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Shirazi, Reza Haji Seyed Mohammad; Bouteligier, Raf; Berkamont, Jean

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EVALUATION OF SEDIMENT REMOVAL EFFICIENCY OF FLUSHING DEVICES REGARDING SEWER SYSTEM CHARACTERISTICS

Reza H.S.M. Shirazi[1], Raf Bouteligier[2] and Jean Berlamont[3]

[1] PhD Student, Department of Civil Engineering, Katholieke Universiteit Leuven
Kasteelpark Arenberg 40, B-3001 Leuven, Belgium, e-mail: Reza.Shirazi@bwk.kuleuven.be
[2] Researcher, ECO–beton Co. (Former K.U.L Researcher)
Hasseltsesteenweg 119, B-3800 Sint-Truiden, Belgium, e-mail: raf.bouteligier @eco-beton.be
[3] Professor, Department of Civil Engineering, Katholieke Universiteit Leuven
Kasteelpark Arenberg 40, B-3001 Leuven, Belgium, e-mail: Jean.Berlamont@bwk.kuleuven.be

ABSTRACT

Flushing devices are considered to be effective in removing settled particles from urban drainage networks and are becoming more frequently used. Modelling analyses with InfoWorks CS software were carried out to investigate the influence of sewer network design and sediment characteristics on the efficiency of a certain type of flushing device. The simulations were done for a sewer network composed of a series of connected pipes with identical diameters with a flushing device installed at the upstream part of the network and for various combinations of pipe diameters (300 mm & 400 mm), pipe slopes (2 mm/m & 3 mm/m), sediment particles (d_{50} equal to 0.2 and 0.3 mm), sediment concentration (50 mg/l & 100 mg/l), and dry weather flow (DWF) (0.005 m^3/s & 0.008 m^3/s). The DWF, sediment particle size and the slope of the sewer pipes have major effect in modifying the sediment bed and in predicting the sediment bed formation. Besides, the effect of flush intervals has proved to be an influencing parameter.

Keywords: flushing device, flush waves, sediment bed, sediment transport, InfoWorks CS

1. INTRODUCTION

Many sewer pipes in combined sewer systems experience considerable fluctuations in flow, ranging from high flow during short-term storm events to longer periods of much lower dry weather flows. In combined sewers when the pipe filling level is very low i.e. during dry weather periods, minimum critical velocities might not be reached (Bertrand-Krajewski, 2002). Thus, deposition generally occurs during these periods and also during decelerating flows when storm runoff is receding. Although the flow of surface runoff into the sewer network generates high shear stresses, this does not guarantee proper sediment transport in downstream sewer pipes due to lack of enough strength of the flow to produce the required shear stresses. Hence deposition is likely to occur, which can generate problems such as hydraulic overloading due to a reduction in flow capacity and the risk of surcharging during storm events increases. Thus, the issue of designing sewer systems to be self-cleansing becomes important. This is however not always possible, particularly in flat regions, where the necessary slopes for sewer pipes to be self-cleansing are not available due to the costs of deep excavations and pumping systems (especially in the most downstream parts of the network due to less available sewer slopes). In this regard, the use of flushing devices that generate controlled flush waves into the sewer system could be an appropriate solution. In fact, flushing devices are considered to be effective in removing settled particles from urban drainage networks (Dettmar et al., 2002; Campisano et al., 2004; Bertrand-Krajewski et al., 2005; Bouteligier et al., 2006).

The present paper deals with modelling analyses carried out to investigate the influence of sewer network and catchment sediment characteristics on the efficiency of a flushing device regarding sediment removal and transport in a sewer network. The research takes account of the hydraulic characteristics of the flushing tank (released flow rate as a function of time). Version 7.5 of InfoWorks CS (Wallingford Software, UK) has been used to calculate the spatially distributed shear stresses as a function of the pipe diameters and slopes to evaluate the eroding capabilities of the generated flush waves. The simulations were done for a sewer network composed of a series of connected pipes with identical diameters with a flushing device installed at the upstream end of the network and for various combinations of the pipe diameters (300mm & 400mm), pipe slopes (2 mm/m & 3 mm/m), sediment particles (with d_{50} equal to 0.2 and 0.3 mm), sediment concentration (50 mg/l & 100 mg/l), and dry weather flow (DWF) (0.005 m^3/s & 0.008 m^3/s). The flushing device (provided by Keramo-Steinzeug, Belgium) consists of a tank with a volume of about 0.45 m^3, releasing a flushing discharge between 27 and 19 l/s that lasts for nearly 20 seconds. Surface runoff stores in the tank until water height exceeds a certain level where the flow is bypassed and the stored water can flow through the outfall of the device and initiates a flush wave into the connected pipe. The flushing device is illustrated in "Figure 1". There is a variation in outflow discharge while the flushing occurs, which is due to the reduction in the initial water level in the tank. Hence, based on Bernoulli's equation, head loss computations and the geometrical characteristics of the flushing device, the outflow from the flushing device (flush wave) is calculated (Bouteligier et al., 2006) as shown in "Figure 2".

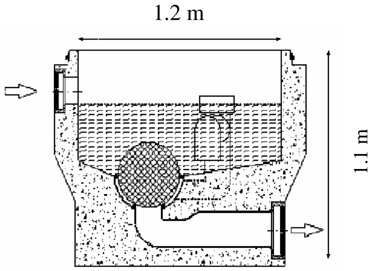

Figure 1 Illustrations of the flushing tank.

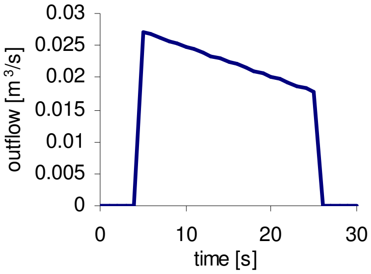

Figure 2 The outflow hydrograph for a flushing cycle.

Sewers should be designed to transport sediment at a rate sufficient to limit the depth of deposition to a specified proportion of the pipe section to maintain the required hydraulic characteristics of the conduit. Since flow rates and sediment loads in sewer systems can vary considerably with time, it is unrealistic to expect to be able to design a sewer network so that no deposition would occur under various flow conditions. The key requirement is to ensure that, averaged over a suitable period of time, sediment would be transported through the sewer pipes at approximately the same rate in comparison with the same system without any long-term build-up of deposits and without having a major adverse effect on the flow capacity of the sewer network (e.g. May, 2001). The magnitude of erosion varies in response to the time varying hydraulics. Along with sufficient flow velocity or bottom shear stress, successive occurrence of high flow conditions which would force deposited particles to unhinge has a substantial effect on resuspension of the deposits. The shear stress is the key parameter responsible for the start of sediment transport when its critical value for certain sediment characteristics is exceeded.

It is known that the propensity for sediment deposition will be different depending upon the location of a sewer in the network (i.e. the inflow the pipe receives from upstream parts of the sewer network) and the physical characteristics of the conduit such as size, shape, gradient etc. (Fraser & Ashley, 1999). In fact, as the generated outflow discharge in each flush is about 20 l/s (see “Figure 2”) the characteristics of receiving pipes (especially pipe diameter and bottom slope) could be important when evaluating the influence of such flush waves through downstream pipes, i.e. there would certainly be notable difference in the generated flush characteristics in connected pipes of various diameters and slopes.

2. METHODOLOGY

2.1 Sediment transport modelling

Reliable modelling requires that, together with general hydraulic results generated by hydrodynamic modelling, the possibility to properly model the impact of sediment accumulation in sewer systems as well as the amount of sediments and pollutants that are transported into receiving waters or treatment plants would be achieved. This indeed demands comprehensive knowledge of the behaviour of sediments inside the sewer pipes and the related phenomena linked to sediment transport (entrainment, deposition, and re-entrainment). For a proper sediment transport modelling, precise definition of sediment characteristics (particle size, density, concentration, etc.) on the catchment and in the sewer network is required. Particle characteristics and prevailing hydraulic conditions are important factors regarding proper estimations of the mode of transport. Thus sediment transport modelling is strongly dependent on the accurate modelling of the hydraulic conditions in the network.

The primary aim of sediment transport modelling is to obtain the track of sediment accumulation in a sewer system. InfoWorks CS (Wallingford Software, United Kingdom) accomplishes this by offering the water quality simulation module comprising three different sediment transport models: Ackers-White (default) based on concentration comparison (Ackers, 1991), Velikanov based on energy dissipation (Zug et al., 1998), and KUL based on shear stress comparison (Bouteligier et al., 2002). For the analyses carried out regarding the erosion and deposition modelling of sediments implementing the flush tank in the most upstream part of the network, the KUL model was implemented.

According to the KUL model, if the actual shear stress τ is below the critical shear stress for deposition ($\tau_{cr\text{-}deposition}$), then deposition will occur. If the actual shear stress value τ is in-between the critical shear stress for deposition and the one for erosion (i.e. $\tau_{cr\text{-}deposition} < \tau < \tau_{cr\text{-}erosion}$), then no erosion or deposition occurs and all suspended sediment is transported along the conduit. If the actual shear stress τ exceeds the critical shear stress for erosion $\tau_{cr\text{-}erosion}$ (i.e. $\tau > \tau_{cr\text{-}erosion}$) then erosion would occur. By performing a water quality simulation in InfoWorks CS, shear stresses are automatically generated. The shear stress is calculated as a function of the water head, the hydraulic radius and the (friction) slope of the flow according to Eq. 1.

$$\tau = \frac{\lambda_c}{8} \rho v^2 \tag{1}$$

where τ is the shear stress [N/m^2], λ_c the composite friction factor [-], ρ the water density [kg/m^3], and v the flow velocity [m/s].

The velocity is assumed to be uniform and is computed according to Eq. 2.

$$v = \sqrt{\frac{8g}{\lambda_c}}\sqrt{RS_0} \tag{2}$$

where R is the hydraulic radius [m] and S_0 the pipe slope [m/m].

The critical shear stresses for deposition and erosion are calculated based on the formula in Eq. 3 and Eq. 4 (Bouteligier et al., 2002).

$$\tau_{cr,deposition} = \gamma_{deposition} g(s-1)\rho d_{50}/1000 \tag{3}$$

$$\tau_{cr,erosion} = \gamma_{erosion} g(s-1)\rho d_{50}/1000 \tag{4}$$

where $\gamma_{deposition}$ is the deposition parameter [-], $\gamma_{erosion}$ the erosion parameter [-] ($\gamma_{deposition} \leq \gamma_{erosion}$), g the gravitational acceleration [m/s^2], s the specific sediment density [-], and d_{50} the sediment particle size [mm].

2.2 Model Setup

A model was created in InfoWorks CS version 7.5 in order to proceed with required simulations. The sewer network consisted of a series of straight and sequentially connected pipes, comprising an overall length of 950 m. Because of the stronger influence of the flushing wave in the upstream part of the sewer network close to the flushing tank and considering the flush tank installed at the most upstream manhole, the chosen lengths of the sewer pipes increased from upstream to downstream so that the variations in the flow characteristics could be modelled in a better way. Accordingly the model comprised (from upstream to downstream) 6 pipes with lengths of 10 m, 5 pipes with lengths of 20 m, 4 pipes with lengths of 35 m, 4 pipes with lengths of 50 m, 2 pipes with lengths of 75 m and 3 pipes with lengths of 100 m. To study the influence of the network characteristics on the flush wave propagation in the sewer stretch, the model was run for various combinations of the pipe diameters, the pipe slopes, the d_{50}, the sediment concentration, and the DWF (as given in section 1). For the simulations concerning the sediment modelling procedures, an inflow of sediments (representing the DWF with certain sediment concentration) was imposed into the upstream manhole of the network. The pollutograph and its corresponding inflow both have been introduced into the model with a timestep of 1 hour with a total duration of 3 days of sediment input and 5 days for the dry weather period and 10 hours for the flushing period after the DWF period. The sediment density was set to 1800 [kg/m^3]. No initial sediment depth was assumed for the sewer pipes and the sediment build-up was initiated based on the imposed pollutograph. For the sediment transport parameters, default values for $\gamma_{deposition}$ and $\gamma_{erosion}$ (see equation 3) were adopted (both equal to 1). An inflow hydrograph, representing the flush wave (see "Figure 8" left) was imposed on the most upstream manhole in the model.

3. RESULTS AND DISCUSSIONS

In general, sediment transport modelling requires that the evolution of sediment massflow and concentration throughout the network would be inspected, and doing so would necessitate the consideration of the changes in flow characteristics such as flow velocity, discharge, sediment concentration, sediment flux, etc. By obtaining the simulation results and evaluating them, the compatibility of what was modelled with what would be expected was observed. Regarding the effect of the flush waves, it was noticed that at the moment the flush wave passes along the pipes, due to the peak of the front head of the flush wave, the sediment depth reduced and the sediment concentration increased correspondingly (due to re-suspension of sediments). It is also worth mentioning that the energy of the flush wave, while passing through the sewer pipe, diminishes below the critical limit required for conveying the suspended sediments and this would lead to re-sedimentation of the suspended particles. Also, the decrease in velocity of the flow leads to a reduction in the sediment concentration. When the velocity decreases due to the reduction in the carrying capacity of the flow, sedimentation and consequently the decrease in the concentration of sediments occurs.

For verifying the effect of variations in sewer network characteristics on the evolution of sediment depths throughout the network (sediment transport), various combinations of these characteristics were considered for the network. The various sewer network combinations are presented in “Table 1”.

Table 1 The various combinations of the sewer network.

Sewer Network Combination	Diameter (mm)	Slope (m/m)	DWF (m^3/s)	Concentration (mg/l)	d_{50} (mm)	Particle Density (kg/m^3)
A	300	0.003	0.008	50	0.3	1800
B	300	0.003	0.008	50	0.2	1800
C	300	0.002	0.008	50	0.2	1800
D	300	0.003	0.005	50	0.2	1800
E	300	0.003	0.008	100	0.2	1800
F	400	0.003	0.008	50	0.2	1800

3.1 The effect of DWF on sediment transport

DWF rate is important in modifying the sediment bed, bearing in mind that this modification is also dependent on the considered sediment particle size and density in the inflowing DWF through the network. It is worth-mentioning that if there is a considerable prevailing flow in the sewer pipe, the flush not only may not be able to generate required bed shear stresses but it could lead instead to a surcharging or even flooding in that pipe. To evaluate the effect of variation in DWF on sediment transport, a comparison has been made between the sewer network combination B (“Figure 3” left) and D (“Figure 3” right). It is noticed that higher DWF results in higher sediment transport rate.

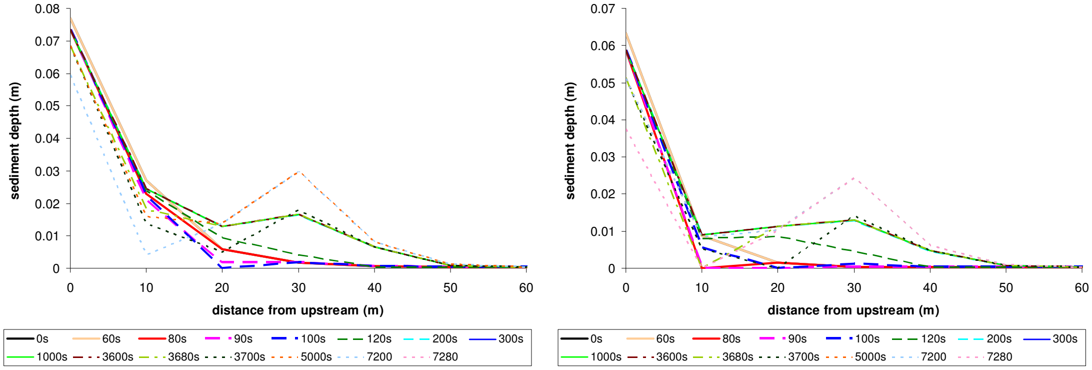

Figure 3 Comparison of the effect of DWFs on sediment transport.

3.2 The effect of particle size on sediment transport

Sediment particle size is a very important parameter in predicting the sediment bed formation, as the d_{50} represents an important influence on the carrying capacity of the sewer flow (when comparing the results of two different sediment fractions with the same density), thus the bed form also follows this concept. Therefore, bigger sediment particle size would lead to faster sedimentation of the suspended particles and faster stabilization of the sediment bed, as also becomes very clear from the simulation results. To evaluate the effect of diverse sediment particle sizes on sediment transport, a comparison has been made between the sewer network combination A (“Figure 4” left), and B (“Figure 4” right). It is noticed that larger sediment particle size leads to a lower sediment transport rate.

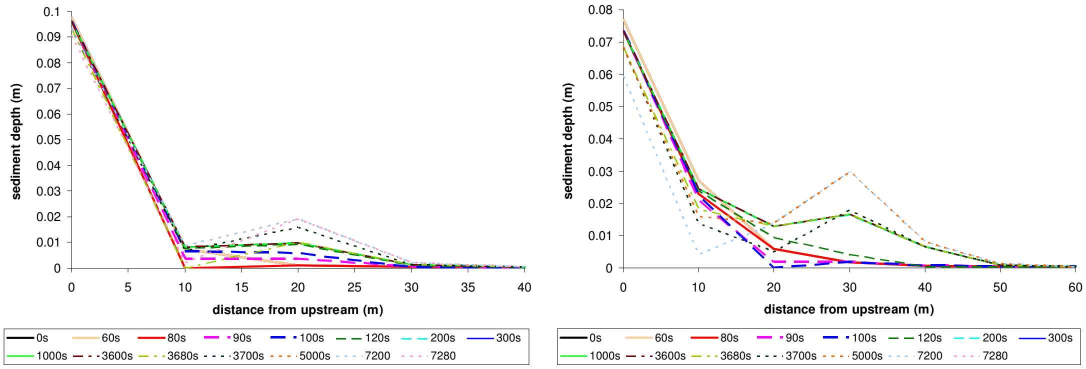

Figure 4 Comparison of the effect of sediment particle size on sediment transport.

3.3 The effect of pipe slope on sediment transport

The other parameter with large influence is the slope of the invert of sewer pipes which plays a very important role on sediment removal and re-suspension and on the deformation of initial sediment bed due to its direct relationship with the amount of generated shear stress. A strong difference in the invert slope would lead to a clear difference in sediment bed evolutions and shapes and especially on the distances along which the sediment particles could be transported. To evaluate the effect of variation in the slope of the invert of sewer pipes on sediment transport, a comparison has been made between the sewer network combination B (“Figure 5” left), and C (“Figure 5” right). It is noticed that steeper pipe slope gives rise to higher sediment transport rate.

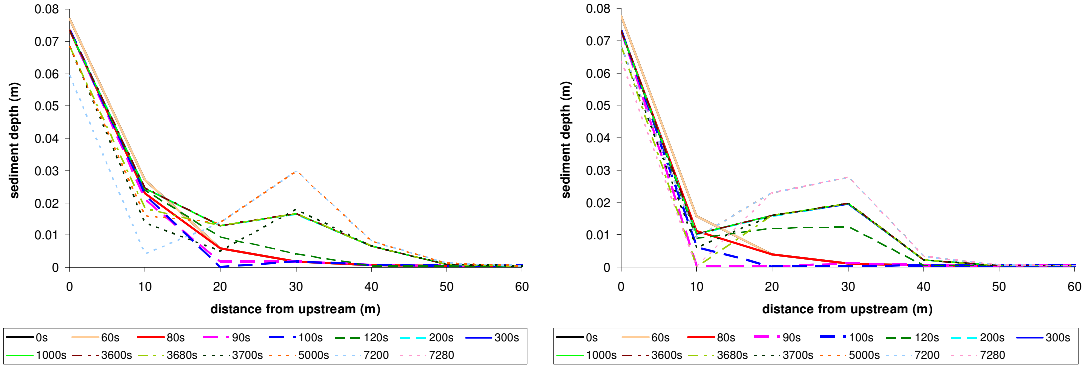

Figure 5 Comparison of the effect of sewer pipe slopes on sediment transport.

3.4 The effect of sediment concentration on sediment transport

Sediment concentration mainly slows down the rhythm of sediment transport and affects sediment bed evolutions due to the availability of more condensed sediment particle mixtures. In fact, the increase in concentration while the flush wave is passing could be due to the eroded sediment which is drifted into suspension within this flow wave (resuspension). When there is a drop in concentration, it usually coincides with the sedimentation in that location. To evaluate the effect of variation in sediment concentration on sediment transport, a comparison has been made between the sewer network combination B (“Figure 6” left), and E (“Figure 6” right). It is noticed that concentration is an influencing parameter concerning sediment transport modelling and results in big changes in sediment behaviour in sewer pipes.

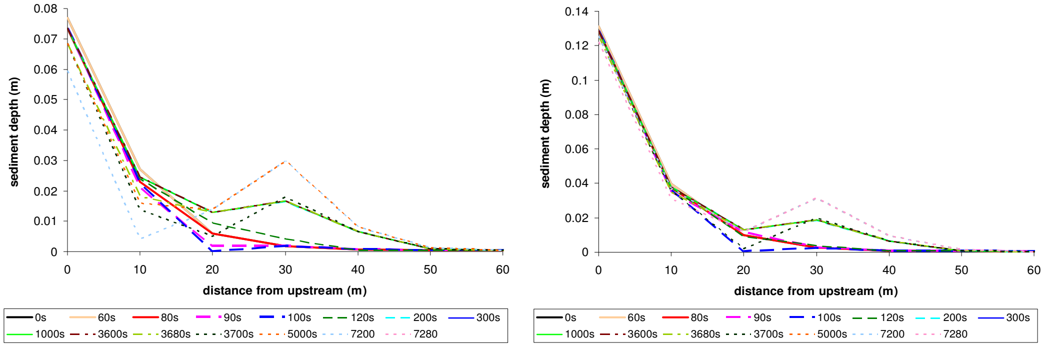

Figure 6 Comparison of the effect of sediment concentration on sediment transport.

3.5 The effect of pipe diameter on sediment transport

Moreover, sewer pipe diameter did not reveal a large influence on the sediment bed modifications (as regards to the performed simulations), although it is know that this parameter is related to the generated shear stresses in sewers. It is important to remember that this could be very dependent on all other defined network and sediment characteristics. It is however possible that due to the small difference between the compared pipe diameters in this paper (300 mm and 400 mm) the influence of the diameter has been insignificant (e.g. if the comparisons have been done for diameters of 300 mm and 1000 mm, then the impacts would be more clear). To evaluate the effect of variation in sewer pipe diameter on sediment transport, a comparison has been made between the sewer network combination B (“Figure 7” left), and F (“Figure 7” right).

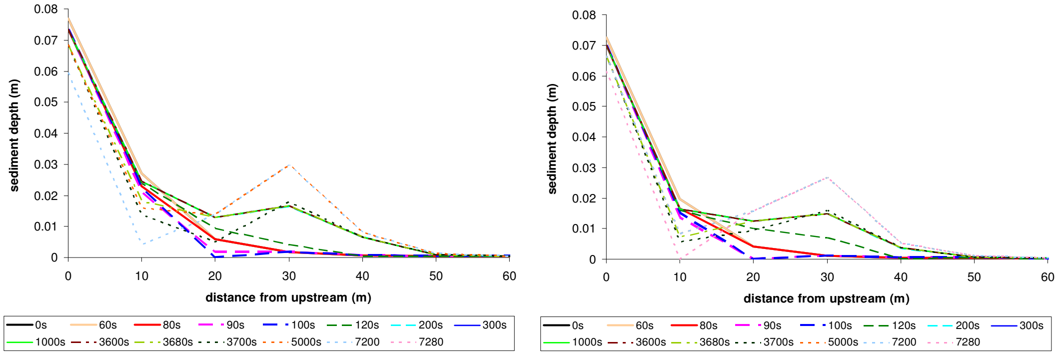

Figure 7 Comparison of the effect of sewer pipe diameter on sediment transport.

3.6 The effect of flushing frequency and interval on sediment transport

The frequency and interval of subsequent flushes are important items in evaluating sediment transport in pipes. Frequent flushing could have obvious effect over sediment erosion and transport in the pipes, as the subsequent flushes would intensify the effect of the previous flush for erosion and transport of sediments. In fact, the higher the frequency of subsequent flushes, the less the chance for sediments to settle down in pipes. Needless to say that this depends on the flushing interval. If there would be long flushing intervals then the frequency of flushing will not be so much of effect. Thus the interval between subsequent flushes could be of considerable important regarding their effect on postponing the simultaneous sedimentation in pipes. To evaluate the effect of the time interval between numerous subsequent flushes on sediment transport, the comparison has been made for the sewer network combination B with two scenarios of normal flushing (see “Figure 8” left) and 10 subsequent flushes with 3 minutes intervals between each two subsequent flushes (see “Figure 8” right). The comparison is illustrated in “Figure 9”. As can be observed, the number of flushes is not much effectual and the main influencing item is the interval between each two subsequent flushes that induces large impacts regarding sediment bed modifications.

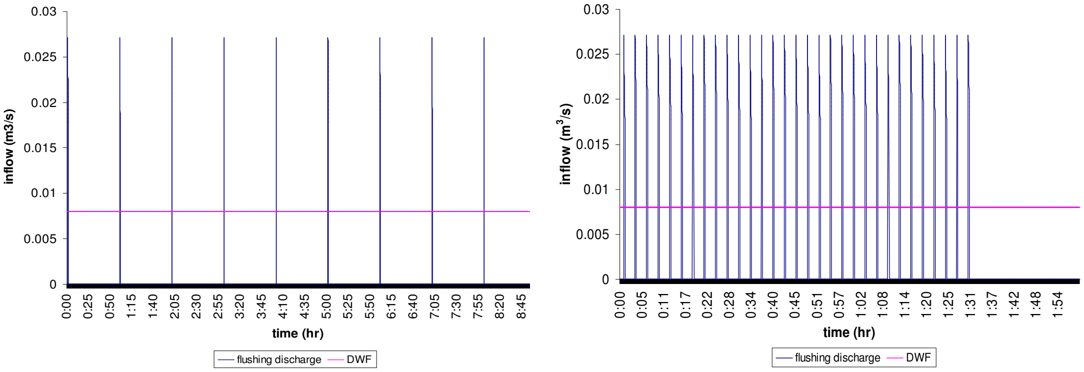

Figure 8 The inflow to the most upstream manhole of the network comprising the regular flushes each hour and flushes with 3 minutes intervals (for a duration of 1:30 hour) together with the constant DWF.

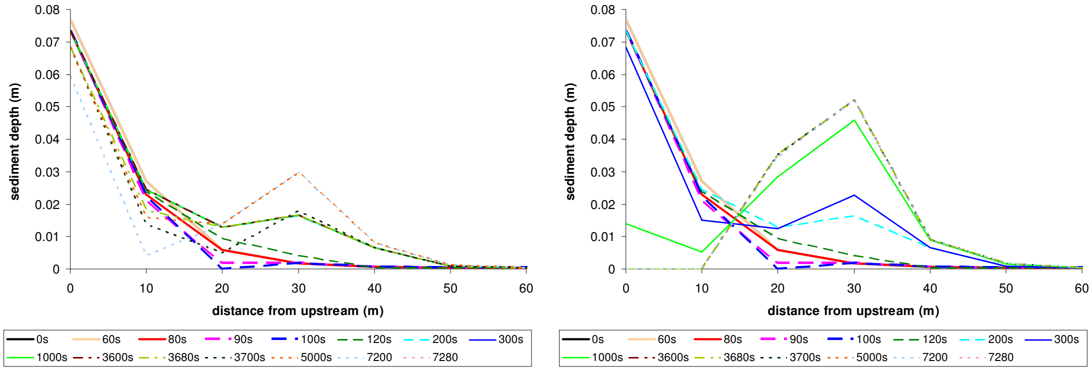

Figure 9 Comparison of the effect of the time interval between subsequent flushes on sediment transport implementing the regular flushes each hour (left) and subsequent flushes with 3 minutes intervals (right).

4. CONCLUSIONS

It was concluded that the results strongly depend on the characteristics of the network in concern. The DWF is found to be an important parameter in modifying the sediment bed. Sediment particle size (d_{50}) is a very influencing parameter in predicting the sediment bed formation, a bigger sediment particle size would lead to faster sedimentation of the entrained particles within the flow and more rapid formation of the sediment bed would result. Although sediment concentration is an inducing parameter referring to the indicated criteria, it did not stimulate large changes in the performed simulations. The other parameter with a big effect is the slope of the invert of sewer pipes, which largely affects the sediment removal, resuspension, and the deformations of initial sediment bed. A big difference in the slope would lead to a clear difference in sediment bed evolutions and shapes and especially on the distances along which the sediment particles could be transported. Whereas frequent (multiple) flushing could have obvious effect on sediment erosion and transport in the pipes, the effect of flush interval has proved to be the more influencing parameter in sediment bed modifications. Regarding the sediment transport simulations in InfoWorks CS (implementing the KUL model) it was discovered that not only the sewer network and sediment characteristics were responsible for modifying the impact of the generated flush waves (released from the flushing device) on sediment beds modifications, but also the model parameters would affect the estimation of sediment transport in a great deal. In this regard, future research needs to further investigate these diverse effects of sewer network characteristics and other influencing parameters to reach to proper conclusions by means of reliable sediment transport modelling to understand more efficient implementation of these flush tanks as urban drainage maintenance tools.

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