A review on sediment transport modelling using HEC-RAS

Rahul P R
M.Tech. Student, Department of Hydrology, Indian Institute of Technology Roorkee, India

P K Sharma
Associate Professor, Department of Civil Engineering, Indian Institute of Technology Roorkee, India

ABSTRACT:

The sediment transport causes erosion of the soil particles on large scale and it can be deposited in the canals or reservoirs hence, their maintenance is also increased. The poorly designed artificial canals are always affected by the siltation due to sediment transport and sometimes their operation is badly affected and huge economic losses have occurred as an after-effect. The sediment transport has great importance in flood monitoring as the flood control schemes mainly depend upon the peak flood levels. Due to the scouring of the channels, the bed levels may be changed each year due to the sediment deposition and the removal of the bed. Hence the flood levels may be changed in the same discharge and sometimes the pattern of the flow of natural channels changes due to the siltation and the flood pattern of the region can be changed. The sedimentation of the reservoirs is an aspect of sediment transport. Due to the siltation into the reservoirs, storage capacity is decreased and it can badly affect the reservoir operations. If the reservoir sedimentation continues for a long extent, the whole reservoir can be silted and it will become useless. As sediment transport poses a lot of problems, studies and research are very much required in this field. In this paper, a review has been undertaken to understand the working of sediment transport modelling using HEC-RAS software.

1. INTRODUCTION

The information on sediment transport is very much essential for the managers and the stakeholders to predict and monitor its effects on the water bodies and the reservoirs. But the models developed in the past were facing a lot of problems like over-parameterisation, the impractical requirement of inputs and unsuitable assumptions and parameters subject to the local conditions and these models were inadequate to provide necessary information on the catchment scale and event-based sediment predictions. But in the recent decade, due to the computerisation and development of computer models, a lot of rapid explorations have evolved in the study of soil erosion and sediment transport (Merritt et al., 2003).

The study of sediment transport is an effective method for analysing the various streams related problems such as reducing the capacities of the river flow. One of the notable real situations observed was reducing the capacity of the flow of river Diyala in northern Iraq. After analysing the situation, a one-dimensional sediment transport model study using HEC RAS was conducted after the field sediment observations. Then the flow capacity of the river was increased by enhancing the elevations of the riverbank wherever required as per the obtained cross sections (Jassam and Abed, 2021).

A similar situation was observed in the river Mersing in Malaysia. The shortage of water has occurred in the river Mersing and which affected hardly the people of town Mersing. The cross sections of the river Mersing were changing due to the erosion and deposition due to the sediment transport. Hence, the sediment transport modelling using HEC RAS has been undertaken with quasi steady flow approach. The long term sediment depositions were observed and necessary recommendations were suggested to the concerned authorities (Luqman et al., 2022).

The topographical condition of the river environment undergoes major changes due to the siltation of the river bed as the rivers are usually transporting the sediment load along its direction of flow. Hence for future predictions of the adverse impacts and flood monitoring, the sediment transport models are considered a primary requirement. In flood monitoring, the sediment transport models can improve the quality of the monitoring by adding the effect of the real-time parameters.

The equations of the non-cohesive sediment transport are used in the sediment transport modules in recent times. But it can develop the models for the cohesive sediment also by simple extensions. The simulation in the model can be done for total sediment or the bed load and suspended load separately. At present, the complicated physics of sediment transport is not well understood and existing models developed upon simple hypothetical assumptions. The sediment/erosion rate can be ascertained by the sediment module. The module also can run parallel with the hydrodynamic modules. By measuring the size of the dune, depth of water, and the rate of flow, the changes in the topography of the river bed can be found and their by bed resistance can be ascertained.

The Computations of the sediment transport in HEC-RAS usually follow the quasi-steady flow approach. An incident or a set of incidents at a particular period is estimated by the analysis of a set of steady flow cross-sections (Fig.1). Then each set of these cross-sections is compared with its time of occurrence result of sediment transport is generated for each of these profiles. The depth calculations are required more for this approach. At the starting of each step of computation, the geometry is computed and then the new hydrodynamic analysis is also updated.

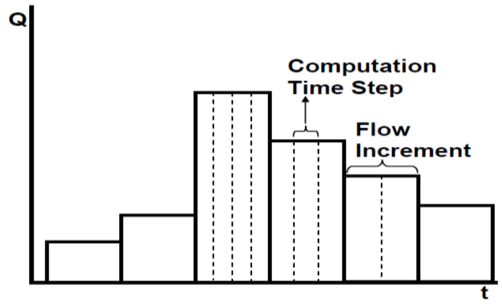

Fig.1 Symbolic diagram of quasi-steady flow (Gibson et al., 2006).

1.1 Input Data Needed

The various input data needed for the system is as enumerated below.

- Fall Diameter of the Sediment.
- Height and Length of the dune at starting.
- The upstream boundary of sediment inflow.
- The geometric standard deviation of grain size of sediment particle.
- The viscosity of the liquid medium.
- Various calibration parameters for deposition of suspended load, distribution of sediment load at various defined points and bed resistance.

1.2 Structure of the System

The sediment transport module can be run parallel to the hydrodynamic module and one by one also. Various steps can be predefined for each of these modules. Usually, the sediment transport module is assigned with larger time steps and in each time step, the calculation of the sediment budget is performed by calculating total deposition or erosion from the local transport system and elements of transport achieved by neighbour elements. As various branches meet at the nodal points, the sediment transport modelling can be done by dividing the total sediment inflow among the branches in proportion to the total outflow discharge. Otherwise, Sediment transport can be divided into user-defined distribution patterns.

1.3 Model Output

The various outputs from the system are total deposition and erosion rates, inflow resistance at each point, time series for sediment concentrations and Changes in dune pattern

As per the net erosion or deposition rates, the cross-section of the rivers can be altered under the selected distribution pattern or the preferable distribution pattern evolved from real observation at a particular site.

Based on the outputs, the impact of the sediment transport on the river bed topography can be analysed and future prediction can be done for flood monitoring, reservoir monitoring, and changes in rating curves and can be applied for other desired applications also (*Flood forecasting manual CWC.pdf*, 1989.)

1.4 Hec-Ras

Nowadays, the modelling of flows in rivers can be achieved through computer simulation packages. The US Army Corps of Engineers Hydrologic Engineering Centres River Analysis Software package (HEC-RAS) is one of the well-known river modelling computer simulation packages currently available. The HEC-RAS is freely available to download and use without restrictions and it is one of the competing tools available now.

The various operations that a user can perform in HEC-RAS are

- One Dimensional Steady flow analysis.
- One and two-dimensional unsteady flow calculations.
- Sediment transport/ mobile bed computations.
- Water Temperature/Water Quality Modeling. (HEC-RAS User’s Manual, US Army Corps of Engineers.)

2. THE SEDIMENT TRANSPORT MODELLING IN HEC-RAS

The sediment transport modelling capacities have been added to the Hydrologic Engineering Centre River Analysis Software package (HEC-RAS) and can be used for performing sediment transport or mobile computations. The hydraulic computation in HEC-RAS is associated with sediment transport, deposition and erosion and computation of changes in the cross-section of the river by using a set of initial boundary conditions and as a result, continuous stimulation of changes in the cross-section pattern occurs as the sediment process subjected to the various hydraulic parameters. The sediment modelling in HEC-RAS is achieved by utilizing the one-dimensional hydraulic parameters with average cross-sections.

The main aim of the sediment transport component of the software is to simulate the 1D and 2D sediment transport evolved from scouring and deposition over long periods. The ability of the sediment transport is measured by the fraction of grain size by facilitating the simulation of different gradations of particles and the creation of larger particles as armours on the bottom layer. The main features of the sediment transport element are the modelling of river networks, use of alternatives for encroachments, dredging in streams, use of various calculations and use of various sediment transport formulae. The model is designed to carry out the sediment transport including deposition and erosion in streams for long period and it will consider the frequencies of change in river flow or discharge and morphological changes including the river geometry. The system can ascertain the reservoir sedimentation and it will enable the safe design of channels by fixing the navigational depth and width of the channel by providing possibilities for erosion, also it can predict maximum probable erosion during the major flood event (HEC-RAS User's Manual, US Army Corps of Engineers).

3. SEDIMENT TRANSPORT MODELS

To solve the various practical sedimentation problems like alternate navigational routes, design of channels, and sedimentation in reservoirs, various modelling studies have been conducted by various authors and put forward practical solutions by predicting the future impacts of erosion and deposition. The various approaches introduced by the authors in sediment modelling in HEC RAS are discussed as follows.

Creech et al. (2018) conducted a one-dimensional sediment transport model using HEC RAS for studying the sedimentation pattern in river Madeira as it is an important waterway for the transportation of agricultural commodities in North West Brazil. The study has been conducted for achieving the three objectives; First is a reference which has to be substantiated for the sediment movement in the Madeira river. Second is to examine the effect of the regional response of the sediment movement and the nature of erosion in the system considering the alternate proposal of the waterway. Third is the systematic arrangement of the river data capabilities of the sediment model of river Madeira. The sediment model has been prepared based on the data collected to study the environmental aspects of the dam Santo Antonio. The model has been shown good performance during a test conducted in a quasi-equilibrium state. The various parameters assigned for the test have been shown very high unpredictability during the test, which is sediment in the upstream, the gradation of bed and the method of sorting of various particles.

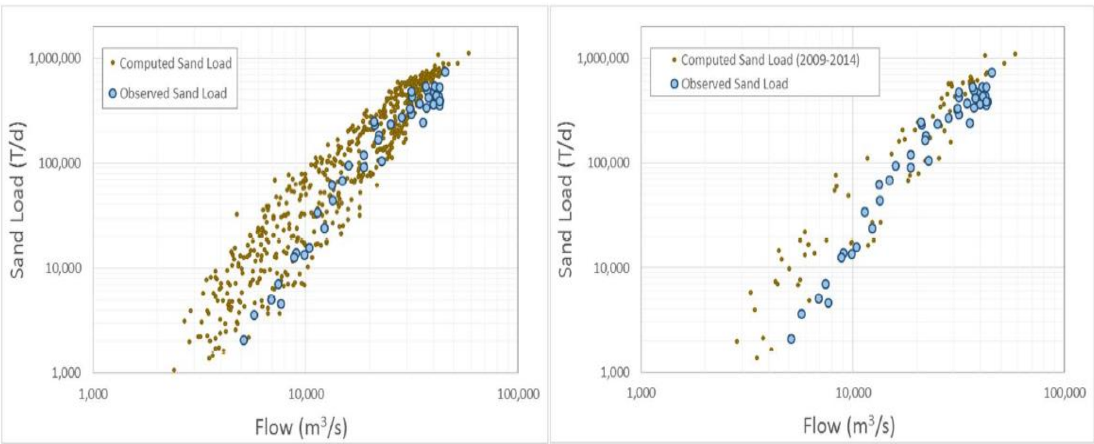

Fig. 2 The sediment load during the flow for the full data and data limited to 2009 to 2014 (Creech et al., 2018).

The HEC RAS model generated by the team can predict the future of the sedimentation pattern and thereby, can be compared with suggested substitutes for the waterway. Forty-seven years of data for the period from 1967 to 2014 have been taken for the modelling part and the modelling has been done by applying various assumptions (Fig 2). The team has suggested river training in some parts of the width of the channel and dredging in some other parts. Hamzeh Haghiabi and Zaredehdasht (2012) conducted studies to find out the various erosion prawn points along the Karun River, Iran for a stretch between Mollasani station upstream and Farsiat station downstream with a length of 100 Km and a total of 113 stations were considered. The various objectives discussed in the papers are mentioned below:

- Determine the relationship of changes in the sediment pattern of the Karun River.
- By applying the bed load, sediment load and bed load continuity equations, find out the bed morphology by model simulation.
- Simulation of the morphology of the bed by using a defined model.

The various inputs to the model was the schematic of the stretch of river, cross-section data at various points, defined boundary conditions and the sediment data collected. The sediment data collected include the grain size and D50 of the river bed and Mollasani and Farsiat (The Upstream and Downstream stations). The Lursen Equation (1) is used as the basis for the calculation of the total sediment load.

The Lursen Equation

$$C_m = 0.01\gamma \left[\frac{ds}{D}\right]^{\frac{7}{6}} \left[\frac{\tau_0}{\tau_c} - 1\right] f\left[\frac{u_*}{\omega}\right] \quad (1)$$

Where, C_m	The density of the sediment particle
γ	Density of the water
ds	Average size of the sediment particle
D	Depth of water
τ_0	Shear Stress
τ_c	Critical Shear Stress
u_*	Shear Velocity of particle
ω	Fall Velocity of the particle

The results from the model for 5 years have shown that there is very much sedimentation in the river Karun. The current situation of the reaches of the river Karun has a clear cut correlation with the model results. The formation of the small islands due to the deposition of the sediments and non-removal of the sand bars created a lot of problems with the morphology of the Karun River. The sudden reduction of the slope of the river and the increase in the manning constant are the major reason for the sedimentation in the river Karun, as per this study.

Ochiere et al. (2015) undertook the simulation of the sediment transport in the underground canal of the south-west Kano Irrigation Scheme (Fig. 3) in Kenya using HEC RAS to evaluate the cause of the dropping of its conveyance capacity over a while due to erosion and sedimentation.

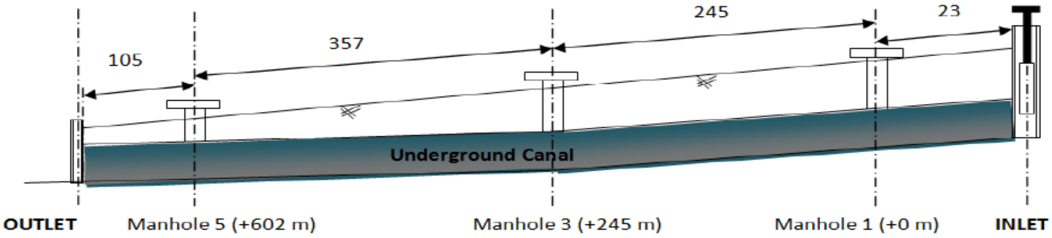

Fig. 3 The Cross-Section of the Underground Canal (Ochiere et al., 2015).

The equation suggested by the Auckers-White has been used in the model to evaluate the sediment transport in the canal. The various parameters required in HEC RAS to run the model have been achieved through direct measurement and Calibration. The simulation has been done to evaluate sediment flux and the rate of deposition and different water levels and discharge conditions by calibrating the system to the current scenario. The equation suggested by the Auckers-White provided the results as various sediment sizes and settlements of the same at different sections at different canal discharges. As this study is suggesting, the minimum deposition pattern has been observed in the higher velocities of the flow. The various input physical parameter used in the model is discussed below.

Table 1 Physical parameters in HEC RAS and its determination (Ochiere et al., 2015).

Description of the Parameter	**Mode of Determination of the physical parameter**
Particle Dia	Sieving of sediment particle
Depth of water	Sounding Rod
Mean Velocity	Current Meter
Kinematic Viscosity	Reference from the HEC RAS user manual
Acceleration due to gravity	Reference from the HEC RAS user manual
Sp. Weight of the Sediment	Reference from the HEC RAS user manual
Sp. Weight of the Water	Reference from the HEC RAS user manual
Hydraulic Radius	Calculation from the depth and top width of water
Slope	Calculation of elevation by dumpy level survey
Water Temperature	Thermometer

The equation (2) suggested by Van Rijn has been used for determining the fall velocity. (Depeweg and Mendez, 2002)

$$V_s = \begin{cases} \frac{(S_s-1)gd}{18v} & 0.001<d<0.1 \text{ mm} \\ \frac{10v}{d}\left[\left(\frac{1+0.001(S_s-1)gd^3}{v^2}\right)^{0.5} - 1\right] & 0.1<d<1 \text{ mm} \\ 1.1[(S_{s-1})gd]^{0.5} & d\geq 1 \text{ mm} \end{cases} \quad (2)$$

The calibration has been done for Manning's constant at the initial stage. The steady flow equation has been used in HEC RAS to run the model and it is assumed that there is equilibrium of energy of the flow with a known water level downstream. The calibration part has been done by using the values of the lower water level and the validation part has been done by using the values of the higher water level. This is because; Manning's constant will work best for the higher water elevations (Parhi et al., 2012). As recommended by Chow (1959), the starting value of Manning's constant has been taken as 0.013 for the canals lined with concrete. It is identified that the finer particle are inducing at the downstream and the Manning's roughness constant reducing. The HEC RAS model results are showing that the sediment transport is occurring for the selected grain size. While the discharge is increasing, the sediment entered into the canal is increasing and accordingly, more sediment will be deposited through the outlet. If the irrigation canal is flowing with a higher sediment load, it cannot be operated during flood season as the slope of the river is higher than the slope of the irrigation canal. Wang et al. (2014) performed study on unsteady flow and sediment modelling in Tuttle creek reservoir in Kanas River using Hec Ras 5. The Tuttle Creek reservoir provides water supply to various cities and also releases water for navigation in the Missouri River. By performing a bathymetry study, it is found that 43% of the total storage volume was reduced due to sediment accumulation. To ascertain the technical feasibility and efficiency of altering the operations of the reservoir to decrease sediment trapping efficiency is analysed by one-dimensional unsteady flow and sediment model by Hec Ras version 5. Model cross sections were derived for the bathymetric surveys performed in 2000 and 2009 using the bed change method to produce a reasonable cross-section shape and deposition pattern. Relationships between flow and suspended sediment load at the three major tributaries to Tuttle Creek Lake are produced using the data from the USGS gauging stations and bed load data expressed as a percentage of sediment loads.

HEC-RAS 5.0 integrates sediment transport features with the unsteady flow module. It uses Saint-Venant equations for coupling sediment transport and helped in reservoir modelling tools to perform the unsteady flow modelling. Hec Ras 4.1 uses the RULES editor to perform operational procedures for unsteady flow. In this study, custom RULES were developed to perform hydraulic calibration challenges. Inflow from the tributaries was added to get a value less than the flow downstream that was recorded. Then computed the daily ungauged inflows were computed from historic daily inflows using a custom rule editor. For the calibration period (20 July 2000 to 14 September 2009) sediment transport was added to the unsteady flow model. Loads and gradations are adjusted to find the total volume and longitudinal distribution of reservoir deposits. By using Hec Ras 5 plot for local volume change and cumulative volume change corresponding to a longitudinal cumulative deposition obtained. Damte et al. (2021) considered one-dimensional hydraulic modelling using HEC RAS to study the erosion, sediment transport and bed characteristics changes of the river Kulfo in the southern part of Ethiopia. The study has been done to ascertain the depth of flow during the flood time using the geometrical survey data of the years 2005 and 2019. The bed material samples of the river have been collected from the specified locations for the computation of the grain size using Manning's Constant. For establishing the rating curve (Fig4), the sediment and the discharge measurements have been undertaken three times a day for three months.

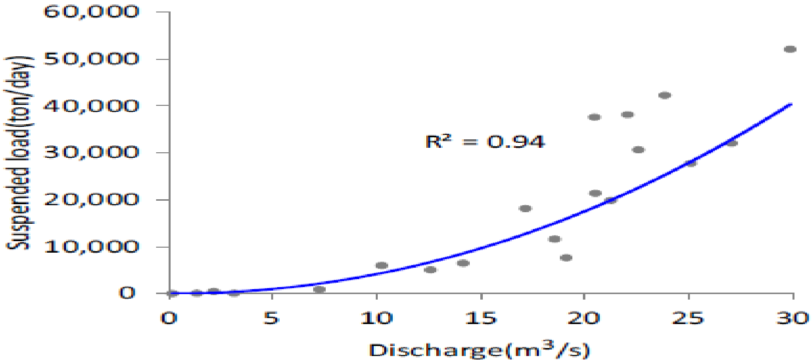

Fig. 4 Rating Curve of the Sediment Measurements. (Damte et al., 2021)

The calibration of the HEC RAS hydraulic model has been done by considering Manning's Constant as the main parameter. The starting values of the Manning's constant were determined by considering the gradation curve along the river stretch and computation of the particle size done using the empirical formulae. There are four methods for the computation of the fall velocity and different sediment transport equations are available. Using this, HEC RAS will enable the model of flow containing the sediment to run different combinations of the equations and those which have more overlap with observed data were taken as the most suitable equation. The results indicated that the river morphology will be changed due to sediment transport and deposition. The cross-section at the same line for the different years has been compared and the sediment deposition was identified.

4. DISCUSSION

The hydraulic computation in HEC-RAS is associated with sediment transport, deposition and erosion and computation of changes in the cross-section of the river by using a set of initial boundary conditions and as a result, continuous stimulation of changes in the cross-section pattern occurs as the sediment process subjected to the various hydraulic parameters. The ability of the sediment transport is measured by the fraction of grain size by facilitating the simulation of different gradations of the particles and the creation of larger particles as armours on the bottom layer.

Creech et al. (2018) conducted a one-dimensional sediment transport using HEC RAS in the river system for studying the navigational capacity. The sediment model generated by the model can predict the future sedimentation pattern and can be used for analyzing the future solution. To study the bed morphology of the river system, (Hamzeh Haghiabi and Zaredehdasht, 2012) has been conducted sediment modelling studies using HEC RAS with the input data of grain size and gradation. The results showed that, there is very much sedimentation in the river system and which is correlated with the current situation of the river. Ochiere et al. (2015) considered the simulation of sediment transport in the underground canal to evaluate the cause of reducing its conveyance capacity due to the sedimentation by using Auckers White equation as the base for sediment transport. They studied the rate of deposition at different flow rates and used the equation suggested by Van Rijn for calculating the fall velocity of the sediment and used the steady flow equation to run the model in HEC RAS. The results identified that the sediment transport occurring for the selected grain size and increasing with the high discharge. Wang et al. (2014) performed a study on unsteady flow and sediment modelling in a reservoir using HEC RAS. From the bathymetry study, it was identified that 43% of the total storage volume was reduced due to sediment accumulation. HEC RAS 5 integrates sediment transport features with an unsteady flow module and it used the Saint-Venant equation for coupling sediment transport. For the calibration period, sediment transport was added to the unsteady flow model and loads and gradation are adjusted to the final total volume and longitudinal distribution of the reservoir deposits. Damte et al. (2021) conducted 1 D hydraulic modelling with HEC RAS to study the sedimentation parameters of the river. The sediment and discharge data observed were used and results of the HEC RAS modelling indicated that the river morphology will be changed due to the sediment transport and deposition.

5. SUMMARY AND RECOMMENDATION

The significance of the sediment transport is important as it creates a lot of problems in the water resources sector and a wide range of practical problems are occurring due to the erosion and deposition of the sediment particle as discussed in the above-cited papers. The sediment transport modelling using HEC RAS is a much applicable method for analysing such problems and creation of solutions and recommendations.

Indian rivers especially in the southern part of the country are much prone to the erosion and deposition of sediments. These rivers are carrying a huge load of sediment annually during the flood season. Each year, there is massive variation in river morphology due to the erosion and deposition of the sediments. Hence, a study on the sedimentation of Indian rivers is very much important to ascertain the future impacts.

While, planning the projects like interlinking, canal design, expanding navigational capacities, irrigation canals etc., the sediment modelling studies have to be carried out prior to these projects to avoid future hindrances. There are immense data sets are available for discharge, water level, cross-sections and sediment observation from the various agencies like CWC and state government departments and PSUs. These data have to be utilised wisely and sediment modelling has to be done for the corresponding rivers for analysing future sedimentation aspects. It will help to effective designs and utilisation of wise alternatives in future.

Acknowledgement

Authors are thankful to Central Water Commission, Department of Water Resources & Ganga Rejuvenation, Ministry of Jal Shakti for providing financial aid to the first author for his Masters program.

References

Central Water Commission. (1989). Manual on flood forecasting. *River Management Wing, New Delhi*.

Creech, C., Castañon, A., Amorim, R., & Gibson, S. (2018). Sediment transport model of the Madeira river using HEC-RAS for waterway design. In *Proc., 13th Brazilian Meeting of Sediment Engineering* (pp. 1-8).

Damte, F., G_Mariam, B., Ayana, M.T., Lohani, T.K., Dhiman, G., Shabaz, M. (2021). Computing the sediment and ensuing its erosive activities using HEC-RAS to surmise the flooding in Kulfo River in Southern Ethiopia. World J. Eng. 18, 948–955.

Depeweg, H., Méndez V, N. (2002). Sediment transport applications in irrigation canals. Irrig. Drain. 51, 167–179.

Gibson, S., Brunner, G., Piper, S., Jensen, M. (2006). Proceedings of the Eighth Federal Interagency Sedimentation Conference (8thFISC), April2-6, 2006, Reno, NV, USA. Proc. Eight Fed. Interag. Sediment. Conf. (8thFISC), April 2-6, 2006, Reno, NV, USA 57–64.

Hamzeh Haghiabi, A., Zaredehdasht, E. (2012). Evaluation of HEC-RAS Ability in Erosion and Sediment Transport Forecasting Sediment transport One-dimensional model HEC-RAS4 model MIKE 11 model introduction investigation conducted for analysis and prediction of. World Appl. Sci. J. 17, 1490–1497

Jassam, W.A., Abed, B.S. (2021). Assessing of the Morphology and Sediment Transport of Diyala River. J. Eng. 27, 47–63.

Luqman, M., Nasir, M., Salleh, M. (2022). Modeling of Sediment Transport at Sungai Mersing By Using HEC-RAS 3, 555–561.

Merritt, W.S., Letcher, R.A., Jakeman, A.J. (2003). A review of erosion and sediment transport models. Environ. Model. Softw. 18, 761–799.

Ochiere.H., O, O.J., N, K.D. (2015). Simulation of Sediment Transport in the Canal Using the Hec-Ras (Hydrologic Engineering Centre -River Analysis System) In an Underground Canal in Southwest Kano Irrigation Scheme – Kenya. Int. J. Eng. Sci. Invent. ISSN Online 4, 2319–6734

Parhi, P.K., Sankhua, R.N., Roy, G.P. (2012). Calibration of Channel Roughness for Mahanadi River, (India) Using HEC-RAS Model. J. Water Resour. Prot. 04, 847–850.

Wang, L.K., Shammas, N.K., Evanylo, G.K., Wang, M.-H.S., Tvvr, E., Taye, M.T., Ntegeka, V., Ogiramoi, N.P., Willems, P., Leuven, U., Division, H., Sinclair, J.L., Shelley, J., Ph, D., Corps, U.S.A., District, K.C., Modeling, V.H., Introduction, V., El-moattassem, P.M., El-sersawy, H.E.M., Brunner, G.W., Gibson, S.A., Boyd, P.M., Gibson, S.A. (2014). Unsteady Flow and Sediment Modeling in a Large. Handb. Environ. Eng. 15, 525–569.