano, E. Creaco, and C. Modica, 'Experimental analysis of the Hydrass flushing gate and laboratory validation of flush propagation modelling', *Water Sci. Technol.*, vol. 54, no. 6–7, p. 101, Oct. 2006.
[14] S. Todeschini, C. Ciaponi, and S. Papiri, 'Experimental and numerical analysis of erosion and sediment transport of flushing waves', pp. 1–10, 2008.
[15] J. Dettmar and P. Staufer, 'Behavior of the activated storage-volume of flushing waves on cleaning performance', in *Proc. 10th Int. Conf. on Urban Drainage*, 2005, no. August, pp. 1–8.
[16] P. Balayn, 'Modélisation du transfert de sédiments lors d'un lâcher d'eau en réseau d'assainissement – approche numérique', 1996.
[17] T. Sakakibara, 'Sediments flushing experiment in a trunk sewer', *Water Sci. Technol.*, vol. 33, no. 9, pp. 229–235, 1996.
[18] J. Dettmar and P. Staufer, 'Modelling of Flushing Waves for Optimising Cleaning Operations', in *Urban Drainage Modelling*, 2004, pp. 241–248.
[19] K. El Kadi A. and A. Paquier, 'Numerical modeling of flushing waves in sewer channels', *Novatech*, vol. session 6., pp. 1285–1292, 2007.
[20] Q. Guo, C. Y. Fan, R. Raghaven, and R. Field, 'Gate and Vacuum Flushing of Sewer Sediment: Laboratory Testing', *J. Hydraul. Eng.*, vol. 130, no. 5, pp. 463–466, 2004.
[21] K. J. J. Williams, S. J. Tait, and R. M. Ashley, 'In-sewer sedimentation associated with active flow control', *Water Sci. Technol.*, vol. 60, no. 1, pp. 55–63, Jan. 2009.
[22] P. Staufer and J. Pinnekamp, 'In situ measurements of shear stresses of a flushing wave in a circular sewer using ultrasound', *Water Sci. Technol.*, vol. 57, no. 9, pp. 1363–1368, 2008.
[23] A. Lorenzen, E. Ristenpart, and W. Pfuhl, 'Flush cleaning of sewers', *Water Sci. Technol.*, vol. 33, no. 9, pp. 221–228, 1996.
[24] M. H. García, *Sedimentation engineering*. 2008.
[25] ORSTOM, 'Méthodes d'analyses utilisées au laboratoire de physique des sols.'
[26] P. Staufer, J. Dettmar, and J. Pinnekamp, 'Upstream processes within a flushing wave', in *Urban Drainage*, 2008, no. 2005, pp. 1–10.
[27] H. Chamley, *Sedimentology*. Springer, 1990.
[28] R. W. Crabtree, 'Sediments in Sewers', *Water Environ. J.*, vol. 3, no. 6, pp. 569–578, 1989.
[29] M. Ahyerre, C. Oms, and G. Chebbo, 'The erosion of organic solids in combined sewers', *Water Sci. Technol.*, vol. 43, pp. 95–102, 2001.
[30] D. Laplace, C. Oms, M. Ahyerre, G. Chebbo, J. Lemasson, and L. Felouzis, 'Removal of the organic surface layer in combined sewer sediment using a flushing gate', *Water Sci. Technol.*, vol. 47, no. 4, pp. 19–26, 2003.
[31] C. Oms, M. C. Gromaire, and G. Chebbo, 'In situ observation of the water-sediment interface in combined sewers, using endoscopy', *Water Sci. Technol.*, vol. 47, no. 4, pp. 11–18, 2003.
[32] W. C. Pisano, J. Barsanti, and J. Joyce, 'Sewer and Tank Sediment Flushing, Case Studies', no. December, p. 113, 1998.

[33] J. L. Bertrand-Krajewski, J. P. Bardin, C. Gibello, and D. Laplace, 'Hydraulics of a sewer flushing gate', *Water Sci. Technol.*, vol. 47, no. 4, pp. 129–136, 2003.
[34] T. Walski, J. Falco, M. McAloon, and B. Whitman, 'Transport of large solids in unsteady flow in sewers', *Urban Water J.*, vol. 8, no. 3, pp. 179–187, Jun. 2011.
[35] P. Staufer, J. Dettmar, and J. Pinnekamp, 'Improvement of water quality by sewer network flushing', *Novatech*, pp. 1317–1324, 2007.
[36] Www.meteociel.fr, 'Meteociel.'.