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Research Article

Factors Affecting the Efficiency of Hydraulic Flushing in Sewer System for Sedimentation Control: A Review

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Abstract

Hydraulic flushing is a popular and cost effective method for sedimentation control in sewer, especially in European countries. The quick release of large water volume leads to a flush wave with high turbulent flow mimicking dam break phenomenon to flush out the sediment accumulated in sewer. This paper presents a review of the existing literature related to the factors that affecting the efficiency of hydraulic flushing in sewer system. these factors generally can be divided into sewer characteristics, sediment characteristics, flushing device characteristics and environmental factors. Each factor will present certain risks to the sewer flushing system such as flushing failed to happen, frequency of flushing reduced, weak flush waves and amount of flushed sediment reduced. However, limited studies exist in the literature on the reliability and risks assessment of these factors on hydraulic flushing performance. Hence, this paper aims to provide enough information for future works to be conducted on the reliability and risk assessment related to sediment flushing system using decision-making tools in order to have an optimum performance for sedimentation control.

***Keywords*:** Hydraulic flushing efficiency; Optimum performance; Risk assessment; Sedimentation; Storm sewer

1. Introduction

Sewer systems are commonly affected by the presence of sediment deposits. The accumulation of sediment deposits will generate hydraulic and environmental problem for the sewer such as potential odor and corrosion conditions, reduce the design flow capacity, increase the risk of surcharges or local flooding during intense rain events and operational difficulties (Crabtree, 1989; Pisano et al., 2003; Bertrand-Krajewski, 2008).

Keeping sewer clean over prolonged period can be done by hydraulic flushing and this action is an economic way to maintain the storm sewer performance (Ristenpart, 1998). Several flushing devices for removal of sediment deposits from sewer system have been in use in close conduit sewer and open channel storm sewer such as vacuum flushing (Guo et al., 2004), Hydrass gate (Bertrand-Krajewski et al., 2005), sluice gate (Campisano et al., 2007) and tipping flush gate (Bong et al., 2013a). These devices operate by releasing large volume of water in short period of time, producing shock wave with high velocities and shear stress which is effective in scouring as well as transporting the sediment particles at the channel bed.

The investigations of flushing devices include the hydraulic characteristics and flushing effects of flush wave on the erosive capacity of sediment deposits (Campisano et al., 2004; Guo et al., 2004; Bertrand-Krajewski et al., 2005; Bong et al., 2013a; Shahsavari et al., 2015). The findings contributed to the knowledge of the criterion for the potential cleaning efficiency of a flushing system.

To simulate sediment flushing in sewer, one of the numerical models that has been used in a number of literature (Schaffner & Steinhard, 2006; Creaco & Bertrand-Krajewski, 2007; Montes et al., 2022) is based on the solution of the De Saint-Venant-Exner equations:

$$\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} = D(U) \tag{1}$$

with the vectors U, F and D given by:

$$U = \begin{bmatrix} A \\ Q \\ A_s \end{bmatrix}, F(U) = \begin{pmatrix} Q \\ V \cdot Q + \frac{F_h}{\rho} \\ \frac{1}{1-\rho_s} \cdot Q_w \end{pmatrix}, D(U) = \begin{bmatrix} 0 \\ g \cdot A \cdot (i - J) \\ 0 \end{bmatrix} \tag{2}$$

Where $x\,[m]$ and $t[s]$ are the spatial and temporal independent variables respectively, $A\,[m^2]$ is the wetted area, $Q\,[m^3/s]$ and $V\,[m/s]$ are the water discharge and flow velocity respectively, $F_h\,[N]$ is the hydrostatic force over the cross section, $\rho\,[kg/m^3]$ is the water density,

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$g\ [m/s^2]$ is the gravity acceleration, i is the channel bottom slope and J is the energy friction slope. As for the sediment, ρ_s is the sediment porosity, $A_s\ [m^2]$ is the sediment cross section area and $Q_s\ [m^3/s]$ is the sediment discharge. The friction slope J is evaluated by the Manning-Strickler equation:

$$J = \frac{Q^2}{k_c^2 A^2 R^{4/3}} \tag{3}$$

With $R\ [m]$ and $k_c\ \left[m^{1/3}/s\right]$ being the hydraulic radius and the Strickler composite roughness coefficient. The solution for Equation (1) requires the use of sediment transport formula; for example Creaco & Bertrand-Krajewski (2007) uses the Meyer-Peter and Muller formula (Meyer-Peter & Muller, 1948).

From Equation (1), (2) and (3), it can be deduced that there are quite a number of variables that can influence the efficiency of sediment flushing in sewer. The objective of this paper is to provide a review on the factors affecting the efficiency of hydraulic sediment flushing system from the work done in the existing literature by classifying the factors into four main components, namely: (1) sewer characteristics, (2) sediment characteristics, (3) flushing device characteristics and (4) environmental factors. However, only limited work available in the literature has been done on the reliability and risk assessment of sediment flushing performance. Hence, the current development in reliability and risk analysis methods which has the potential to be used for hydraulic flushing design and management are also being presented. It is hope that this paper will provide enough information for future works to be conducted on the reliability and risk assessment related to sediment flushing system in order to improve the flush system performance.

2. Sewer Characteristics

Sediment appears regularly at the section with mild sewer slope, bends of the storm sewer and sudden widening of the cross-sectional diameter (Lorenzen et al., 1996). Boundary conditions of sewer such as initial downstream water level and bottom roughness of sewer have major influence on the movement of flush waves. Besides, in European countries; closed conduits sewer system are more commonly used as compared to open channel sewer system in most developing countries. Closed conduit sewers allow high water level stored for flushing device operation without overflowing. The condition is different in open sewer where it could not allow high water level to avoid overflow and nuisance (Bong et al., 2016). Higher water level will allow more volume of water to be released during the hydraulic flushing operation. This will improve the scouring efficiency of the sediment bed downstream of the flush device. Referring to Equation (1), (2) and (3), sewer characteristic such as the geometry, slope and roughness will influence the wetted area A, sediment cross section A_s, channel bottom slope i, hydraulic radius R, friction slope J and roughness coefficient k_c.

2.1 Sewer Geometry

The erosion and deposition processes depended on the geometry of sewer cross section (Safari et al., 2014). U-shape and V-shape channels have centre cross-fall resulted in thicker sediment layer to be accumulated in the centre. Hence, flushing for this thicker layer will requires higher shear stress or velocity to be effective as compared to other type of cross-section. It was also observed that trapezoidal shaped open storm sewers had a tendency to have higher percentage of blockage due to sediment when compared to rectangular shaped open storm sewers (Bong et al., 2014). This may be due to the design of trapezoidal shaped open storm sewers which are normally to carry slower flow in collector system while rectangular shaped open storm sewers are normally for trunk or main sewer systems which carry higher flow.

2.2 Longitudinal sewer slope

An increase in channel slope will result in a more effective hydraulic flushing (Campisano et al., 2007). This scenario is due to water flows faster in steeper slope due to gravity and thus enhancing erosion of sediment deposits. It was observed that more bed materials were entrained at higher slope during flushing operation regardless of the distance from the flushing device. Penn et al. (2018) recommended to increase the slope of new sewer during design to prevent accumulation of gross solids. However, this increase should not at the expense of keeping the water depth higher than the required threshold (Penn et al., 2018).

2.3 Initial downstream water level

The efficiency of the hydraulic flushing will decrease with the increase in the water level downstream of the flush device. A high initial water level in the sewer provided the sediment bed a better sheltering against advancing flush wave (Gendreau et al., 1993). According to the findings by Schaffner & Steinhardt (2013), even low downstream water level of only 0.10 m could lead to a loss of effective flushing distance of 75% due to energy dissipation of the upcoming surges. Similar findings also showed that with a deeper depth, the downstream water can dramatically reduce the bottom shear stress and the flushing wave entirely losses its scouring effect (Yang et al., 2019).

2.4 Bottom roughness

The shear stresses generally increase with higher roughness while the velocity drops. The flush wave running on smooth surface reaches the end of the storm sewer faster at lower shear stress (Schaffner & Steinhardt, 2013). An increase of bottom roughness led to an increase of the shear stress but the flow velocity slows down indicating a loss of flushing and cleaning efficiency (Schaffner & Steinhardt, 2013).

3. Sediment Characteristics

To forecast the sediment flushing efficiency, it is important to understand the erosion process of sediment in storm sewer channel. The required shear stress for sediment erosion process highly dependent on the sediment deposit characteristics. The classical Shields (1936) equation in Equation (4) shows the influence of the sediment characteristics in terms of the balance between particle weight and boundary shear stress:

$$\theta_c = \frac{\tau_c}{gd(\rho_s - \rho)} \qquad (4)$$

Where θ_c is the dimensionless shear stress known as Shields parameter (Shields, 1936), τ_c is the critical shear stress [N/m^2], g is the acceleration of gravity [m/s^2], d is the grain size [m], ρ_s is the sediment density [kg/m^3] and ρ is the fluid density [kg/m^3]. The Shields equation is widely used to determine the incipient motion condition when the sediment particle starts to move. A higher flow velocity gradient produces bed shear stress higher than the critical shear stress (which causes incipient motion), hence characterizes the ability of the flow to keep the solid in motion and to avoid deposition (Lorenzen et al., 1996). This will affect the sediment discharge Q_s as mentioned in Equation (2). The cross section area of sediment A_s also will affect the sediment discharge Q_s since the sediment discharge is a function of the sediment cross section area and the sediment velocity (Montes et al., 2022). Besides, the cohesiveness of the sediment will influence the porosity ρ_s which determine the easiness of the particles to be suspended by the incoming flush.

3.1 Level of consolidation, cohesiveness and porosity

Consolidation process exerts a significant influence on the erosion behaviour of sewer sediment. Post changes (consolidation and biological reaction) lead to the development of cohesive sediment bed. In terms of cohesiveness, the actual shear stress during the critical conditions was observed to be much higher than the required shear stress for non-cohesive sediment (Nalluri & Alvarez, 1992). This shows that non-cohesive sediment is easier to be flushed as compared to cohesive sediment (Dettmar et al., 2002). This phenomenon was further verified through flushing experiment where erosive effects in cohesive sediment beds were observed to be smaller than in granular sediments during initial flushes whereas erosion in cohesive sediments proved to be higher during subsequent flushes (Campisano et al., 2008). However, while the mode of erosion of a non-cohesive sediment is particle-by-particle, the erosion of a cohesive sediment is characterised by rapid dislodgement of large pieces of sediment once the critical shear stress is exceeded (Todeschini et al., 2008). As for porosity or void ratio, the length of flushed sediment also increases with increasing void ratio (Campisano et al., 2007). This is due to flush water easily penetrate sediment with high void ratio. Larger non-cohesive sediments also tend to have higher void ratio and flushed water easily penetrate into the sediment and more sediment particles are suspended by incoming surge and transported to downstream end.

3.2 Grain size and relative density

Grain size and relative density of deposited sediment affect the resistance of particles against mobility by the flow. Smaller grain size will cause higher scouring effect when flushed (Campisano et al., 2007). Sediment with grain size smaller than 2 mm is easier to be flushed to downstream (Shahsavari et al., 2015). For coarser sediment, the flushing efficiency will decrease. Single flush by a flush device with sharp crested weir can only break down mainly particles with diameter less than 2 mm (Shahsavari et al., 2015). Besides, structure of sediment bed is crucial for the removal effectiveness of the flush. Sediment consists of silts, construction and street asphalt debris have high density and will cover the bed structure, causing it hard to be removed (Shahsavari et al., 2015).

3.3 Thickness

Sediment deposit thickness affects the incipient motion of particles and storm sewer ability to erode the deposits (Ab Ghani, 1993). As the thickness of sediment deposit increased, the critical velocity required for incipient motion also increased (Bertrand-Krajewski et al., 2005; Bong et al., 2013b). Thicker sediment deposit might cause formation of micro-bed forms leading to additional resistance and friction between sediment particles resulting in higher critical velocity to move the particles. Hence, number of flushes needed for particle removal increases as the sediment bed deposit thickness increased (Bong et al., 2013a). Recent study has defined the sediment bed thickness into two layers, namely: i) “pavement layer” which is the active transport layer at the top of the deposit and contain sediment particles that are reliable to frequent vertical movements; and ii) “sub-pavement layer” that contains particles liable to occasional vertical movements to and from the pavement layer (Campisano et al., 2019) in developing a model for non-uniform sediment transport induced by flushing. Another recent study has shown that as sediment thickness increased, the scouring rate at the front section slightly decreases whereas the opposite is observed at the middle and end sections (Liu et al., 2021).

4. Flushing Device Characteristics

Generally, the operations of the flushing device involve two stages: (1) storage stage where water build up to a predetermined level for the device to operate; and (2) water released from the device and generate flush wave towards the downstream end of the storm sewer. The amount of water stored prior to device operation will determine the volume of the flush (Fan et al., 2001; Walski et al., 2011) and influence the water discharge Q and flow velocity V during flushing which is related to the sediment bed velocity and sediment transport in sewer (Montes et al., 2021). Furthermore, the height of water stored by the device prior to flushing will determine the extent of the flush wave in the sewer (Dettmar, 2007).

4.1 Location of flushing device

Location of flush device affects the wave velocity contributed to scouring of the sediment deposits. Sediment deposits in the sewer downstream section that is too far from the flush device remains almost unaltered after flushing (Lorenzen et al., 1996). The greatest cleaning effects with complete bed erosion were observed close to the flush device due to the maximum wave energy in that area (Ristenpart, 1998). The influence of flushing is restricted to a limited distance.

4.2 Upstream water level

The initial water level and stored volume that are designed for the flush device operation affects 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 (Lorenzen et al., 1996; Guo et al., 2004). Higher upstream water level resulted in higher potential energy per unit weight of water for flushing, creating higher scouring effects resulting in increased weight of flushed sediment (Guo et al., 2004). Flush wave moves further downstream as upstream water level increases which resulted in the effect of height of flushing on the flushing length is more dominant than the flushing volume (Dettmar, 2007).

4.3 Duration and frequency of flushing

More stored water volume resulted in longer single flush duration which plays the key role in the duration of the erosion process (Campisano et al., 2007). Self-cleansing criterion was assumed to be fulfilled when the generated shear stresses lasted for a minimum duration of 10s higher than 3 N/m^2 so that the effect on sediment transport would be sufficient (Shirazi et al., 2008). Study by Walski et al. (2011) has shown that for longer duration pulses (flushes) which originated close to the sediment, the flow rate appeared to be more important than the volume. However, for short pulses (flushes) with some distance between the flushing device and the sediment, peak attenuation reduced the flow and the volume of the pulse (flush) was more important (Walski et al., 2011). The frequency of flush events and the time of arrival of a flush are important qualities in determining the efficiency of hydraulic flushing (Lorenzen et al., 1996; Ristenpart, 1998). Single flush might significantly modify the sediment composition and structures depending on the type of the flow (Shahsavari et al., 2017). Short flushing duration is more efficient in terms of total volume of sediment being removed from the storm sewer as compared to long flushing duration (Bong et al., 2017). However, in terms of mean sediment bed advancement, longer flushing duration will move the sediment bed front further as compared to short duration flush. This is due to longer duration flushing allowed more time for sediment transport processes to happen; resulting in more sediment particles were carried further from the initial sediment bed position. Hence, flushing devices with short flushing duration and high frequency are more efficient than long flushing duration with less flushing frequency (Bong et al., 2017).

5. Environmental Factors

Environmental factors are considered external factors that are generally beyond control in designing flush device for hydraulic flushing. Nevertheless, these external factors need to be taken into consideration in the planning and maintenance of flush devices since it will affect the flush efficiency. For example, the frequency of rainfall may have effect on the sediment build up in sewer which affect the sediment thickness while debris in sewer may disturb the operation of the flushing devices.

5.1 Rainfall

Rainfall is an active factor that impact erosion and transport of sediment in sewer (Jean et al., 2018), especially for combined sewer system (CSS) and storm sewer. Frequency and intensity of rainfall in tropical climate tend to be higher than those in temperate climate. Thus, frequent rainfall will increase the number of hydraulic flushing operation of flushing devices. Besides, the intensity of rainfall affects the downstream water level in open storm sewer. It is probable that the flush may not has the same effect as if there is a low water level downstream of the storm sewer (Lorenzen et al., 1996). Moreover, frequent rainfall will reduce the sediment build up in sewer (Yu et al., 2022), hence reducing the thickness of the sediment bed.

5.2 Debris

Debris transported by the flow might disturb the flushing device operation (Bertrand-Krajewski et al., 2003). Maintenance of the flushing device and cleaning of litter caught at the device need to be done when necessary to maintain the system performance and avoid backflow or overflow of water during the device operation (Bong et al., 2016).

6. Risk Assessment of Sewer Sediment Flushing

The factors as listed in the previous sections will impact the flushing devices operation as well as the efficiency of the sediment removal. This may lead to severe adverse effect on the sewer system such as blockage and overflow. Table 1 shows the risks on the hydraulic flushing system and the related factors.

Table 1
Risks on the hydraulic flushing system and the related factors.

Risks	Factors
Flushing failed to happen	Debris, initial downstream water level too high
Frequency of flushing reduced	Rainfall, initial upstream and downstream water level
Weak flush waves	Initial upstream and downstream water level, sewer characteristics, debris causing flush device malfunction
Amount of flushed sediment reduced	Initial upstream and downstream water level, high bottom roughness, sediment characteristics, sediment bed thickness, location of flushing devices, sewer characteristics

Each factor will determine the design and selection of suitable hydraulic flushing system. Hence, the design of hydraulic flushing system for sewer sediment removal is a decision-making process involving multiple tasks including site investigation, hydraulic investigation, data analysis and numerical modeling to determine the factors as listed in the previous sections. In each task, risk and uncertainty might exist to influence the satisfactory performance of the system as it consists of a collection of storage, flushing and convey process. According to the Urban Water Resources Research Council of American Society of Civil Engineers and the Water Environment Federation; risk is defined as: "*An expression of potential adverse measured in terms of inconvenience, damage, safety, or even professional liability or political retribution*" (ASCE & WEF, 1992). Risk can be equated with the probability of failure and can be evaluated through Risk Priority Number (RPN) which is the multiplication of three ranked rating; namely severity (S), occurrence (O) and detection (D) (McDermott et al., 2008) as shown in Equation (5):

$$RPN = S \times O \times D \tag{5}$$

Risk analysis must be conducted systematically by considering the formulating design parameters and guiding the decision-making process. According to Korving et al. (2009), uncertainties in risk analysis can primarily be divided into two categories: natural variability and epistemic uncertainty for their study on sewer system rehabilitation. Variability represents spatial and temporal variability in nature (for example rainfall) while uncertainty represents the lack of sufficient data (statistical uncertainty) and the lack of knowledge about the physical system (model uncertainty) (Korving et al., 2009).

Further work on the reliability and risk analysis for sewer sediment flushing system is suggested to be done using simulation and modeling such as artificial intelligence (AI), multi-criterion decision making (MCDM) approach and mathematical programming (MP) and other approaches such as Monte Carlo simulation to obtain accurate and robust risk evaluation. Artificial intelligence such as Artificial Neural Networks (ANNs) and Support Vector Machines (SVMs) has been used in predicting structural sewer condition (Sousa et al., 2014). Multi-criteria Decision Making (MCDM) such as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) has been used in decision-making for urban sewer network plan selection (Wu & Abdul-Nour, 2020); while Grey Theory has been found to be suitable for inexact, short sample and incomplete data (Ip et al., 2009). Mathematical programming (MP) such as Linear Programming has been used for optimal design of sewer line (Swamee & Sharma, 2013). Other approaches such as Monte Carlo simulation has been used to estimate uncertainty in sewer sediment depth prediction (Schellart et al., 2010) and probabilistic approach using Bayesian Network for risk assessment to prioritize network inspection (Anbari et al., 2017). Figure 1 summarizes the factors that can affect the efficiency of hydraulic flushing and the input into decision-making tools to design a hydraulic flushing system for sewer with optimum performance.

7. Conclusion

Hydraulic flushing is one of the most popular method to sedimentation control in sewer system. A number of studies have been conducted to determine the factors that affect the efficiency of hydraulic flushing in sewer which generally can be classify into four main components, namely: (1) sewer characteristics, (2) sediment characteristics (3) flushing device characteristics and (4) environmental factors. However, limited studies have been done on the reliability and risk of these factors on hydraulic flushing performance. Moreover, only limited studies exist on the use of decision-making tools for sewer network planning and management. Therefore, further studies are encouraged in assessing the reliability and risk of hydraulic flushing in sewer using decision-making tool in order to have an optimum performance for sedimentation control.

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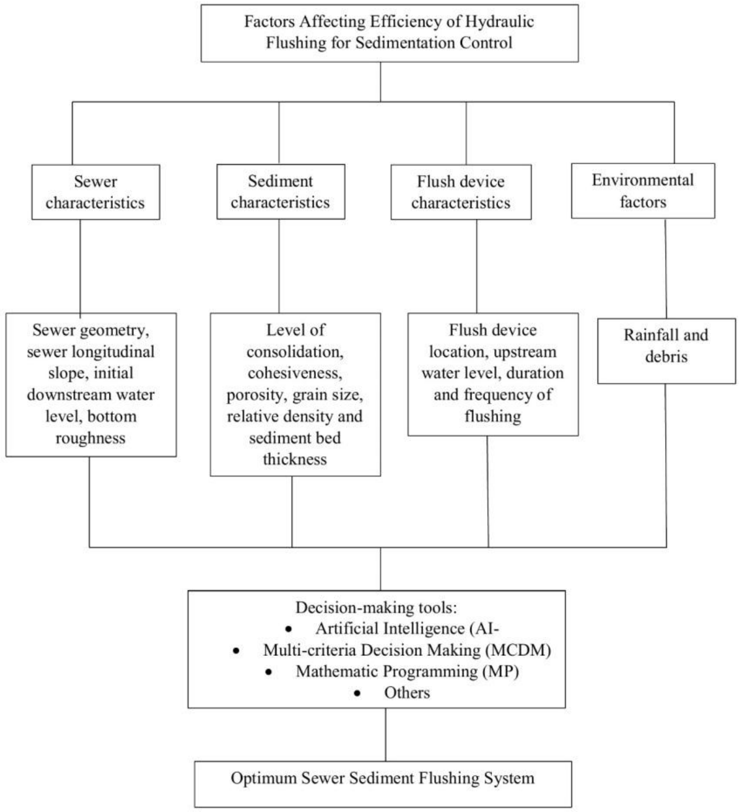

Fig. 1. Factors affecting efficiency of hydraulic flushing system and the variables for decision making for optimum sewer sediment flushing performance

References

Ab Ghani, A. (1993). *Sediment transport in sewers* [Doctoral dissertation, University of Newcastle upon Tyne, UK].

Anbari, M. J., Tabesh, M., & Roozbahani, A. (2017). Risk assessment model to prioritize sewer pipes inspection in wastewater collection networks. *Journal of Environmental Management*, *190*, 91–101. https://doi.org/10.1016/j.jenvman.2016.12.052

ASCE & WEF (1992). *Design and Construction of Urban Stormwater Management Systems*. American Society of Civil Engineers. https://doi.org/10.1061/9780872628557

Bertrand-Krajewski, J.-L. (2008). Flushing urban sewers until the beginning of the 20th century. *11th International Conference on Urban Drainage*, Edinburgh, Scotland, UK.

Bertrand-Krajewski, J.-L., Bardin, J.-P., Gibello, C., & Laplace, D. (2003). Hydraulics of a sewer flushing gate. *Water Science and Technology*, *47*(4), 129–136. https://doi.org/10.2166/wst.2003.0237

Bertrand-Krajewski, J.-L., Campisano, A., Creaco, E., & Modica, C. (2005). Experimental analysis of the Hydrass flushing gate and field validation of flush propagation modelling. *Water Science and Technology*, *51*(2), 129–137. https://doi.org/10.2166/wst.2005.0040

Bong, C. H. J., Lau, T. L., & Ab Ghani, A. (2013a). Hydraulics characteristics of tipping sediment flushing gate. *Water Science and Technology*, *68*(11). https://doi.org/10.2166/wst.2013.498

Bong, C. H. J., Lau, T. L., & Ghani, A. A. (2013b). Verification of equations for incipient motion studies for a rigid rectangular channel. *Water Science and Technology*, *67*(2). https://doi.org/10.2166/wst.2012.580

Bong, C. H. J., Lau, T. L., & Ab. Ghani, A. (2014). Sediment size and deposition characteristics in Malaysian urban concrete drains - a case study of

Kuching City. *Urban Water Journal*, *11*(1). https://doi.org/10.1080/1573062X.2012.750371

Bong, C. H. J., Lau, T. L., & Ab. Ghani, A. (2016). Potential of tipping flush gate for sedimentation management in open stormwater sewer. *Urban Water Journal*, *13*(5). https://doi.org/10.1080/1573062X.2014.994002

Bong, C. H. J., Lau, T. L., & Ab Ghani, A. (2017). Duration of hydraulic flushing and its effect on sediment bed movement. *37th IAHR World Congress*, Kuala Lumpur, Malaysia.

Bong, C. H. J., Lau, T. L., & Ghani, A. A. (2013b). Verification of equations for incipient motion studies for a rigid rectangular channel. *Water Science and Technology*, *67*(2). https://doi.org/10.2166/wst.2012.580

Campisano, A., Creaco, E., & Modica, C. (2004). Experimental and numerical analysis of the scouring effects of flushing waves on sediment deposits. *Journal of Hydrology*, *299*(3), 324–334. https://doi.org/https://doi.org/10.1016/j.jhydrol.2004.08.009

Campisano, A., Creaco, E., & Modica, C. (2007). Dimensionless Approach for the Design of Flushing Gates in Sewer Channels. *Journal of Hydraulic Engineering*, *133*(8), 964–972. https://doi.org/10.1061/(ASCE)0733-9429(2007)133:8(964)

Campisano, A., Creaco, E., & Modica, C. (2008). Laboratory investigation on the effects of flushes on cohesive sediment beds. *Urban Water Journal*, *5*(1), 3–14. https://doi.org/10.1080/15730620701726259

Campisano, A., Modica, C., Creaco, E., & Shahsavari, G. (2019). A model for non-uniform sediment transport induced by flushing in sewer channels. *Water Research*, *163*, 114903. https://doi.org/https://doi.org/10.1016/j.watres.2019.114903

Crabtree, R. W. (1989). Sediments in Sewers. *Water and Environment Journal*, *3*(6), 569–578. https://doi.org/https://doi.org/10.1111/j.1747-6593.1989.tb01437.x

Creaco, E., & Bertrand-Krajewski, J.-L. (2007). Modelling the flushing of sediments in a combined sewer. *Novatech*, Lyon, France.

Dettmar, J. (2007). A new planning procedure for sewer flushing. *Novatech*, Lyon, France.

Dettmar, J., Rietsch, B., & Lorenz, U. (2002). Performance and operation of flushing devices - results of a field and laboratory study. *9th International Conference on Urban Drainage*, 1–10.Portland, Oregon, USA.

Fan, C.-Y., Field, R., Pisano, W. C., & Barsanti, J. (2001). Sewer and tank flushing for sediment, corrosion, and pollution control. *Journal of Water Resources Planning and Management*, *127*(3), 194–201.

Gendreau, N., le Guennec, B., Poinot-Chazal, J. P., & Sechet, P. (1993). Sediment motion under flood wave - use of partial release of stored water by a weir. *6th International Conference on Urban Storm Drainage*, 760–765.

Guo, Q., Fan, C.-Y., Raghaven, R., & Field, R. (2004). Gate and Vacuum Flushing of Sewer Sediment: Laboratory Testing. *Journal of Hydraulic Engineering*, *130*(5), 463–466. https://doi.org/10.1061/(ASCE)0733-9429(2004)130:5(463)

Ip, W. C., Hu, B. Q., Wong, H., & Xia, J. (2009). Applications of grey relational method to river environment quality evaluation in China. *Journal of Hydrology*, *379*(3–4), 284–290. https://doi.org/10.1016/j.jhydrol.2009.10.013

Jean, M.-È., Duchesne, S., Pelletier, G., & Pleau, M. (2018). Selection of rainfall information as input data for the design of combined sewer overflow solutions. *Journal of Hydrology*, *565*, 559–569. https://doi.org/https://doi.org/10.1016/j.jhydrol.2018.08.064

Korving, H., van Noortwijk, J. M., van Gelder, P. H. A. J. M., & Clemens, F. H. L. R. (2009). Risk-based design of sewer system rehabilitation. *Structure and Infrastructure Engineering*, *5*(3), 215–227. https://doi.org/10.1080/15732470601114299

Liu, C., Lv, W., Liu, Q., Zhou, J., Wang, Y., Zhang, X., & Zhou, J. (2021). Analysis and calculation of sediment scouring rate at different locations of storm sewer. *Water Science and Technology*, *84*(6), 1340–1353. https://doi.org/10.2166/wst.2021.334

Lorenzen, A., Ristenpart, E., & Pfuhl, W. (1996). Flush cleaning of sewers. *Water Science and Technology*, *33*(9), 221–228. https://doi.org/10.1016/0273-1223(96)00390-3

McDermott, R. E., Mikulak, R. J., & Beauregard, M. R. (2008). *The Basics of FMEA* (2nd ed.). CRC Press.

Meyer-Peter, E., & Muller, R. (1948). Formulas for bed-load transport. *2nd Congress of the International Association of Hydraulic Research*, Stockholm, Sweden.

Montes, C., Kapelan, Z., & Saldarriaga, J. (2021). Predicting non-deposition sediment transport in sewer pipes using Random forest. *Water Research, 189*. https://doi.org/10.1016/j.watres.2020.116639

Montes, C., Ortiz, H., Vanegas, S., Kapelan, Z., Berardi, L., & Saldarriaga, J. (2022). Sediment transport prediction in sewer pipes during flushing operation. *Urban Water Journal*, *19*(1), 1–14. https://doi.org/10.1080/1573062X.2021.1948077

Nalluri, C., & Alvarez, E. M. (1992). The Influence of Cohesion on Sediment Behaviour. *Water Science and Technology*, *25*(8), 151–164. https://doi.org/10.2166/wst.1992.0189

Penn, R., Schuetze, M., Jens, A., & Friedler, E. (2018). Tracking and simulation of gross solids transport in sewers. *Urban Water Journal*, *15*(6), 584–591. https://doi.org/10.1080/1573062X.2018.1529190

Pisano, W. C., O'Riordan, O. C., Ayotte, F. J., Barsanti, J. R., & Carr, D. L. (2003). Automated Sewer and Drainage Flushing Systems in Cambridge, Massachusetts. *Journal of Hydraulic Engineering*, *129*(4), 260–266. https://doi.org/10.1061/(ASCE)0733-9429(2003)129:4(260)

Ristenpart, E. (1998). Solids transport by flushing of combined sewers. *Water Science and Technology*, *37*(1), 171–178. https://doi.org/10.2166/wst.1998.0042

Safari, M. J. S., Mohammadi, M., & Gilanizadehdizaj, G. (2014). On the effect of cross sectional shape on incipient motion and deposition of sediments in fixed bed channels. *Journal of Hydrology and Hydromechanics*, *62*(1), 75–81. https://doi.org/10.2478/johh-2014-0003

Schaffner, J., & Steinhard, J. (2006). Numerical investigation of the self-acting flushing system HydroFlush GS in Frankenberg/Germany. *2th Conference on Sewer Operation and Maintenance*, Vienna, Austria.

Schaffner, J., & Steinhardt, J. (2013). Numerical investigations on the influence of hydraulic boundary conditions on the efficiency of sewer flushing. *7th International Conference on Sewer Processes and Networks*, Sheffield, UK https://www.researchgate.net/publication/280567477

Schellart, A. N. A., Tait, S. J., & Ashley, R. M. (2010). Estimation of Uncertainty in Long-Term Sewer Sediment Predictions Using a Response Database. *Journal of Hydraulic Engineering*, *136*(7), 403–411. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000193

Shahsavari, G., Arnaud-Fassetta, G., Bertilotti, G. R., Campisano, A., & Riou, F. (2015). Bed evolution under one-episode flushing in a trunk sewer in Paris, France. *International Journal of Civil and Environmental Engineering*, *9*(7), 759–768. https://www.researchgate.net/publication/276275265

Shahsavari, G., Arnaud-Fassetta, G., & Campisano, A. (2017). A field experiment to evaluate the cleaning performance of sewer flushing on non-uniform sediment deposits. *Water Research*, *118*, 59–69. https://doi.org/https://doi.org/10.1016/j.watres.2017.04.026

Shields, A. (1936). *Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung* [Doctoral dissertation, Mitt. Preuss. Versuchsanst. Wasserbau Schiffbau].

Shirazi, R. H. S. M., Bouteligier, R., Willems, P., & Berlamont, J. (2008). Preliminary results of investigating proper location of flushing tanks in combined sewer networks for optimum effect. *11th International Conference on Urban Drainage*, Edinburgh, Scotland, UK.

Sousa, V., Matos, J. P., & Matias, N. (2014). Evaluation of artificial intelligence tool performance and uncertainty for predicting sewer structural condition. *Automation in Construction*, *44*, 84–91. https://doi.org/https://doi.org/10.1016/j.autcon.2014.04.004

Swamee, P. K., & Sharma, A. K. (2013). Optimal design of a sewer line using Linear Programming. *Applied Mathematical Modelling*, *37*(6), 4430–4439. https://doi.org/https://doi.org/10.1016/j.apm.2012.09.041

Todeschini, S., Ciaponi, C., & Papiri, S. (2008). Experimental and numerical analysis of erosion and sediment transport of flushing waves. *11th International Conference on Urban Drainage*, Edinburgh, Scotland, UK.

Walski, T., Falco, J., McAloon, M., & Whitman, B. (2011). Transport of large solids in unsteady flow in sewers. *Urban Water Journal*, *8*(3), 179–187. https://doi.org/10.1080/1573062X.2011.581298

Wu, Z., & Abdul-Nour, G. (2020). Comparison of Multi-Criteria Group Decision-Making Methods for Urban Sewer Network Plan Selection. *CivilEng*, *1*(1), 26–48. https://doi.org/10.3390/civileng1010003

Yang, H., Zhu, D. Z., Zhang, Y., & Zhou, Y. (2019). Numerical investigation on bottom shear stress induced by flushing gate for sewer cleaning. *Water Science and Technology*, *80*(2), 290–299. https://doi.org/10.2166/wst.2019.269

Yu, D., Dian, L., Hai, Y., Randall, M. T., Liu, L., Liu, J., Zhang, J., Zheng, X., & Wei, Y. (2022). Effect of rainfall characteristics on the sewer sediment, hydrograph, and pollutant discharge of combined sewer overflow. *Journal of Environmental Management*, *303*, 114268. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.114268

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Doi: 10.22094/joie.2022.1951664.1936