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1 **Sediment Transport Prediction in Sewer Pipes During Flushing Operation**

2 Carlos Montes<sup>a\*</sup>, Hachly Ortiz<sup>b</sup>, Sergio Vanegas<sup>c</sup>, Zoran Kapelan<sup>d</sup>, Luigi Berardi<sup>e</sup> and  
3 Juan Saldarriaga<sup>f</sup>

4 <sup>a</sup>*Department of Civil and Environmental Engineering, Universidad de los Andes, Bogotá,*  
5 *Colombia; e-mail: cd.montes1256@uniandes.edu.co*

6 <sup>b</sup>*Department of Civil and Environmental Engineering, Universidad de los Andes, Bogotá,*  
7 *Colombia; e-mail: hv.ortiz@uniandes.edu.co*

8 <sup>c</sup>*Department of Civil and Environmental Engineering, Universidad de los Andes, Bogotá,*  
9 *Colombia; e-mail: sm.vanegas@uniandes.edu.co*

10 <sup>d</sup>*Department of Water Management, Delft University of Technology, Delft, Netherlands;*  
11 *e-mail: Z.Kapelan@tudelft.nl*

12 <sup>e</sup>*Department of Engineering and Geology, Università degli Studi "G. d'Annunzio" Chieti,*  
13 *Pescara, Italy; e-mail: luigi.berardi@unich.it*

14 <sup>f</sup>*Department of Civil and Environmental Engineering, Universidad de los Andes, Bogotá,*  
15 *Colombia; e-mail: jsaldarr@uniandes.edu.co*

16 \*Corresponding author; Correspondence address: Cra 1 Este No. 19A – 40 Bogota  
17 (Colombia); Tel.: +57-1-339-49-49 (ext. 1765)

# Sediment Transport Prediction in Sewer Pipes During Flushing Operation

## Abstract

This paper presents a novel model for predicting the sediment transport rate during flushing operation in sewers. The model was developed using the Evolutionary Polynomial Regression Multi-Objective Genetic Algorithm (EPR-MOGA) methodology applied to new experimental data collected. Using the new model, a series of design charts were developed to predict the sediment transport rate and the required flushing operation time for several pipe diameters. Accurate results (i.e. sediment transport rates) were obtained when applied to a case study in a combined sewer pipe in Marseille, as reported in the literature. The novelty of the model is the inclusion of the pipe slope, the inflow “dam break” hydrograph, and the sediment properties as explanatory parameters. The new model can be used to predict flushing efficiency and design new flushing cleaning schedules in sewer systems.

Keywords: flushing efficiency; sediment transport; sewer cleansing; sewer flushing.

## 1. INTRODUCTION

Sediment deposition and accumulation are well-known issues in sewer systems modelling. The presence of permanent deposits of material at the bottom of sewer pipes produces several problems, such as reduced flow capacity and premature combined sewer overflows (Ashley et al. 2004; Rodríguez et al. 2012). Flushing waves, also known as surge flushing technique, have been identified as an efficient (Bong et al. 2016; Yang et al. 2019) and cost-effective (Campisano et al. 2019, 2007) method for solving these problems. It aims to remove the deposited sediments by generating waves, which are produced by the upstream storage and further discharge of water volumes. These flushing

43 waves increase the bottom shear stress and induce the scour and resuspension of the  
44 deposited material.

45         The above flushing technique has been applied in several case studies following  
46 operational and management practice guides (British Standard Institution, 2014; Fan,  
47 2004; Hlavinek et al. 2005; NEIWPC, 2003) in countries such as Germany, France, the  
48 USA and the UK. As an example, Hlavinek et al. (2005) suggest flushing waves to  
49 remove settled deposits in sewers ranging from 100 mm to 1200 mm pipe diameter with  
50 a mandatory cleaning frequency once in 1 to 5 years. However, these guides do not  
51 specify important flushing parameters such as the hydraulic and pipe characteristics (i.e.  
52 length, slope and hydraulic roughness, among others), sediment properties and flushing  
53 volume. The lack of information on these specifications has contributed to the fact that  
54 existing flushing practices tend to be oversized. As an instance, Dettmar (2007) compared  
55 design tables developed by using extensive field studies and mathematical simulations  
56 (Chebbo et al. 1996; Dettmar, 2005; Lainé et al. 1998) and concluded that smaller  
57 flushing volumes and water storage heights achieve the same flushing length and  
58 efficiency in removing the volume of deposited sediments, compared to operational and  
59 management practice guides.

60         In the last decades, several studies have quantified the flushing efficiency in terms  
61 of: (a) reduction of volume and/or weight of sediments (Bong et al. 2016; Campisano et  
62 al. 2019, 2008, 2004; Creaco and Bertrand-Krajewski, 2009; Guo et al. 2004; Ristenpart,  
63 1998; Shahsavari et al. 2017), (b) changes in deposited bed thickness (Bong et al. 2016,  
64 2013a; Campisano et al. 2019, 2008, 2007, 2004; Dettmar et al. 2002; Ristenpart, 1998;  
65 Shahsavari et al., 2017; Shirazi et al. 2014), (c) variation of concentrations of total  
66 suspended solids (Ristenpart, 1998; Sakakibara, 1996), (d) increase in the bottom shear

67 stress (Bertrand-Krajewski et al. 2003; Campisano et al. 2008; Campisano and Modica,  
68 2003; Dettmar et al. 2002; Ristenpart, 1998; Schaffner and Steinhardt, 2006; Yang et al.  
69 2019), (e) length of the channel that can be potentially cleaned (Bertrand-Krajewski et al.  
70 2003; Bong et al. 2013; Dettmar et al. 2002; Shahsavari et al. 2017; Yang et al. 2019) and  
71 (f) stored water volume discharged (Bertrand-Krajewski et al. 2003; Dettmar et al. 2002;  
72 Fan et al. 2001). These studies were carried out in both laboratory and real sewer flumes  
73 using different sediment characteristics, stored water volumes and geometrical  
74 characteristics of the flume. As a result, a list of parameters affecting the flushing  
75 efficiency was identified and classified in three main groups: (i) flushing hydraulics, (ii)  
76 pipe geometry and (iii) sediment properties. Flushing hydraulic parameters include water  
77 velocity ( $V_f$ ), shear stress ( $\tau$ ), the water level in the pipe ( $Y$ ), flowrate ( $Q$ ), stored water  
78 head ( $h_o$ ) and stored water volume discharged ( $V_a$ ). In the pipe geometry, parameters as  
79 the slope ( $S_o$ ), diameter ( $D$ ), length ( $L$ ), cross-section shape factor ( $\beta$ ) and composite  
80 roughness ( $k_c$ ) have been included. Finally, sediment properties include mean particle  
81 diameter ( $d$ ), sediment thickness ( $y_s$ ) and width ( $W_b$ ), specific gravity ( $SG$ ), porosity ( $\eta$ )  
82 and density ( $\rho_s$ ).

83         The previous three groups of parameters have been used for implementing  
84 numerical models useful to quantify the flushing efficiency. Models found in the literature  
85 are focused on (i) solving complex mathematical structures, (ii) proposing simple  
86 dimensionless equations for estimating sediment transport rates and (iii) using Machine  
87 Learning (ML) and Artificial Intelligence (AI) techniques for finding patterns in data and  
88 predicting bedload and suspended load transport.

89         In the first approach, the one-dimensional Saint-Venant equations (Campisano et  
90 al. 2006; Campisano and Modica, 2003; De Sutter et al. 1999), coupled with the Exner

91 equation for uniform (Campisano et al. 2007, 2004; Creaco and Bertrand-Krajewski,  
 92 2009; Shirazi et al. 2014) and non-uniform (Campisano et al. 2019) sediments, are used  
 93 for predicting bed sediment thickness changes during the flushing operation. More  
 94 complex models involve the two-dimensional (Caviedes-Voullième et al. 2017; Yu and  
 95 Duan, 2014) and three-dimensional (Schaffner and Steinhardt, 2006) solutions of the  
 96 Saint-Venant equations. An example of the literature models is as follows:

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

97 where  $U$ ,  $F(U)$  and  $D(U)$  are defined as follows:

$$U = \begin{bmatrix} A \\ Q \\ A_s \end{bmatrix}; F(U) = \begin{bmatrix} Q \\ V_f Q + \frac{F_h}{\rho} \\ \frac{1}{1-\rho} Q_s \end{bmatrix}; D(U) = \begin{bmatrix} 0 \\ gA \left( S_o - \frac{V_f^2}{k_c^2 R^{4/3}} \right) \\ 0 \end{bmatrix} \quad (2)$$

98 where  $F_h$  is the hydrostatic force over the cross-section,  $\rho$  the water density,  $R$  the  
 99 hydraulic radius,  $A$  is the cross section wetted area,  $A_s$  is the cross-section sediment bed  
 100 area and  $Q_s$  the sediment flow rate.

101 In the second approach mentioned above, several authors have developed  
 102 analytical equations for predicting the number of flushes required to move the deposited  
 103 sediment bed (Bong et al. 2013; Chebbo et al. 1996). Likewise, the effects of pipe slope,  
 104 bottom roughness, storage water level, and downstream water level, among others (Yang  
 105 et al. 2019; Kuriqi et al. 2020) have also been studied in the past. As an example, Bong  
 106 et al. (2013) proposed the following equation, where  $n_f$  is the number of flushes required  
 107 to move the deposited sediment bed by 1 m:

$$n_f = 251.43y_s + 6.57 \quad (3)$$

108           In the third approach, several studies using ML and AI have been developed for  
109 predicting both bedload and suspended load transport in sewers, flumes, and streams.  
110 Several techniques as Artificial Neural Networks (Wan Mohtar et al. 2018; Bajirao et al.  
111 2021), Random Forests (Khosravi et al. 2020; Safari 2020; Montes et al. 2021), and  
112 Vector Machines (Ebtehaj et al. 2017), among others, have been trained with  
113 experimental data collected at laboratory scale and tested with benchmark data found in  
114 the literature. These models outperform traditional regression formulas during the  
115 training stage but tend to underperform when applied to external datasets collected in  
116 sewers and flumes (Montes et al. 2021), i.e. during the testing stage.

117           Numerical studies mentioned above, based on the solution of the Saint-Venant  
118 and Exner coupled-equations for sediment transport under unsteady flow conditions,  
119 show similar predictions of the sediment thickness changes compared to the experimental  
120 data collected, i.e. the models show good accuracy prediction. Despite the solutions and  
121 simulations based on Saint Venant-Exner equations showing good accuracy, in practice,  
122 the application for operational and management practices is complex and non-pragmatic.  
123 Also, the analytical and dimensionless equations proposed by Bong et al. (2013) and  
124 Yang et al. (2019), do not include important parameters such as the pipe/flume geometry  
125 and the sediment characteristics. Finally, AI and ML models are largely black-box models  
126 (Montes et al. 2021), limiting their interpretability for practical applications.

127           The above gaps are addressed here by developing a new parsimonious regression-  
128 based model using the Evolutionary Polynomial Regression – Multi-Objective Genetic  
129 Algorithm (EPR-MOGA) (Giustolisi and Savic, 2009) strategy. EPR-MOGA is a data-  
130 driven method which combines genetic algorithm with evolutionary computing for  
131 finding polynomial structures. Due to its characteristics, the returned symbolic

132 expressions can be compared with existing models in terms of the input variables,  
133 exponent coefficients, and technical insight on the phenomenon (Montes et al. 2020a)  
134 while reducing the risk of overfitting.

135 This paper aims to propose a new model for predicting the sediment transport rate  
136 during flushing operations in sewers. The novelty of this model is the inclusion of  
137 flushing “dam break” hydrograph, pipe geometry, and deposited sediment characteristics  
138 in a simple polynomial expression. The new model developed here can be used to  
139 optimize flushing schemes and reduce the volume of water required for cleaning sewers.

## 140 **2. EXPERIMENTAL METHODS AND DATA COLLECTION**

141 The collection of experimental data was carried out in two pipes with diameters of 209  
142 mm and 595 mm (Montes et al. 2020b), both located at the Hydraulics Laboratory of the  
143 University of the Andes, Colombia. A sediment bed with a near-uniform thickness and  
144 width was prepared at the bottom of the pipes, using uniformly graded sediment material  
145 ranging from 0.21 mm to 2.6 mm. These particles had a specific gravity between 2.57  
146 and 2.67, which was calculated using the pycnometer method (ASTM D854-14, 2014).  
147 The experiments were carried out under unsteady flow conditions, simulating the “dam  
148 break” waves produced during a flushing event. The methodology used for data collection  
149 and further details of both experimental setups are described below.

### 150 ***2.1. 209 mm pipe setup***

151 The 209 mm diameter acrylic pipe had a length of 10.58 m and was supported on six  
152 hydraulic jacks, which allowed to vary the pipe slope between 0.64% and 1.20%. This  
153 pipe was connected to a 200 mm solenoid valve, which controlled the inflow into the  
154 setup from a 3.5 m<sup>3</sup> upstream tank. A downstream tank with a V-Notch weir was used to



155 measure the water discharge. A real-time water level sensor was used to measure the  
156 water height over the weir to calculate the water discharge rate using the V-Notch  
157 equation. The calculated discharge was also checked using an ABB- Electromagnetic  
158 flowmeter sensor installed upstream of the pipe. Two additional real-time water level  
159 sensors were installed along the pipe, aiming to measure the stage hydrograph produced  
160 by the flushing waves. Figure 1 shows the general scheme of the experimental setup.

161 The experimental data was collected as follows. Firstly, the solenoid valve was  
162 fully opened, allowing a base flowrate ranging from  $0.002 \text{ l s}^{-1}$  to  $0.414 \text{ l s}^{-1}$ . The opening  
163 of this valve simulates the ‘dam break hydrograph’ produced during a flushing operation  
164 in a real sewer pipe (e.g. using a Hydrass or a Hydrosel self flushing gate). Secondly, a  
165 sediment bed with near-uniform thickness and width was located at the bottom of the  
166 pipe. At this point, the base flowrate helped the formation of the deposited bed along a  
167 3.3 m section. Thirdly, the solenoid valve was completely closed for storing a volume of  
168 water between  $0.10 \text{ m}^3$  and  $0.31 \text{ m}^3$  in the upstream tank. Fourthly, the solenoid valve  
169 was opened between 60% and 100% and the opening time was set to 15 sec for all tests.  
170 When the first discharged wave reached the sediment bed, the movement of the bed was  
171 tracked over time. The sediment velocity ( $V_s$ ) was calculated using the values of the time  
172 and deposited bed displacement during the peak flow. The above procedure was repeated  
173 for different accumulated upstream water volume and percentage of the solenoid valve  
174 opening.

175 **[Figure 1 near here]**

176 ***2.2. 595 mm pipe setup***

177 The pipe was 10.5 m long and supported on a mechanical steel truss, which allowed to  
178 modify the slope in a range between 0.04% and 3.44%. The base flow for the experiments,

179 ranging from  $1.03 \text{ l s}^{-1}$  to  $9.98 \text{ l s}^{-1}$ , was provided by a 40 BHP pump that supplied water  
180 to a  $30 \text{ m}^3$  upstream storage which was directly connected to the pipe. For evaluating  
181 unsteady flow conditions in this pipe, a second 10 BHP submersible pump was located  
182 inside the downstream tank. This pump was directly connected to the upstream tank and  
183 was controlled with a variable frequency drive programmed before the experiment to  
184 create a pulse with a maximum peak flow of  $30 \text{ l s}^{-1}$ . Three water level sensors were used  
185 to record water depths in the experimental setup. Two of them were installed in the pipe  
186 to collect the stage hydrograph, and one was installed in the upstream tank. Full details  
187 of the experimental setup were described in Montes et al. (2020b) and are shown in Figure  
188 2.

189 **[Figure 2 near here]**

190 For this setup, the data was collected as follows. Firstly, the pipe slope was  
191 adjusted using the mechanical steel truss and measured with a dumpy level. Secondly, the  
192 flow control valve on the upstream tank was opened to supply a base flow to the pipe.  
193 Thirdly, a deposited sediment bed with a near-uniform width was prepared at the bottom  
194 of the pipe over a minimum length of 1.5 m. At this point, to compare the flushing  
195 efficiency under similar conditions, the maximum sediment bed velocity was verified as  
196  $0.03 \text{ m s}^{-1}$ . If this condition was not fulfilled, the pipe slope or the base flow were changed.  
197 Fourthly, the submersible pump, with its variable frequency drive, was activated to  
198 simulate the ‘dam break hydrograph’, which is similar to those produced by the flushing  
199 gates in real sewers. The water levels were recorded each 0.025 sec and the position of  
200 the sediment bed was tracked. The sediment velocity was calculated using the same  
201 procedure followed on the acrylic setup.

202 **2.3. Experimental data collected**

203 Using the experimental rig and approach described above, a total of 57 and 64  
204 experiments were carried out in the 209 mm acrylic pipe and 595 mm PVC pipe,  
205 respectively. Several variables related to the pipe geometry, sediment properties, and  
206 flushing hydraulics, including the base time ( $t_b$ ), peak time ( $t_p$ ), base flow ( $Q_b$ ), and peak  
207 flow ( $Q_p$ ) were recorded in each experiment, as shown in Figure 3. The experimental data  
208 collected in both acrylic and PVC pipes are presented in Table 1, where  $S_o$  is the pipe  
209 slope,  $D$  the pipe diameter,  $Y$  the water level in the pipe,  $R$  the hydraulic radius,  $d$  the  
210 mean particle diameter,  $SG$  the specific gravity,  $y_s$  the sediment thickness,  $V_f$  the water  
211 velocity, and  $V_s$  the sediment velocity.

212 **[Figure 3 near here]**

213 **[Table 1 near here]**

214 A flushing discharge hydrograph and a plot showing the sediment bed position  
215 related with each run are presented in Table 1. The shape and magnitude of the  
216 hydrograph are directly related to the sediment bed velocity, and consequently, the  
217 sediment bed position. As an example, for six runs, the variation in the sediment bed  
218 position and hydrograph characteristics, in both acrylic and PVC pipe, are presented in  
219 Figure 4. Full details of each run shown in Figure 4 are presented in Table 1.

220 **[Figure 4 near here]**

221 Figure 4A and Figure 4B show the relation between the flushing discharge  
222 hydrograph and the sediment bed position for tests conducted on the acrylic pipe. As seen  
223 in these figures, particle size is a more important variable in defining the sediment  
224 position, compared to the peak flow in the hydrograph. Even though the run 82 considers

225 a higher peak flow ( $Q_p = 5.55 \text{ l s}^{-1}$ ), the final position of the sediment bed (= 0.41 m) is  
226 lower than the run 96 (= 2.62 m) when the peak flow is lower ( $Q_p = 2.08 \text{ l s}^{-1}$ ). This occurs  
227 because the particle diameter is more relevant compared to the peak flow.

228 Figure 4C and Figure 4D show the relation between the flushing discharge  
229 hydrograph and the sediment bed position for tests in 595 mm setup. The relationship  
230 between the discharge hydrograph and the sediment bed position is proportional. For run  
231 no. 36 and 61, the mean particle diameter was 2.60 mm, but the pipe slope was 1.65%  
232 and 1.82%, respectively. Figure 4D shows that maintaining the mean particle diameter  
233 constant as the pipe slope increases, the final bed position increases.

### 234 3. MODEL DEVELOPMENT

#### 235 3.1. Graphical analysis

236 A graphical analysis was developed to visualize the relationships between the variables  
237 collected in each experiment. The relationship between sediment velocity and flow  
238 velocity ( $V_s/V_f$ ) was plotted against other dimensionless parameters, as shown in Figure  
239 5. These dimensionless parameters have been previously identified as relevant for  
240 predicting sediment transport in sewer pipes in previous literature (Ab Ghani and  
241 Azamathulla, 2011; Ebtehaj and Bonakdari, 2016; May et al. 1996; Kuriqui et al. 2020;  
242 Montes et al. 2021). Two of these parameters include the dimensionless grain size ( $d/R$ )  
243 and the Shields parameter ( $\psi$ ), defined in Eq. (4):

$$\psi = \frac{RS_o}{(SG - 1)d} \quad (4)$$

244 Based on the results shown in Figure 5, the following observations can be made:

- 245 • In general, higher values of the Shields parameter lead to higher values of  $V_s/V_f$ .  
246 This can be clearly seen in the acrylic pipe (Figure 5a) because of the constant  
247 slope value adopted in the experimental rig. Furthermore, high values of  $S_o$  and  
248  $R$  lead to higher sediment velocities due to higher critical shearing stress (i.e. the  
249 applied forces are higher than the submerged weight of the particle). In contrast,  
250 deposited materials with high density of particle diameters result in lower  
251 sediment velocities.
- 252 • The direct relationship between  $V_s/V_f$  and the Shields parameter coincides with  
253 the inversely proportional relationship between  $V_s/V_f$  and  $d/R$ , shown in Figure  
254 5c and Figure 5d. This is observed because the Shields parameter includes the  
255 ratio  $R/d$ , as shown in Eq. (4).
- 256 • Figure 5e shows the inversely proportional relationship between  $V_s/V_f$  and the  
257 dimensionless parameter  $Q_b/Q_p$ , meaning that higher and steeper discharge  
258 hydrographs (i.e. lower ratios  $Q_b/Q_p$ ) show higher  $V_s/V_f$  values.
- 259 • In general, based on what was previously mentioned, higher values of  $S_o$  and  $R$   
260 and lower values of  $d$ ,  $SG$ , and  $Q_b/Q_p$  lead to higher sediment velocities  $V_s$ .

261 **[Figure 5 near here]**

### 262 **3.2. Evolutionary Polynomial Regression model**

263 A new regression-based model was developed here to predict the dimensionless ratio  
264  $V_s/V_f$  during flushing operation. The new model includes the group of parameters  
265 identified in previous studies (Ab Ghani and Azamathulla, 2011; Ebtehaj and Bonakdari,  
266 2016; May et al. 1996; Montes et al. 2021) and the graphic analysis carried out for the  
267 experimentally collected data, as shown in Figure 5.

268 Evolutionary polynomial regression (EPR) is a hybrid regression technique that  
 269 combines numerical and symbolic regression (Giustolisi and Savic, 2006, 2004). In its  
 270 original formulation, it used single objective genetic algorithms to explore the formula  
 271 space, and then it estimates the least-squares regression coefficients. This technique has  
 272 proved to be effective when the number of polynomial terms is not large (Giustolisi and  
 273 Savic, 2009). To solve these issues, Giustolisi and Savic (Giustolisi and Savic, 2009)  
 274 introduced the EPR technique combined with a Multi-Objective Genetic Algorithm  
 275 (MOGA). This novel technique maximises the model accuracy (i.e. minimises the sum  
 276 of squared errors) and minimises the number of polynomial coefficients, and therefore  
 277 improves the exploration of the space of symbolic formulas. EPR-MOGA considers some  
 278 pseudo-polynomial expressions such as (Giustolisi and Savic, 2009):

$$\hat{\mathbf{Y}} = a_0 + \sum_{j=1}^m a_j (\mathbf{X}_1)^{ES(j,1)} \cdot \dots \cdot (\mathbf{X}_k)^{ES(j,k)} \cdot f((\mathbf{X}_1)^{ES(j,k+1)}) \cdot \dots \cdot f((\mathbf{X}_k)^{ES(j,2k)}) \quad (5)$$

279 where  $\hat{\mathbf{Y}}$  is the vector of model predictions;  $ES$  and  $j$  the matrix of candidate exponents  
 280 and the inner function, respectively, both selected by the user;  $m$  the number of terms;  
 281  $a_0$  the bias term;  $a_j$  the adjustable parameters estimated by linear least squares and  $\mathbf{X}_j$  the  
 282 candidate explanatory variables. The inner function  $f$  defined by the user can be  
 283 logarithmic, exponential, tangent hyperbolic, or secant hyperbolic, and must be selected  
 284 according to the physics of the problem studied. The EPR technique returns a range of  
 285 models showing the influence of different explanatory factors by progressively adding  
 286 these as input variables to monomial formulas, starting from the most important ones. For  
 287 each EPR identified model, the following performance indices are calculated: the  
 288 Bayesian Information Criterion ( $BIC$ ) and the Coefficient of Determination ( $R^2$ ), as  
 289 shown in Eq. (6) and Eq. (7), respectively.

$$BIC = \left(1 + d \frac{\log(n)}{n}\right) \left(\sum_{i=1}^n (Y^* - Y)^2\right) \quad (6)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (Y^* - Y)^2}{\sum_{i=1}^n (Y^* - \bar{Y}^*)^2} \quad (7)$$

290 where  $Y^*$  and  $Y$  are the observed and calculated data, respectively,  $n$  is the number of  
 291 data,  $d$  the number of parameters included in the model and  $\bar{Y}^*$  the mean of observed  
 292 data. The Coefficient of Determination measures the fraction of variance that can be  
 293 explained. Note that this coefficient varies between 0 and 1, where 1 denotes a perfect  
 294 match between observed and calculated data. The Bayesian Information Criterion  
 295 measures the trade-off between accuracy and parsimony of the model. This measure  
 296 penalises formulas with large number of parameters. The model with the lowest BIC  
 297 value is selected as optimal.

298 The new model was constructed to predict the dimensionless relation  $V_s/V_f$ , i.e.  
 299 the vector of model predictions  $\hat{Y}$  is defined as  $V_s/V_f$ . The matrix of candidate exponents  
 300 was defined with values ranging from -2.50 to 2.50, considering steps of 0.1, i.e.  $ES =$   
 301  $[-2.50, -1.40, \dots, 1.40, 2.50]$ . The matrix of candidate explanatory variables is defined  
 302 as follows:

$$\mathbf{X}_j = \left[ \psi, \frac{d}{R}, \frac{Q_b}{Q_p}, \frac{y_s}{R}, \frac{t_b}{t_p}, \beta \right] \quad (8)$$

303 Using previous considerations, and randomly splitting the experimental data  
 304 collected on the 209 mm and 595 mm pipes, for both training (75% of the data) and testing  
 305 (25% of the data) stages, the results shown in Table 2 were obtained using the EPR-  
 306 MOGA strategy.

307 **[Table 2 near here]**

308 Table 2 shows the Pareto front (i.e. range of models) generated by the EPR,  
 309 together with the corresponding  $BIC$  and  $R^2$  values. For example, the best 1 input variable  
 310 model includes only the Shields parameter as an explanatory variable for predicting the  
 311  $V_s/V_f$  ( $V_s/V_f = 0.17\psi^{0.5}$ ). This is the least complex, i.e. most parsimonious model hence,  
 312 unsurprisingly, it has a rather low prediction accuracy ( $BIC = -48.21$  and  $R^2 = 0.38$ ). In  
 313 contrast, the 6-variable model includes all candidate explanatory factors  $\left( V_s/V_f = \right.$   
 314  $2.48\psi^{1.4} \left( \frac{Q_b}{Q_p} \right)^{-0.3} \left( \frac{d}{R} \right)^{0.9} \left( \frac{y_s}{R} \right)^{0.1} \left( \frac{t_b}{t_p} \right)^{-0.2} \beta \left. \right)$ , resulting in low parsimony model but with  
 315 improved prediction accuracy ( $BIC = -92.22$  and  $R^2 = 0.64$ ). Based on this, the model  
 316 that shows the best trade-off between accuracy and parsimony is the model with 3 input  
 317 variables. This model is shown in Eq. (9).

$$\frac{V_s}{V_f} = 8.13 \left( \frac{d}{R} \right)^{0.90} \left( \frac{RS_o}{(SG-1)d} \right)^{1.40} \left( \frac{Q_b}{Q_p} \right)^{-0.30} \quad (9)$$

318 Or rearranging the above formula to simplify the  $d/R$  term:

$$\frac{V_s}{V_f} = 8.13 \left( \frac{d}{R} \right)^{-0.50} \left( \frac{S_o}{(SG-1)} \right)^{1.40} \left( \frac{Q_b}{Q_p} \right)^{-0.30} \quad (10)$$

319 The obtained model was used to estimate the flushing efficiency in larger pipes  
 320 considering different flow conditions and sediment characteristics. Further details are  
 321 described in the section below. The model's accuracy can be seen in Figure 6 for both  
 322 training and testing datasets.

323 **[Figure 6 near here]**

324 As it can be seen from the above equation and figure, Eq. (10) is consistent with  
 325 the graphical analysis presented in Figure 6. Further, it can be seen from the model  
 326 obtained that  $\frac{S_o}{(SG-1)}$  is the most important feature for predicting the sediment velocity



327 during the flushing cleaning operation - the more the pipe slope increases, the higher the  
328 particle velocity is (note that the  $\frac{S_o}{(SG-1)}$  parameter comes from the Shields parameter).  
329 The Shields parameter shows the ratio between the hydrodynamic forces acting on the  
330 particles and the resistance due to gravity. This parameter has been identified as one of  
331 the most relevant for predicting the incipient motion in sewers (Delleur, 2001; Safari et  
332 al. 2018; Wan Mohtar et al. 2018). As mentioned above,  $V_s/V_f$  is inversely proportional  
333 to  $d/R$ , which is consistent with the results shown by EPR-MOGA model.

#### 334 4. RESULTS AND DISCUSSION

335 The new model shown in Eq. (10) was used to generate charts to estimate flushing  
336 efficiency as a function of the characteristics of the discharged hydrograph, the pipe  
337 geometry and the sediment properties. In this context, two flushing-efficiency measures  
338 were defined as a function of the area of deposited bed ( $A_s$ ) and the sediment velocity.  
339 The first measure,  $Q_s$ , is the volume of sediment removed by unit time (i.e. the sediment  
340 flow rate =  $A_s V_s$ ). The second measure,  $t_e$ , is the flushing time required to clean 1.0 m of  
341 the pipe (=  $1/V_s$ ). Figure 7 and Figure 8 were constructed for several pipe diameters using  
342 previous measures. To construct these figures, the less-significant variables identified by  
343 the EPR-MOGA model (as shown in Table 2) remained constant. The sediment thickness  
344 was defined as  $y_s/D = 1\%$ , the specific gravity of the sediments as 2.6, and the relation  
345 between the base and peak time of the hydrograph as  $t_b/t_p = 5.0$ .

346 **[Figure 7 near here]**

347 The following observations can be made from Figure 7 and Figure 8:

- 348 •  $Q_s$  is inversely proportional to  $d$  and  $Q_b/Q_p$ . In addition,  $Q_s$  seems to be near-  
349 steady for particle diameters greater than 1.5 mm in pipes with diameters less than

350 800 mm. All above for the same pipe slope and  $Q_b/Q_p$  relation. Increasing the  
351 pipe slope directly increase the sediment transport rate.

352 • As the  $Q_b/Q_p$  ratio increases, the sediment removal rate decreases. For example,  
353 in Figure 7a, when  $Q_b/Q_p = 0.25$  in a 1200 mm diameter pipe containing a  
354 deposited sediment bed with  $d = 1$  mm,  $Q_s = 0.5 \times 10^{-4}$  m<sup>3</sup>/s, while for  $Q_b/Q_p =$   
355  $0.75$  the  $Q_s$  value changes to  $0.2 \times 10^{-4}$  m<sup>3</sup>/s, that is 60% less (as shown in Figure  
356 7c).

357 • Flushing discharges seem to be more efficient in larger sewer pipes. The sediment  
358 transport rate can be five times higher in 2000 mm diameter pipes, compared to  
359 1200 mm diameter pipes.

360 • Figure 8 shows a direct relationship between  $t_e$  and  $d$  and  $Q_b/Q_p$ . Based on this,  
361 as  $d$  increases and  $Q_p$  decreases, the required flushing time to clean 1 meter of the  
362 pipe increases. For example, in Figure 8d when  $Q_b/Q_p = 0.25$  in a 800 mm  
363 diameter pipe containing a deposited sediment bed with  $d = 1.5$  mm,  $t_e = 20$  sec,  
364 while for  $Q_b/Q_p = 0.75$  the  $t_e$  value changes to 45 sec, that is 125% more (as  
365 shown in Figure 8f)

366 • The flushing time decreases as the  $S_o$  and  $D$  increase. That is, flushing is a more  
367 efficient technique in large and steep pipes.

368 **[Figure 8 near here]**

#### 369 **4.1. Model comparison**

370 To test the accuracy of the model shown in Eq. (10), the case study described in Laplace  
371 et al. (2003) was used. This case study is located in Marseille, France, on a combined  
372 sewer network. Specifically, this study considers an ovoid section of 1700 mm, 120 m  
373 long with a bottom slope of 0.03%. A near-uniform deposited bed of 140 mm thickness

374 was observed along the entire length of the flume. The deposited bed was characterised  
375 as coarser upstream ( $d = 8$  mm) and finer downstream ( $d = 0.6$  mm). Full details are  
376 shown in Laplace et al. (2003).

377 Using a Hydrass-flushing gate located inside the section, a series of flushes were  
378 conducted for testing the efficiency on removing the deposited material. During each  
379 flush, a total volume of  $6.0 \text{ m}^3$  of water was discharged into the pipe. As reported by  
380 Laplace et al. (2003), the mass of particles eroded during the first flush was  $6.3$  kg, i.e.  
381 the removal rate was  $1.08$  kg of material per  $1.0 \text{ m}^3$  of water ( $= 1.08 \text{ kg m}^{-3}$ ).

382 Two existing procedures are compared with the new EPR-MOGA model  
383 presented in Eq. (10): the model proposed by Bong et al. (2013) (i.e. Eq. (3)) and the  
384 design tables shown by Dettmar (2007). To compare the results, several initial conditions  
385 are defined based on the case study description, which are outlined as follows:

- 386 (1) Thickness of the deposited bed ( $y_s$ ) =  $0.14$  m
- 387 (2) Peak flow during flushing operation ( $Q_p$ ) =  $100 \text{ l s}^{-1}$
- 388 (3) Specific gravity of the sediments ( $SG$ ) =  $2.60$
- 389 (4) Mean particle diameter ( $d$ ) =  $0.6 - 8.0$  mm
- 390 (5) Mass of material per meter of pipe =  $54.22 \text{ kg m}^{-1}$

391 According to Bong et al. (2013), the number of flushes required to move  $1$  m of  
392 deposited material can be estimated by applying Eq. (3). For this equation, the number of  
393 flushes is only a function of the thickness of the deposited bed. As a result,  $42$  flushes ( $=$   
394  $250.6 \text{ m}^3$  of water) can potentially remove  $54.22$  kg of the deposited material (i.e. the  
395 removal rate is  $0.21 \text{ kg m}^{-3}$ ). Design tables proposed by Dettmar (2007) suggest a flushing

396 volume of 48 m<sup>3</sup> for a basic cleaning of the 150 m long sewer (i.e. a full removing of the  
397 deposited material). No removal rates are provided by Dettmar (2007).

398 Finally, using the new model proposed in this study, a range of removal rates are  
399 obtained as a function of the mean particle diameter. Potentially, a flushing volume of  
400 10.18 m<sup>3</sup> can remove 14.5 kg of deposited material with a mean particle diameter of 0.6  
401 mm (i.e. the removal rate is 0.40 kg m<sup>-3</sup>). By changing the particle size of the deposited  
402 material to 8.3 mm, the removal rate is 1.25 kg m<sup>-3</sup>.

403 **[Table 3 near here]**

404 As shown in Table 3, a direct comparison of the method proposed by Dettmar  
405 (2007) and the results reported by Laplace et al. (2003) is not possible. However, this  
406 method seems to underestimate the real volume required to remove the deposited bed.  
407 Relevant parameters such as the mean particle diameter and the sewer hydraulics are not  
408 included in this method. Due to the pipe slope in the case of study is almost flat, obtaining  
409 minimum shear stress of 5.0 N m<sup>-2</sup> for cleaning the pipe, according to Dettmar (2007),  
410 requires larger flows.

411 The model presented by Bong et al. (2013) is a good approach for determining the  
412 number of flushes required to move the deposited material. However, because of the non-  
413 inclusion of relevant pipe hydraulics and sediment parameters, the results are  
414 underestimated, compared to the values reported by Laplace et al. (2003).

#### 415 ***4.2. Model considerations***

416 The new model presented here shows good prediction accuracy with the data  
417 reported by Laplace et al. (2003). This is explained by the inclusion of relevant parameters  
418 for predicting the removal rate during the flushing operation. The model also shows good

419 extrapolation capabilities under different sewer diameters and a wide range of variations  
420 of the mean particle diameter.

421 The Shields parameter was selected as the most important one due to the highest  
422 value in the regression coefficient and the Pareto solution provided by the EPR-MOGA  
423 strategy. This was expected since this parameter determines the threshold condition of  
424 sediment initiation motion. The sediment thickness parameter is less important for  
425 defining the sediment velocity during the flushing operation due to the low regression  
426 coefficient presented in Table 2. As a result, the model can be used in both combined and  
427 storm sewers, where the sediment thickness ranges from 10 mm to 100 mm and 10 mm  
428 to 330 mm, respectively (Bong et al. 2016).

429 The model includes the peak flow as an explanatory variable for predicting  
430 sediment transport rate. Higher peak flow implies a higher removal rate since higher shear  
431 stresses are generated at the bottom of the pipe. The observed shear stress values (ranging  
432 from  $2.0 \text{ N/m}^2$  to  $6.5 \text{ N/m}^2$  in the PVC pipe) are consistent with those reported in the  
433 literature for the erosion and transport of bed material (Dettmar, 2007; Campisano et al.  
434 2008; Yang et al. 2019). However, since the model only considers transport as bedload,  
435 some fine particles may be eroded and transported in suspension (which has been  
436 identified as one of the major sources of pollution in CSO (Laplace et al. 2003; Saul et  
437 al. 2003)), due to the high turbulence of the flow. This is particularly important in well-  
438 graded materials where wide ranges of mean particle sizes are present.

439 Even though the new model was developed considering a wide range of variations  
440 in input variables, some limitations exist. The granular material used in the experiments  
441 cannot represent the cohesive properties of sediments found in real sewer systems. As a  
442 result, an increased bed resistance to erosion can be seen in practice (Campisano et al.

443 2019). In addition, the lowest pipe slope value considered during the tests was 0.644%,  
444 which is higher than the minimum self-cleansing value recommended in several industry  
445 design codes and water utilities design manuals (e.g. Health Research Inc. (2004), as  
446 quoted by Montes et al. (2019)).

## 447 **5. CONCLUSIONS**

448 This study proposes a simple model to predict the sediment transport rate in practice based  
449 on data collected from a set of 121 lab experiments conducted on a 209 mm diameter  
450 acrylic pipe and 595 mm diameter PVC pipe. The data collected this way were processed  
451 using the EPR-MOGA modelling technique. A new model for predicting the sediment  
452 velocity during flushing operation was developed and used for constructing design charts.  
453 Based on the results obtained, the following conclusions are made:

- 454 (1) The new model developed and presented here can predict the sediment transport  
455 rate during flushing discharges accurately in practice. This model includes the  
456 group of parameters that most affect the flushing efficiency in sewer pipes.
- 457 (2) The sediment transport rate is principally affected by four parameters: pipe slope,  
458 pipe diameter, particle diameter and discharged peak flow. In pipes with large  
459 diameters and slopes, the flushing is more effective. This is because of the high  
460 regression exponents for both  $\frac{S_o}{(SG-)}$  and  $d/R$  variables obtained in the EPR-  
461 MOGA model presented here. The sediment transport is not significantly affected  
462 by the value of the deposited sediment thickness.
- 463 (3) The new model proposed outperforms the simplified models and methods  
464 reported in the literature in terms of removal sediment rate prediction. This is seen  
465 by the better prediction accuracy shown when compared to the case study reported  
466 by Laplace et al. (2003).

467 (4) Existing models such as Bong et al. (2013) and Dettmar (2007) for predicting  
468 sediment transport tend to underestimate the total volume of water required to  
469 clean a deposited sediment bed. The EPR-MOGA model is more accurate in  
470 predicting the sediment transport rate as this model includes parameters affecting  
471 the flushing efficiency, such as flushing hydraulics, pipe geometry and sediment  
472 properties.

473 Based on the conclusions mentioned above, the new flushing model can be useful  
474 for designing flushing schemes during the operational stage of existing sewer pipes in  
475 engineering practice. Further research is recommended to test the model proposed in real  
476 sewer pipes under different sediment (i.e. cohesive materials) and hydraulic conditions.

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#### 484 **REFERENCES**

- 485 Ab Ghani, A., and Azamathulla, H. 2011. "Gene-Expression Programming for Sediment  
486 Transport in Sewer Pipe Systems." *Journal of Pipeline Systems Engineering and*  
487 *Practice* 2(3): 102–106. [https://doi.org/10.1061/\(ASCE\)PS.1949-1204.0000076](https://doi.org/10.1061/(ASCE)PS.1949-1204.0000076)
- 488 Ashley, R., Bertrand-Krajewski, J., Hvitved-Jacobsen, T., and Verbanck, M., 2004. *Solids*  
489 *in Sewers: Characteristics, Effects and Control of Sewer Solids and Associated*  
490 *Pollutants*. London: IWA Publishing. <https://doi.org/10.2166/9781780402727>
- 491 ASTM D854-14, 2014. *Standard Test Methods for Specific Gravity of Soil Solids by*

- 492 *Water Pycnometer*. West Conshohocken, PA: ASTM International.
- 493 Azamathulla, H., Ab Ghani, A., and Fei, S., 2012. “ANFIS-based approach for predicting  
494 sediment transport in clean sewer.” *Applied Soft Computing Journal* 12(3): 1227–  
495 1230. <https://doi.org/10.1016/j.asoc.2011.12.003>
- 496 Bajirao, T., Kumar, P., Kumar, M., Elbeltagi, A., and Kuriqi, A. 2021. “Superiority of  
497 Hybrid Soft Computing Models in Daily Suspended Sediment Estimation in Highly  
498 Dynamic Rivers.” *Sustainability* 13(2): 542. <https://doi.org/10.3390/su13020542>
- 499 Bertrand-Krajewski, J., Bardin, J., Gibello, C., and Laplace, D. 2003. “Hydraulics of a  
500 sewer flushing gate.” *Water Science and Technology* 47(4), 129–136.  
501 <https://doi.org/10.2166/wst.2003.0237>
- 502 Bong, C., Lau, T., and Ab Ghani, A. 2016. “Potential of tipping flush gate for  
503 sedimentation management in open stormwater sewer.” *Urban Water Journal* 13(5):  
504 486–498. <https://doi.org/10.1080/1573062X.2014.994002>
- 505 Bong, C., Lau, T., Ab Ghani, A., and Chan, N. “Sediment deposit thickness and its effect  
506 on critical velocity for incipient motion.” *Water Science and Technology* 74(8):  
507 1876-1884. <https://doi.org/10.2166/wst.2016.376>
- 508 Bong, C., Lau, T., and Ab Ghani, A. 2013. “Hydraulics characteristics of tipping sediment  
509 flushing gate.” *Water Science and Technology* 68(11): 2397–2406.  
510 <https://doi.org/10.2166/wst.2013.498>
- 511 British Standard Institution, 2014. *Management and Control of Operational Activities in*  
512 *Drain and Sewer Systems Outside Buildings. Part 1: Cleaning*. London, UK.
- 513 Campisano, A., Creaco, E., and Modica, C. 2008. “Laboratory investigation on the effects  
514 of flushes on cohesive sediment beds.” *Urban Water Journal* 5(1): 3–14.  
515 <https://doi.org/10.1080/15730620701726259>
- 516 Campisano, A., Creaco, E., and Modica, C. 2007. “Dimensionless Approach for the  
517 Design of Flushing Gates in Sewer Channels.” *Journal of Hydraulic Engineering*  
518 133(8): 964–972. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2007\)133:8\(964\)](https://doi.org/10.1061/(ASCE)0733-9429(2007)133:8(964))
- 519 Campisano, A., Creaco, E., and Modica, C. 2006. “Experimental analysis of the hydrass  
520 flushing gate and laboratory validation of flush propagation modelling.” *Water*  
521 *Science and Technology* 54(6-7): 101–108. <https://doi.org/10.2166/wst.2006.608>
- 522 Campisano, A., Creaco, E., and Modica, C. 2004. “Experimental and numerical analysis  
523 of the scouring effects of flushing waves on sediment deposits.” *Journal of*  
524 *Hydrology* 299(3-4): 324–334. <https://doi.org/10.1016/j.jhydrol.2004.08.009>
- 525 Campisano, A., and Modica, C. 2003. “Flow velocities and shear stresses during flushing  
526 operations in sewer collectors.” *Water Science and Technology* 47(4): 123–128.  
527 <https://doi.org/10.2166/wst.2003.0236>
- 528 Campisano, A., Modica, C., Creaco, E., and Shahsavari, G. 2019. “A model for non-  
529 uniform sediment transport induced by flushing in sewer channels.” *Water Research*  
530 163: 114903. <https://doi.org/10.1016/j.watres.2019.114903>



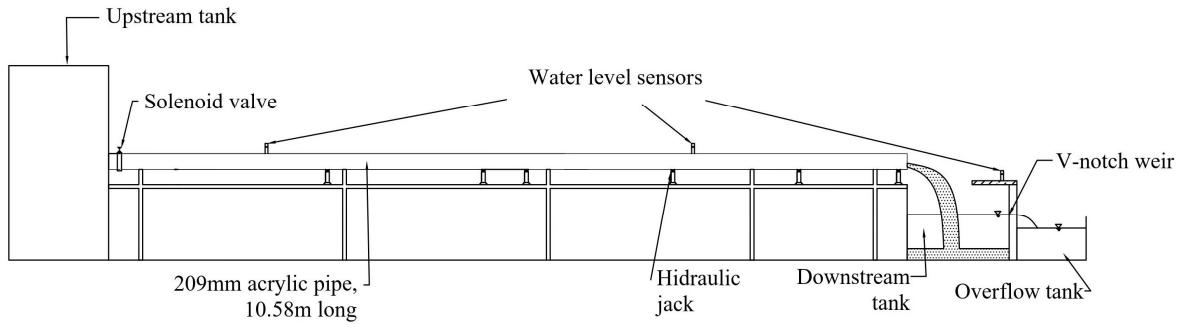
- 531 Caviedes-Voullième, D., Morales-Hernández, M., Juez, C., Lacasta, A., and García-  
532 Navarro, P. 2017. “Two-dimensional numerical simulation of bed-load transport of  
533 a finite-depth sediment layer: Applications to channel flushing.” *Journal of*  
534 *Hydraulic Engineering* 143(9):04017034.  
535 [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001337](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001337)
- 536 Chebbo, G., Laplace, D., Bachoc, A., Sanchez, Y., and Le Guennec, B. 1996. “Technical  
537 solutions envisaged in managing solids in combined sewer networks.” *Water*  
538 *Science and Technology* 33(9): 237–244. [https://doi.org/10.1016/0273-  
539 1223\(96\)00392-7](https://doi.org/10.1016/0273-1223(96)00392-7)
- 540 Creaco, E., and Bertrand-Krajewski, J. 2009. “Numerical Simulation of flushing effect  
541 on sewer sediments and comparison of Four sediment transport formulas.” *Journal*  
542 *of Hydraulic Research* 47(2): 195–202. <https://doi.org/10.3826/jhr.2009.3363>
- 543 De Sutter, R., Huygens, M., and Verhoeven, R. 1999. “Unsteady flow sediment transport  
544 in a sewer model.” *Water Science and Technology* 39(9): 121–128.  
545 [https://doi.org/10.1016/S0273-1223\(99\)00224-3](https://doi.org/10.1016/S0273-1223(99)00224-3)
- 546 Delleur, J. 2001. “New results and research needs on sediment movement in urban  
547 drainage.” *Journal of Water Resources Planning and Management* 127(3): 186-193.  
548 [https://doi.org/10.1061/\(ASCE\)0733-9496\(2001\)127:3\(186\)](https://doi.org/10.1061/(ASCE)0733-9496(2001)127:3(186))
- 549 Dettmar, J. 2007. “A new planning procedure for sewer flushing.” Paper presented at the  
550 NOVATECH 2007 – Sixth International Conference on Sustainable Techniques and  
551 Strategies in Urban Water Management, Lyon, June 25-28.
- 552 Dettmar, J. 2005. “Beitrag zur Verbesserung der Reinigung von Abwasserkanälen.” PhD  
553 diss., RWTH Aachen University.
- 554 Dettmar, J., Rietsch, B., and Lorenz, U. 2002. “Performance and Operation of Flushing  
555 Devices - Results of a Field and Laboratory Study.” *Global Solutions for Urban*  
556 *Drainage: Proceedings of the Ninth International Conference on Urban Drainage:*  
557 1–10. [https://doi.org/10.1061/40644\(2002\)291](https://doi.org/10.1061/40644(2002)291)
- 558 Ebtehaj, I., and Bonakdari, H. 2016. “Bed Load Sediment Transport in Sewers at Limit  
559 of Deposition.” *Scientia Iranica* 23(3): 907–917.  
560 <https://doi.org/10.24200/sci.2016.2169>
- 561 Ebtehaj, I., Bonakdari, H., Shamshirband, S., Ismail, Z., and Hashim, R. 2017. “New  
562 approach to estimate velocity at limit of deposition in storm sewers using vector  
563 machine coupled with firefly algorithm.” *Journal of Pipeline Systems Engineering*  
564 *and Practice* 8(2): 04016018.  
565 [https://doi.org/10.1061/\(ASCE\)PS.1949-1204.0000252](https://doi.org/10.1061/(ASCE)PS.1949-1204.0000252)
- 566 Fan, C. 2004. *Sewer Sediment and Control A Management Practices Reference Guide*.  
567 U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-04/059.
- 568 Fan, C., Field, R., Pisano, W., Barsanti, J., Joyce, J., and Sorenson, H. 2001. “Sewer and  
569 Tank Flushing for Sediment, Corrosion, and Pollution Control.” *Journal of Water*  
570 *Resources Planning and Management* 127(3): 194–201.

- 571 [https://doi.org/10.1061/\(ASCE\)0733-9496\(2001\)127:3\(194\)](https://doi.org/10.1061/(ASCE)0733-9496(2001)127:3(194))
- 572 Giustolisi, O., and Savic, D. 2009. “Advances in data-driven analyses and modelling  
573 using EPR-MOGA.” *Journal of Hydroinformatics* 11(3-4): 225–236.  
574 <https://doi.org/10.2166/hydro.2009.017>
- 575 Giustolisi, O., and Savic, D. 2006. “A symbolic data-driven technique based on  
576 evolutionary polynomial regression.” *Journal of Hydroinformatics* 8(4): 207–222.  
577 <https://doi.org/10.2166/hydro.2006.020>
- 578 Giustolisi, O., and Savic, D. 2004. “A Novel Genetic Programming Strategy:  
579 Evolutionary Polynomial Regression.” *Proceedings of the 6th International  
580 Conference on Hydroinformatics*: 787–794.  
581 [https://doi.org/10.1142/9789812702838\\_0097](https://doi.org/10.1142/9789812702838_0097)
- 582 Guo, Q., Fan, C., Raghaven, R., and Field, R. 2004. “Gate and Vacuum Flushing of Sewer  
583 Sediment: Laboratory Testing.” *Journal of Hydraulic Engineering* 130(5): 463–  
584 466. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2004\)130:5\(463\)](https://doi.org/10.1061/(ASCE)0733-9429(2004)130:5(463))
- 585 Health Research Inc. (2004). “Recommended standards for wastewater facilities.” *A  
586 Report of the Wastewater Committee* 12224(518): 1–102.
- 587 Hlavinek, P., Malanik, S., Raclavsky, J., Sulcova, V., Montero, C., and Villanueva, A.  
588 2005. *WP4 Deliverable 11: Survey of Operational Options*. Brno.
- 589 Khosravi, K., Cooper, J., Daggupati, P., Thai Pham, B., and Tien Bui, D. 2020. “Bedload  
590 transport rate prediction: Application of novel hybrid data mining techniques”  
591 *Journal of Hydrology* 585: 124774 <https://doi.org/10.1016/j.jhydrol.2020.124774>
- 592 Kuriqui, A., Koçileri, G., and Ardiçlioğlu, M. 2020. “Potential of Meyer-Peter and Müller  
593 approach for estimation of bed-load sediment transport under different hydraulic  
594 regimes” *Modeling Earth Systems and Environment* 6: 129-137.  
595 <https://doi.org/10.1007/s40808-019-00665-0>
- 596 Lainé, S., Phan, L., Malabat, D., and Duffros, B. 1998. “Flush Cleaning of Sewer Using  
597 the Hydras-Valve.” Paper presented at the 4th International Conference on Urban  
598 Drainage Modelling, London, September 21-24.
- 599 Laplace, D., Oms, C., Ahyerre, M., Chebbo, G., Lemasson, J., and Felouzis, L. 2003.  
600 “Removal of the organic surface layer in combined sewer sediment using a flushing  
601 gate.” *Water Science and Technology* 47(4): 19–26.  
602 <https://doi.org/10.2166/wst.2003.0211>
- 603 May, R., Ackers, J., Butler, D., and John, S. 1996. “Development of design methodology  
604 for self-cleansing sewers.” *Water Science and Technology* 33(9): 195–205.  
605 [https://doi.org/10.1016/0273-1223\(96\)00387-3](https://doi.org/10.1016/0273-1223(96)00387-3)
- 606 Montes, C., Bohorquez, J., Borda, S., and Saldarriaga, J. 2019. “Impact of Self-Cleansing  
607 Criteria Choice on the Optimal Design of Sewer Networks in South America.” *Water  
608 (Switzerland)* 11(6): 1148. <https://doi.org/10.3390/w11061148>
- 609 Montes, C., Berardi, L., Kapelan, Z., and Saldarriaga, J. 2020a. “Predicting bedload

- 610 sediment transport of non-cohesive material in sewer pipes using evolutionary  
611 polynomial regression – multi-objective genetic algorithm strategy.” *Urban Water*  
612 *Journal* 17(2): 154-162. <https://doi.org/10.1080/1573062X.2020.1748210>
- 613 Montes, C., Vanegas, S., Kapelan, Z., Berardi, L., and Saldarriaga, J. 2020b. “Non-  
614 deposition self-cleansing models for large sewer pipes.” *Water Science and*  
615 *Technology* 81(3): 606–621. <https://doi.org/10.2166/wst.2020.154>
- 616 Montes, C., Kapelan, Z., and Saldarriaga, J. 2021. “Predicting non-deposition sediment  
617 transport in sewer pipes using Random forest.” *Water Research* 189, 116639.  
618 <https://doi.org/10.1016/j.watres.2020.116639>
- 619 NEIWPC, 2003. Optimizing Operation, Maintenance, and Rehabilitation of Sanitary  
620 Sewer Collection Systems. Lowell, MA.
- 621 Ristenpart, E. 1998. “Solids transport by flushing of combined sewers.” *Water Science*  
622 *and Technology* 37(1): 171–178. [https://doi.org/10.1016/S0273-1223\(97\)00767-1](https://doi.org/10.1016/S0273-1223(97)00767-1)
- 623 Rodríguez, J., McIntyre, N., Díaz-Granados, M., and Maksimović, Č. 2012. “A database  
624 and model to support proactive management of sediment-related sewer blockages.”  
625 *Water Research* 46(15): 4571–4586. <https://doi.org/10.1016/j.watres.2012.06.037>
- 626 Safari, M. 2020. “Hybridization of multivariate adaptive regression splines and random  
627 forest models with an empirical equation for sediment deposition prediction in open  
628 channel flow.” *Journal of Hydrology* 590: 125392.  
629 <https://doi.org/10.1016/j.jhydrol.2020.125392>
- 630 Safari, M., Mohammadi, M., and Ab Ghani, A. 2018. “Experimental studies of self-  
631 cleansing drainage system design: A review.” *Journal of Pipeline Systems*  
632 *Engineering and Practice* 9(4): 04018017. [https://doi.org/10.1061/\(ASCE\)PS.1949-1204.0000335](https://doi.org/10.1061/(ASCE)PS.1949-1204.0000335)
- 634 Sakakibara, T. 1996. “Sediments flushing experiment in a trunk sewer.” *Water Science*  
635 *and Technology* 33(9): 229–235. [https://doi.org/10.1016/0273-1223\(96\)00391-5](https://doi.org/10.1016/0273-1223(96)00391-5)
- 636 Saul, A., Skipworth, P., Tait, S., and Rushforth, P. 2003. “Movement of Total Suspended  
637 Solids in Combined Sewers.” *Journal of Hydraulic Engineering* 129(4): 298-307.  
638 [https://doi.org/10.1061/\(ASCE\)0733-9429\(2003\)129:4\(298\)](https://doi.org/10.1061/(ASCE)0733-9429(2003)129:4(298))
- 639 Schaffner, J., and Steinhardt, J. 2006. “Numerical investigation of the self-acting flushing  
640 system HydroFlush GS in Frankenberg/Germany.” Paper presented at the 2th  
641 Conference on Sewer Operation and Maintenance, Vienna, October.
- 642 Shahsavari, G., Arnaud-Fassetta, G., and Campisano, A. 2017. “A field experiment to  
643 evaluate the cleaning performance of sewer flushing on non-uniform sediment  
644 deposits.” *Water Research* 118: 59–69 <https://doi.org/10.1016/j.watres.2017.04.026>
- 645 Shirazi, R., Campisano, A., Modica, C., and Willems, P. 2014. “Modelling the erosive  
646 effects of sewer flushing using different sediment transport formulae.” *Water*  
647 *Science and Technology* 69(6): 1198–1204. <https://doi.org/10.2166/wst.2013.810>
- 648 Wan Mohtar, W., Afan, H., El-Shafie, A., Bong, C., and Ab Ghani, A. 2018. “Influence

- 649 of bed deposit in the prediction of incipient sediment motion in sewers using  
650 artificial neural networks.” *Urban Water Journal* 15(4): 296-302.  
651 <https://doi.org/10.1080/1573062X.2018.1455880>
- 652 Yang, H., Zhu, D., Zhang, Y., and Zhou, Y. 2019. “Numerical investigation on bottom  
653 shear stress induced by flushing gate for sewer cleaning.” *Water Science and  
654 Technology* 80(2): 290–299. <https://doi.org/10.2166/wst.2019.269>
- 655 Yu, C., and Duan, J. 2014. “Two-Dimensional Finite Volume Model for Sediment  
656 Transport in Unsteady Flow.” *World Environmental and Water Resources Congress  
657 2014*: 1432–1441. <https://doi.org/10.1061/9780784413548.144>

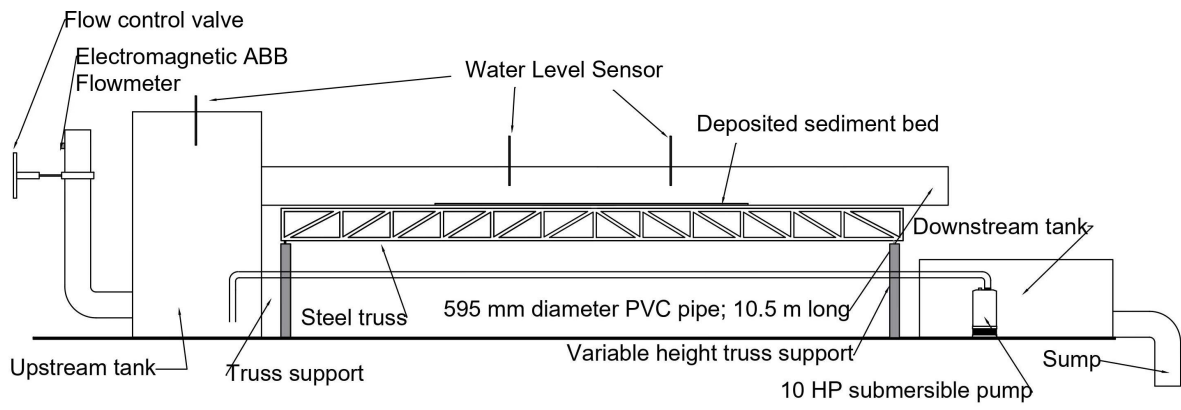
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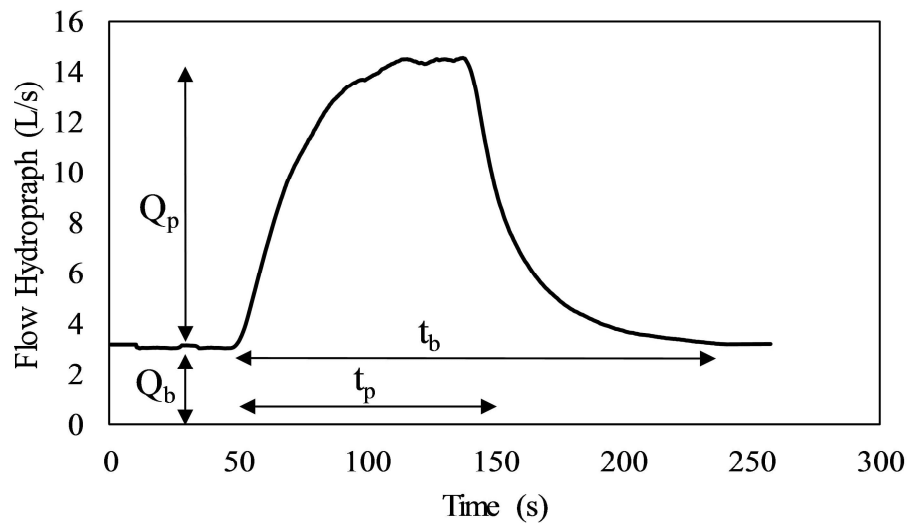
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Figure 1. Experimental setup used to collect the unsteady flow data in the 209 mm acrylic pipe.



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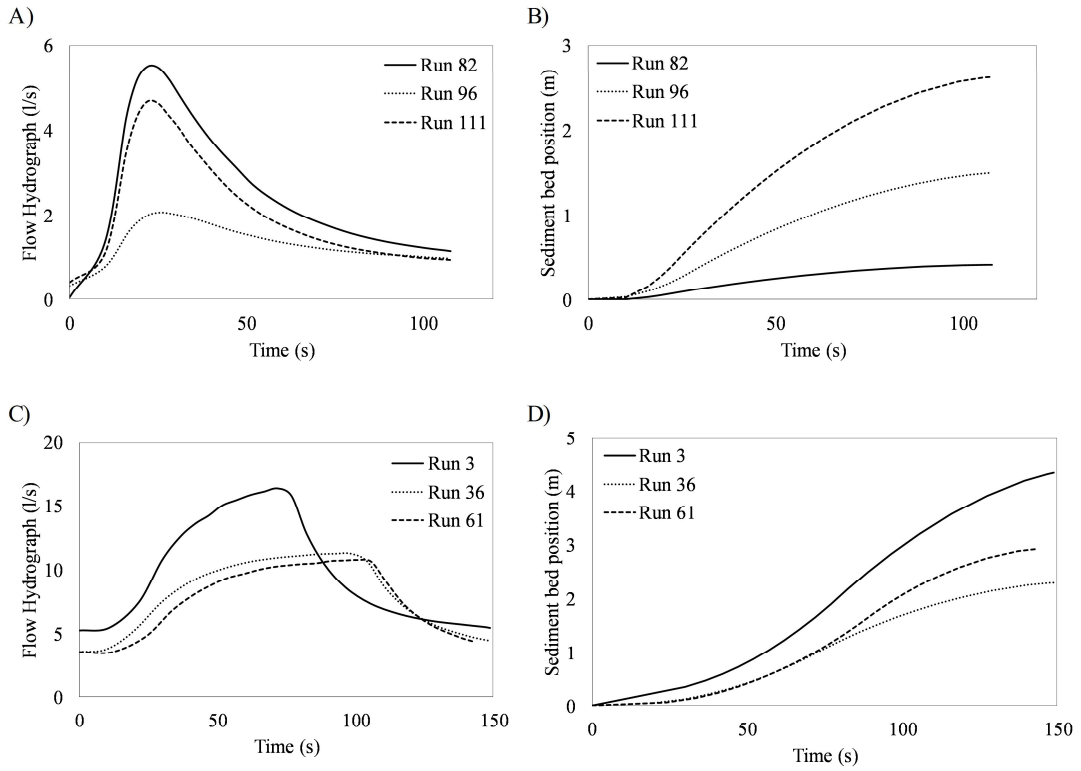
663 Figure 2. Experimental setup used to collect the unsteady flow data in the 595 mm PVC  
 664 pipe.



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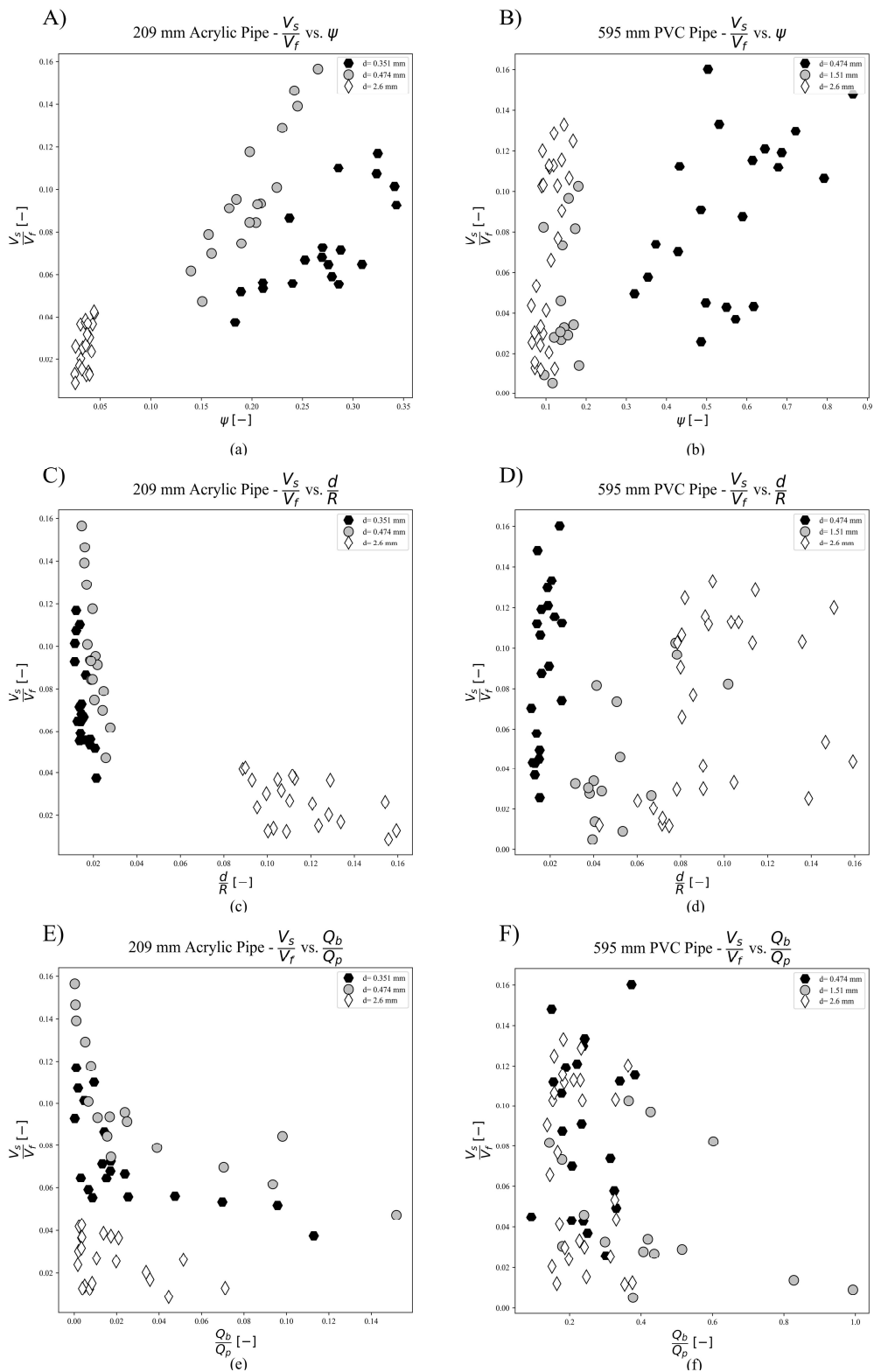
Figure 3. Variable definition of the flushing discharge hydrograph.



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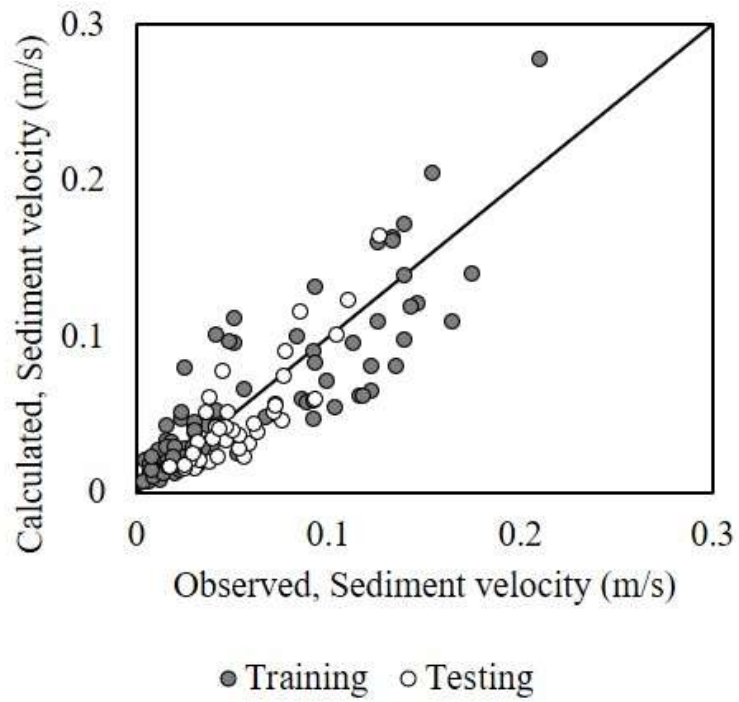
Figure 4. Example of flow hydrographs and sediment bed position for several experiments shown in Table 1.





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671 Figure 5. Plots showing the relationships between the dimensionless velocity ( $V_s/V_f$ )  
 672 and other dimensionless variables in both acrylic and PVC pipe. Clustered results by  
 673 particle diameter.



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Figure 6. EPR-MOGA model accuracy for both training and testing stage.

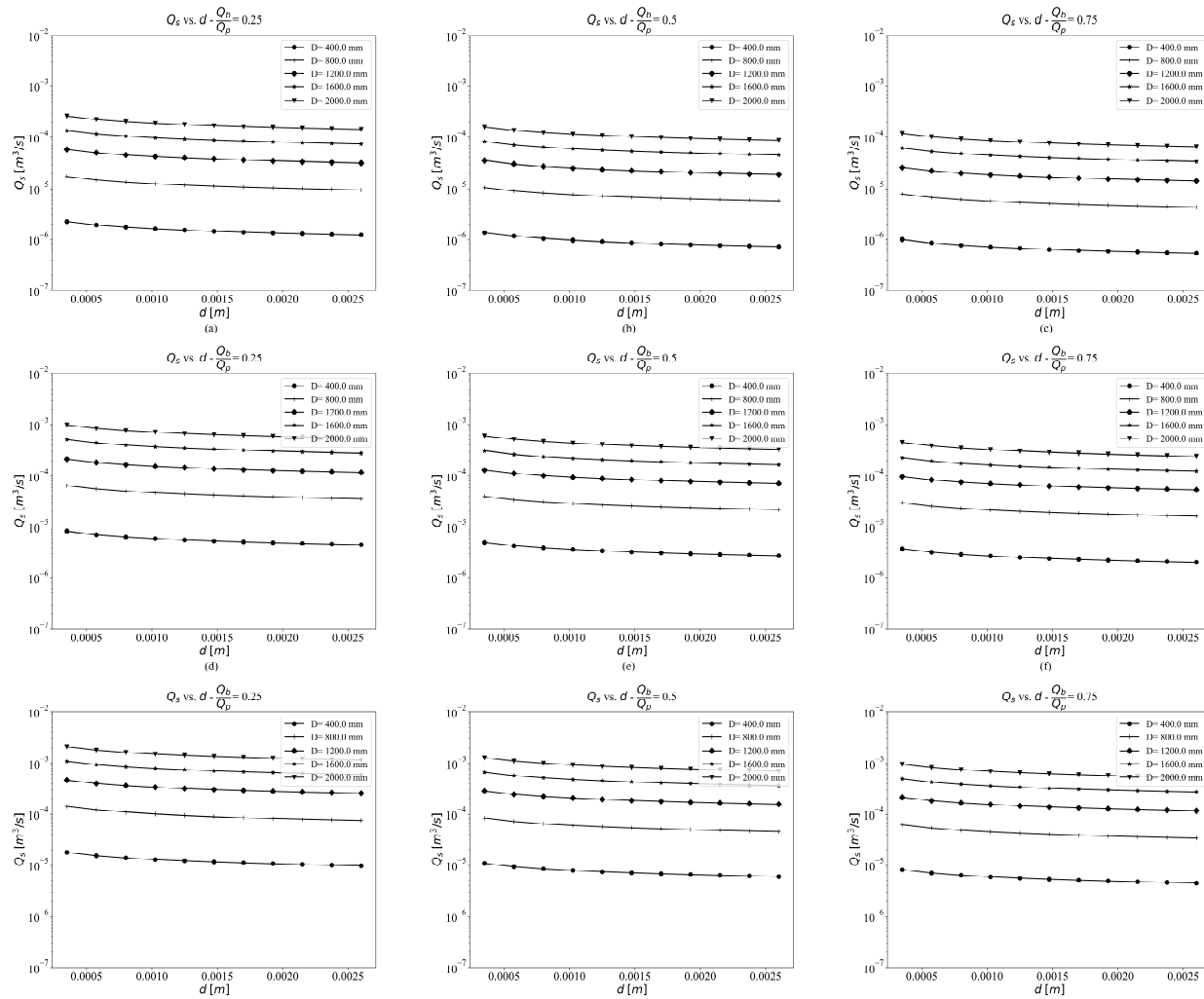


Figure 7. Efficiency of flushing discharge vs particle diameter for several base and peak flow relations ( $0.25 < Q_b/Q_p < 0.75$ ) and pipe slope: a), b) and c)  $S_o = 0.5\%$ ; d), e) and f)  $S_o = 1.0\%$  and g), h) and i)  $S_o = 1.5\%$ .

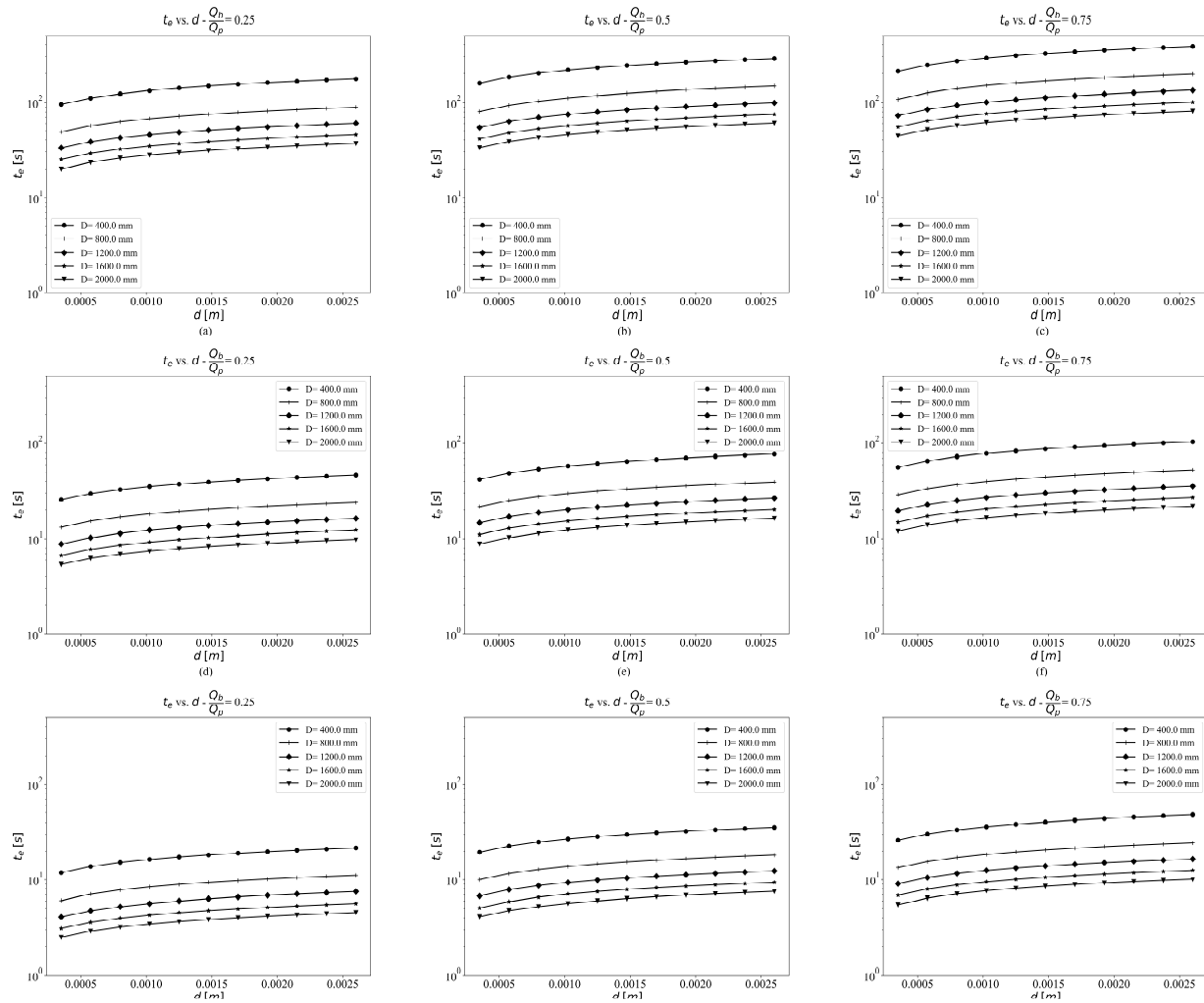


Figure 8. Flushing time vs particle diameter for several base and peak flow relations ( $0.25 < Q_b/Q_p < 0.75$ ) and pipe slope: a), b) and c)  $S_o = 0.5\%$ ; d), e) and f)  $S_o = 1.0\%$  and g), h) and i)  $S_o = 1.5\%$ .

Table 1. Experimental data collected for studying flushing waves efficiency on sewer pipes.

| Run no. | $S_o$<br>(%) | $D$<br>(mm) | $Y$<br>(mm) | $R$<br>(mm) | $d$<br>(mm) | $SG$<br>(-) | $y_s$<br>(mm) | $t_b$<br>(s) | $t_p$<br>(s) | $Q_b$<br>(l s <sup>-1</sup> ) | $Q_p$<br>(l s <sup>-1</sup> ) | $V_f$<br>(m s <sup>-1</sup> ) | $V_s$<br>(m s <sup>-1</sup> ) |
|---------|--------------|-------------|-------------|-------------|-------------|-------------|---------------|--------------|--------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 1       | 0.805        | 595         | 70.35       | 41.96       | 0.47        | 2.66        | 10.14         | 154          | 59           | 5.27                          | 25.48                         | 1.02                          | 0.07                          |
| 2       | 0.805        | 595         | 57.43       | 34.62       | 0.47        | 2.66        | 8.26          | 141          | 57           | 5.45                          | 16.76                         | 0.89                          | 0.05                          |
| 3       | 0.805        | 595         | 53.61       | 31.34       | 0.47        | 2.66        | 10.53         | 131          | 57           | 5.45                          | 16.49                         | 0.82                          | 0.04                          |
| 4       | 1.186        | 595         | 57.82       | 36.46       | 0.47        | 2.66        | 2.49          | 121          | 59           | 4.89                          | 20.53                         | 1.20                          | 0.05                          |
| 5       | 1.229        | 595         | 54.70       | 31.17       | 0.47        | 2.66        | 12.55         | 115          | 55           | 4.81                          | 15.97                         | 0.99                          | 0.03                          |
| 6       | 1.229        | 595         | 61.66       | 36.67       | 0.47        | 2.66        | 9.91          | 120          | 55           | 5.07                          | 20.27                         | 1.14                          | 0.04                          |
| 7       | 1.229        | 595         | 50.94       | 31.92       | 0.47        | 2.66        | 3.90          | 183          | 58           | 1.03                          | 11.10                         | 1.09                          | 0.05                          |
| 8       | 1.229        | 595         | 67.63       | 39.54       | 0.47        | 2.66        | 12.15         | 124          | 57           | 5.03                          | 24.47                         | 1.19                          | 0.05                          |
| 9       | 1.229        | 595         | 62.04       | 37.24       | 1.51        | 2.66        | 8.97          | 39           | 33           | 9.98                          | 12.06                         | 1.16                          | 0.02                          |
| 10      | 1.525        | 595         | 42.69       | 22.71       | 1.51        | 2.66        | 13.54         | 117          | 58           | 5.17                          | 11.84                         | 0.87                          | 0.02                          |
| 11      | 2.034        | 595         | 37.55       | 19.29       | 1.51        | 2.66        | 13.28         | 111          | 59           | 4.92                          | 11.54                         | 0.89                          | 0.09                          |
| 12      | 2.331        | 595         | 35.95       | 19.45       | 1.51        | 2.66        | 10.96         | 182          | 57           | 3.99                          | 10.93                         | 0.97                          | 0.10                          |
| 13      | 0.763        | 595         | 67.43       | 38.31       | 1.51        | 2.66        | 14.87         | 113          | 56           | 4.42                          | 11.71                         | 0.90                          | 0.00                          |
| 14      | 0.763        | 595         | 70.23       | 39.60       | 1.51        | 2.66        | 15.99         | 126          | 69           | 9.13                          | 22.46                         | 0.92                          | 0.03                          |
| 15      | 0.763        | 595         | 81.75       | 47.82       | 1.51        | 2.66        | 13.12         | 135          | 63           | 9.40                          | 31.43                         | 1.07                          | 0.04                          |
| 16      | 1.123        | 595         | 58.13       | 34.59       | 1.51        | 2.66        | 9.55          | 118          | 60           | 9.23                          | 17.93                         | 1.04                          | 0.03                          |
| 17      | 1.123        | 595         | 64.66       | 37.76       | 1.51        | 2.66        | 11.97         | 118          | 57           | 9.37                          | 22.36                         | 1.10                          | 0.04                          |
| 18      | 1.186        | 595         | 57.59       | 29.85       | 1.51        | 2.66        | 19.13         | 149          | 79           | 3.59                          | 20.04                         | 0.92                          | 0.07                          |
| 19      | 1.186        | 595         | 52.88       | 28.98       | 1.51        | 2.66        | 14.70         | 149          | 88           | 3.95                          | 16.45                         | 0.91                          | 0.04                          |
| 20      | 1.186        | 595         | 64.30       | 36.57       | 1.51        | 2.66        | 14.31         | 195          | 93           | 3.51                          | 24.52                         | 1.09                          | 0.09                          |
| 21      | 0.847        | 595         | 69.70       | 40.25       | 1.51        | 2.66        | 13.64         | 185          | 55           | 3.72                          | 20.71                         | 0.99                          | 0.03                          |
| 22      | 0.847        | 595         | 51.24       | 28.32       | 1.51        | 2.66        | 13.83         | 104          | 8            | 7.28                          | 7.33                          | 0.76                          | 0.01                          |
| 23      | 1.589        | 595         | 32.25       | 14.83       | 1.51        | 2.66        | 14.35         | 118          | 82           | 4.36                          | 7.24                          | 0.65                          | 0.05                          |
| 24      | 0.847        | 595         | 63.16       | 36.41       | 2.60        | 2.64        | 12.98         | 120          | 76           | 4.71                          | 12.53                         | 0.92                          | 0.01                          |
| 25      | 0.847        | 595         | 66.11       | 36.30       | 2.60        | 2.64        | 17.48         | 156          | 86           | 4.10                          | 16.57                         | 0.90                          | 0.01                          |
| 26      | 0.847        | 595         | 72.84       | 43.20       | 2.60        | 2.64        | 10.93         | 161          | 83           | 4.13                          | 20.88                         | 1.06                          | 0.03                          |
| 27      | 0.847        | 595         | 105.64      | 61.10       | 2.60        | 2.64        | 15.39         | 167          | 65           | 4.11                          | 24.98                         | 1.34                          | 0.02                          |
| 28      | 1.059        | 595         | 62.36       | 34.80       | 2.60        | 2.64        | 15.48         | 143          | 75           | 4.22                          | 11.91                         | 0.99                          | 0.01                          |
| 29      | 1.059        | 595         | 54.15       | 28.78       | 2.60        | 2.64        | 16.77         | 154          | 83           | 4.02                          | 16.63                         | 0.85                          | 0.03                          |
| 30      | 1.186        | 595         | 59.13       | 33.26       | 2.60        | 2.64        | 14.30         | 143          | 67           | 3.69                          | 19.77                         | 1.01                          | 0.03                          |
| 31      | 1.186        | 595         | 67.08       | 38.56       | 2.60        | 2.64        | 13.76         | 148          | 74           | 3.57                          | 23.71                         | 1.14                          | 0.02                          |
| 32      | 1.483        | 595         | 39.34       | 18.73       | 2.60        | 2.64        | 16.36         | 176          | 88           | 3.45                          | 10.96                         | 0.73                          | 0.02                          |

| Run no. | $S_o$<br>(%) | $D$<br>(mm) | $Y$<br>(mm) | $R$<br>(mm) | $d$<br>(mm) | $SG$<br>(-) | $y_s$<br>(mm) | $t_b$<br>(s) | $t_p$<br>(s) | $Q_b$<br>(l s <sup>-1</sup> ) | $Q_p$<br>(l s <sup>-1</sup> ) | $V_f$<br>(m s <sup>-1</sup> ) | $V_s$<br>(m s <sup>-1</sup> ) |
|---------|--------------|-------------|-------------|-------------|-------------|-------------|---------------|--------------|--------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 33      | 1.483        | 595         | 46.74       | 24.88       | 2.60        | 2.64        | 14.66         | 136          | 80           | 3.52                          | 15.45                         | 0.91                          | 0.03                          |
| 34      | 1.483        | 595         | 53.25       | 28.81       | 2.60        | 2.64        | 15.54         | 186          | 72           | 3.39                          | 19.73                         | 1.01                          | 0.04                          |
| 35      | 1.483        | 595         | 59.57       | 32.28       | 2.60        | 2.64        | 16.95         | 184          | 79           | 3.42                          | 23.61                         | 1.10                          | 0.07                          |
| 36      | 1.653        | 595         | 38.51       | 16.34       | 2.60        | 2.64        | 19.13         | 134          | 82           | 3.75                          | 11.36                         | 0.69                          | 0.03                          |
| 37      | 1.653        | 595         | 46.08       | 23.02       | 2.60        | 2.64        | 17.21         | 141          | 84           | 3.76                          | 15.96                         | 0.90                          | 0.09                          |
| 38      | 1.653        | 595         | 52.56       | 28.02       | 2.60        | 2.64        | 16.18         | 146          | 70           | 3.71                          | 20.08                         | 1.04                          | 0.12                          |
| 39      | 1.653        | 595         | 59.13       | 33.13       | 2.60        | 2.64        | 14.58         | 147          | 64           | 3.64                          | 23.79                         | 1.19                          | 0.12                          |
| 40      | 1.568        | 595         | 38.73       | 18.76       | 0.47        | 2.66        | 15.60         | 135          | 87           | 3.64                          | 11.58                         | 0.76                          | 0.06                          |
| 41      | 1.568        | 595         | 46.16       | 24.41       | 0.47        | 2.66        | 14.80         | 142          | 81           | 3.73                          | 15.96                         | 0.92                          | 0.08                          |
| 42      | 1.568        | 595         | 53.90       | 29.62       | 0.47        | 2.66        | 14.77         | 146          | 87           | 3.66                          | 20.35                         | 1.07                          | 0.09                          |
| 43      | 1.568        | 595         | 59.10       | 34.08       | 0.47        | 2.66        | 12.39         | 151          | 81           | 3.75                          | 24.25                         | 1.20                          | 0.13                          |
| 44      | 1.822        | 595         | 37.55       | 18.70       | 0.47        | 2.66        | 14.29         | 140          | 87           | 4.06                          | 11.92                         | 0.82                          | 0.09                          |
| 45      | 1.822        | 595         | 45.29       | 22.96       | 0.47        | 2.66        | 16.33         | 148          | 88           | 4.00                          | 16.48                         | 0.95                          | 0.13                          |
| 46      | 1.822        | 595         | 51.59       | 29.70       | 0.47        | 2.66        | 11.33         | 152          | 81           | 3.95                          | 20.87                         | 1.17                          | 0.14                          |
| 47      | 2.034        | 595         | 35.08       | 19.49       | 0.47        | 2.66        | 9.71          | 121          | 84           | 3.97                          | 10.64                         | 0.92                          | 0.15                          |
| 48      | 2.034        | 595         | 42.85       | 24.99       | 0.47        | 2.66        | 9.05          | 161          | 89           | 3.26                          | 14.75                         | 1.11                          | 0.13                          |
| 49      | 2.034        | 595         | 50.35       | 30.68       | 0.47        | 2.66        | 6.79          | 7            | 78           | 3.56                          | 20.07                         | 1.32                          | 0.14                          |
| 50      | 2.034        | 595         | 54.22       | 33.47       | 0.47        | 2.66        | 5.64          | 178          | 60           | 3.56                          | 23.79                         | 1.42                          | 0.21                          |
| 51      | 2.246        | 595         | 34.90       | 21.54       | 0.47        | 2.66        | 4.68          | 127          | 75           | 4.36                          | 11.38                         | 1.09                          | 0.13                          |
| 52      | 2.246        | 595         | 42.64       | 25.31       | 0.47        | 2.66        | 7.95          | 159          | 77           | 3.78                          | 15.90                         | 1.19                          | 0.15                          |
| 53      | 2.246        | 595         | 35.17       | 17.28       | 2.60        | 2.64        | 13.82         | 131          | 78           | 4.07                          | 11.19                         | 0.86                          | 0.10                          |
| 54      | 2.246        | 595         | 42.78       | 22.75       | 2.60        | 2.64        | 13.58         | 142          | 88           | 3.62                          | 15.55                         | 1.06                          | 0.14                          |
| 55      | 2.246        | 595         | 47.24       | 27.46       | 2.60        | 2.64        | 9.96          | 146          | 85           | 3.62                          | 19.82                         | 1.24                          | 0.17                          |
| 56      | 2.246        | 595         | 52.77       | 31.74       | 2.60        | 2.64        | 8.10          | 142          | 79           | 3.72                          | 23.74                         | 1.40                          | 0.18                          |
| 57      | 2.076        | 595         | 36.93       | 19.14       | 2.60        | 2.64        | 12.77         | 136          | 85           | 3.90                          | 11.87                         | 0.90                          | 0.09                          |
| 58      | 2.076        | 595         | 43.16       | 24.38       | 2.60        | 2.64        | 10.84         | 11           | 77           | 3.69                          | 16.02                         | 1.09                          | 0.12                          |
| 59      | 2.076        | 595         | 50.20       | 28.50       | 2.60        | 2.64        | 11.99         | 153          | 92           | 3.67                          | 20.34                         | 1.21                          | 0.14                          |
| 60      | 2.076        | 595         | 54.70       | 32.31       | 2.60        | 2.64        | 9.85          | 154          | 79           | 3.79                          | 24.16                         | 1.35                          | 0.14                          |
| 61      | 1.822        | 595         | 36.34       | 17.74       | 2.60        | 2.64        | 14.46         | 123          | 84           | 3.54                          | 10.84                         | 0.79                          | 0.04                          |
| 62      | 1.822        | 595         | 43.56       | 25.20       | 2.60        | 2.64        | 9.63          | 162          | 85           | 3.20                          | 15.12                         | 1.05                          | 0.12                          |
| 63      | 1.822        | 595         | 50.97       | 30.34       | 2.60        | 2.64        | 8.79          | 171          | 78           | 3.18                          | 19.05                         | 1.21                          | 0.09                          |
| 64      | 1.822        | 595         | 56.21       | 32.54       | 2.60        | 2.64        | 11.66         | 168          | 87           | 3.25                          | 23.71                         | 1.25                          | 0.11                          |
| 65      | 0.644        | 209         | 34.99       | 20.17       | 2.60        | 2.64        | 5.60          | 101          | 18           | 0.08                          | 3.80                          | 0.55                          | 0.02                          |
| 66      | 0.644        | 209         | 49.27       | 27.29       | 2.60        | 2.64        | 8.22          | 101          | 16           | 0.01                          | 6.60                          | 0.68                          | 0.02                          |

| Run no. | $S_o$<br>(%) | $D$<br>(mm) | $Y$<br>(mm) | $R$<br>(mm) | $d$<br>(mm) | $SG$<br>(-) | $y_s$<br>(mm) | $t_b$<br>(s) | $t_p$<br>(s) | $Q_b$<br>(l s <sup>-1</sup> ) | $Q_p$<br>(l s <sup>-1</sup> ) | $V_f$<br>(m s <sup>-1</sup> ) | $V_s$<br>(m s <sup>-1</sup> ) |
|---------|--------------|-------------|-------------|-------------|-------------|-------------|---------------|--------------|--------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 67      | 0.644        | 209         | 51.63       | 27.99       | 2.60        | 2.64        | 9.89          | 101          | 14           | 0.02                          | 6.84                          | 0.68                          | 0.02                          |
| 68      | 0.644        | 209         | 28.15       | 16.32       | 2.60        | 2.64        | 4.98          | 101          | 20           | 0.14                          | 1.99                          | 0.48                          | 0.01                          |
| 69      | 0.644        | 209         | 30.78       | 16.70       | 2.60        | 2.64        | 7.96          | 101          | 19           | 0.11                          | 2.45                          | 0.47                          | 0.00                          |
| 70      | 0.644        | 209         | 40.49       | 23.10       | 2.60        | 2.64        | 6.26          | 101          | 17           | 0.08                          | 4.73                          | 0.61                          | 0.02                          |
| 71      | 0.644        | 209         | 53.26       | 29.33       | 2.60        | 2.64        | 8.49          | 101          | 15           | 0.02                          | 7.37                          | 0.71                          | 0.03                          |
| 72      | 0.644        | 209         | 35.58       | 20.28       | 2.60        | 2.64        | 6.26          | 101          | 20           | 0.12                          | 3.62                          | 0.55                          | 0.01                          |
| 73      | 0.644        | 209         | 40.61       | 23.32       | 2.60        | 2.64        | 5.82          | 101          | 18           | 0.06                          | 4.58                          | 0.62                          | 0.02                          |
| 74      | 0.644        | 209         | 45.95       | 25.29       | 2.60        | 2.64        | 8.76          | 101          | 17           | 0.03                          | 5.42                          | 0.64                          | 0.01                          |
| 75      | 0.644        | 209         | 52.17       | 28.92       | 2.60        | 2.64        | 7.96          | 101          | 16           | 0.03                          | 7.22                          | 0.71                          | 0.03                          |
| 76      | 0.644        | 209         | 29.87       | 16.87       | 2.60        | 2.64        | 6.26          | 101          | 21           | 0.11                          | 2.06                          | 0.48                          | 0.01                          |
| 77      | 0.644        | 209         | 33.61       | 19.44       | 2.60        | 2.64        | 5.39          | 101          | 19           | 0.10                          | 2.75                          | 0.54                          | 0.01                          |
| 78      | 0.644        | 209         | 44.28       | 24.82       | 2.60        | 2.64        | 7.45          | 101          | 18           | 0.02                          | 5.17                          | 0.64                          | 0.02                          |
| 79      | 0.644        | 209         | 47.12       | 26.13       | 2.60        | 2.64        | 8.22          | 101          | 18           | 0.01                          | 5.90                          | 0.66                          | 0.02                          |
| 80      | 0.644        | 209         | 38.03       | 21.54       | 2.60        | 2.64        | 6.72          | 101          | 19           | 0.08                          | 3.80                          | 0.58                          | 0.01                          |
| 81      | 0.644        | 209         | 41.49       | 23.59       | 2.60        | 2.64        | 6.49          | 101          | 18           | 0.05                          | 4.59                          | 0.62                          | 0.02                          |
| 82      | 0.644        | 209         | 43.13       | 23.90       | 2.60        | 2.64        | 8.22          | 101          | 17           | 0.04                          | 5.55                          | 0.61                          | 0.01                          |
| 83      | 0.644        | 209         | 44.99       | 24.43       | 2.60        | 2.64        | 9.60          | 101          | 16           | 0.02                          | 6.11                          | 0.62                          | 0.02                          |
| 84      | 0.644        | 209         | 38.93       | 21.05       | 2.60        | 2.64        | 9.31          | 101          | 18           | 0.04                          | 4.51                          | 0.55                          | 0.01                          |
| 85      | 0.644        | 209         | 47.10       | 25.93       | 2.60        | 2.64        | 8.76          | 101          | 17           | 0.02                          | 5.83                          | 0.65                          | 0.01                          |
| 86      | 0.644        | 209         | 38.30       | 22.59       | 0.47        | 2.66        | 3.91          | 101          | 17           | 0.10                          | 4.36                          | 0.62                          | 0.06                          |
| 87      | 0.644        | 209         | 51.25       | 29.60       | 0.47        | 2.66        | 3.68          | 101          | 16           | 0.00                          | 7.36                          | 0.76                          | 0.11                          |
| 88      | 0.644        | 209         | 52.44       | 29.99       | 0.47        | 2.66        | 4.65          | 101          | 15           | 0.01                          | 7.64                          | 0.75                          | 0.10                          |
| 89      | 0.644        | 209         | 29.07       | 17.09       | 0.47        | 2.66        | 4.40          | 101          | 19           | 0.21                          | 2.22                          | 0.50                          | 0.03                          |
| 90      | 0.644        | 209         | 33.05       | 19.59       | 0.47        | 2.66        | 3.91          | 101          | 17           | 0.19                          | 2.65                          | 0.56                          | 0.04                          |
| 91      | 0.644        | 209         | 41.19       | 24.21       | 0.47        | 2.66        | 3.86          | 101          | 18           | 0.04                          | 4.99                          | 0.65                          | 0.08                          |
| 92      | 0.644        | 209         | 56.85       | 32.46       | 0.47        | 2.66        | 3.51          | 101          | 15           | 0.00                          | 8.02                          | 0.81                          | 0.13                          |
| 93      | 0.644        | 209         | 39.63       | 23.20       | 0.47        | 2.66        | 4.40          | 101          | 17           | 0.07                          | 4.08                          | 0.62                          | 0.05                          |
| 94      | 0.644        | 209         | 43.42       | 25.52       | 0.47        | 2.66        | 3.46          | 101          | 17           | 0.08                          | 4.99                          | 0.68                          | 0.06                          |
| 95      | 0.644        | 209         | 47.40       | 27.47       | 0.47        | 2.66        | 4.21          | 101          | 16           | 0.04                          | 5.56                          | 0.71                          | 0.07                          |
| 96      | 0.644        | 209         | 30.86       | 18.45       | 0.47        | 2.66        | 3.46          | 101          | 19           | 0.32                          | 2.08                          | 0.54                          | 0.03                          |
| 97      | 0.644        | 209         | 32.77       | 19.21       | 0.47        | 2.66        | 4.59          | 101          | 20           | 0.11                          | 2.80                          | 0.54                          | 0.04                          |
| 98      | 0.644        | 209         | 42.21       | 24.97       | 0.47        | 2.66        | 3.03          | 101          | 19           | 0.41                          | 4.22                          | 0.67                          | 0.06                          |
| 99      | 0.644        | 209         | 37.41       | 21.71       | 0.47        | 2.66        | 5.18          | 101          | 19           | 0.09                          | 3.79                          | 0.59                          | 0.05                          |
| 100     | 0.644        | 209         | 41.66       | 24.19       | 0.47        | 2.66        | 4.86          | 101          | 17           | 0.07                          | 4.63                          | 0.64                          | 0.05                          |

| Run no. | $S_o$<br>(%) | $D$<br>(mm) | $Y$<br>(mm) | $R$<br>(mm) | $d$<br>(mm) | $SG$<br>(-) | $y_s$<br>(mm) | $t_b$<br>(s) | $t_p$<br>(s) | $Q_b$<br>(l s <sup>-1</sup> ) | $Q_p$<br>(l s <sup>-1</sup> ) | $V_f$<br>(m s <sup>-1</sup> ) | $V_s$<br>(m s <sup>-1</sup> ) |
|---------|--------------|-------------|-------------|-------------|-------------|-------------|---------------|--------------|--------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 101     | 0.644        | 209         | 43.34       | 25.14       | 0.47        | 2.66        | 4.78          | 101          | 18           | 0.06                          | 5.71                          | 0.66                          | 0.06                          |
| 102     | 0.644        | 209         | 48.65       | 28.13       | 0.47        | 2.66        | 4.21          | 101          | 16           | 0.03                          | 6.67                          | 0.72                          | 0.09                          |
| 103     | 0.644        | 209         | 36.32       | 21.27       | 0.35        | 2.65        | 4.59          | 101          | 18           | 0.06                          | 4.24                          | 0.58                          | 0.05                          |
| 104     | 0.644        | 209         | 51.00       | 29.01       | 0.35        | 2.65        | 5.60          | 101          | 15           | 0.01                          | 6.81                          | 0.73                          | 0.08                          |
| 105     | 0.644        | 209         | 50.99       | 29.11       | 0.35        | 2.65        | 5.18          | 101          | 15           | 0.01                          | 6.90                          | 0.73                          | 0.09                          |
| 106     | 0.644        | 209         | 28.62       | 16.45       | 0.35        | 2.65        | 5.39          | 101          | 18           | 0.23                          | 2.00                          | 0.48                          | 0.02                          |
| 107     | 0.644        | 209         | 32.66       | 18.92       | 0.35        | 2.65        | 5.26          | 101          | 17           | 0.19                          | 2.67                          | 0.53                          | 0.03                          |
| 108     | 0.644        | 209         | 42.79       | 24.72       | 0.35        | 2.65        | 5.18          | 101          | 16           | 0.07                          | 4.80                          | 0.65                          | 0.04                          |
| 109     | 0.644        | 209         | 54.41       | 30.76       | 0.35        | 2.65        | 5.60          | 101          | 17           | 0.00                          | 7.36                          | 0.76                          | 0.07                          |
| 110     | 0.644        | 209         | 37.13       | 21.55       | 0.35        | 2.65        | 5.18          | 101          | 18           | 0.10                          | 3.75                          | 0.59                          | 0.03                          |
| 111     | 0.644        | 209         | 41.56       | 24.21       | 0.35        | 2.65        | 4.59          | 101          | 17           | 0.08                          | 4.71                          | 0.64                          | 0.05                          |
| 112     | 0.644        | 209         | 45.08       | 25.81       | 0.35        | 2.65        | 5.73          | 101          | 17           | 0.07                          | 5.47                          | 0.67                          | 0.05                          |
| 113     | 0.644        | 209         | 54.08       | 30.60       | 0.35        | 2.65        | 5.60          | 101          | 15           | 0.03                          | 7.31                          | 0.76                          | 0.08                          |
| 114     | 0.644        | 209         | 29.46       | 16.96       | 0.35        | 2.65        | 5.39          | 101          | 20           | 0.19                          | 2.02                          | 0.49                          | 0.03                          |
| 115     | 0.644        | 209         | 33.04       | 18.92       | 0.35        | 2.65        | 5.90          | 101          | 19           | 0.13                          | 2.74                          | 0.53                          | 0.03                          |
| 116     | 0.644        | 209         | 44.81       | 25.64       | 0.35        | 2.65        | 5.82          | 101          | 17           | 0.04                          | 5.18                          | 0.66                          | 0.04                          |
| 117     | 0.644        | 209         | 48.43       | 27.71       | 0.35        | 2.65        | 5.39          | 101          | 17           | 0.02                          | 5.88                          | 0.70                          | 0.05                          |
| 118     | 0.644        | 209         | 39.31       | 22.65       | 0.35        | 2.65        | 5.60          | 101          | 18           | 0.09                          | 3.92                          | 0.60                          | 0.04                          |
| 119     | 0.644        | 209         | 41.99       | 24.16       | 0.35        | 2.65        | 5.60          | 101          | 17           | 0.08                          | 4.59                          | 0.63                          | 0.04                          |
| 120     | 0.644        | 209         | 43.59       | 25.04       | 0.35        | 2.65        | 5.60          | 101          | 18           | 0.04                          | 5.64                          | 0.65                          | 0.04                          |
| 121     | 0.644        | 209         | 44.65       | 25.62       | 0.35        | 2.65        | 5.60          | 101          | 17           | 0.06                          | 6.12                          | 0.66                          | 0.07                          |



Table 2. Pareto solution provided by the EPR-MOGA strategy.

| Number of<br>Inputs | Terms of monomial formula |        |                   |               |                 |                   |         | Performance<br>Index |       |
|---------------------|---------------------------|--------|-------------------|---------------|-----------------|-------------------|---------|----------------------|-------|
|                     | Coefficient ( $a_j$ )     | $\psi$ | $\frac{Q_b}{Q_p}$ | $\frac{d}{R}$ | $\frac{y_s}{R}$ | $\frac{t_b}{t_p}$ | $\beta$ | <i>BIC</i>           | $R^2$ |
| 1                   | 0.17                      | 0.50   | -                 | -             | -               | -                 | -       | -48.21               | 0.38  |
| 2                   | 0.14                      | 0.60   | -0.10             | -             | -               | -                 | -       | -66.19               | 0.48  |
| 3                   | 8.13                      | 1.40   | -0.30             | 0.90          | -               | -                 | -       | -104.55              | 0.63  |
| 4                   | 11.47                     | 1.50   | -0.30             | 1.00          | 0.10            | -                 | -       | -100.56              | 0.64  |
| 5                   | 121.48                    | 2.10   | -0.20             | 1.60          | 0.80            | 0.10              | -       | -96.49               | 0.64  |
| 6                   | 2.48                      | 1.40   | -0.30             | 0.90          | 0.10            | -0.20             | 1.00    | -92.22               | 0.64  |

Table 3. Comparison of results for predicting the flushing efficiency in Laplace et al. (2003) case of study.

| <b>Reference</b>      | <b>Removal rate<br/>[kg m<sup>-3</sup>]</b> | <b>Observations</b>   |
|-----------------------|---|---|
| Laplace et al. (2003) | 0.93  | Original case of Study reported in a trunk combined sewer in Marseille, France  |
| Dettmar (2007)        | -   | Volume of water value reported to clean a pipe section of 150 m long. Relevant parameters as pipe slope and particle diameter are not considered.                         |
| Bong et al. (2013)    | 0.21  | Good approximation. Experimental model (Eq. (3)) obtained with a constant flume slope of 0.001.   |
| EPR-MOGA Eq. (10)     | 0.4 – 1.25                                  | Good performance for predicting the removal rate during flushing waves operation. Model consider relevant parameters as the mean particle diameter and the pipe geometry. |