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# Non-deposition self-cleansing models for large sewer pipes

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Multiple literature models 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 diameter smaller than 500 mm. To address this issue, new experimental data was collected on a larger, 595 mm pipe located in the University of Los Andes laboratory. Two new self-cleansing models were developed by 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 literature models were then evaluated and compared on latest collected and previously published datasets. Models were compared in terms of prediction accuracy measured by using the Root Mean Squared Error and Mean Absolute Percentage Error. The results obtained show that 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.

Keywords: bedload; deposited bed; non-deposition; sediment transport; self-cleansing.

## 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, among other problems (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 leads 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*. (2017) and Alihosseini & Thamsen (2019), among other studies). 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 ($C_v$), among others.

According to Safari *et al*. (2018), above and similar experimental works have studied two self-cleansing design 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 and 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 to predict 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*. (2017) conducted experiments in a trapezoidal channel and proposed an equation which includes the cross-section shape factor ($\beta$). Recently, Montes *et al*. (2018) collected experimental data from Ab Ghani (1993) and using an Evolutionary Polynomial Regression Multi-Objective Strategy (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, as it can be seen from the above, none of these studies analysed this in the context of larger sewer pipes. As a result, all non-deposition self-cleansing models are only useful to design 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:

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

where $g$ the gravitational acceleration; $\lambda$ 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; $\nu$ the kinematic viscosity of water; $D$ the pipe diameter; and $a$, $b$, $c_1$, $c_2$, $c_3$ coefficients, which depends of each study. For example, in the Ab Ghani (1993)'s model, $a$ = 3.08, $b$ = 0.21, $c_1$ = -0.53, $c_2$ = -0.09 and $c_3$ = -0.21:

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

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. By contrast, 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. El-Zaemey (1991)'s experiments were carried out in a 305 mm diameter pipe using bed sediment thickness of 47 mm, 77 mm and 120 mm, and granular sediments ranging from 0.53 mm to 8.4 mm. 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*. (2017) used the Particle Swarm Optimization (PSO) algorithm to improve the May (1993) model; Good results were obtained with this new model. Recently, Safari and Shirzad (2019) defined an optimum deposited bed thickness providing design charts, and a new self-cleansing model for sewers with deposited bed was proposed.

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, El-Zaemey (1991)'s model is in the form, where $Y$ is the water level and $W_b$ the deposited bed width:

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

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 to design new sewer infrastructure. However, various limitations have been identified by using 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) suggest 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 are developed. A 595 mm diameter PVC is used to collecting experimental data. The aim is improving 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 University of Los Andes Hydraulics Laboratory, Colombia. This pipe is supported on a variable steel truss allowing pipe slopes between 0.042% and 3.44%. The pipe is directly connected to a 30 $m^3$ upstream tank which is supplied through a 40 HP pump. The flow rate is controlled using a manually operated valve allowing it to vary from 0.6 L $s^{-1}$ to 67.3 L $s^{-1}$. The pipe has four-point gauges to measure the water depth along the entire length of the flume. A sediment feeder is 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 varies from 2.64 to 2.67, which was calculated using a pycnometer method-procedure, according to ASTM D854-10 (ASTM D854-14, 2014). Figure 1 shows the general scheme of the experimental setup.

**[Figure 1 near here]**

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 are similar for both cases; however, the main difference is related to the sediment supply to the PVC pipe, which depends on the criterion to be studied. In this context, for non-deposition without deposited bed criterion, the sediment feeder supplies the material until the particles can barely move with the water and do not form a permanent deposit at the bottom of the pipe. In contrast, for non-deposition with deposited bed, sediment is supplied to form a deposited loose bed along the entire length of the flume. This methodology follows the guidelines of several previous experimental works carried out by different authors (e.g. Novak & Nalluri 1975; Perrusquía 1991; Ab Ghani 1993; Ota 1999; Vongvisessomjai *et al.* 2010, Safari *et al.* 2017 and Alihosseini & Thamsen 2019, among others experimental studies). 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 is described as follows. Firstly, the pipe slope is mechanically adjusted and the value is measured using a dumpy level. Secondly, the flow control valve is opened and a constant flow of water is supplied to the pipe. The flowrate is measured with a real-time electromagnetic flowmeter which is connected directly to the pipe feeding the upstream tank. Thirdly, the water levels are measured using the four-point gauges. The downstream tailgate is adjusted until the water depth varies less than $\pm$ 2 mm between the four-point gauges, which is the condition in which uniform flow conditions can be assumed (Ab Ghani 1993). Using the values recorded of flowrate and water level, the mean velocity is computed. Fourthly, when uniform flow conditions are achieved, the sediment is supplied to the pipe. The sediment feeder is slowly opened until the non-deposition condition is obtained. This condition, also known as "flume traction", (i.e. no presence of separated dunes or deposition of stationary material at the bottom of the pipe) is checked by visual inspection. Finally, the sediment supply rate ($\dot{m}$) is estimated by weighing the amount of material that passes in a given time at the outlet of the sediment feeder. The sediment discharge is estimated as $Q_s = \dot{m}/\rho_s$, where $\rho_s$ is the particle density. The calculated sediment discharge is used to compute the volumetric sediment concentration ($C_v = Q_s/Q$). The above experimental procedure is 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.

**[Table 1 near here]**

***Non-deposition with deposited bed***

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

**[Table 2 near here]**

### *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 are used to evaluate the performance of the self-cleansing models proposed in this study.

**[Table 3 near here]**

## NEW SELF-CLEANSING MODELS

The Least Absolute Shrinkage and Selection Operator (LASSO) (Tibshirani 1996) regression method is used in this study to develop new self-cleansing models. The LASSO method can be seen as an extension of the 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 solves itself the problem of multicollinearity by increasing the bias of the regression in seek of decrease in the variance. Additionally, it uses the absolute value of the coefficients in the shrinkage penalty, what 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:

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

where $y_i$ are the observed values; $n$ the number of data; $\beta_0$ the intercept value; $\beta_j$ the model parameter $j$; $x_{ij}$ the input variable set and $\lambda_L \sum_{j=1}^{p} \left|\beta_j\right|$ 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 (Ebtehaj & Bonakdari 2016a, b; May *et al*. 1996) 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 which predict better the sediment transport. These input variables can be divided in 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 resistant: defined by the Darcy friction factor. Based on the above mentioned, the input variables vector $x_{ij}$ should includes the previous variables to predict the particle Froude number.

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

$$\min\left[\sum_{i=1}^{n}\left(\ln({F_{Ro}}_i^*)-\ln\left(\beta_0+\sum_{j=1}^{p}\beta_j x_{ij}\right)\right)^2+\lambda_L\sum_{j=1}^{p}|\beta_j|\right]$$
$$=\min\left[\sum_{i=1}^{n}\left(\ln({F_{Ro}}_i^*)-\ln({F_R}_i^*)\right)^2+\lambda_L\sum_{j=1}^{p}|\beta_j|\right] \quad (5)$$

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

where ${F_{Ro}}_i^*$ and ${F_R}_i^*$ are the observed and estimated particle Froude number, defined as:

$${F_{Ro}}_i^*=\frac{V_L}{\sqrt{gd(SG-1)}} \quad (7)$$

$${F_R}_i^*=\beta_0+\sum_{j=1}^{p}\beta_j x_{ij} \quad (8)$$

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, $\lambda$ 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. Applying the LASSO method to 107 experimental data collected, the following model is obtained for the non-deposited conditions (linearized version shown in equation 9 and non-linear in equation 10):

$$\ln\left({F_R}_i^*\right)=1.566+0.058\ln(\lambda)-0.593\ln\left(\frac{d}{R}\right)+0.209\ln(C_v) \quad (9)$$

$${F_R}_i^*=4.79\lambda^{0.058}\left(\frac{d}{R}\right)^{-0.593}C_v^{0.209} \quad (10)$$

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

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

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

## VALIDATION OF SELF-CLEANSING MODELS

Self-cleansing models shown in equations (10) and (12) are tested with the datasets obtained from the literature (as shown in Table 3) with the aim to (a) further evaluate the accuracy of the self-cleansing models shown here and (b) compare these to literature models, all under 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), are tested with the data collected on the 595 mm PVC pipe to further assess their prediction accuracy under these conditions.

Model prediction accuracy is estimated using two performance indicators, Root Mean Squared Error (RMSE) and Mean Absolute Percentage Error (MAPE):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left({F_{Ro}}_i^* - {F_R}_i^*\right)^2}{n}} \tag{13}$$

$$\mathrm{MAPE} = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{{F_{Ro}}_i^* - {F_R}_i^*}{{F_{Ro}}_i^*}\right| \tag{14}$$

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.

**[Table 4 near here]**

The following observations can be made from Table 4:

- 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 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 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 are 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.
- 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

of this model. In addition, this model has good prediction performance when the 595 mm pipe diameter data (for ${F_{Ro}}_i^* < 8.0$) is used (as shown in Figure 2), for the same reason abovementioned.

- Ota (1999) model uses a similar group of input variables to estimate the self-cleansing velocity. This model has similar prediction results to 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 (${F_R}_i^* > 7.0$), as shown in Figure 2.
- 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 Ab Ghani (1993)'s 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 less than 500 mm.
- Montes *et al*. (2018) model tends to represent better than previous self-cleansing models, the observed data for all the datasets evaluated. This model has the same structure as 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 similar structure than 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 are 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.

**[Figure 2 and Figure 3 near here]**

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

**[Table 5 near here]**

The following can be observed from Table 5:

- El-Zaemey (1991) model tends to represent correctly 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 has poor performance 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.
- Ab Ghani (1993) model has the same structure as El-Zaemey (1991) 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. 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 this, this model is still inferior to the new model shown in Equation (12) for the data collected on a large diameter pipe.

- May (1993) model tends to underestimate the minimum self-cleansing values on large sewer pipes, as shown in Figure 4c. As a result, particle deposition problems could be presented in real sewer systems. Additionally, this model has as an input the dimensionless transport parameter ($\eta$), which was calculated for a limit 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 on May (1993).
- Safari *et al*. (2017) model results are similar to May (1993) and Ab Ghani (1993) models when are compared in large sewer pipes, i.e. our data. These models tend to underestimate the minimum self-cleansing velocity in large sewer pipes. However, better results than El-Zaemey (1991) can be observed, as shown in Table 5.
- Safari and Shirzad (2019) model results are similar to May (1993) and Safari *et al.* (2017), 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 ($\eta$) and the calculation of velocity is explicit. Results tend to not be satisfactory in large sewer pipes (as shown in Figure 4).
- 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 literature model. 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.

**[Figure 4 and Figure 5 near here]**

## CONCLUSIONS

This paper study the non-deposition criteria applied in large sewer pipes. A set of 107 data and 54 data, for non-deposition without deposited bed and deposited bed, respectively, were 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 LASSO technique two new self-cleansing models were obtained for each non-deposition criterion. These new models were tested with data collected from literature and the performance was measured by using the Root Mean Squared Error and Mean Absolute Percentage Error.

Based on the results obtained, the following conclusions are made:

(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 literature models. This is especially true for predictions made on larger diameter pipes (500 mm and above).

(2) The existing literature self-cleansing models 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 data sets 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 considering 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.

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## SUPPLEMENTARY MATERIAL

The following files are available online:

(1) Video of sediment transport as flume traction

(2) Video of sediment moving as a deposited loose bed.

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

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

Table 3. Self-cleansing models found in literature useful to predict the non-deposition conditions in sewer pipes.

Table 4. Performance of literature and the new self-cleansing model (Equation (10)) obtained for non-deposition without deposited bed criterion. Bolded values show the best performing model on each data set analysed.

Table 5. Performance of literature models and the new self-cleansing model (Equation (12)) obtained for non-deposition with deposited bed criterion. Bolded values show best performing model on each data set analysed.

Figure 1. Schematic diagram of the experimental setup.

Figure 2. Comparison of performance of non-deposition without deposited bed models using the experimental data collected on 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).

Figure 3. Comparison of performance of Equation (10) using the experimental data collected on 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).

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

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

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 |
| 41 | 0.47 | 2.66 | 43 | 100.77 | 0.17 | 0.79 |

| Run No. | $d$ (mm) | $SG$ (-) | $C_v$ (ppm) | $R$ (mm) | $S_o$ (%) | $V_l$ (m/s) |
|---|---|---|---|---|---|---|
| 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 |
| 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 |

| Run No. | $d$ (mm) | $SG$ (-) | $C_v$ (ppm) | $R$ (mm) | $S_o$ (%) | $V_l$ (m/s) |
|---|---|---|---|---|---|---|
| 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 |

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 | 1214 | 20.87 | 0.975 | 0.87 | 0.61 | 93 |
| 10 | 1.51 | 2.66 | 3283 | 14.96 | 1.822 | 0.82 | 0.51 | 85 |
| 11 | 1.51 | 2.66 | 9596 | 20.34 | 2.076 | 1.12 | 1.03 | 120 |
| 12 | 1.51 | 2.66 | 4419 | 22.08 | 1.992 | 1.15 | 0.51 | 85 |
| 13 | 1.51 | 2.66 | 10275 | 9.63 | 5.424 | 0.87 | 0.30 | 65 |
| 14 | 1.51 | 2.66 | 2980 | 29.03 | 1.525 | 1.16 | 0.86 | 110 |
| 15 | 1.51 | 2.66 | 2249 | 23.84 | 1.525 | 1.00 | 0.30 | 65 |
| 16 | 1.51 | 2.66 | 6227 | 15.90 | 2.500 | 1.06 | 0.58 | 90 |
| 17 | 1.51 | 2.66 | 2128 | 35.73 | 0.847 | 1.06 | 1.12 | 125 |
| 18 | 1.51 | 2.66 | 7400 | 22.25 | 2.034 | 1.21 | 0.71 | 100 |
| 19 | 1.51 | 2.66 | 3702 | 23.67 | 2.034 | 1.11 | 0.45 | 80 |
| 20 | 1.51 | 2.66 | 4172 | 25.03 | 2.034 | 1.21 | 0.78 | 105 |
| 21 | 2.6 | 2.64 | 2951 | 28.40 | 1.525 | 1.16 | 0.86 | 110 |
| 22 | 2.6 | 2.64 | 4435 | 23.02 | 1.992 | 1.23 | 0.58 | 90 |
| 23 | 2.6 | 2.64 | 4962 | 20.49 | 2.119 | 1.04 | 0.45 | 80 |
| 24 | 2.6 | 2.64 | 9101 | 14.96 | 2.585 | 1.07 | 0.51 | 85 |
| 25 | 2.6 | 2.64 | 2213 | 40.97 | 1.314 | 1.18 | 0.58 | 90 |
| 26 | 2.6 | 2.64 | 4995 | 33.33 | 1.568 | 1.21 | 0.64 | 95 |
| 27 | 2.6 | 2.64 | 3432 | 36.12 | 1.398 | 1.24 | 0.58 | 90 |
| 28 | 2.6 | 2.64 | 2408 | 44.25 | 1.271 | 1.39 | 1.12 | 125 |
| 29 | 2.6 | 2.64 | 1968 | 52.01 | 1.059 | 1.26 | 0.86 | 110 |
| 30 | 2.6 | 2.64 | 1615 | 55.59 | 1.017 | 1.29 | 0.71 | 100 |
| 31 | 1.22 | 2.67 | 2327 | 15.26 | 1.653 | 0.90 | 0.35 | 70 |
| 32 | 1.22 | 2.67 | 4759 | 17.26 | 1.653 | 1.11 | 0.45 | 80 |
| 33 | 1.22 | 2.67 | 3162 | 22.01 | 1.653 | 1.17 | 0.64 | 95 |
| 34 | 1.22 | 2.67 | 1710 | 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 | 1052 | 20.90 | 0.890 | 0.81 | 0.38 | 73 |
| 37 | 1.22 | 2.67 | 1660 | 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 | 3365 | 9.01 | 1.525 | 0.88 | 0.18 | 50 |
| 40 | 1.22 | 2.67 | 2527 | 29.46 | 1.144 | 1.28 | 0.67 | 97 |
| 41 | 1.22 | 2.67 | 652 | 34.59 | 0.720 | 1.01 | 0.51 | 85 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 42 | 1.22 | 2.67 | 460 | 37.32 | 0.678 | 0.90 | 0.45 | 80 |
| 43 | 1.22 | 2.67 | 1504 | 17.05 | 1.059 | 0.75 | 0.25 | 60 |
| 44 | 1.22 | 2.67 | 5697 | 12.11 | 2.203 | 1.20 | 0.33 | 68 |
| 45 | 0.47 | 2.66 | 2516 | 8.43 | 1.398 | 1.39 | 0.49 | 83 |
| 46 | 0.47 | 2.66 | 2594 | 9.46 | 1.610 | 1.20 | 0.33 | 68 |
| 47 | 0.47 | 2.66 | 8522 | 10.34 | 2.373 | 1.05 | 0.29 | 64 |
| 48 | 0.47 | 2.66 | 6424 | 14.12 | 2.373 | 1.53 | 0.32 | 67 |
| 49 | 0.47 | 2.66 | 5317 | 15.06 | 1.822 | 1.36 | 0.71 | 100 |
| 50 | 0.47 | 2.66 | 2572 | 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 | 1918 | 24.86 | 1.229 | 1.05 | 0.35 | 70 |
| 54 | 0.47 | 2.66 | 5131 | 21.53 | 1.780 | 1.30 | 0.38 | 73 |

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) | $\frac{V_l}{\sqrt{gd(SG-1)}} = 4.32{C_v}^{0.23}\left(\frac{d}{R}\right)^{-0.68}$ | 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) | $\frac{V_l}{\sqrt{gd(SG-1)}} = 1.95{C_v}^{0.17}\left(\frac{W_b}{Y}\right)^{-0.40}\left(\frac{d}{D}\right)^{-0.57}\lambda^{0.10}$ | With deposited bed | 290 | 305 | 0.53 – 8.4 | 7.0 – 917 |
| Ab Ghani (1993) | $\frac{V_l}{\sqrt{gd(SG-1)}} = 3.08{C_v}^{0.21}D_{gr}^{-0.09}\left(\frac{d}{R}\right)^{-0.53}\lambda_s^{-0.21}$ | Without deposited bed | 221 | 154, 305 and 450 | 0.46 – 8.30 | 0.76 – 1,450 |
| Ab Ghani (1993) | $\frac{V_l}{\sqrt{gd(SG-1)}} = 1.18{C_v}^{0.16}\left(\frac{W_b}{Y}\right)^{-0.18}\left(\frac{d}{D}\right)^{-0.34}\lambda^{-0.31}$ | 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 |

| Reference | Model | Non-deposition criterion | No. Data | Pipe diameter (mm) | Particle diameter (mm) | Sediment Concentration (ppm) |
|---|---|---|---|---|---|---|
| Ota (1999) | $C_v = 0.00017\left[\frac{V_l}{\sqrt{gd(SG-1)}}\left(\frac{d}{R}\right)^{2/3}\right]^{3.645}$ | 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.* (2017) | $\eta = 0.95 - \frac{2.83}{\exp\left[8.36\left(\frac{\lambda_g \theta_f V_l{}^2}{8g(SG-1)D}\right)\right]}$ | With deposited bed | Data from May (1993) | | | |
| Safari and 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) | | | |

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

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

$\theta_f$: 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, $V_t = 0.125(gd(SG-1))^{0.5}\left(\frac{Y}{d}\right)^{0.47}$

$\eta$: Dimensionless parameter of transport.

Table 4. Performance of literature and the new self-cleansing model (Equation (10)) obtained for non-deposition without deposited bed criterion. Bolded values show the best performing model on each data set analysed.

| **Data Set** | **Performance Index** | **Self-cleansing model** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **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** |

Table 5. Performance of literature models and the new self-cleansing model (Equation (12)) obtained for non-deposition with deposited bed criterion. Bolded values show best performing model on each data set analysed.

| **Data Set** | **Performance Index** | **Self-cleansing model** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **El-Zaemey (1991)** | **Ab Ghani** (1993) | **May (1993)** | **Safari *et al.* (2017)** | **Safari and 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** |

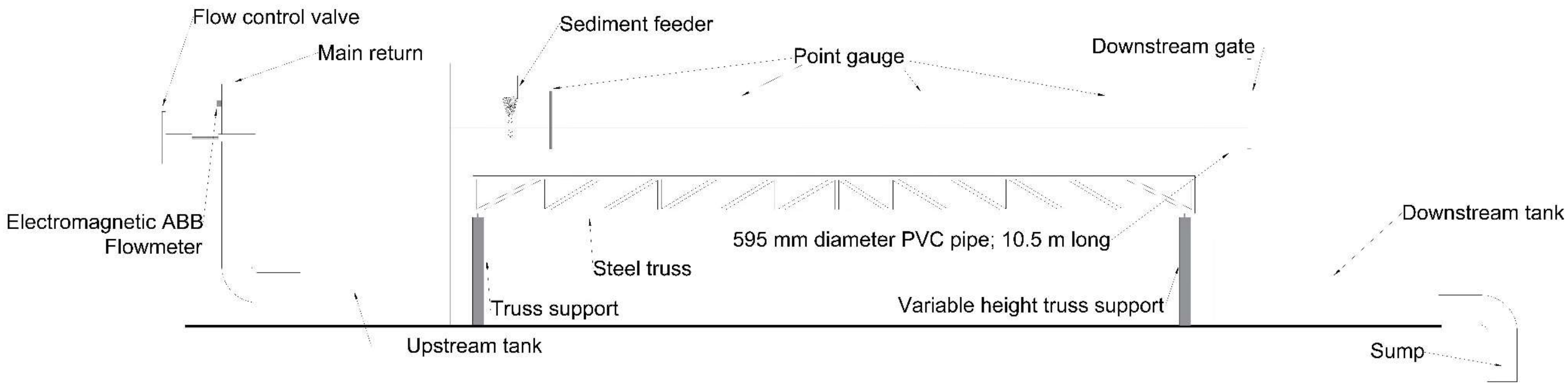


Figure 1. Schematic diagram of the experimental setup

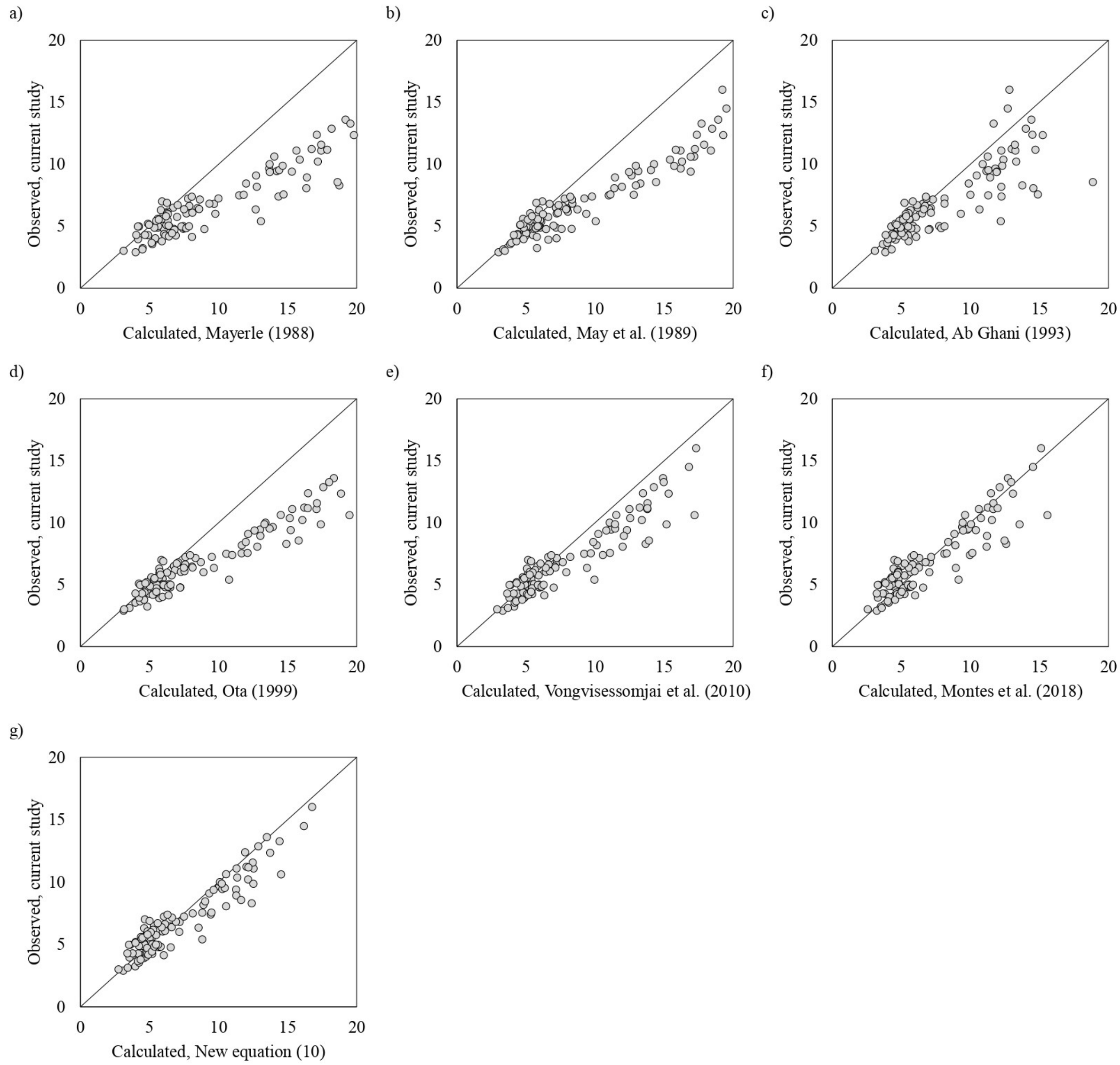


Figure 2. Comparison of performance of non-deposition without deposited bed models using the experimental data collected on 595 mm PVC pipe. Model from: a) Mayerle (1988); b) May *et al*. (1989); c) Ab Ghani (1993); d) Ota (1999); e) Vongvisessomjai *et al*. (2010); f) Montes *et al*. (2018) and g) Equation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

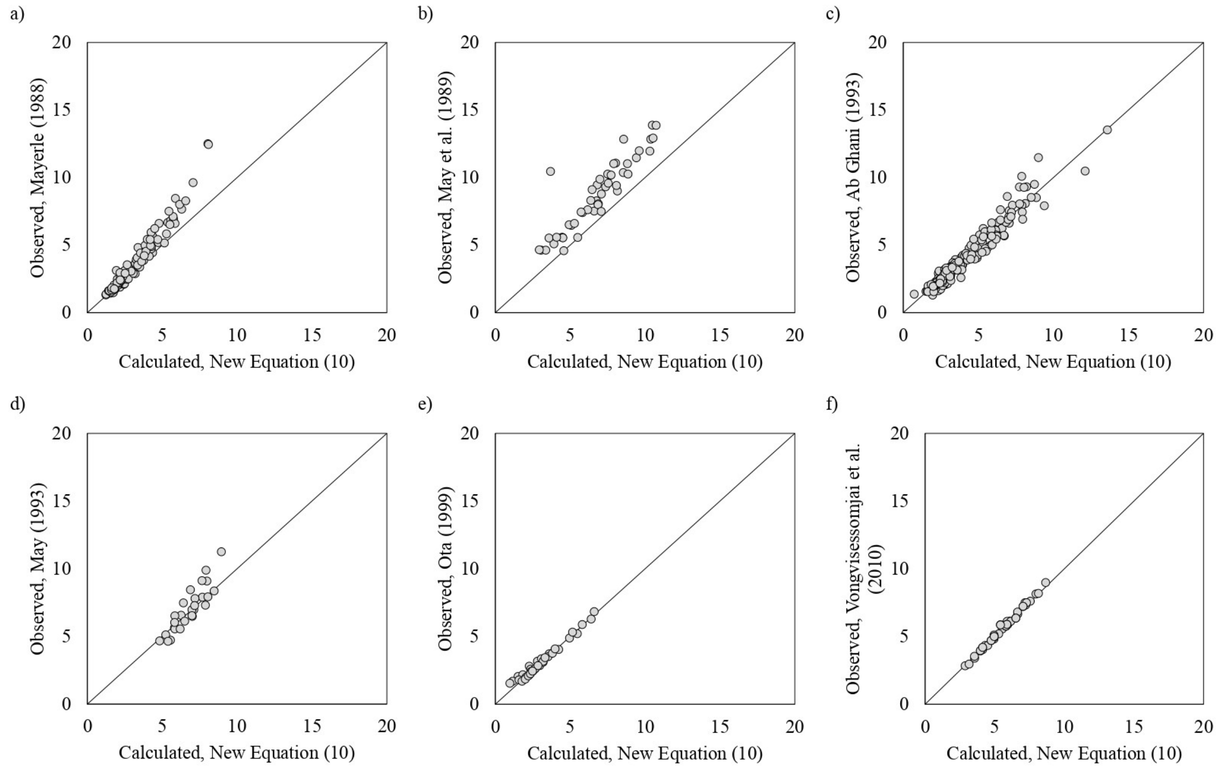


Figure 3. Comparison of performance of Equation (10) using the experimental data collected from literature. Data from: a) Mayerle (1988); b) May *et al*. (1989); c) Ab Ghani (1993); d) May (1993); e) Ota (1999) and f) Vongvisessomjai *et al*. (2010).

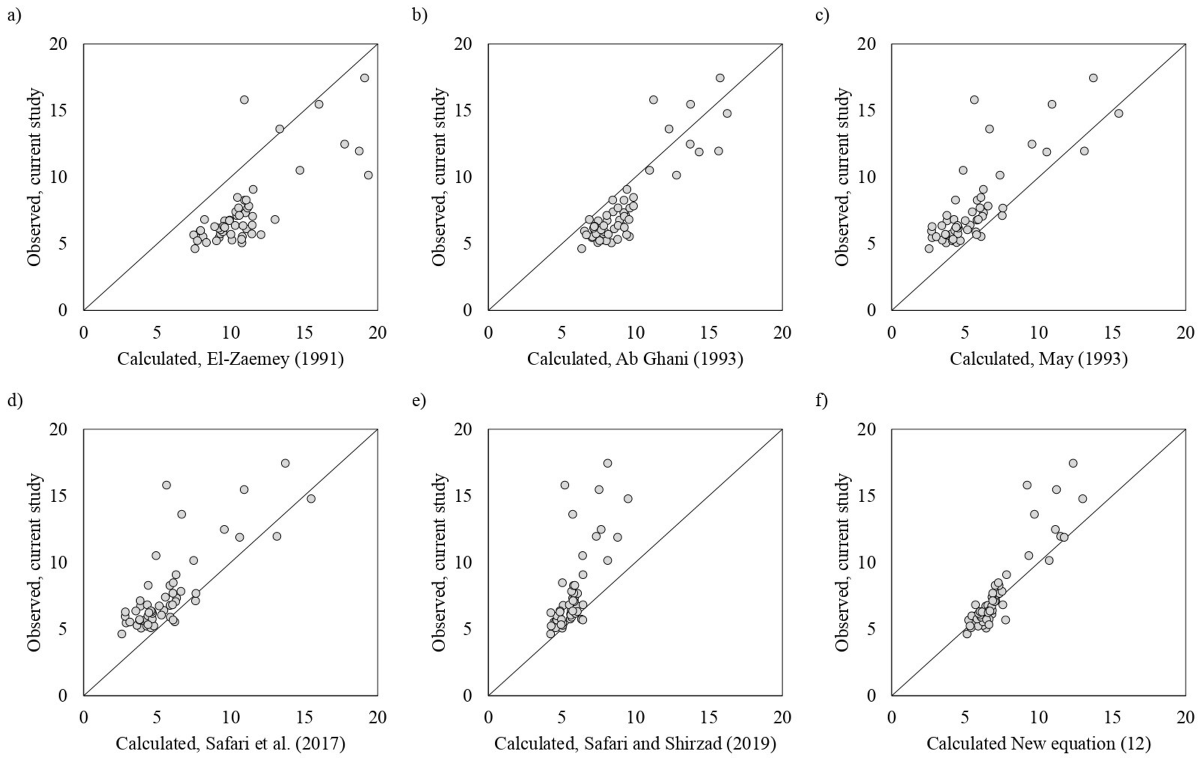


Figure 4. Comparison of performance of non-deposition with deposited bed models using the experimental data collected on 595 mm PVC pipe. Model from: a) El-Zaemey (1991); b) Ab Ghani (1993); c) May (1993); d) Nalluri *et al*. (1997); e) Safari *et al*. (2017) and f) Equation (12).

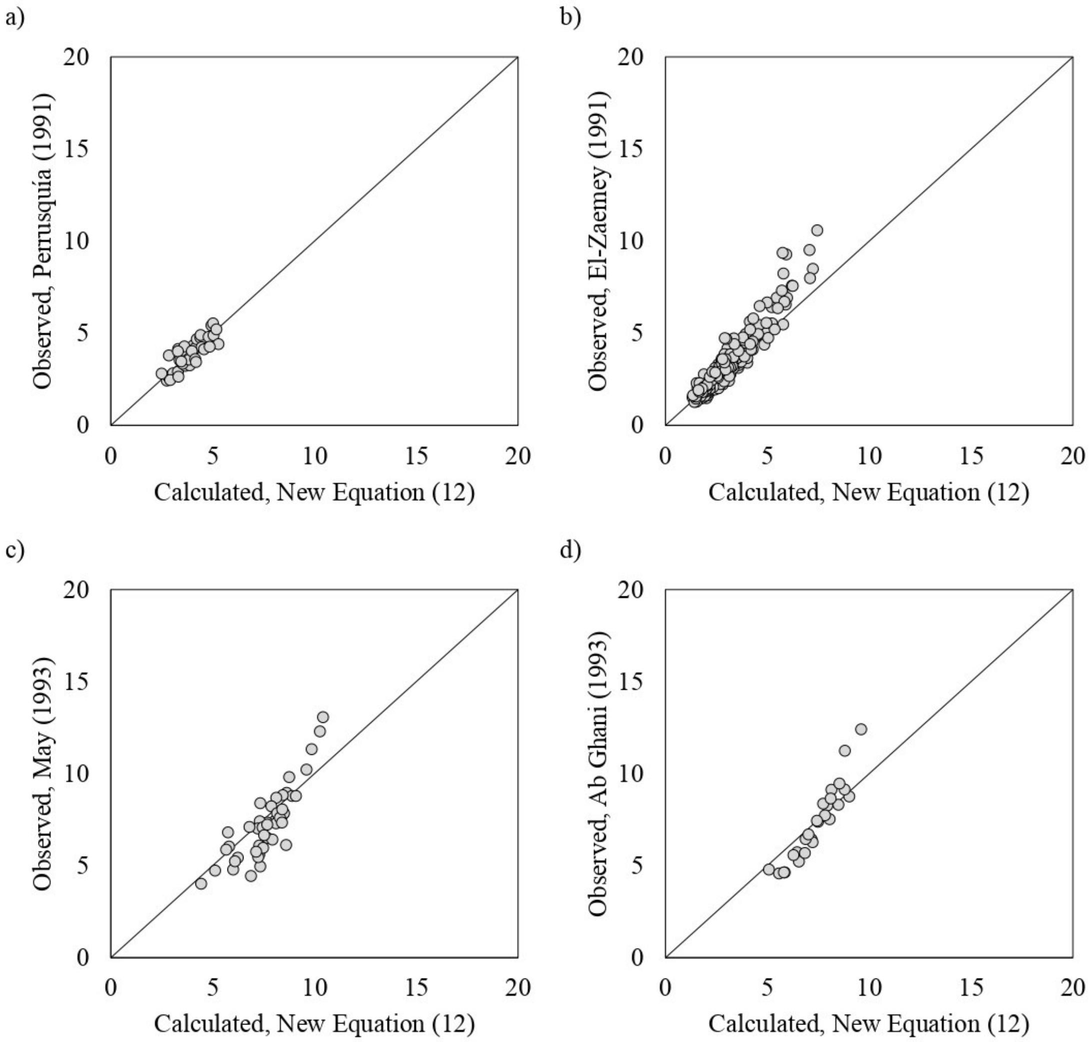


Figure 5. Comparison of performance of Equation (12) using the experimental data collected from literature. Data from: a) Perrusquía (1991); b) El-Zaemey (1991); c) May (1993); and d) Ab Ghani (1993).