Sediment transport functions in HEC-RAS 4.0 and their evaluation using data from sediment flushing of Wlingi reservoir - Indonesia

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Abstract. This paper presents a study carried out to assess the accuracy of several sediment transport functions commonly applied in HEC-RAS 4.0 against data from the sediment flushing of Wlingi reservoir in 2016. Another aim of this assessment is to evaluate the viability of selected transport equations to simulate riverbed changes during the sediment-flushing event. Thus, the best scenario of sediment flushing could be determined according to their efficiencies. The overall accuracy of the transport function indicated by RMSE values in descending order were those of Laursen-Copeland and Ackers and White, Meyer-Peter and Muller, and Wilcock formulas, when applied to the observed data. The study also indicated that Laursen-Copeland formula had parameters that were commonly well-characterized by the riverbed of Wlingi reservoir. Further, it was suitable to be utilised to assess the achievement of sediment flushing in Wlingi reservoir, while others seem less satisfactory.

Keywords: transport functions, HEC-RAS, sediment flushing, Wlingi reservoir

1. Introduction

The rate of transportation of sediment in rivers relies on many factors including water discharge, flow velocity, flow depth, energy slope, size and gradation of particles, shear stress, stream power, and water temperature. It is very essential to recognize the approaches used in the development of sediment transport functions in order to be assured of its applicability to a specified stream. Usually, sediment transport functions (TF) estimate rates of sediment transportation from a certain set of steady-state hydraulic parameters as well as sediment characteristics. The result of sediment transport depends heavily on which transport function is selected [1, 2]. The liability of the application of these sediment transport functions is subject to the researcher and the available data. Thus, carefully examining the variety of assumptions, hydraulic factors, and sizes of sediment material for which each function have been developed, and selecting the transport function developed under conditions that represent the system of interest most closely, are the most appropriate considerations to simulate sediment transport.

HEC-RAS (referred hereinafter as the model) is a one-dimensional model of open-channel flow intended to simulate flow profiles and to predict changes in the riverbed resulting from erosion and/or deposition over moderate interval of time. Several sediment transport formula have now been available to simulate sediment transport in HEC-RAS version 4.0 and higher. Because specific transport functions
were developed under specific conditions, it is possible to expect a broad range of results from one sediment transport function to another. It is therefore necessary to confirm the accuracy of the prediction of sediments to a significant quantity of measured data with comparable characteristics. The four sediment transport functions selected as the best predictors are briefly presented here.

Ackers and White (1973) developed a transport function for a total sediment load based on flume data for sand to fine gravel with relatively uniform gradation. Ackers and White solved the dimensional analysis of transport function and did not consider the grain shear partition. They matched the coefficients to the function primarily based on experiments that cover various conditions of bedform configurations such as plane bed, ripples, and dunes [1].

\[
G_{gr} = C \left( \frac{F_{gr} - A}{A} \right)^m
\]  

(1)

where \(G_{gr}\) = Sediment transport parameter, \(C\) = Coefficient, \(F_{gr}\) = Parameter of sediment mobility, and \(A\) = Parameter for critical sediment mobility.

**Laursen-Copeland.** Similar to Ackers-White, Laursen (1968) developed a total load function originally relying on flume data. It is a fundamental function of excess shear and a ratio of the shear velocity to the fall velocity. The function was later extended by Copeland (1989) and made suitable for graded beds. The function was parametrized by Laursen with material that slightly expanded into the silt range [1].

\[
c_{rm} = 0.01 \gamma \left( \frac{d_s}{D} \right)^{7/6} \left( \frac{\tau_c}{\tau} - 1 \right) f \left( \frac{u_0}{\omega} \right)
\]  

(2)

where \(d_s\) = mean diameter of particle, \(D\) = effective depth of flow, \(\tau_c/\tau\) = ratio bed shear stresses, and \(\omega\) = fall velocity.

**Meyer-Peter and Müller.** One of the earliest-developed sediment transport functions is the Meyer-Peter and Müller (MPM) in 1948. It is a simple relationship of excess shear. It is still one of the most commonly used transport functions. Later, Wong and Parker (2006) improved it by developing a new relationship for MPM [1].

\[
q_b = 3.97 (\tau^* - \tau_c^*)^{1.6}
\]  

(3)

**Wilcock.** Wilcock and Crowe (2003) established a bedload function intended for graded beds containing both gravel and sand. Wilcock and Crowe determined a dimensionless reference shear stress as a function of the quantity of sand on the bed surface. Here,

\[
\tau_{rm}^* = 0.021 + 0.015 e^{-20FS}
\]  

(4)

where \(\tau_{rm}^*\) is the reference shear stress and FS is the sand quantity in percent [1].

In the present study, the evaluation of these sediment transport functions against sediment flushing data from Wlingi reservoir in 2016 is conducted.

2. Materials and Methods

The object of the study is Wlingi reservoir in East Java. Data of inflow discharge, cross-sectional geometry area, bed level pre- and post-flushing and sediment properties were required to run the model [3, 4]. The particle fall velocity followed Ruby since it has been shown to be sufficient for silt, sand, and gravel. In the model, the input parameters that control the processes were adjusted during calibration to obtain better agreement between model output and actual observations. Here, model iterations had been
performed to improve predictions. Prior to calibration, initial boundary conditions had been established for discharges and hydraulic parameters. For the hydraulic boundary conditions, the initial Manning’s value had been modified during calibration based on examination of the water level at the reservoir during the flushing period. The schematic of the model is outlined in Figure 1 (left) and the calibration and modification menu for the selected transport function is presented in window menu, in Figure 1 (right).

Figure 1. General schematic plan for the Wlingi reservoir and TF-calibration and modification in the HEC RAS v4.0.

To evaluate the appropriateness of the calculated and measured value of the released sediment, the root-mean-square error (RMSE) was applied. A lower RMSE value indicates that the model results agree well with the observed value. Better results are given as the root-mean-square value approaches zero.

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (X_{\text{obs}} - X_{\text{mod}})^2}
\]

where:
- \(X_{\text{obs}}\) = measured sediment (m³)
- \(X_{\text{mod}}\) = computed sediment (m³)
- \(n\) = total number of cross section

Meanwhile, the discrepancy ratio (r) was used to test the liability of a selected transport formula. If the r-value is closer to 1, it indicates that the formula is suitable to be used as a predictor for the scope of this study.

\[
r = \frac{Q_{\text{model}}}{Q_{\text{observed}}}
\]

As for regulations, it was not possible to extend the flushing duration (Figure 2); the alternative scenario for the existing sediment flushing was performing a trial of changing the inflow discharge within its possible ranges. The flushing efficiency was computed according to the Mahmood formula [5]:

\[
Fe = \frac{V_2 - V_1}{V_0}
\]

where \(Fe\) = sediment flushing efficiency, \(V_2\) = storage capacity after flushing (m³), \(V_1\) = storage capacity before flushing (m³), and \(V_0\) = volume of released water (m³).
Figure 2. The existing flushing schedule for Wlingi reservoir in 2016.

Figure 3 illustrates the summary of the major steps of carried out in the present study.

3. Results and Discussion
By running the model with default parameter values of HEC-RAS, the test of the four transport functions showed that all models delivered under-predicted sediment discharge and were insensitive to changes in the Manning’s n values of the channel. Therefore, a variable which quantifies the force or energy needed to mobilize the sediment material for each of the four transport functions had been adjusted. The calibration of each formula are briefly described below.
The adjustment of variables of Ackers-White were carried out for threshold mobility (A), critical sediment mobility parameter (C), and exponential (m), as seen in Figure 4. By trial and error, optimal values were obtained for $A = 0.005$, $C = 0.25$, and $m = 1.78$. The calibrated model yielded a volume of sediment being transported to the downstream of approximately $815,935 \text{ m}^3$, while the measured volume was $1,026,500 \text{ m}^3$. By comparing the erosion and sedimentation that resulted through all channel geometries, the given RMSE value was approximately $2.302$ metres and the discrepancy ratio was $0.79$.

![Figure 4. The adjustment values for Ackers-White.](image)

The critical shear stress ($\tau_{c^*}$) was also adjusted for Laursen-Copeland and MPM, as seen in Figure 5. Here, the optimum $\tau_{c^*}$ was $0.0004$, which gave $1,061,107 \text{ m}^3$ of sediment being released. Overall, the RMSE values of erosion and deposition along the reservoir was $2.159$ metres and the discrepancy ratio was $1.03$.

![Figure 5. The calibrated $\tau_{c^*}$ parameter for Laursen-Copeland.](image)

In contrast to the previous transport functions, by replacing the initial value $\tau_{c^*}$ of Meyer-Peter and Müller (MPM) by the Wong and Parker correction value, the result of the volume of released sediment did not differ much with the initial or default value. Since it is a bedload function established from sand...
and gravel flume experiments under the configuration of a plane bed, the transport function of MPM appeared to be most relevant in gravel systems. In fact, the reservoir sediment mostly consisted of silt and volcanic ash [4]. Therefore, MPM seem to give results that under-predict the transport of finer materials in Wlingi reservoir. Therefore, the Meyer-Peter and Müller formula in the simulation of sediment flushing could not be regarded as a suitable predictor here. In addition, it was regarded that Wilcock’s equation could not be used as further assessment. The sand quantity parameter was very susceptible to the Wilcock equation. As the sand quantity rises, the reference shear falls, and the excess bed shear and the total transport increases [1]. It looks to be best suited for large-scale gravel and sand material applications. In addition, there was still a low discrepancy proportion between the two transport functions.

By comparing the results of the model’s erosion and sedimentation process with the measured reservoir bed, Figure 6 and Figure 7 (left) demonstrates the erosion and sedimentation model production for major cross-sections. This reveals which parts involved erosion or deposition of the entire cross-section. Since the selected transport function of the model is a function for calculating clay and silt depending on fall velocity [1], the variations were mostly attributed to the existence of cohesive particles with more than gravity behaviour (fall velocity). In reality, volcanic ash mainly affected reservoir sedimentation [4]. The inclusion of cohesive parameters should address this behaviour of cohesive sedimentation (settlement, flocculation, consolidation, and so on). This is one of the current study's limitations. There was also mechanical extraction of sediments during the flushing event that the model did not encounter. In the current research, the model was intended for non-cohesive sediment transport (sand and coarse silt) with limited capacity to simulate cohesive sediment transport processes. Considering this limitation and the tolerance options related to performance, it is considered that the achieved value of the present study could now be adopted (with RMSE = 2.159). As a summary, Laursen-Copeland was chosen as the greatest predictor, followed by Ackers and White. The results of each transport function for modelling sediment flushing in Wlingi reservoir in 2016 are summarized in Table 1.

![Figure 6](image)

**Figure 6.** Erosion and deposition in the bottom surface of main channel of Wlingi reservoir.

To determine the sensitivity of the discharge inflow, various scenarios of inflow discharge with the selected transport function were performed. Flushing with the 10 percent increase in the scenario of inflow discharge could provide extra efficiency, by 0.05. Overall, Table 2 showed that there were no important variations in sediment outcomes. Thus, the current flushing schedule was still acceptable as a good scenario by considering the economic value of the additional addition of inflow water. In comparison with reservoir flushing practices among global reservoirs [6], as shown in the Figure 7 (right), the flushing efficiency of the Wlingi reservoir also fell in the acceptable range.
Figure 7. Erosion and deposition in the main channel (left) and the proposed flushing effectiveness of Wlingi reservoir among worldwide reservoirs (right)

Table 1. Summary of the model performance with different transport functions against observed data

| Transport Function | Flushed sediment by HECRAS model (m$^3$) | Observed sediment (m$^3$) | TF variables | Discrepancy ratio (r) |
|-------------------|------------------------------------------|---------------------------|--------------|----------------------|
| Ackers and White  | 757.32                                    | 815,935.34                | A = 0.005    | 0.79                 |
|                   |                                           |                           | C = 0.25     |                      |
|                   |                                           |                           | m = 1.78     |                      |
| Laursen-Copeland  | 5,690.06                                  | 1,061,107                 | $\tau_c^* = 0.0039$ | 1.03                |
|                   |                                           |                           | $\tau_c^* = 0.0004$ |                      |
|                   |                                           |                           |              |                      |
| Meyer-Peter and Müller | 69.5                                     | 7,123.06                  | $\tau_c^* = 0.047$ | 0.01                |
|                   |                                           |                           | $\tau_c^* = 0.0495$ |                      |
| Wilcock           | 60.01                                     | 660.01                    | Not Available| Not Available        |

Table 2. Flushing efficiency for different scenarios of flushing with the Laursen-Copeland formula

| Scenario | Inflow discharge | Sediment vol. (m$^3$) | Water vol. (m$^3$) | Efficiency (%) |
|----------|-----------------|-----------------------|--------------------|----------------|
| 1        | Existing        | 1,061,107             | 21,592,800         | 0.049          |
| 2        | Increase by 10% | 1,181,359             | 23,752,080         | 0.050          |
| 3        | Increase by 20% | 1,243,634             | 25,911,360         | 0.048          |
| 4        | Decrease by 10% | 896,025               | 19,433,520         | 0.046          |
| 5        | Decrease by 20% | 831,612               | 17,274,240         | 0.048          |

4. Conclusion
The transportation formulas of HEC-RAS have distinct theoretical foundations from each other and each is more susceptible to certain variables than others. A study was performed to evaluate effectively the
precision of several sediment transport formulas frequently used in HEC-RAS 4.0 against data from Wlingi reservoir sediment flushing in 2016.

The findings of this research emphasize that the formula of Laursen-Copeland and Ackers and White reach an excellent performance. These transport formulas are appropriate for this research to be used as a predictor. It is suggested to extend the current research to other flushing years and recognize the existence of cohesive product sediments and extra quantity of mechanical removal of sediments at each flushing period in order to gain better outcomes.

In conclusion, since the model is mainly intended for simulating sediment transport of non-cohesive material (sand and silt) with extra but limited ability to simulate sediment transport processes of cohesive material (medium silt to fine clay), the model may not achieve the best results, particularly in reservoirs with high concentrations of cohesive material sediment. However, the model is still useful in assessing and evaluating the performance of sediment flushing in Wlingi reservoir.

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