Sediment transport modeling in deposited bed sewers: unified form of May's equations using the particle swarm optimization algorithm

Mir Jafar Sadegh Safari, Akbar Shirzad and Mirali Mohammadi

ABSTRACT

May proposed two dimensionless parameters of transport (η) and mobility (Fs) for self-cleansing design of sewers with deposited bed condition. The relationships between those two parameters were introduced in conditional form for specific ranges of Fs, which makes it difficult to use as a practical tool for sewer design. In this study, using the same experimental data used by May and employing the particle swarm optimization algorithm, a unified equation is recommended based on η and Fs. The developed model is compared with original May relationships as well as corresponding models available in the literature. A large amount of data taken from the literature is used for the models' evaluation. The results demonstrate that the developed model in this study is superior to May and other existing models in the literature. Due to the fact that in May’s dimensionless parameters more effective variables in the sediment transport process in sewers with deposited bed condition are considered, it is concluded that the revised May equation proposed in this study is a reliable model for sewer design.

Key words | bed load, deposited bed, particle swarm optimization, sediment transport, self-cleansing, sewer

INTRODUCTION

Sewer system design considering sediment transport process is an important issue as a hydraulic engineering practice. Deposition of sediment in sewer systems decreases the transport capacity of the channel because of decrease in flow area and increase in channel bed roughness. The self-cleansing concept is an engineering practice for solving the sedimentation problems in sewer systems. There are several self-cleansing criteria, such as incipient deposition (Safari et al. 2014, 2015, 2016), non-deposition without deposited bed (Ab Ghani 1993; May 1995; May et al. 1996; Vongvisessomjai et al. 2010; Ota & Perrusquia 2013; Safari 2016; Safari et al. 2017) and with deposited bed conditions (El-Zaemey 1991; Ab Ghani 1993; May 1993; Nalluri et al. 1997).

It was reported by Ab Ghani (1993) that self-cleansing velocity is dependent on sewer size, in which larger sewers require higher self-cleansing velocity. However, large sewer design based on non-deposition without the deposited bed criterion produces uneconomical design results in which the channel needs a steeper slope (Ab Ghani 1993; May 1993; Ackers et al. 1996). May (1993) demonstrated that the presence of a small depth of deposited bed increases bed load sediment transport capacity of the flow in which transport occurs in the surface layer of the bed (Butler et al. 2003). It is reported that a deposited bed thickness of 1–2% of pipe diameter is appropriate for channel design (Nalluri et al. 1997; Butler et al. 2003). There have been several studies carried out with deposited bed condition, such as those of May (1993), May et al. (1996), El-Zaemey (1991), Perrusquia (1992, 1993), Ab Ghani (1993), Nalluri et al. (1994, 1997), Nalluri & Ab Ghani (1996), Ackers et al. (1996), and Butler et al. (2003). The method proposed by May (1993) is the most common method that is used in many guidelines for sewer design (Ackers et al. 1996; May et al. 1996; Butler et al. 2003). However, the relationship proposed by May (1993) has a conditional form and has four different ranges for mobility parameter (Fs), which makes it difficult to use as a practical tool for channel design. Therefore, in this study it is aimed to provide a unified form of May (1993) relationships using the particle swarm optimization algorithm.

doi: 10.2166/wst.2017.267
optimization (PSO) technique. According to our best knowledge, there is no study in the literature applying PSO technique for modeling sediment transport in deposited bed sewers. To this end, for the first time, this study uses PSO as a powerful tool to develop a model using laboratory experimental data. Capability of this meta-heuristic evolutionary algorithm for solving engineering optimization problems has been proven (Montalvo et al. 2008, 2010; Ezzeldin et al. 2014). The PSO, which was introduced by Kennedy & Eberhart (1995), was derived from the collective motion of a group of migrating birds in reaching an unknown target point.

This study attempts to present a unified form of May (1993) relationships for modeling sediment transport over deposited bed in sewers using the PSO technique. The developed model is evaluated using experimental data taken from different sources and compared with the available models in the literature to show its computation ability.

**MAY (1993) METHOD**

May (1993) pointed out that the sediment transport formulae which are developed using dimensional analysis demonstrate a deficiency in terms of grouping the parameters and expression of effective variables involved. It was a main motivation to develop a theoretical sediment transport model for sewer pipes. May (1993) assumed that effective shear stress ($\tau_s$) at the channel bottom on the surface layer of the deposited bed can be defined by:

$$\tau_s = \rho \frac{\lambda_s V}{8} (V - V_p)^2$$  \hspace{1cm} (1)

according to the well-known Darcy–Weisbach equation, in which $\rho$ is the fluid density, $\lambda_s$ is the effective friction factor, and $V$ and $V_p$ are the flow and sediment velocities, respectively. It was shown that effective shear stress ($\tau_s$) can be linked to the active deposited bed thickness ($t_a$) in which sediment transport occurs as:

$$t_a = \frac{(1 + e)\tau_s}{\rho g (s - 1) \tan \phi}$$  \hspace{1cm} (2)

where $e$ is the voids ratio of the deposited bed layer (volume of voids/volume of particles), $g$ is the gravitational acceleration, $s$ is the relative density of sediment, and $\phi$ is the angle of friction acting on the underside of the active layer. May (1993) indicated that volumetric sediment discharge ($Q_s$) in the with deposited bed condition can be defined as:

$$Q_s = \frac{\alpha W_{bs} V_p}{(1 + e)}$$  \hspace{1cm} (3)

where $\alpha$ is the constant of proportionality and $W_{bs}$ is the deposited bed width. Substituting Equations (1) and (2) into Equation (3) and knowing $C_v = Q_s/Q$ ($C_v$ is the volumetric sediment concentration and $Q$ is the flow discharge):

$$C_v = \alpha \left( \frac{W_{bs}}{D} \right) \left( \frac{D^2}{A} \right) \left[ \frac{\lambda_s V^2}{8g(s - 1)D \tan \phi} \right] \left( \frac{V_p}{V} \right)^2$$  \hspace{1cm} (4)

is obtained, where $D$ is the pipe diameter and $A$ is the flow cross-section area. May (1993) assumed that the last terms in Equation (4), in which the parameter of $V_p/V$ is used, can be related to the mobility of sediment particles at the surface layer of the deposited bed. May (1993) found that the Shields (1936) parameter is appropriate for measurement of mobility as:

$$F_s^2 = \frac{\tau_s}{\rho g (s - 1) d} = \frac{\lambda_s V^2}{8g (s - 1) d}$$  \hspace{1cm} (5)

where $d$ is sediment median size. Based on the analysis given above, May (1993) introduced two dimensionless parameters of transport ($\eta$) and mobility ($F_s$), respectively, as:

$$\eta = C_v \left( \frac{D}{W_{bs}} \right) \left( \frac{A}{D^2} \right) \left[ \frac{\lambda_s V^2}{8g(s - 1)D} \right]^{-1}$$  \hspace{1cm} (6)

$$F_s = \left[ \frac{\lambda_s V^2}{8g(s - 1) d} \right]^{1/2}$$  \hspace{1cm} (7)

The effective friction factor ($\lambda_s$) should be linked to the grain shear stress, which is responsible for bed load sediment transport. Therefore, the grain friction factor ($\lambda_g$) is considered, and it can be calculated by the Colebrook–White equation, defined as:

$$\frac{1}{\sqrt{\lambda_g}} = -2 \log \left[ \frac{d}{12R} + 0.6275 \frac{v}{\sqrt{R \lambda_g}} \right]$$  \hspace{1cm} (8)

where $R$ is the hydraulic radius and $v$ is the kinematic viscosity of fluid. Based on experimental data, May (1993) found that $\lambda_s$ and $\lambda_g$ are related to each other through the following relationship as:

$$\lambda_s = \lambda_g \tanh \left( \frac{Re^*}{25} \right)$$  \hspace{1cm} (9)
where $Re^*$ is the particle Reynolds number defined as:

$$Re^* = \frac{u_*d}{\nu} \quad (10)$$

where $u_*$ is the shear velocity given as:

$$u_* = \sqrt{\frac{\tau}{\rho}} \quad (11)$$

where $\tau$ is the average shear stress on the channel boundary.

May (1993) showed $\tanh(Re^*/25)$ as transition factor ($\theta_f$) which is given by:

$$\theta_f = \frac{\exp(Re^*/12.5) - 1}{\exp(Re^*/12.5) + 1} \quad (12)$$

Consequently, the final forms of dimensionless parameters of transport ($\eta$) and mobility ($F_s$) are, respectively, given as:

$$\eta = C_\tau \left( \frac{D}{W_b} \right) \left( \frac{A}{D^2} \right) \left[ \frac{\lambda_g \theta_f V^2}{8g(s - 1)d} \right]^{-1} \quad (13)$$

$$F_s = \left[ \frac{\lambda_g \theta_f V^2}{8g(s - 1)d} \right]^{1/2} \quad (14)$$

In order to find the relationship between $F_s$ and $\eta$, May (1993) used his own experimental data to compute $F_s$ and $\eta$ and plotted the results as shown in Figure 1, and suggested the following relationships:

$$\eta = 0 \quad F_s \leq 0.10 \quad (15)$$

$$\eta = 1.60(F_s - 0.10) \quad 0.10 < F_s \leq 0.225 \quad (16)$$

$$\eta = 0.20 + 2.13(F_s - 0.225)^{0.60} \quad 0.225 < F_s \leq 0.40 \quad (17)$$

$$\eta = 0.95 \quad 0.40 < F_s \leq 0.65 \quad (18)$$

As is seen above, the relationship between $F_s$ and $\eta$ has conditional form, which makes it difficult to use as a practical tool. Therefore, it seems to be better to unify the relationship between $F_s$ and $\eta$ and develop a simple and practical formula applicable for channel design.

**Experimental Data**

Available experimental data for the condition of non-deposition with deposited bed are used in this study. May’s (1993) experimental data are used for developing the model, while those of El-Zaemey (1991), Perrusquia (1992, 1993), and Ab Ghani (1993) are used for the model evaluation. May (1993) conducted experiments in a pipe of 450 mm diameter using four sediment sizes ranging from 0.47 to 0.72 mm with variable deposited bed thicknesses. El-Zaemey (1991) conducted experiments in a circular channel with a diameter of 305 mm using six different sediments with sizes ranging from 0.53 to 8.4 mm with deposited bed thicknesses of 47 mm, 77 mm, and 120 mm. Perrusquia (1992, 1993) performed experiments in a 225 mm diameter circular channel using two sediment sizes of 0.9 mm and 2.5 mm. In Perrusquia’s (1992) experiments, the 45 mm deposited bed thickness was adapted, while in Perrusquia’s...
(1993) experiments, five deposited bed thicknesses ranging from 5 to 24 mm were considered. Ab Ghani (1993) conducted experiments with the same equipment used in May (1995); however, only the 0.72 mm sediment size was used. Ranges of the experimental data used in this study are given in Table 1.

### THE PSO ALGORITHM

In the PSO algorithm, which is inspired by the social behavior of birds, birds or particles are considered as valueless particles in an n-dimensional search space. Particles keep track of their positions in the search space relevant to their best positions or solutions, which are named pbest. Another best value or position is called gbest, which is the overall best value or position found so far by any particle in the group (Khokhar et al. 2012). Indeed, in this algorithm, the rate of position change or velocity of each particle toward its best previous position (pbest) and also toward the global best position (gbest) varies continually. If the ith particle in the n-dimensional space is considered as \( x_i = (x_{i1}, x_{i2}, \ldots, x_{in}) \), the best previous position of this particle would be \( \text{pbest}_i = (\text{pbest}_{i1}, \text{pbest}_{i2}, \ldots, \text{pbest}_{in}) \). The best particle between all particles can be represented as \( \text{gbest} = (\text{gbest}_1, \text{gbest}_2, \ldots, \text{gbest}_n) \). \( v_i = (v_{i1}, v_{i2}, \ldots, v_{in}) \) stands for the velocity of the ith particle. The velocities and positions of particles are adjusted using the equations below (Izquierdo et al. 2008):

\[
\begin{align*}
\dot{x}_{i}^{t+1} &= w \dot{x}_i^t + c_1 r_1 (\text{pbest}_i - x_i^t) + c_2 r_2 (\text{gbest} - x_i^t) \tag{19} \\
\dot{x}_{i}^{t+1} &= \dot{x}_i^t + \dot{x}_i^{t+1}, \quad i = 1, 2, \ldots, n_{\text{pop}} \tag{20}
\end{align*}
\]

in which \( n_{\text{pop}} \) is the number of particles, \( t \) is the iteration indicator, \( \dot{x}_i^t \) and \( \dot{x}_i^{t+1} \) are, respectively, the velocities of the ith particle at iterations \( t \) and \( t + 1 \), \( w \) is the inertia weight factor, \( c_1 \) and \( c_2 \) are the acceleration coefficients that pull each particle towards its best previous position and the global best position, respectively, \( r_1 \) and \( r_2 \) are the uniform random numbers between [0,1], \( x_i^t \) and \( x_i^{t+1} \) are, respectively, the positions of the ith particle at iterations \( t \) and \( t + 1 \). The terms \( r_1 (\text{pbest}_i - x_i^t) \) and \( r_2 (\text{gbest} - x_i^t) \) are named as the cognitive and social components, respectively. The acceleration constants \( c_1 \) and \( c_2 \) are often considered equal to 2.0 (Khokhar et al. 2012). In this study, the objective function is considered as below:

\[
\begin{align*}
\text{Minimize:} \quad & \text{MSE} = \frac{\sum_{k=1}^{ND} (\eta_{\text{obs}_k} - \eta_{\text{cal}_k})^2}{ND} \\
& = \alpha_1 + \alpha_2 \exp(\alpha_3 + \alpha_4 F_{sk}) 
\end{align*} \tag{21}
\]

in which \( \text{MSE} \) is the mean square of error, \( ND \) is the total number of experimental data, \( \eta_{\text{obs}_k} \) is the kth observed value for the parameter of transport, \( \eta_{\text{cal}_k} \) is the kth calculated value for the parameter of transport obtained using the PSO model, \( F_{sk} \) is the kth observed value for the parameter of mobility, \( \alpha_1, \alpha_2, \alpha_3, \) and \( \alpha_4 \) are the decision variables.

### PERFORMANCE INDEXES

Two statistical performance indexes, mean absolute percentage error (MAPE) and concordance coefficient (CC), are used for evaluation of models’ accuracy, which is essential for the models’ credibility. MAPE computes errors by comparison of the measured and calculated outputs defined as:

\[
\text{MAPE} = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{V_c - V_m}{V_m} \right| \times 100 \tag{22}
\]

in which \( V_c \) and \( V_m \) are, respectively, the calculated and measured flow velocities and \( n \) is the number of data. CC is the concordance between the measured and calculated outputs with a perfect agreement at 1. It is computed by:

\[
\text{CC} = \frac{2\sigma_m\sigma_c}{\sigma_m^2 + \sigma_c^2 + (V_m - V_c)^2} \tag{23}
\]

in which \( r \) is the correlation coefficient, \( \sigma_m \) and \( \sigma_c \) are the standard deviation of the measured and calculated velocity,
and $\overline{V_m}$ and $\overline{V_c}$ are the average of the measured and calculated flow velocities, respectively.

**RESULTS AND DISCUSSION**

The parameters of the PSO model are determined by implementing sensitivity analysis. Values of these parameters are: $c_1 = c_2 = 2$, $w = 2$, $n_{pop} = 500$, and maximum iteration $= 500$. The minimum value for the objective function is 0.0824, which is found after 170 iterations (85,000 times evaluating the objective function). Values of decision variables for this solution are: $\alpha_1 = 0.9508$, $\alpha_2 = -2.8310$, $\alpha_3 = 0.0037$, and $\alpha_4 = -8.3575$. Neglecting $\alpha_3 = 0.0037$:

$$\eta = 0.95 - \frac{2.83}{\exp(8.36F_s)} \quad 0.13 \leq F_s \leq 0.67 \tag{24}$$

is proposed as the unified form of May (1993) relationship as shown in Figure 2.

The unified form of May (1993) relationship developed in this study (Equation (24)) is compared with the original form of May (1993) relationships (Equations (15)–(18)) and also the models of El-Zaemey (1991), Ab Ghani (1993), and Nalluri et al. (1997), shown in Table 2 in terms of computation of flow self-cleansing velocity, using MAPE and CC in Table 3.

At a first glance at Table 3, it is seen that the unified form of May (1993) relationship (Equation (24)) outperforms its original form (Equations (15)–(18)) on four different data sources. It can be said, since both of them are established on the same experimental data and using the same transport ($\eta$) and mobility ($F_s$) parameters, the PSO technique generates a better model that is more simple and precise in comparison with its conventional form. The MAPE of May (1993) relationships on different data sources are in the range of 22.93% to 74.39%, while they are 10.07% to 23.68% for Equation (24). Although the original May (1993) relationships (Equations (15–18)) give acceptable results on the May (1995) and Ab Ghani (1993) data, they provide poor results on the El-Zaemey (1991) and Perrusquia (1992, 1993) data. However, the unified model obtained in this study (Equation (24)) generates good results on the El-Zaemey (1991) and Perrusquia (1992, 1993) data and perfect results on the May (1993) and Ab Ghani (1993) data (Table 3). Consequently, the model developed in this study is found superior to the conventional form of May (1993) relationships.

The developed model in this study is further compared with available models in the literature, i.e., El-Zaemey (1991), Ab Ghani (1993), and Nalluri et al. (1997) models on four data sets of El-Zaemey (1991), Perrusquia (1992, 1993), May (1993), and Ab Ghani (1993). This evaluation can be considered as a validation of the developed model. As shown in Table 3, the performance of different models on El-Zaemey (1991) data indicates that the El-Zaemey (1991) model (Equation (25)) outperforms all other models, which is not an unexpected result, as the model was established on its own data. However, the developed model in this study (Equation (24)) gives better results among the other models. The May (1993) model (Equations (15)–(18)) has a poorer performance on El-Zaemey (1991) data.

![Figure 2](https://iwaponline.com/wst/article-pdf/76/4/992/451380/wst076040992.pdf)

**Figure 2** | $F_s$ versus $\eta$ (Equation (24)).
Evaluation of models on Perrusquia (1992, 1993) data shows that the best performances belong to the Ab Ghani (1993) model and the developed model in this study. However, other models have high computation errors over 30%. A good performance of the developed model in this study should be noticed on May (1993) data. Although the May (1993) model (Equations (15)–(18)) was established on its own data, its computation ability is not high as the developed model in this study and the Ab Ghani (1993) model. Consequently, from a general point of view, it can be noted that the developed model in this study (Equation (24)) outperforms all other models, as it provides acceptable results on different data sources in terms of computation of flow self-cleansing velocity.

Figures 3–6 show the comparisons of five models on four data sets in terms of goodness-of-fit by scatter plots. It is seen from Figure 3 that the May (1993) model (Equations (15)–(18)) partially overestimates and underestimates on El-Zaemey (1991) data, while the developed model in this study (Equation (24)) and the El-Zaemey model (Equation (25)) provide results close to the line of best fit, although Equation (24) slightly underestimates on El-Zaemey (1991) data. The proposed models by Ab Ghani (1993) (Equation (26)) and Nalluri et al. (1997) (Equation (27)) overestimate and underestimate on El-Zaemey (1991) data, respectively. Referring to Figure 4, it can be found that the best performances belong to Equations (24) and (26), while other models have no high precision for computing self-cleaning velocity on Perrusquia (1992, 1993) data. Considering the models’ performances on May (1993) data (Figure 5), it is shown that Equation (24) shares the best performance with Equation (26), while the other models’ results show significant scatter for computing self-cleansing velocity. Finally, Figure 6 indicates that Equation (24) outperforms all other models on Ab Ghani

### Table 2 | Sediment transport models for deposited bed sewers

<table>
<thead>
<tr>
<th>Reference</th>
<th>Model</th>
<th>Equation no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>El-Zaemey (1991)</td>
<td>$V = 1.95C_0^{0.17} \left( \frac{W_s}{Y} \right)^{-0.40} \left( \frac{d}{D} \right)^{-0.57} \lambda^{10}$</td>
<td>(25)</td>
</tr>
<tr>
<td>Ab Ghani (1993)</td>
<td>$V = 1.18C_0^{0.16} \left( \frac{W_s}{Y} \right)^{-0.18} \left( \frac{d}{D} \right)^{-0.34} \lambda^{-0.31}$</td>
<td>(26)</td>
</tr>
<tr>
<td>Nalluri et al. (1997)</td>
<td>$V = 1.98C_0^{0.13} D_{gr}^{-0.10} \left( \frac{d}{R} \right)^{-0.60} \lambda^{0.14}$</td>
<td>(27)</td>
</tr>
</tbody>
</table>

$\lambda$: channel friction factor with the presence of sediment (Darcy–Weisbach); $D_{gr}$: dimensionless grain size parameter ($- (\nu - 1)\rho^2 / \gamma^{1/2}$).

### Table 3 | Performance of self-cleansing models on experimental data based on MAPE and CC

<table>
<thead>
<tr>
<th>Reference</th>
<th>MAPE %</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>El-Zaemey (1991) data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>May (1993), Equations (15)–(18)</td>
<td>74.39</td>
<td>−0.06</td>
</tr>
<tr>
<td>Present study, Equation (24)</td>
<td>23.68</td>
<td>0.22</td>
</tr>
<tr>
<td>El-Zaemey (1991), Equation (25)</td>
<td>10.30</td>
<td>0.65</td>
</tr>
<tr>
<td>Ab Ghani (1993), Equation (26)</td>
<td>29.83</td>
<td>0.25</td>
</tr>
<tr>
<td>Nalluri et al. (1997), Equation (27)</td>
<td>51.51</td>
<td>0.05</td>
</tr>
<tr>
<td>Perrusquia (1992, 1993) data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>May (1993), Equations (15)–(18)</td>
<td>39.02</td>
<td>0.14</td>
</tr>
<tr>
<td>Present study, Equation (24)</td>
<td>19.05</td>
<td>0.21</td>
</tr>
<tr>
<td>El-Zaemey (1991), Equation (25)</td>
<td>36.51</td>
<td>−0.04</td>
</tr>
<tr>
<td>Ab Ghani (1993), Equation (26)</td>
<td>8.81</td>
<td>0.49</td>
</tr>
<tr>
<td>Nalluri et al. (1997), Equation (27)</td>
<td>33.62</td>
<td>0.00</td>
</tr>
<tr>
<td>May (1993) data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>May (1993), Equations (15)–(18)</td>
<td>29.63</td>
<td>0.48</td>
</tr>
<tr>
<td>Present study, Equation (24)</td>
<td>13.49</td>
<td>0.83</td>
</tr>
<tr>
<td>El-Zaemey (1991), Equation (25)</td>
<td>61.95</td>
<td>0.16</td>
</tr>
<tr>
<td>Ab Ghani (1993), Equation (26)</td>
<td>14.94</td>
<td>0.79</td>
</tr>
<tr>
<td>Nalluri et al. (1997), Equation (27)</td>
<td>18.05</td>
<td>0.24</td>
</tr>
<tr>
<td>Ab Ghani (1993) data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>May (1993), Equations (15)–(18)</td>
<td>22.93</td>
<td>0.73</td>
</tr>
<tr>
<td>Present study, Equation (24)</td>
<td>10.07</td>
<td>0.91</td>
</tr>
<tr>
<td>El-Zaemey (1991), Equation (25)</td>
<td>76.49</td>
<td>0.11</td>
</tr>
<tr>
<td>Ab Ghani (1993), Equation (26)</td>
<td>19.64</td>
<td>0.61</td>
</tr>
<tr>
<td>Nalluri et al. (1997), Equation (27)</td>
<td>18.55</td>
<td>0.07</td>
</tr>
</tbody>
</table>
(1993) data, whereas the May (1993) and Nalluri et al. (1997) models (Equations (15)–(18) and (27)) underestimate and El-Zaemey (1991) and Ab Ghani (1993) models (Equations (25) and (26)) overestimate the self-cleansing velocity.

It has to be emphasized that the model computation ability is significantly related to the parameters used and the applied technique for model development. This fact can best justify the robustness of the developed model in this study (Equation (24)). The transport ($\eta$) and mobility ($F_s$) parameters proposed by May (1993) seem to have sufficient physical background, as they used more effective variables in comparison with other models available in the literature. May (1993) used the values of shear stress and velocity simultaneously as independent variables in both transport and mobility parameters. As the channel has a deposited bed, considering resistance to flow seems to be quite important for modeling the sediment transport. Using grain friction factor in the model as a responsible parameter for bed load sediment transport helps the model to have higher accuracy. Therefore, it can be said that the May (1993) method is the best one for designing deposited bed sewers, as has been demonstrated previously by

![Figure 3](image3.png) | Performances of self-cleansing models based on goodness-of-fit on El-Zaemey (1991) data.

![Figure 4](image4.png) | Performances of self-cleansing models based on goodness-of-fit on Perrusquia (1992, 1993) data.

![Figure 5](image5.png) | Performances of self-cleansing models based on goodness-of-fit on May (1993) data.

![Figure 6](image6.png) | Performances of self-cleansing models based on goodness-of-fit on Ab Ghani (1993) data.
ACKERS ET AL. (1996), MAY ET AL. (1996), AND BUTLER ET AL. (2003). On the other hand, the applied technique for model development helps to provide a more accurate model, as the developed model in this study (Equation (24)) is obtained using the PSO algorithm. It has already been reported by SAFARI ET AL. (2016) that soft computing techniques are powerful tools for modeling in comparison with conventional regression techniques. It is approved in this study as well, due to the developed model (Equation (24)) outperforming all conventional regression models existing in the literature. In comparison of the MAY (1993) method with other models available in the literature, it should be noted that self-cleaning velocity in the MAY (1993) method is obtained implicitly; however, other models in the literature have explicit form. Nowadays, in the computer age, it can be solved using a program code, as is done in this study.

CONCLUSION

The well-known May relationships are revised as a unified equation to make it simple to use as a practical tool for channel design using the PSO technique. The results demonstrate that the transport and mobility parameters proposed by May have enough physical background to model sediment transport in deposited bed sewers. The evaluation of models on a variety of data sources taken from the literature indicates that the developed model in this study outperforms May’s original relationships as well as all available models in the literature. The high computation capability of the developed model in this study can be linked to the use of more effective parameters in sediment transport process in deposited bed sewers and applied technique for model development. Additional to parameters used in alternative studies for modeling of sediment transport in deposited sewers, in this study, grain shear stress and grain friction factors are considered as responsible parameters for bed load sediment transport. Consequently, it is found that flow velocity, shear stress, pipe size, sediment size and density and, more importantly, flow resistance in deposited bed condition are quite essential parameters for modeling sediment transport in deposited bed sewers, as used for model development in this study.

ACKNOWLEDGEMENTS

The first author would like to thank the International Affairs of National Elites Foundation of Iran (BMN) for financial support of this study, which was carried out during his stay as a post-doctorate research associate in Urmia University and University of Tabriz, Iran. Very special gratitude goes to Prof. Magsud Solimanpur, vice chancellor for research of Urmia University, and Dr Behnam Mohammadi-Ivatloo from Technology Affairs Management (TAM) of University of Tabriz for their support during this study.

REFERENCES


Perrusquia, G. S. 1993 *An Experimental Study from Flume to Stream Traction in Pipe Channels*. Chalmers University of Technology, Sweden, Report B57.


First received 14 March 2017; accepted in revised form 24 April 2017. Available online 18 May 2017.