Non-deposition self-cleansing models for large sewer pipes

Carlos Montes, Sergio Vanegas, Zoran Kapelan, Luigi Berardi and Juan Saldarriaga

ABSTRACT

Multiple models from the literature and experimental datasets have been developed and collected to predict sediment transport in sewers. However, all these models were developed for smaller sewer pipes, i.e. using experimental data collected on pipes with diameters smaller than 500 mm. To address this issue, new experimental data were collected on a larger, 595 mm pipe located in a laboratory at the University of los Andes. Two new self-cleansing models were developed using this dataset. Both models predict the sewer self-cleansing velocity for the cases of non-deposition with and without deposited bed. The newly developed and existing models were then evaluated and compared on the basis of the most recently collected and previously published datasets. Models were compared in terms of prediction accuracy measured by the root mean squared error and mean absolute percentage error. The results obtained show that in the existing literature, self-cleansing models tend to be overfitted, i.e. have a rather high prediction accuracy when applied to the data collected by the authors, but this accuracy deteriorates quickly when applied to the datasets collected by other authors. The newly developed models can be used for designing both small and large sewer pipes with and without deposited bed condition.

Key words | bedload, deposited bed, non-deposition, sediment transport, self-cleansing

Carlos Montes (corresponding author)
Department of Civil and Environmental Engineering,
Universidad de los Andes,
Bogotá,
Colombia
E-mail: *cd.montes1256@uniandes.edu.co*

Sergio Vanegas
Department of Civil and Environmental Engineering,
Universidad de los Andes,
Bogotá,
Colombia

Zoran Kapelan
Department of Water Management,
Delft University of Technology,
Delft,
The Netherlands

Luigi Berardi
Dipartimento di Ingegneria e Geologia,
Università degli Studi Gabriele d'Annunzio Chieti e Pescara,
Pescara,
Italy

Juan Saldarriaga
Department of Civil and Environmental Engineering,
Universidad de los Andes,
Bogotá,
Colombia

INTRODUCTION

Understanding sediment transport is important for designing self-cleansing sewer systems. Sewer deposits are the source of several problems, such as the reduction of hydraulic capacity, blockage and premature overflows (Shirazi *et al.* 2014; Ebtehaj *et al.* 2016; Torres *et al.* 2017; Kargar *et al.* 2019; Montes *et al.* 2019; Safari 2019). Traditionally, conventional minimum velocities and shear stress values have been suggested to define self-cleansing conditions, both in academic literature (Yao 1974; Ackers *et al.* 1996) and industry design manuals (British Standard Institution 1987; Great Lakes 2004). Several authors (Yao 1974; Nalluri & Ab Ghani 1996) have shown that the use of these traditional criteria and conventional values is likely to lead to overdesigning the slope for small diameter pipes (i.e. pipes with diameter D smaller than 500 mm). To address this issue, laboratory investigations have been carried out (e.g. May *et al.* 1989; Ab Ghani 1993; Vongvisessomjai *et al.* 2010; Safari *et al.* 2017a; Alihosseini & Thamsen 2019). These studies focused on estimating the self-cleansing conditions and developing corresponding predictive models in which the minimum self-cleansing velocity (V_l) is a function of several input variables, such as the mean particle diameter (d), the hydraulic radius (R), the specific gravity of sediments (SG), the dimensionless grain size (D_{gr}) or the volumetric sediment concentration (C_v).

According to Safari *et al.* (2018), the above and similar experimental works have studied two self-cleansing design

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criteria: (i) criteria for bed sediment motion and (ii) criteria for sediment non-deposition in sewer pipes. Both criteria are useful for predicting the self-cleansing conditions. In this paper, the non-deposition design criterion is studied using an experimental approach.

Traditionally, non-deposition self-cleansing design criteria have been classified in two general groups (Vongvisessomjai *et al.* 2010; Safari *et al.* 2018): (i) non-deposition without deposited bed and (ii) non-deposition with deposited bed of sediments.

The first group, non-deposition without deposited bed, is a conservative and frequently used criterion for designing self-cleansing sewer systems. In this context, Robinson & Graf (1972) defined critical mean velocity (or minimum self-cleansing velocity, as presented in this study) as the condition in which particles begin deposition and form a stationary deposit at the bottom of the sewer pipe, i.e. the particles do not form a permanent deposit.

Several studies have been carried out in this field, in which models are proposed for the prediction of a minimum self-cleansing velocity that guarantees the non-deposition of particles in sewer pipes. In this context, Mayerle (1988) analysed the sediment transport in a 152 mm diameter pipe using uniform sand ranging from 0.50 mm to 8.74 mm, and sediment concentration between 20 and 1,275 ppm. May *et al.* (1989) analysed sediment transport in a 300 mm diameter concrete pipe using non-cohesive material with a mean particle diameter of 0.72 mm. May (1993) used a 450 mm diameter concrete pipe to study the transport of sands with a mean particle diameter of 0.73 mm. Ab Ghani (1993) studied the non-deposition sediment transport without deposited bed in three sewer pipes of 154 mm, 305 mm and 450 mm, varying the particle diameter from 0.46 mm to 8.3 mm. Ota (1999) carried out experiments in a 305 mm sewer pipe varying the particle diameter from 0.714 mm to 5.612 mm. Vongvisessomjai *et al.* (2010) developed two models for bedload transport and two models for suspended load transport using data collected in two pipes of 100 mm and 150 mm diameter. Safari *et al.* (2017a) conducted experiments in a trapezoidal channel and proposed an equation which includes the cross-section shape factor (β). Recently, Montes *et al.* (2018) collected experimental data from Ab Ghani (1993) and using an evolutionary polynomial regression multi-objective genetic algorithm (EPR-MOGA) developed new self-cleansing models.

The above studies resulted in a series of predictive models for the estimation of self-cleansing velocity but none of them analysed self-cleansing velocity in the context of larger sewer pipes. As a result, all non-deposition self-cleansing models are only useful for designing small sewer pipes ($D < 500$ mm).

Usually, the equations reported in the literature for non-deposition without deposited bed criterion are in the form of:

$$\frac{V_l}{\sqrt{gd(SG-1)}} = aC_v^b\left(\frac{d}{R}\ or\ \frac{d}{D}\right)^{c_1} D_{gr}^{c_2}\,\lambda^{c_3} \tag{1}$$

where g the gravitational acceleration; λ the Darcy's friction factor; D_{gr} the dimensionless grain size $\left(=d\left(\frac{SG-1}{\nu^2}\right)^{\frac{1}{3}}\right)$; SG the specific gravity of sediments; ν the kinematic viscosity of water; D the pipe diameter; and a, b, c_1, c_2, c_3 are coefficients, which vary with each study. For example, in the Ab Ghani (1993) model, $a = 3.08$, $b = 0.21$, $c_1 = -0.53$, $c_2 = -0.09$ and $c_3 = -0.21$:

$$\frac{V_l}{\sqrt{gd(SG-1)}} = 3.08C_v^{0.21}\left(\frac{d}{R}\right)^{-0.53} D_{gr}^{-0.09}\lambda^{-0.21} \tag{2}$$

The second group, non-deposition with deposited bed, is a less conservative criterion used for the design of large self-cleansing sewer systems ($D > 500$ mm) (Safari *et al.* 2018). In this criterion, a small permanent sediment bed is allowed at the bottom of the pipe. Several investigations (May *et al.* 1989; El-Zaemey 1991; Ab Ghani 1993; Butler *et al.* 1996) have found that a permanent sediment bed, with mean proportional sediment depth (y_s/D) close to 1.0%, increases the sediment transport capacity. However, strong supervision of the systems is required because it is close to critical condition (Vongvisessomjai *et al.* 2010).

Based on the aforementioned, several studies have been carried out for describing this phenomenon using predictive numerical models based on experimental data. Experiments by El-Zaemey (1991) were carried out in a 305 mm diameter pipe using bed sediment thicknesses of 47 mm, 77 mm and 120 mm, and granular sediments ranging from 0.53 mm to 8.4 mm in size. Perrusquía (1992) studied the sediment transport in a 225 mm diameter concrete pipe using uniform-sized sands of 0.9 mm and 2.5 mm. May (1993) conducted experiments in a 450 mm diameter pipe using two uniform sands with a mean particle diameter of 0.73 mm and 0.47 mm. Ab Ghani (1993) used a 450 mm diameter pipe varying the deposited bed width (W_b) from 47 mm to 384 mm. Nalluri *et al.* (1997) used the data collected from El-Zaemey (1991) and modified the May *et al.* (1989) model to predict self-cleansing conditions in deposited bed sewers. Safari *et al.* (2017b) used the particle swarm optimization (PSO) algorithm to improve the May (1993) model; good results were obtained with this new model. Recently, Safari & Shirzad (2019) defined an optimum deposited bed thickness, and proposed a new self-cleansing model for sewers with deposited bed.

Models found in the literature to predict the non-deposition bedload transport with deposited bed are in terms of the deposited bed width or the mean proportional sediment bed. As an example, a model was outlined by El-Zaemey (1991) in the following form, where Y is the water level and W_b the deposited bed width:

$$\frac{V_l}{\sqrt{gd(SG-1)}} = 1.95C_v^{0.17}\left(\frac{W_b}{Y}\right)^{-0.40}\left(\frac{d}{D}\right)^{-0.57}\lambda^{0.10} \tag{3}$$

As can be seen from the aforementioned, several authors have studied the sediment transport modes to develop new self-cleansing criteria. Each author has developed predictive models which are useful for designing new sewer infrastructure. However, various limitations have been identified in the use of self-cleansing models. For example, Safari *et al.* (2018) pointed out that non-deposition without deposited bed is useful only in small sewers; for large pipe diameters, the non-deposition with deposited bed criterion must be applied. However, models developed for deposited bed conditions present poor accuracy when different datasets are used (Nalluri *et al.* 1997). Recently, Safari *et al.* (2018) highlighted the poor performance of the equations found in this criterion and recommend further experimental research in this field. In addition, Perrusquía (1992) suggested further experimental work, especially in large sewer pipe diameters (i.e. pipe diameter large than 500 mm).

In this study, new self-cleansing models for non-deposition without deposited bed and deposited bed were developed. A 595 mm diameter PVC was used to collect experimental data. The aim was to improve sediment transport prediction in large sewer pipes, based on a new experimental dataset.

EXPERIMENTAL METHODS

Experimental data were collected on a 595 mm diameter and 10.5 m long PVC pipe, located in the Hydraulics Laboratory of the University of los Andes, Colombia. This pipe was supported on a variable steel truss, allowing pipe slopes between 0.042% and 3.44%. The pipe was directly connected to a 30 m^3 upstream tank which was supplied through a 40 HP pump. The flow rate was controlled using a manually operated valve, allowing it to vary from 0.6 L s^{-1} to 67.3 L s^{-1}. The pipe had four-point gauges to measure the water depth along the entire length of the flume. A sediment feeder was used to supply granular material with a mean particle diameter ranging from 0.35 mm to 2.60 mm to the PVC pipe. The specific gravity of sediments varied from 2.64 to 2.67, which was calculated using the pycnometer method, according to ASTM D854-10 (ASTM D854-14 2014). Figure 1 shows the general scheme of the experimental setup.

The experiments were carried out under uniform flow conditions, i.e. no variations in flowrate and water depth, for both non-deposition criteria. The data collection strategies were similar for both cases; however, the main difference related to the sediment supply to the PVC pipe, which depended on the criterion to be studied. In this context, for the non-deposition without deposited bed criterion, the sediment feeder supplied the material until the particles barely moved with the water and did not form a permanent deposit at the bottom of the pipe. In contrast, for non-deposition with deposited bed, sediment was supplied to form a deposited loose bed along the entire length of the flume.

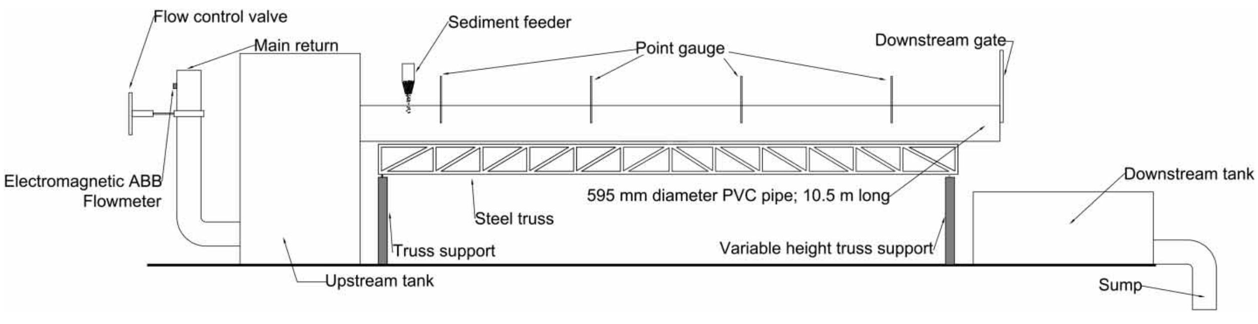

Figure 1 | Schematic diagram of the experimental setup.

This methodology followed the guidelines of several previous experimental works carried out by different authors (e.g. Novak & Nalluri 1975; Ota 1999; Perrusquía 1991; Ab Ghani 1993; Vongvisessomjai et al. 2010; Safari et al. 2017a; Alihosseini & Thamsen 2019). The methodology used to collect the data in both cases is described below.

Non-deposition without deposited bed

The first case considered in this paper is the non-deposition without deposited bed condition. The collection of experimental data was as follows. Firstly, the pipe slope was mechanically adjusted and the value was measured using a dumpy level. Secondly, the flow control valve was opened and a constant flow of water was supplied to the pipe. The flowrate was measured with a real-time electromagnetic flowmeter which was connected directly to the pipe feeding the upstream tank. Thirdly, the water levels were measured using the four-point gauges. The downstream tailgate was adjusted until the water depth varied less than ±2 mm between the four-point gauges, which is the condition in which uniform flow conditions could be assumed (Ab Ghani 1993). Using the values recorded of flowrate and water level, the mean velocity was computed. Fourthly, when uniform flow conditions were achieved, the sediment was supplied to the pipe. The sediment feeder was slowly opened until the non-deposition condition was obtained. This condition, also known as 'flume traction', (i.e. no separated dunes present and no deposition of stationary material at the bottom of the pipe) was checked by visual inspection. Finally, the sediment supply rate ($\ddot{m}$) was estimated by weighing the amount of material that passed in a given time at the outlet of the sediment feeder. The sediment discharge was estimated as $Q_s = \ddot{m}/\rho_s$, where ρ_s is the particle density. The calculated sediment discharge was used to compute the volumetric sediment concentration ($C_v = Q_s/Q$).

The experimental procedure above was repeated for several flowrates, pipe slopes and sediment sizes. A total of 107 data for the non-deposition without deposited bed condition were collected using above experimental approach, as shown in Table 1.

Non-deposition with deposited bed

The methodology used to collect the experimental data for the non-deposition with deposited bed case was similar

Table 1 | Non-deposition without deposited bed experimental data collected in the 595 mm PVC pipe

Run no.	d (mm)	SG (–)	C_v (ppm)	R (mm)	S_o (%)	V_l (m/s)
1	1.51	2.66	10,119	9.88	1.78	0.61
2	1.51	2.66	11,609	7.27	1.78	0.51
3	1.51	2.66	3,940	11.83	1.57	0.67
4	1.51	2.66	3,803	14.41	1.57	0.84
5	1.51	2.66	3,892	18.89	1.22	1.02
6	1.51	2.66	3,681	14.41	0.96	0.77
7	1.51	2.66	19,957	7.92	3.43	0.63
8	1.51	2.66	14,854	9.23	3.43	0.77
9	1.51	2.66	16,731	10.53	3.43	0.97
10	1.51	2.66	13,608	12.48	2.74	0.75
11	1.51	2.66	13,841	10.53	2.74	0.75
12	0.35	2.65	8,720	9.88	2.70	0.80
13	0.35	2.65	6,431	10.53	1.43	0.73
14	0.35	2.65	588	14.41	0.25	0.45
15	0.35	2.65	736	16.98	0.25	0.56
16	0.35	2.65	700	20.16	0.25	0.62
17	0.35	2.65	726	23.32	0.68	0.71
18	0.35	2.65	1,227	25.82	0.68	0.77
19	0.35	2.65	2,499	19.53	1.23	0.85
20	0.35	2.65	2,280	20.79	0.89	0.93
21	0.35	2.65	1,909	27.38	0.89	0.93
22	0.35	2.65	4,155	14.41	1.36	0.71
23	0.35	2.65	3,279	18.89	1.36	0.84
24	0.35	2.65	2,498	22.06	1.36	0.97
25	0.35	2.65	2,051	25.51	1.36	1.02
26	0.47	2.66	4,012	13.77	1.36	0.74
27	0.47	2.66	2,804	18.89	1.36	0.88
28	0.47	2.66	3,153	22.06	1.36	0.98
29	0.47	2.66	3,410	25.20	1.36	1.02
30	0.47	2.66	1,837	27.07	0.89	0.91
31	0.47	2.66	1,658	24.26	0.89	0.84
32	0.47	2.66	1,668	20.16	0.89	0.80
33	0.47	2.66	3,276	14.41	0.89	0.66
34	0.47	2.66	796	28.93	0.42	0.82
35	0.47	2.66	667	33.85	0.42	0.87
36	0.47	2.66	913	40.80	0.42	0.98
37	0.47	2.66	1	79.69	0.04	0.45
38	0.47	2.66	17	95.27	0.04	0.56
39	0.47	2.66	20	107.70	0.04	0.65
40	0.47	2.66	47	119.29	0.08	0.73

(continued)

Table 1 | continued

Run no.	d (mm)	SG (–)	C_V (ppm)	R (mm)	S_o (%)	V_l (m/s)
41	0.47	2.66	43	100.77	0.17	0.79
42	0.47	2.66	6	88.37	0.17	0.60
43	1.22	2.67	955	22.37	0.68	0.77
44	1.22	2.67	1,043	25.20	0.68	0.81
45	1.22	2.67	1,150	28.00	0.68	0.85
46	1.22	2.67	1,341	30.78	0.68	0.91
47	1.22	2.67	1,130	33.24	0.68	0.90
48	1.22	2.67	1,421	38.40	0.68	1.02
49	1.22	2.67	943	39.90	0.42	0.96
50	1.22	2.67	826	33.85	0.42	0.86
51	1.22	2.67	745	24.89	0.42	0.71
52	1.22	2.67	13	72.82	0.17	0.50
53	1.22	2.67	14	88.12	0.17	0.62
54	1.22	2.67	20	93.57	0.08	0.60
55	1.22	2.67	44	106.11	0.08	0.67
56	1.22	2.67	30	103.58	0.08	0.58
57	1.22	2.67	1,748	28.93	0.89	1.01
58	1.22	2.67	1,639	25.82	0.89	0.94
59	1.22	2.67	1,099	19.84	0.89	0.83
60	1.22	2.67	3,322	18.89	1.10	0.90
61	1.22	2.67	2,123	14.41	1.10	0.71
62	1.22	2.67	2,185	23.00	1.10	1.02
63	1.22	2.67	2,645	22.69	1.40	1.04
64	1.22	2.67	2,791	18.25	1.40	0.95
65	1.22	2.67	3,692	14.41	1.40	0.71
66	2.60	2.64	83	80.73	0.21	0.75
67	2.60	2.64	129	90.37	0.21	0.87
68	1.51	2.66	21	90.86	0.04	0.60
69	1.51	2.66	62	89.12	0.04	0.79
70	1.51	2.66	44	87.37	0.04	0.74
71	1.51	2.66	68	86.36	0.13	0.75
72	1.51	2.66	54	74.69	0.13	0.66
73	1.51	2.66	70	72.02	0.21	0.70
74	1.51	2.66	96	78.91	0.21	0.76
75	1.51	2.66	66	84.84	0.21	0.78
76	1.51	2.66	76	86.61	0.04	0.76
77	1.51	2.66	80	88.37	0.04	0.78
78	1.51	2.66	2,729	17.62	1.19	1.10
79	1.51	2.66	1,701	20.48	0.72	0.87
80	1.51	2.66	2,086	18.89	0.93	0.99
81	1.51	2.66	4,066	9.23	1.19	0.62

(*continued*)

Table 1 | continued

Run no.	d (mm)	SG (–)	C_V (ppm)	R (mm)	S_o (%)	V_l (m/s)
82	1.51	2.66	6,869	7.92	1.91	0.78
83	1.51	2.66	6,253	7.92	1.78	0.78
84	2.60	2.64	18	92.83	0.04	0.59
85	2.60	2.64	23	101.71	0.04	0.64
86	2.60	2.64	527	48.77	0.47	1.14
87	2.60	2.64	903	38.10	0.47	1.00
88	2.60	2.64	1,068	29.55	0.47	0.88
89	2.60	2.64	541	57.39	0.47	1.24
90	2.60	2.64	1,373	41.69	1.23	1.41
91	2.60	2.64	2,800	33.24	1.23	1.22
92	0.35	2.65	83	42.88	0.04	0.41
93	0.35	2.65	86	50.52	0.04	0.57
94	0.35	2.65	176	55.97	0.04	0.64
95	0.35	2.65	188	63.01	0.04	0.74
96	0.35	2.65	32	82.28	0.04	0.61
97	0.35	2.65	85	103.34	0.04	0.80
98	0.35	2.65	500	54.55	2.54	1.21
99	0.35	2.65	843	42.88	2.54	1.09
100	0.35	2.65	963	33.85	2.54	1.00
101	2.60	2.64	3,025	11.51	0.89	0.61
102	2.60	2.64	1,945	19.53	0.89	0.88
103	2.60	2.64	1,869	26.14	0.89	1.06
104	2.60	2.64	1,726	31.71	0.89	1.11
105	2.60	2.64	999	32.93	0.59	1.05
106	2.60	2.64	994	40.20	0.59	1.13
107	2.60	2.64	824	48.77	0.59	1.19

to the one used for the non-deposition without deposited bed case. The main difference related to the supply of sediment into the pipe, as the non-deposition with deposited bed case required constant sediment thickness throughout the entire length of the test. The whole data collection strategy was as follows. Firstly, an initial pipe slope was mechanically adjusted, and the flow control valve was opened. As a result, a constant water flow was supplied to the pipe, and its value was recorded with the real-time electromagnetic flowmeter. Secondly, the sediment feeder was slowly opened until the material formed a permanent deposited loose bed, which was continuously monitored by visual inspection. Thirdly, the water levels were recorded using the four-point gauges, and uniform conditions were checked for. If non-uniform conditions were observed, the downstream tailgate was varied until water level differences were smaller than ±2 mm between the four-point gauges. In this step, if the non-deposition with deposited bed condition changed (because a permanent deposit or dunes formed by the change in water level), the pipe slope and the tailgate were iteratively adjusted until uniform flow conditions and a constant sediment width had been observed for at least 15 min. Fourthly, the water level, the pipe slope and the sediment width values were recorded, and the sediment thickness (using the sediment width value) and flow velocity (using flowrate and water level) were calculated. Finally, the sediment supply rate was measured at the outlet of the pipe. The sediment that passed in a given time was collected, dried and weighed, and the sediment discharge was calculated, as described in the 'Non-deposition without deposited bed' section. Five samples of sediments were collected to validate that the sediment supply rate was constant during the entire test. The volumetric sediment concentration was computed using the sediment discharge and the flowrate.

The experimental procedure described was repeated for several flowrates, pipe slopes and sediment sizes. A total of 54 experiments were carried out to collect data for the non-deposition with deposited bed case. The experimental data collected this way is presented in Table 2.

Literature data

Other datasets were collected from the literature for the self-cleansing models shown in Table 3. A total of 483 and 400 data for non-deposition without deposited bed and with deposited bed, respectively, were collected. These data were used to evaluate the performance of the self-cleansing models proposed in this study.

NEW SELF-CLEANSING MODELS

The least absolute shrinkage and selection operator (LASSO) (Tibshirani 1996) regression method was used in this study to develop new self-cleansing models. The LASSO method can be seen as an extension of ordinary least squares (OLS), because it minimizes the value of the residual sum of squares (RSS). However, this is a shrinkage method for feature selection which itself solves the problem of multicollinearity by increasing the bias of the regression in search of decrease in the variance. Additionally, it uses the absolute value of the coefficients in the shrinkage penalty, which allows this method to reduce some of the regression coefficients to an exact value of zero. This helps to avoid problems related to model interpretation and overfitting (James et al. 2013). The LASSO method coefficients minimize the following expression:

$$\min\left[\sum_{i=1}^{n}\left(y_i-\left(\beta_0+\sum_{j=1}^{p}\beta_j x_{ij}\right)\right)^2+\lambda_L\sum_{j=1}^{p}|\beta_j|\right] = \min\left[\mathrm{RSS}+\lambda_L\sum_{j=1}^{p}|\beta_j|\right] \tag{4}$$

where y_i are the observed values; n the number of data; β_0 the intercept value; β_j the model parameter j; x_{ij} the input variable set and $\lambda_L\sum_{j=1}^{p}|\beta_j|$ the shrinkage penalty (James et al. 2013).

Selection of model input variables to represent the particle Froude number are made based on the variables that have the greatest impact on sediment transport. Several authors (May et al. 1996; Ebtehaj & Bonakdari 2016a, 2016b) found that the size and roughness of the pipe (represented by the Darcy friction factor and the pipe diameter), the relative flow depth, the diameter of particle size, the specific gravity of sediments and the volumetric sediment concentration are the input variables that best predict sediment transport. These input variables can be divided into four dimensionless groups called: (i) transport: defined by the volumetric sediment concentration; (ii) sediment: defined by the dimensionless grain size, the specific gravity of sediments and the d/D variable; (iii) transport mode: defined by d/R, D^2/A, y_s/D, W_b/Y and R/D; and (iv) flow resistance: defined by the Darcy friction factor. Based on these, the input variables vector x_{ij} should include the previous variables to predict the particle Froude number.

Two new self-cleansing models were developed for the two sediment non-deposition conditions already mentioned. The R package 'glmnet' (Friedman et al. 2010) was used to apply the LASSO method. In both cases the model output variable was the threshold particle Froude number F^*_{Ri} and the model input variables were selected automatically from the set x_{ij} by solving the following regression problem:

$$\min\left[\sum_{i=1}^{n}\left(\ln(F^*_{Roi})-\ln\left(\beta_0+\sum_{j=1}^{p}\beta_j x_{ij}\right)\right)^2+\lambda_L\sum_{j=1}^{p}|\beta_j|\right] = \min\left[\sum_{i=1}^{n}(\ln(F^*_{Roi})-\ln(F^*_{Ri}))^2+\lambda_L\sum_{j=1}^{p}|\beta_j|\right] \tag{5}$$

$$x_{ij}=\left[\frac{Y}{D}, D_{gr}, \lambda, \frac{d}{R}, \frac{d}{D}, \frac{d}{A}, \frac{D^2}{A}, C_v, \frac{W_b}{Y}, \frac{y_s}{D}\right] \tag{6}$$

Table 2 | Non-deposition with deposited bed data experimentally collected in the 595 mm PVC pipe

Run no.	d (mm)	SG (-)	C_v (ppm)	R (mm)	S_o (%)	V_l (m/s)	y_s/D (%)	W_b (mm)
1	1.51	2.66	786	23.46	0.975	0.73	0.94	115
2	1.51	2.66	763	22.76	0.720	0.80	0.13	43
3	1.51	2.66	744	26.57	0.763	0.83	0.25	60
4	1.51	2.66	982	28.63	0.763	0.96	0.21	55
5	1.51	2.66	389	35.25	0.508	0.86	0.38	73
6	1.51	2.66	702	32.62	0.763	0.93	1.12	125
7	1.51	2.66	939	39.54	0.805	1.05	0.86	110
8	1.51	2.66	632	51.01	0.720	0.90	0.58	90
9	1.51	2.66	1,214	20.87	0.975	0.87	0.61	93
10	1.51	2.66	3,283	14.96	1.822	0.82	0.51	85
11	1.51	2.66	9,596	20.34	2.076	1.12	1.03	120
12	1.51	2.66	4,419	22.08	1.992	1.15	0.51	85
13	1.51	2.66	10,275	9.63	5.424	0.87	0.30	65
14	1.51	2.66	2,980	29.03	1.525	1.16	0.86	110
15	1.51	2.66	2,249	23.84	1.525	1.00	0.30	65
16	1.51	2.66	6,227	15.90	2.500	1.06	0.58	90
17	1.51	2.66	2,128	35.73	0.847	1.06	1.12	125
18	1.51	2.66	7,400	22.25	2.034	1.21	0.71	100
19	1.51	2.66	3,702	23.67	2.034	1.11	0.45	80
20	1.51	2.66	4,172	25.03	2.034	1.21	0.78	105
21	2.6	2.64	2,951	28.40	1.525	1.16	0.86	110
22	2.6	2.64	4,435	23.02	1.992	1.23	0.58	90
23	2.6	2.64	4,962	20.49	2.119	1.04	0.45	80
24	2.6	2.64	9,101	14.96	2.585	1.07	0.51	85
25	2.6	2.64	2,213	40.97	1.314	1.18	0.58	90
26	2.6	2.64	4,995	33.33	1.568	1.21	0.64	95
27	2.6	2.64	3,432	36.12	1.398	1.24	0.58	90
28	2.6	2.64	2,408	44.25	1.271	1.39	1.12	125
29	2.6	2.64	1,968	52.01	1.059	1.26	0.86	110
30	2.6	2.64	1,615	55.59	1.017	1.29	0.71	100
31	1.22	2.67	2,327	15.26	1.653	0.90	0.35	70
32	1.22	2.67	4,759	17.26	1.653	1.11	0.45	80
33	1.22	2.67	3,162	22.01	1.653	1.17	0.64	95
34	1.22	2.67	1,710	30.22	1.229	0.97	0.40	75
35	1.22	2.67	987	31.51	1.229	1.17	0.51	85
36	1.22	2.67	1,052	20.90	0.890	0.81	0.38	73
37	1.22	2.67	1,660	31.19	0.466	0.80	0.45	80
38	1.22	2.67	488	27.58	0.636	0.89	0.55	88
39	1.22	2.67	3,365	9.01	1.525	0.88	0.18	50
40	1.22	2.67	2,527	29.46	1.144	1.28	0.67	97
41	1.22	2.67	652	34.59	0.720	1.01	0.51	85

(*continued*)

Table 2 | continued

Run no.	d (mm)	SG (-)	C_v (ppm)	R (mm)	S_o (%)	V_l (m/s)	y_s/D (%)	W_b (mm)
42	1.22	2.67	460	37.32	0.678	0.90	0.45	80
43	1.22	2.67	1,504	17.05	1.059	0.75	0.25	60
44	1.22	2.67	5,697	12.11	2.203	1.20	0.33	68
45	0.47	2.66	2,516	8.43	1.398	1.39	0.49	83
46	0.47	2.66	2,594	9.46	1.610	1.20	0.33	68
47	0.47	2.66	8,522	10.34	2.373	1.05	0.29	64
48	0.47	2.66	6,424	14.12	2.373	1.53	0.32	67
49	0.47	2.66	5,317	15.06	1.822	1.36	0.71	100
50	0.47	2.66	2,572	17.63	1.314	1.10	0.39	74
51	0.47	2.66	547	19.78	0.847	0.92	0.35	70
52	0.47	2.66	764	27.60	0.890	0.89	0.30	65
53	0.47	2.66	1,918	24.86	1.229	1.05	0.35	70
54	0.47	2.66	5,131	21.53	1.780	1.30	0.38	73

where F^*_{Roi} and F^*_{Ri} are the observed and estimated particle Froude number, defined as:

$$F^*_{Roi} = \frac{V_L}{\sqrt{gd(SG-1)}} \tag{7}$$

$$F^*_{Ri} = \beta_0 + \sum_{j=1}^{p} \beta_j x_{ij} \tag{8}$$

where V_L is the self-cleansing velocity, g is gravitational constant, SG is the specific gravity of the sediment, S_o the pipe slope, D the pipe diameter, A the wetted area, R the hydraulic radius, D_{gr} the dimensionless grain size, λ the Darcy friction factor, d is mean particle diameter, Y the water level, C_v the volumetric sediment concentration and W_b the bed sediment width. By applying the LASSO method to 107 experimental data collected, the following model was obtained for the non-deposited conditions (linearized version shown in Equation (9) and non-linear in Equation (10)):

$$\ln(F^*_{Ri}) = 1.566 + 0.058\ln(\lambda) - 0.593\ln\left(\frac{d}{R}\right) + 0.209\ln(C_v) \tag{9}$$

$$F^*_{Ri} = 4.79\lambda^{0.058}\left(\frac{d}{R}\right)^{-0.593} C_v^{0.209} \tag{10}$$

The same analysis was carried out for the non-deposition with deposited bed condition. The 54 data collected in the laboratory were used as observed information. The model obtained was similar to the one for non-deposition without deposited bed condition (see Equations (9) and (10)) with the difference being that the input variables y_s/D and D_{gr} appear in the final expression:

$$\ln(F_{Ri}{}^*) = 1.764 - 0.169\ln(D_{gr}) + 0.144\ln(C_v) - 0.104\ln\left(\frac{y_s}{D}\right) - 0.305\ln\left(\frac{d}{R}\right) - 0.059\ln(\lambda) \tag{11}$$

$$F^*_{Ri} = 5.83D_{gr}^{-0.169}C_v^{0.144}\left(\frac{y_s}{D}\right)^{-0.104}\left(\frac{d}{R}\right)^{-0.305}\lambda^{-0.059} \tag{12}$$

VALIDATION OF SELF-CLEANSING MODELS

The self-cleansing models shown in Equations (10) and (12) were tested with the datasets obtained from the literature (as shown in Table 3) with the aim of (a) further evaluating the accuracy of the self-cleansing models shown here and (b) comparing these to literature models, all under the different hydraulic conditions and sediment characteristics, used in the literature. In addition, the literature self-cleansing models shown in Table 3, all of which were developed with the data collected on smaller pipes (i.e. less than 500 mm), were tested with the data collected on the 595 mm PVC pipe to further assess their prediction accuracy under these conditions.

Table 3 | Literature self-cleansing models for predicting the non-deposition sediment conditions in sewer pipes

Reference	Model	Non-deposition criterion	No. data	Pipe diameter (mm)	Particle diameter (mm)	Sediment concentration (ppm)
Mayerle (1988). Data collected from Safari *et al.* (2018)	$\frac{V_l}{\sqrt{gd(SG-1)}} = 4.32C_v^{0.23}\left(\frac{d}{R}\right)^{-0.68}$	Without deposited bed	106	152	0.50–8.74	20–1,275
May *et al.* (1989)	$C_v = 0.0211\left(\frac{Y}{D}\right)^{0.36}\left(\frac{D^2}{A}\right)\left(\frac{d}{R}\right)^{0.60}\left[1-\frac{V_t}{V_l}\right]^4\left[\frac{V_l^2}{gD(SG-1)}\right]^{1.5}$	Without deposited bed	48	298.8	0.72	0.31–443
Perrusquía (1991)	Only experimental data	With deposited bed	38	225	0.9	18.7–408
El-Zaemey (1991)	$\frac{V_l}{\sqrt{gd(SG-1)}} = 1.95C_v^{0.17}\left(\frac{W_b}{Y}\right)^{-0.40}\left(\frac{d}{D}\right)^{-0.57}\lambda^{0.10}$	With deposited bed	290	305	0.53–8.4	7.0–917
Ab Ghani (1993)	$\frac{V_l}{\sqrt{gd(SG-1)}} = 3.08C_v^{0.21}D_{gr}^{-0.09}\left(\frac{d}{R}\right)^{-0.53}\lambda_s^{-0.21}$	Without deposited bed	221	154, 305 and 450	0.46–8.30	0.76–1,450
Ab Ghani (1993)	$\frac{V_l}{\sqrt{gd(SG-1)}} = 1.18C_v^{0.16}\left(\frac{W_b}{Y}\right)^{-0.18}\left(\frac{d}{D}\right)^{-0.34}\lambda^{-0.31}$	With deposited bed	26	450	0.72	21–1,269
May (1993)	Only experimental data	Without deposited bed	27	450	0.73	2–38
May (1993)	$\eta = C_v\left(\frac{D}{W_b}\right)\left(\frac{A}{D^2}\right)\left[\frac{\lambda_g\theta_f V_l^2}{8g(SG-1)D}\right]^{-1}$	With deposited bed	46	450	0.47–0.73	3.5–8.23
Ota (1999)	$C_v = 0.001965\left[\frac{V_l}{\sqrt{gd(SG-1)}}\left(\frac{d}{R}\right)^{2/3}\right]^{3.645}$	Without deposited bed	36	305	0.71–5.6	4.2 –59.4
Vongvisessomjai *et al.* (2010)	$\frac{V_l}{\sqrt{gd(SG-1)}} = 4.31C_v^{0.226}\left(\frac{d}{R}\right)^{-0.616}$	Without deposited bed	45	100 and 150	0.20–0.43	4–90
Safari *et al.* (2017b)	$\eta = 0.95 - \frac{2.83}{\exp\left[8.36\left(\frac{\lambda_g\theta_f V_l^2}{8g(SG-1)D}\right)\right]}$	With deposited bed	Data from May (1993)			
Safari & Shirzad (2019)	$\frac{V_l}{\sqrt{gd(SG-1)}} = 3.66C_v^{0.16}\left(\frac{d}{R}\right)^{-0.40}\left(\frac{y_s}{Y}\right)^{-0.10}$	With deposited bed	Data from El-Zaemey (1991), Perrusquía (1991), May (1993) and Ab Ghani (1993)			
Montes *et al.* (2018)	$\frac{V_l}{\sqrt{gd(SG-1)}} = 3.35C_v^{0.20}\left(\frac{d}{R}\right)^{-0.60}$	Without deposited bed	Data from Ab Ghani (1993)			

λ_s: Darcy's friction factor with sediment, $\lambda_s = 0.0014C_v^{-0.04}\left(\frac{W_b}{Y}\right)^{0.34}\left(\frac{R}{d}\right)^{0.24}D_{gr}^{0.54}$.

D_{gr}: Dimensionless grain size, $D_{gr} = \left(\frac{gd^3(SG-1)}{\nu^2}\right)^{1/3}$.

λ_g: Grain friction factor, $\frac{1}{\sqrt{\lambda_g}} = -2\log\left[\frac{d}{12R} + \frac{0.6275\nu}{V_l R\sqrt{\lambda_g}}\right]$, where ν is the kinematic viscosity of fluid.

θ_f: Transition factor, $\theta_f = \frac{\exp\left[\frac{Re^*}{12.5}\right]-1}{\exp\left[\frac{Re^*}{12.5}\right]+1}$, where Re^* is the particle Reynolds number, $Re^* = \sqrt{\frac{\lambda}{8}}\left(\frac{V_l d}{\nu}\right)$.

V_t: Incipient motion threshold velocity, $V_t = 0.125(gd(SG-1))^{0.5}\left(\frac{Y}{d}\right)^{0.47}$.

η: Dimensionless parameter of transport.

Model prediction accuracy is estimated using two performance indicators, root mean squared error (RMSE) and mean absolute percentage error (MAPE):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(F^*_{Roi} - F^*_{Ri})^2}{n}} \quad (13)$$

$$\mathrm{MAPE} = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{F^*_{Roi} - F^*_{Ri}}{F^*_{Roi}}\right| \quad (14)$$

Note that a value of RMSE and MAPE close to 0 indicates high model prediction accuracy, i.e. good fit between the observed and predicted data. The RMSE and MAPE values obtained for the case of non-deposition without deposited bed are presented in Table 4.

The following observations can be made from Table 4:

- The Mayerle (1988) model seems to be overfitted as it has high prediction accuracy (RMSE = 4.119; MAPE = 10.079) only for the data collected in their own experiments. When this model is applied to other datasets, the results are not satisfactory. For example, when the Mayerle (1988) model is applied to the data collected in our experiments, poor performance is obtained (as shown in Figure 2). This is due to the inability of this model to extrapolate predictions beyond the range of data that was used for its development.
- Results obtained by using the May *et al.* (1989) model were similar to the Mayerle (1988) model results. If the May *et al.* (1989) model is used for designing large self-cleansing sewer pipes, the model tends to overestimate the minimum velocity required to avoid particle deposition. Additionally, an incipient motion threshold velocity is required to use this model. This value needs to be estimated on the basis of experimental data and regression equations obtained for certain sediment characteristics which is not pragmatic. In this context, Safari *et al.* (2018) outlined several studies that attempt to predict incipient motion threshold velocity using equations based on experimental data.
- The Ab Ghani (1993) model presents better results in comparison with Mayerle (1988) and May *et al.* (1989) models. The model includes two additional input variables (the dimensionless grain size and the Darcy friction factor) to predict the particle Froude number. However, the value of the exponent related to the dimensionless grain size is low (−0.09), which shows that this variable is not a significant input for this model. In addition, this model has good prediction performance when the 595 mm pipe diameter data (for $F^*_{Roi} < 8.0$) is used (as shown in Figure 2), for the same abovementioned previously.
- The Ota (1999) model uses a similar group of input variables to estimate the self-cleansing velocity. This model

Table 4 | Performance of models found in the literature and the new self-cleansing model (Equation (10)) obtained for non-deposition without deposited bed criterion

		Self-cleansing model						
Dataset	**Performance index**	**Mayerle (1988)**	**May *et al.* (1989)**	**Ab Ghani (1993)**	**Ota (1999)**	**Vongvisessomjai *et al.* (2010)**	**Montes *et al.* (2018)**	**New model, Equation (10)**
Mayerle (1988)	*RMSE*	4.119	3.273	3.376	3.502	3.310	3.170	**3.147**
	MAPE	10.079	15.194	**9.636**	10.439	10.762	14.500	12.504
May *et al.* (1989)	*RMSE*	4.321	3.433	3.545	3.652	3.472	3.330	**3.302**
	MAPE	**12.400**	17.822	16.637	16.593	17.657	21.657	21.810
May (1993)	*RMSE*	4.151	3.291	3.392	3.511	3.328	3.189	**3.167**
	MAPE	37.349	9.706	10.738	**8.110**	9.536	9.226	8.331
Ab Ghani (1993)	*RMSE*	1.598	0.567	0.603	0.762	0.569	**0.500**	0.510
	MAPE	26.965	9.338	10.350	11.930	10.278	**8.730**	9.435
Ota (1999)	*RMSE*	4.068	3.210	3.306	3.424	3.234	3.093	**3.066**
	MAPE	19.632	12.396	9.644	10.313	7.461	7.174	**6.807**
Vongvisessomjai *et al.* (2010)	*RMSE*	3.956	3.132	3.222	3.332	3.159	3.031	**3.007**
	MAPE	24.764	8.274	6.748	4.626	2.036	5.337	**2.012**
Current study	*RMSE*	4.041	3.177	3.276	3.387	3.208	3.072	**3.047**
	MAPE	40.327	29.304	23.307	28.990	19.203	15.639	**14.471**

Values in bold type show the best performing model in each dataset analysed.

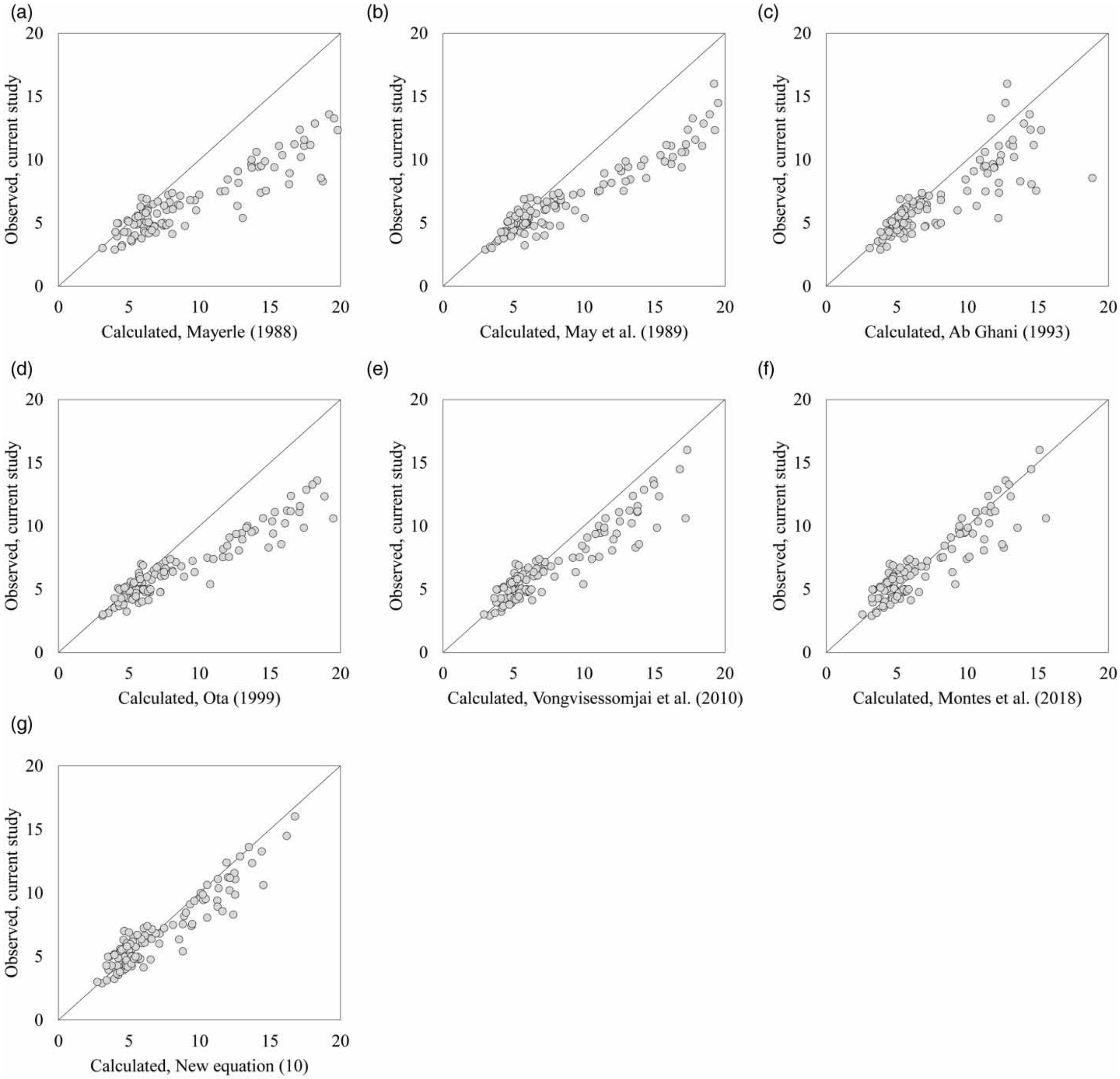

Figure 2 | Comparison of performance of non-deposition without deposited bed models using the experimental data collected for the 595 mm PVC pipe. (a) Mayerle (1988); (b) May *et al.* (1989); (c) Ab Ghani (1993); (d) Ota (1999); (e) Vongvisessomjai *et al.* (2010); (f) Montes *et al.* (2018); and (g) Equation (10).

has similar prediction results to the Mayerle (1988) and May *et al.* (1989) models, with acceptable accuracy for small particle Froude numbers and poor prediction accuracy for larger particle Froude number values ($F_{Ri}^{*} > 7.0$), as shown in Figure 2.

- The Vongvisessomjai *et al.* (2010) model shows good performance in general for all datasets. However, when this equation is applied to the 595 mm PVC pipe diameter data, the model tends to overestimate the particle Froude number (as shown in Figure 2). In comparison with the Ab Ghani (1993) model, this model is simpler and does not consider the dimensionless grain size and the Darcy friction factor in the estimation of the modified Froude number (structure is similar to Ota (1999) equation) which is an advantage. This model seems to be more general and good in the prediction on self-cleansing conditions for pipe diameters of less than 500 mm.
- The Montes *et al.* (2018) model tends to represent the observed data for all the datasets evaluated better than

previous self-cleansing models. This model has the same structure as the Vongvisessomjai et al. (2010) and Ota (1999) models, with values of exponents of different input variables being slightly different. The model shows high accuracy for all datasets but is still inferior to the new model shown in Equation (10) (see below).

- The new model shown in Equation (10) has high prediction accuracy for all datasets, especially for the data collected using larger sewer pipes. Even when this model is applied to existing data in the literature, better results are obtained than those obtained using literature self-cleaning models (as shown in Figure 3 and Table 4). This model has a similar structure to the Vongvisessomjai et al. (2010) and Montes et al. (2018) equations.

As the previous results show, all the traditional self-cleansing models found in the literature presents poor performance/accuracy when tested with the new experimental dataset. As Figure 2 shows, all the models tend to overestimate the threshold velocity. This confirms the assumption that traditional self-cleansing models can make accurate predictions only for small sewer pipes, i.e. pipes with diameter <500 mm.

The results obtained for the case of non-deposition with deposited bed data are shown in Table 5.

The following can be observed from Table 5:

- The El-Zaemey (1991) model tends to correctly represent the self-cleansing conditions for Perrusquía (1991) data and their own data. However, for Ab Ghani (1993) and our data collected on the 595 mm PVC pipe, this model's performance is poor, with low fitting levels obtained (as shown in Figure 4). This model tends to overestimate the minimum self-cleansing velocity, which leads to installing steeper and hence more costly pipes.
- The Ab Ghani (1993) model has the same structure as the El-Zaemey (1991) model, as both models consider the same group of input variables to calculate the threshold self-cleansing velocity. The results obtained tend to present good accuracy for all datasets. The Ab Ghani (1993) model has acceptable accuracy even on our data collected on the 595 mm PVC pipe (as shown in Figure 4), with RMSE and MAPE values of 2.117 and 27.483, respectively. Having said that, this model is still inferior to the new model shown in Equation (12) for the data collected on a large diameter pipe.

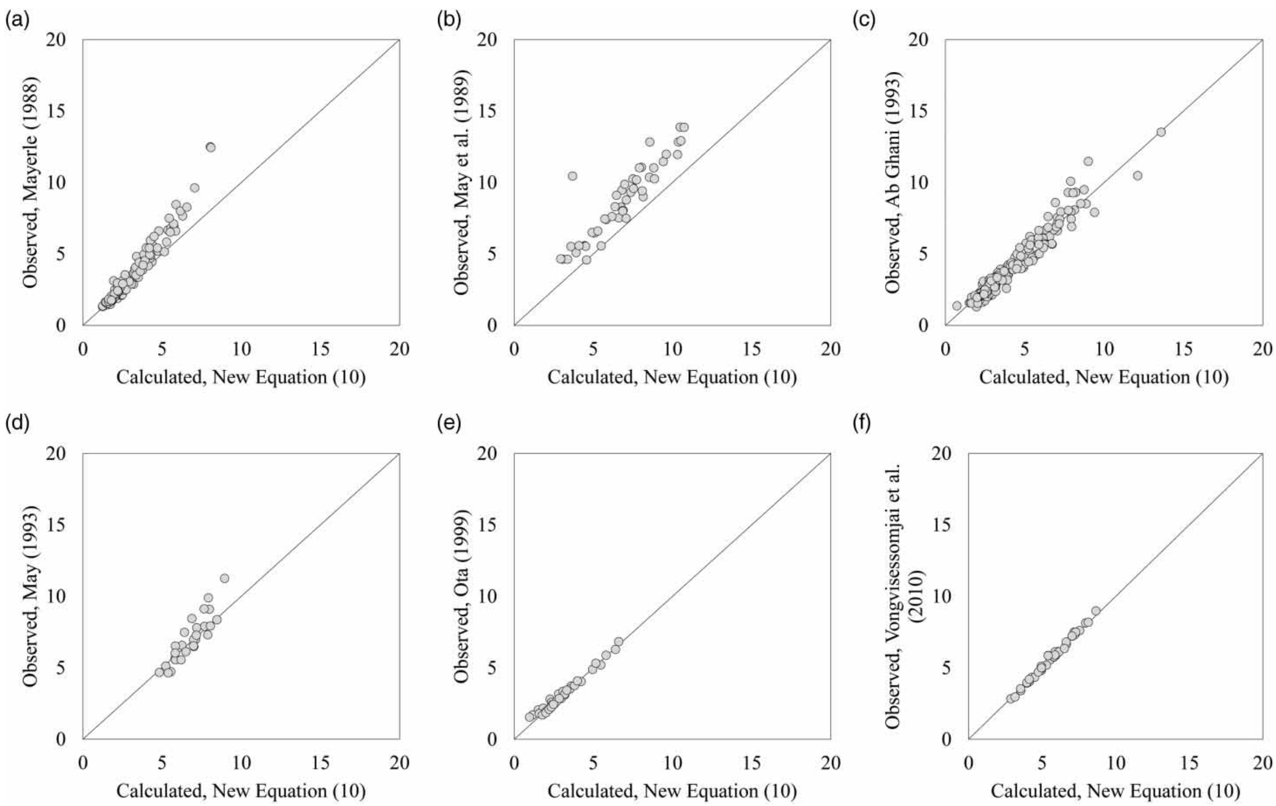

Figure 3 | Comparison of performance of Equation (10) using the experimental data collected in the literature. Data from: (a) Mayerle (1988); (b) May et al. (1989); (c) Ab Ghani (1993); (d) May (1993); (e) Ota (1999); and (f) Vongvisessomjai et al. (2010).

Table 5 | Performance of models found in the literature and the new self-cleansing model (Equation (12)) obtained for non-deposition with deposited bed criterion

		Self-cleansing model					
Dataset	**Performance index**	**El-Zaemey (1991)**	**Ab Ghani (1993)**	**May (1993)**	**Safari *et al.* (2017b)**	**Safari & Shirzad (2019)**	**New model, Equation (12)**
Perrusquía (1991)	*RMSE*	0.786	0.576	2.669	2.883	0.521	**0.464**
	MAPE	17.411	10.833	63.261	71.279	10.550	**10.348**
El-Zaemey (1991)	*RMSE*	**0.494**	0.814	2.580	2.749	0.757	0.659
	MAPE	**10.436**	13.408	60.744	71.963	14.251	11.922
May (1993)	*RMSE*	3.409	1.153	3.561	3.562	1.409	**1.014**
	MAPE	49.757	11.702	45.381	47.177	18.734	**11.154**
Ab Ghani (1993)	*RMSE*	5.105	2.407	3.724	3.722	1.316	**1.161**
	MAPE	72.772	33.614	47.580	48.831	16.544	**14.178**
Current study	*RMSE*	4.217	2.117	2.753	2.696	3.059	**1.565**
	MAPE	54.510	27.483	27.487	26.186	21.047	**10.355**

Values in bold type show the best performing model in each dataset analysed.

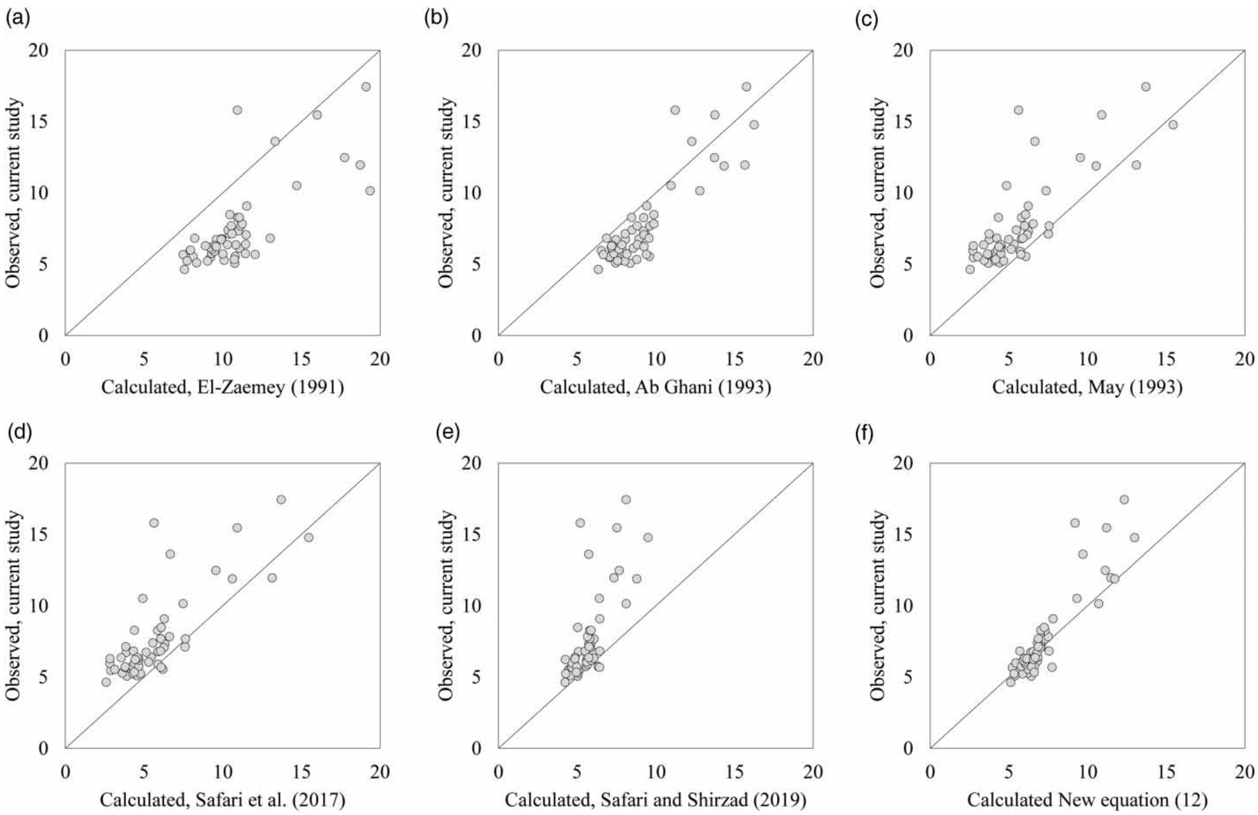

Figure 4 | Comparison of performance of non-deposition with deposited bed models using the experimental data collected for the 595 mm PVC pipe. Models from: (a) El-Zaemey (1991); (b) Ab Ghani (1993); (c) May (1993); (d) Nalluri *et al.* (1997); (e) Safari *et al.* (2017b); and (f) Equation (12).

- The May (1993) model tends to underestimate the minimum self-cleansing values on large sewer pipes, as shown in Figure 4(c). As a result, particle deposition problems could arise in real sewer systems. Additionally, this model has as an input the dimensionless transport parameter (η), which was calculated for limited sediment and hydraulic conditions. Based on the above, this transport parameter is difficult to estimate, and its prediction does not present good accuracy with experimental data. Full details can be found in May (1993).

- The Safari *et al.* (2017b) model results are similar to the May (1993) and Ab Ghani (1993) models when compared for large sewer pipes, i.e. our data. These models tend to underestimate the minimum self-cleansing velocity in large sewer pipes. However, the results are better than for El-Zaemey (1991), as shown in Table 5.
- The Safari & Shirzad (2019) model results are similar to May (1993) and Safari *et al.* (2017b), i.e. the self-cleansing calculation tends to be underestimated in large sewer pipes. In contrast, this model presents a simpler structure because it does not consider the dimensionless parameter of transport (η) and the calculation of velocity is explicit. Results tend not to be satisfactory for large sewer pipes (as shown in Figure 4).
- The new model shown in Equation (12) estimates the self-cleansing conditions across all experimental datasets with acceptable accuracy, as shown in Figure 5. This model is explicit for calculating self-cleansing velocity and considers similar group of parameters than the models in the literature. Based on the results obtained, this model can be used to design new self-cleansing sewer pipes considering the non-deposition with deposited bed criterion.

CONCLUSIONS

In this study the non-deposition criteria was applied to large sewer pipes. A set of 107 data and 54 data, for non-deposition without deposited bed and deposited bed, respectively, was collected at laboratory scale. These experiments were carried out varying steady flow conditions and sediment characteristics. The data collected were used to test the performance of typical self-cleansing equations found in the literature. In addition, based on the LASSO technique, two new self-cleansing models were obtained for each non-deposition criterion. These new models were tested with data collected from the literature and their performance was measured by using RMSE and MAPE.

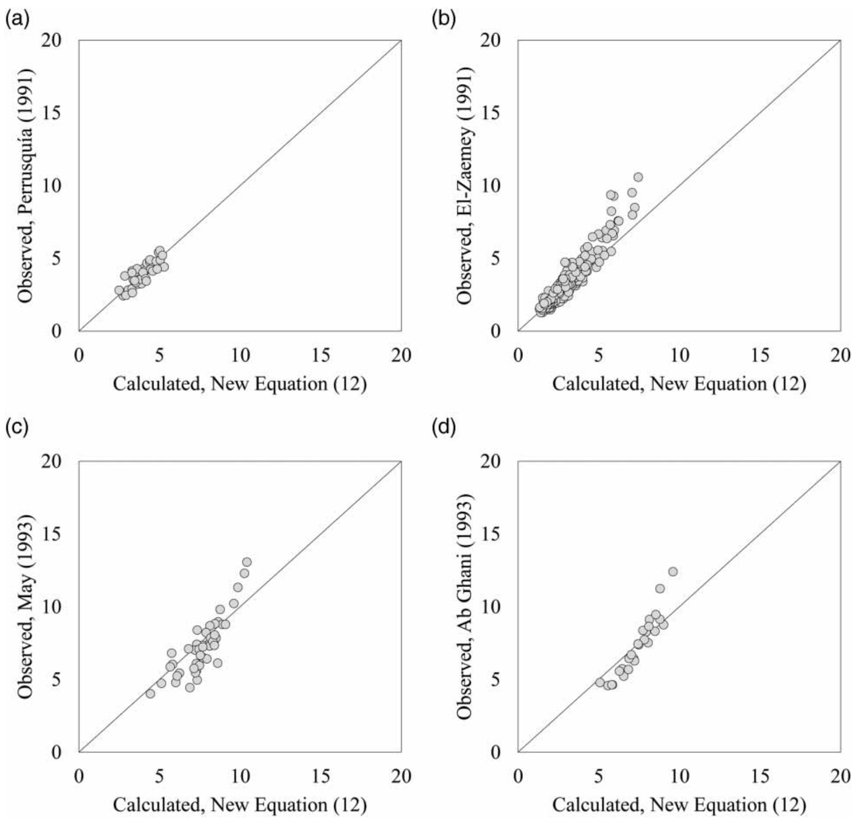

Figure 5 | Comparison of performance of Equation (12) using the experimental data collected from the literature. Data from: (a) Perrusquía (1991); (b) El-Zaemey (1991); (c) May (1993); and (d) Ab Ghani (1993).

The following conclusions are based on the results obtained:

(1) The two new self-cleansing models developed and presented here have overall best predictive performance for two different sediment non-deposition criteria when compared to a selection of well-known models from the literature. This is especially true for predictions made on larger diameter pipes (500 mm and above).
(2) The existing self-cleansing models from the literature tend to be overfitted, i.e. demonstrate a rather high prediction accuracy when applied to the data collected by the authors, but this accuracy deteriorates quickly when applied to the datasets collected by other authors. For large sewer pipes, these models, being developed for datasets collected on smaller diameter pipes, tend to overestimate the threshold self-cleansing velocities, especially in the case of non-deposition without deposited bed.

Further research is recommended to test the performance of new models in larger sewer pipes and with different pipe materials, sediment characteristics and hydraulic conditions. In addition, experiments under non-steady conditions are essential to test the sediment dynamics in real sewer systems.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wst.2020.154. Supplementary material 1: https://youtu.be/YC_AEBMqYC0. Supplementary material 2: https://youtu.be/ivyoBba8V-c.

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