Application of ArcGIS and HEC-RAS in Assessing Sedimentation in Godavari River Reach

S. Kiran, Anwesna Poudyal, Samer Pradhan, and Monalisha Gautom

Abstract   Assessment of sediment load is paramount in understanding the process of erosion and deposition in rivers. Excess sedimentation is hazardous as it reduces the carrying capacity of the river and destabilizes the channel banks. In this study, the transport model in Hydrologic Engineering Centre's River Analysis System (HEC-RAS) is coupled with quasi-unsteady flow series to quantify the sediment discharge and assess erosion and deposition at each cross section along the Godavari River reach. The topography of the river reach is extracted and digitized using HEC-GeoRAS tool in ArcGIS. To accurately reproduce the natural hydraulic behaviour in the river reach, the cross-sectional lines are positioned at optimal spacing and approximately perpendicular to the direction of river flow. The Manning's roughness coefficient (n) is calibrated using one-dimensional unsteady flow model in HEC-RAS. The unsteady model computes the hydraulic properties and provides simultaneous solutions for discharge and stage at each computational time step for all cross sections. The sediment continuity equation is solved for non-equilibrium sediment transport over the control volume along with the hydraulic sorting and armouring. Results from the simulated models are compared and calibrated against observed field measurements. Weighted coefficient of determination (ωr^2), Nash–Sutcliffe efficiency (E), modified Nash–Sutcliffe efficiency (E_1) and Modified index of agreement (d_1) are used to provide an objective assessment about the closeness between the simulated and observed values. Among the transport models in HEC-RAS, the Wilcock-Crowe model provides more accurate estimates of sediment discharge and deposition and erosion at each cross section along river reach.

Keywords   Sediment transport · Godavari river · ArcGIS · HEC-RAS · Wilcock-crowe

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1 Introduction

Influx of excess sediment impacts erosion and aggradation in dynamic rivers and modifies the channel characteristics altering the river's morphology. Extreme climatic conditions, nature of topography, land use pattern and terrain slope are few among the several natural factors that enhance the rate of sediment yield in a river. Unsustainable farming techniques and inadequate watershed management have also contributed to an increase in the influx of sediment load. Excess sedimentation is hazardous as it reduces the carrying capacity of the river and destabilizes the channel banks. Assessment of sediment load in rivers is paramount in understanding the process of erosion and deposition. It will also provide vital information required in planning, designing and managing water resource systems.

Godavari River originates in the Western Ghats and flows eastwards across the Deccan plateau into Bay of Bengal. The study reach extends from Peruru to Polavaram which is approximately 268 km in distance. Width of the channel in the study reach varies from 700 m at its narrowest to 3000 m at its widest sections. Due to its high erosion rate, which differs from one part of the basin to another, Godavari River is characterized by excessive sediment discharge. Almost 95% of the sediment load in Godavari River is predominantly monsoonal or transported during the wet season [1].

Several studies have been carried out to simulate the sediment transport process in natural flows. The hydraulic characteristics of the channel are emulated in the model through Manning's roughness coefficient. Stability of finite difference scheme is influenced by the weighting factor and computational time step during calibration of Manning's roughness coefficient [2]. Though sediment transport is unsteady, most formulae have limited applicability and can be used only to evaluate the transport capacity in steady uniform flows. To overcome this limitation, one-dimensional sediment transport algorithms adopted the quasi-unsteady approach. A comparison between the unsteady and quasi-unsteady sediment transport models indicated that the unsteady model made no significant improvement in accuracy over the quasi-unsteady model [3]. The quasi-unsteady transport model provided approximate results for erosion and deposition in meandering channels, assuming equilibrium between the volumetric sediment discharge and transport capacity [4]. However, it is unlikely and unrealistic to assume the flux in the system to be in equilibrium as the process of sediment transport is often complex and imbalanced. For a credible model assessment, the combination of different efficiency measures should be consistent. The sensitivity in each efficiency criteria has to be considered before application. The over and under predictions are to be reflected along with other attributes of transport, providing a more comprehensive evaluation of model results [5].

With the advancement in technology, simulation of sediment transport using sophisticated algorithms has enabled robust modelling and prediction of the sediment dynamics in river systems. For this process, several modelling packages like FLUENT, CFX, PHOENIX, FLUIVAL, MIKE 21, CCHE2D, CCHE1D and HEC-RAS are used. In this study, the hybrid one-dimensional HEC-RAS (version 5.0.7)

model developed by Hydrologic Engineering Centre of the US Army Corps of Engineers is considered [6]. Among the four river analysis components in HEC-RAS, the unsteady flow condition is used in calibrating Manning's roughness coefficient and the quasi-unsteady sediment transport model is used in determining the sediment discharge in the river reach.

2 Methodology

2.1 Geometry

The geometric data which includes the river path, cross section, flow lines and bank stations are extracted from the digital elevation model (DEM) having a spatial resolution of 1- arc second. DEM is obtained from the satellite images of Shuttle Radar Topography Mission (SRTM) by the U.S. Geological Survey (USGS). The reach of Godavari River between Perur and Polavaram (refer Fig. 1 and Table 1) is digitized in ArcGIS.

To accurately depict the hydraulic conditions in the river reach, the cross-sectional lines are approximately perpendicular to the direction of flow. The optimum spacing
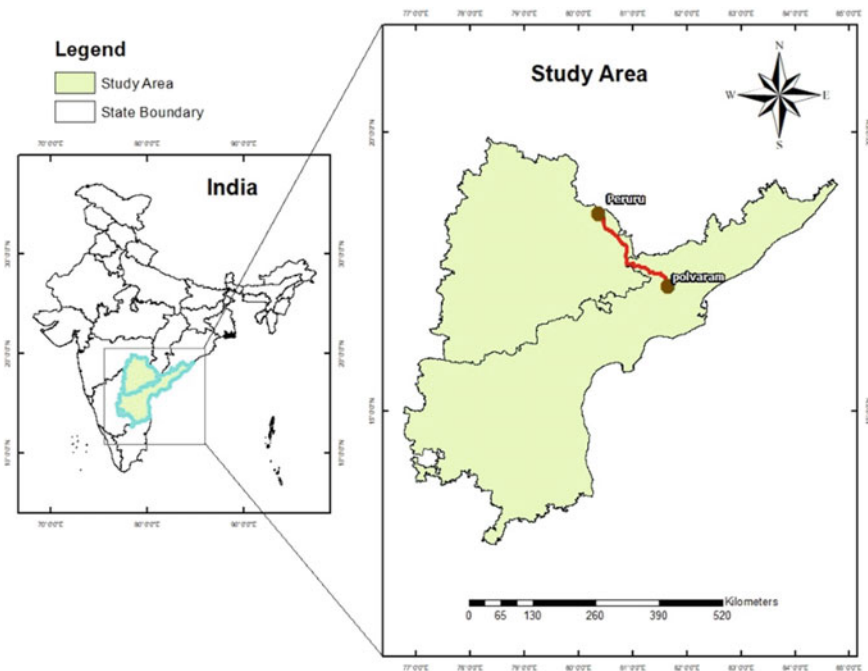

Fig. 1 Location of study area

Table 1 Location of upstream and downstream boundary stations

Station	Latitude	Longitude	Boundary
Perur	18° 33′ 00″	80° 22′ 00″	Upstream
Polavaram	17° 14′ 45″	81° 39′ 35″	Downstream

between the cross-sectional lines is proportional to bankfull surface width of the channel. The inclusion of additional cross sections may not necessarily increase the model accuracy once the optimal spacing is attained [7]. The river reaches in this study has been divided into 105 cross sections with an average distance of 2.5 km between each cross section as shown in Fig. 2. HEC-GeoRAS extension in ArcGIS is used to create the geometry file and export it into HEC-RAS where bank stations at each cross section are adjusted to bankfull depth manually.
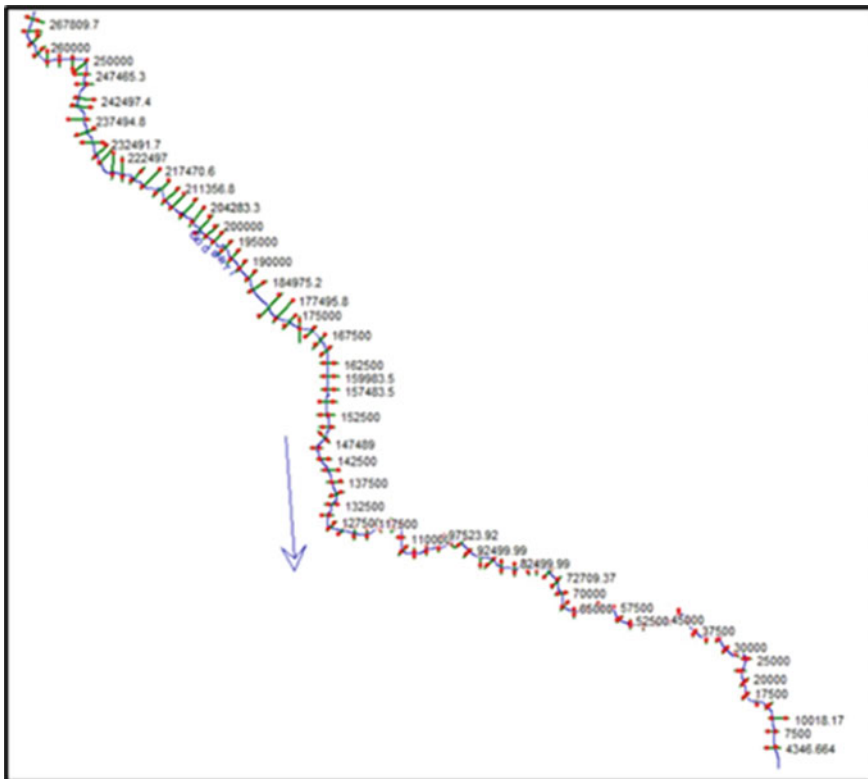

Fig. 2 Study reach of Godavari River between Perur and Polavaram

2.2 One-Dimensional Unsteady Flow Model

The Manning's roughness coefficient is calibrated using the one-dimensional unsteady flow model. The governing equation for one-dimensional unsteady flow in HEC-RAS is the Saint Venant equation which comprises the continuity equation (Eq. 1) and momentum equation (Eq. 2) solved using the four-point implicit scheme. The model computes the hydraulic properties to provide simultaneous solutions for discharge and stage at each computational time step for all cross sections.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (QV)}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \tag{2}$$

where A is the cross-sectional flow area, Q is the flow discharge, q is the lateral inflow per unit length, V is the velocity of flow, z is the water surface elevation and S_f is friction slope.

Stability of the unsteady flow model in HEC-RAS depends upon the computational intervals chosen. At large time steps, certain peak flows in the inflow hydrograph might be missed at some cross sections. Continuous monitoring of inflow hydrograph, to identify the change in flow rate from one time step to another, improves the stability of the unsteady flow model.

2.3 Sediment Transport Model

In HEC-RAS the Exner's equation (Eq. 3) is used to route sediment continuity wherein it computes the difference between the inflowing and outflowing sediment load in a control volume.

$$\left(1 - \lambda_p\right) B \frac{\partial \eta}{\partial t} = - \frac{\partial Q_s}{\partial x} \tag{3}$$

where, λ_p is the porosity of bed surface layer, B is the channel width, η bed surface elevation and Q_s is the transported sediment load.

If the transport capacity of the control volume is lesser than the inflowing sediment supply, the surplus sediment load is stored in the bed surface layer as a multiphase sediment–water mixture, causing sediment deposition. The deficit is removed from the control volume if the transport capacity exceeds the inflowing sediment supply, resulting in sediment erosion. The change in the elevation of the bed surface layer is indicated by the porosity of the multiphase mixture [8]. In HEC-RAS, the sediment transport potential of the control volume is computed independently for each

grain class using empirical sediment transport algorithms that translate the hydrodynamic conditions at each cross section into transport. The total transport capacity is computed by assessing the proportion of all grain classes involved in the transport [9].

The boundary condition at upstream cross section is the quasi-unsteady inflow hydrograph. In a quasi-unsteady condition, the continuous inflow hydrograph is transformed into a series of discrete intervals consisting of steady flow profiles over the flow duration. Sediment transport computations in HEC-RAS assume no change occurs in the elevation of the bed surface layer over a computational time step. The 24-h flow duration is further subdivided into variable computational intervals to reduce model instability as higher flows tend to increase the change in bed surface elevation. The boundary condition at the downstream cross section is the normal depth which requires the channel slope to be given as input. The slope of the river reach between Perur and Polavaram is calculated from the profile of the geometry in HEC-RAS. The mean diameters of the bed sediment particles are obtained from samples collected along various points in the river bed. The bed sediment gradations are first defined in a database and then assigned to the upstream and downstream cross sections respectively. For intermediate cross sections, the bed gradations are interpolated from the samples. The mean diameters of the bed material at Perur and Polavaram are 1.31 mm and 1.09 mm respectively. The sediment flow characteristics are defined using a rating curve consisting of five flow-load points encompassing the entire range of flow. The erodible limits are set within the bank extents. Unlike the equilibrium load condition where sediment discharge is equated to its transport capacity in a control volume, non-equilibrium transport model computes the boundary sediment load based on inflow hydrograph and sample load points.

3 Results and Discussion

3.1 Calibration of Manning's Roughness Coefficient (N)

The inflow hydrograph, from 1st September 2017 to 31st October 2017, defined at the upstream boundary is continuously monitored for large changes inflows. The computational intervals are adjusted when the difference in flow rate between time steps exceeds the critical value. The Manning's roughness coefficient (n) is calibrated by simulating the unsteady flow model for different values of n along the cross section. To evaluate the performance of the hydraulic model, simulated discharge values are compared with observed measurements at Polavaram station (refer Fig. 3). Weighted coefficient of determination (ωr^2), Nash–Sutcliffe efficiency (E), modified Nash–Sutcliffe efficiency (E_1) and Modified index of agreement (d_1) are considered to provide an objective assessment of how well a simulated model fits the recorded observations for different values of Manning's coefficient. HydroGOF function in R

Fig. 3 Observed and simulated discharge for different Manning's roughness coefficient (*n*) values at Polavaram station
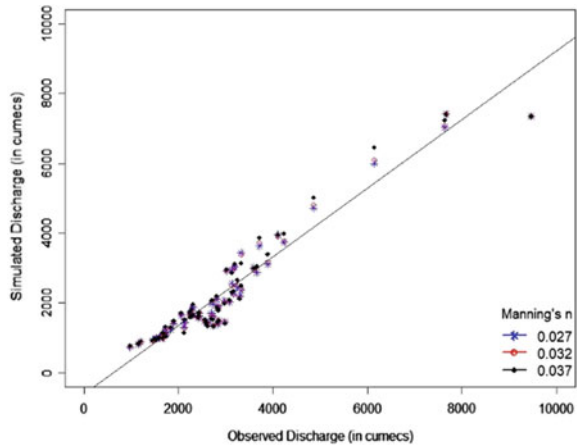

Table 2 Efficiency criteria for different values of manning's roughness coefficient (*n*)

Manning's roughness coefficient (*n*)	ωr^2	E	E_1	d_1
0.027	0.749	0.723	0.278	0.705
0.032	0.753	0.727	0.295	0.714
0.037	0.752	0.728	0.298	0.715

is used in the estimation of efficiency measures. The most appropriate value of n is selected based on these efficiency measures.

From the results presented Table 2 and Fig. 2, it can be observed that Manning's roughness coefficient of 0.037 has the best values for E, E_1 and d_1. Hence, 0.037 is chosen as the final calibrated value of *n* for sediment analysis.

3.2 Sediment Transport Function

To compute the total transport capacity, the model is simulated for the entire flow duration combining various sediment transport functions with armouring techniques and fall velocities. It involves routing of sediment at cross sections considering the sediment dynamics. The simulated sediment discharge at Polavaram station is compared with the recorded observations to select the most suitable transport function. The performance of various sediment transport models is summarized in Table 3.

It is crucial to identify transport functions that define sediment transport accurately. For evaluation of model performance based on ωr^2, information about the gradient integrated into its calculation is also considered. Gradient values closer to one indicate good agreement. The Wilcock-Crowe transport function had a gradient

Table 3 Efficiency criteria indicating model performance with different sediment transport functions

Transport function	Sorting method	ωr^2	E	E_1	d_1
Acker's White	Thomas (Ex 5)	0.264	0.237	−0.004	0.533
Engelund-Hansen	Thomas (Ex 5)	0.476	0.576	0.168	0.620
	Active Layer	0.466	0.561	0.161	0.615
Laursen (Copeland)	Thomas (Ex 5)	0.326	0.341	0.138	0.576
Tofaleti	Thomas (Ex 5)	0.173	−0.021	−0.147	0.476
Meyer Peter Muller	Thomas (Ex 5)	0.252	0.200	0.007	0.532
Wilcock-Crowe	Active Layer	0.585	0.736	0.365	0.699
MPM- Tofaleti	Thomas (Ex 5)	0.227	0.112	−0.060	0.507
Yang	Active Layer	0.358	0.412	0.153	0.587

of 0.675 which was higher than the other gradients and also produced the best result of 0.585 for ωr^2.

E values closer to one indicate good correlation and for lower values E_1 the model performance is interpreted as poor. Efficiency criteria lesser than zero indicates the mean of the observed time series would produce better predictions than the model. From Table 3, it is observed that there is poor agreement between the modelled and observed hydraulic behaviour when Tofaleti, MPM-Tofaleti and Acker's White transport functions are considered. The values of E and E_1 for Tofaleti, E_1 for MPM-Tofaleti and Acker's White are all less than zero indicating poor model performance. The Wilcock-Crowe function gave the best values for E (0.736) and E_1 (0.365) amongst the functions considered in this study. It also has the best value of 0.699 for d_1 (Value of 1 implies perfect fit). The sediment discharge at Polavaram, computed using the Wilcock-Crowe transport function, is compared with the recorded observations at the station (refer Fig. 4).

The efficiency measures produced more accurate and consistent results for the Wilcock-Crowe transport function. It is therefore used in computing the erosion and aggradation at each cross section along the river reach.

3.3 Predication of Mean Effective Invert Change

The surplus or deficit sediment load at a cross section is transformed into equivalent values of depth, indicating aggradation or erosion at that section. The mean effective invert change provides the average change in bed elevation at a cross section after the flow duration. In sedimentation analysis, the mean effective channel invert provides a more realistic measure of erosion and deposition at station over the invert change which only considers the lowest point of elevation in a cross section at the end of simulation.

Fig. 4 Measured and simulated sediment discharge using Wilcock-Crowe transport function at Polavaram station
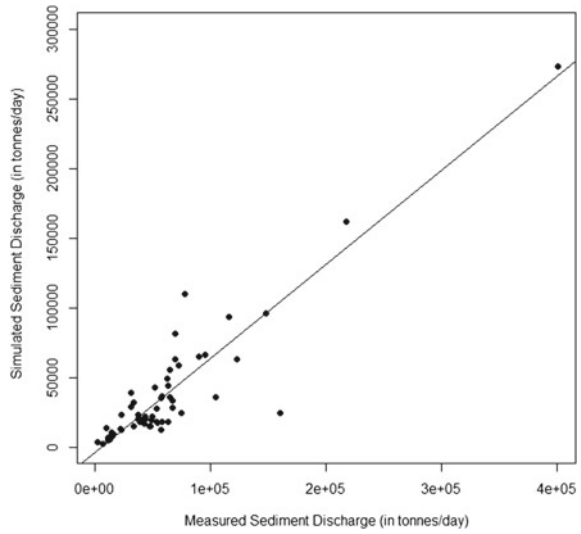
The bed elevation changes across 105 river stations, computed using the Wilcock-Crowe transport function, are shown in Fig. 5. The river stations are denoted from upstream to downstream. It is observed, at certain stations there is an alternating pattern of high erosion followed by deposition. These patterns could be consistently associated with abrupt changes in the relative elevation of the river's profile between successive cross sections. Significant erosion and deposition are observed in the river
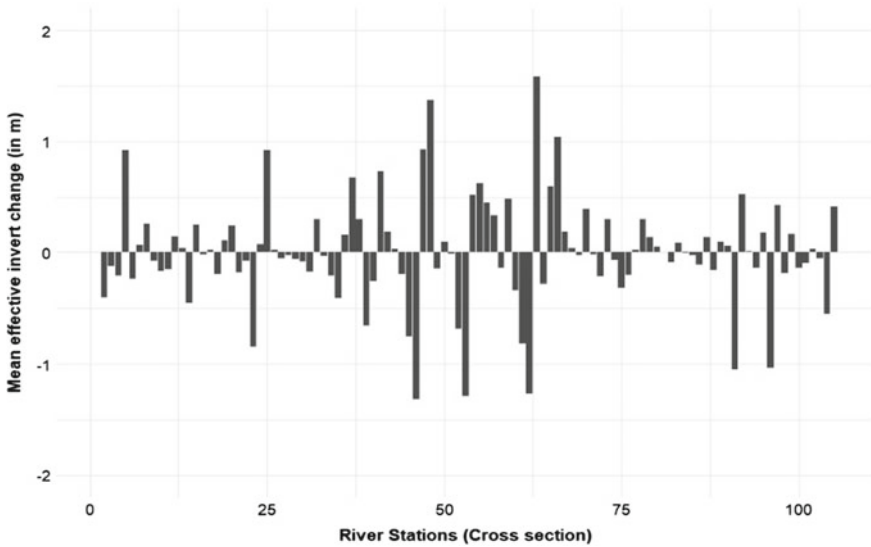

Fig. 5 Mean effective invert change across different cross sections

reach between stations 44 and 67 where the river reach undergoes a sharp change in its direction of flow. A gradual rise in erosion and deposition behaviour is also noted towards the end, between stations 90 and 97, where the river again changes its direction of flow. Maximum depth of erosion of 1.316 m is observed at river station 46. The deposition is maximum at the 63rd river station with a depth of 1.583 m.

4 Conclusion

In this study, we have considered the reach of Godavari River between Perur and Polavaram stations. Unsteady flow conditions were chosen over the conventional steady flow approach to determine Manning's roughness coefficient. To reproduce the natural hydraulic behaviour of the river reach, the model was calibrated by adjusting n values. Manning's roughness coefficient of 0.037 was selected based on the efficiency criteria.

Sedimentation along the river reach was computed using one-dimensional non-equilibrium sediment transport model. The most appropriate transport function was decided by calibrating the sediment discharge at downstream boundary. Values of ωr^2, E, E_1 and d_1 were comparatively higher for the Wilcock- Crowe transport function which provided a better estimation on sediment discharge in river reach between Perur and Polavaram. It should be noted that not all criteria will accurately quantify the model performance based on flow dynamics. Hence, it is imperative to choose criterion's that are positively correlated and provide a consistent assessment. The average change in bed elevation, depicted using the mean effective invert change, revealed that erosion and deposition in the river reach are influenced by both abrupt variations in the riverbed geometry and the change in direction of flow.

The maximum erosion and deposition were observed in these zones. It is noted that the accuracy of the model depends primarily on the quality of topographic data, hydraulic conditions in the river reach and the sediment transport function chosen. The characteristics of these empirical functions are to be compared with that of the flow scenario before incorporating it into the analysis. It is essential to understand and identify the limitations in each sediment transport function especially when they are associated with the modelling of sediment dynamics in natural flows.

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