

# Hydrodynamic flow modeling and effect of roughness on river stage forecasting

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## Abstract

In recent times, undesirable climatic conditions have been attributed to climate change. The intensity of rainfall has amplified extremely, causing floods in many areas worldwide. It is desirable to regulate and minimize the consequences of floods and excess downpour. Using geospatial data for the development of hydraulic models and mapping of simulation results has become standard practice for floodplain assessment. The objective of the current investigation is to use one-dimensional floodplain modeling of the Bhima River between Lonikand and Rahu using the RAS-mapper tool (HEC-RAS). The modeled river reach is about 67 km long, near the Pune administrative division of Maharashtra, India. The hydrodynamic flow computations were carried out for the years 2005 and 2017. A total of 595 cross sections along the main river was employed for hydrodynamic flow simulations. In this study, cross-sections and past observed flood data have been used to develop a 1-D integrated hydraulic model of the Bhima River. The simulated water levels are also validated with observed water levels and found to be reasonably correlated.

## Keywords

Flood modeling, channel roughness, HEC-RAS hydrodynamic modeling.

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## 1. Introduction

In recent years the hydrological cycle has been escalating and hastening because of climate change, with consequences that include increasing frequency and magnitude of floods (Kvocka et al. 2015). Floods are the most common and extreme catastrophes in a tropical country like India. Floods cannot be completely avoided, but the accompanying threats could be minimized, if flood prone areas are known in advance (Sahoo, Sreeja 2015). Therefore, recognizing flood risk zones and flood inundation mapping (FIM) are key steps for framing flood management strategies (Sahoo, Sreeja 2015). Correct geometry and flow data inputs are basic requirements of a good hydraulic model, but the performance of the simulations also varies by model type, e.g., one dimensional (1-D), two dimensional (2-D) or combined (1-D & 2-D) types. 1-D models are used extensively to simulate flow in the main river channel and in certain cases very effective in predicting flood extent (Vozinaki et al. 2016). Computational effectiveness and simple parameterization in dealing with flows in large and complex networks have been established by 1-D modelling (Ahmad, Hassan 2011). Horritt and Bates (2002) checked performance of 1-D modelling for hydraulic simulation by carrying out numerous studies and concluded that 1-D models have sufficient skill for good estimation of flood level and flood travel time, so that it can be used for prediction of flood extent. Timbadiya et al. (2012) developed a calibrated HEC-RAS-based model using flood peaks of observed and simulated floods; root mean squared error (RMSE) demonstrated that predicted flood levels were satisfactory. In the present study, a 1-D hydrodynamic model has been developed by using the Hydrologic Engineering Center's River Analysis System (HEC-RAS, V. 5.0.7) developed by the U.S. Army Corps of Engineers (USACE).

## 2. Governing equations

$$\frac{\delta A}{\delta t} + \frac{\delta Q}{\delta x} - q = 0 \quad \text{Continuity equation} \quad (1)$$

$$\frac{\delta Q}{\delta t} + \frac{\delta}{\delta x} \left( \frac{\beta Q^2}{A} \right) + g * A * \left( \frac{\delta h}{\delta x} + S_f \right) = 0 \quad \text{Momentum equation} \quad (2)$$

where:  $Q$  – discharge [ $\text{m}^3/\text{sec}$ ];  $A$  – cross-sectional area [ $\text{m}^2$ ];  $g$  – acceleration due to gravity [ $\text{m}/\text{sec}^2$ ];  $\beta$  – momentum correction factor;  $h$  – elevation of the water surface(stage) in meters above a specified datum;  $s_o$  – bed slope (Longitudinal channel bottom slope);  $t$  – temporal coordinate;  $x$  – longitudinal coordinate.

## 3. Numerical solution methods

Numerical techniques for the solution of expanded Saint-Venant equations can be given by implicit finite difference techniques with the most widely used Preissmann technique. In this technique all derivative terms and other parameters are calculated by using unknowns at the forward timeline ( $j+1$ ) in  $x-t$  grid as shown below.

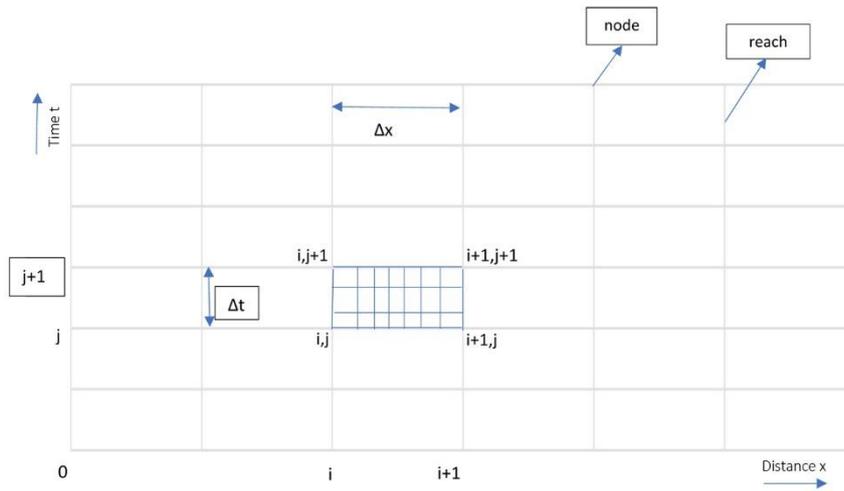


Fig. 1. The distance-time grid to developed implicit finite difference scheme.

In this scheme, grid size is taken as  $(i, j)$  where:  $i$  is the space interval;  $j$  is the time interval, and the four grid points from the  $(j)^{\text{th}}$  and  $(j+1)^{\text{th}}$  timelines are taken to approximate for the differential equation. A weighing factor,  $(\theta = 0.5)$  is used in the approximation of all terms of the equation except for the time derivatives in order to adjust the influence of the points  $(j)$  and  $(j+1)$ . Partial differential equations of continuity and momentum are obtained as a result of approximation by the Preissmann implicit finite difference scheme.

Water level  $(h) = f(A, B)$ , where  $A$  is the cross-sectional area;  $B$  is the channel top width

$$h_N^{j+1} - h(t) = 0$$

Where  $h_N^{j+1}$  is the stage to be computed at downstream and  $h(t)$  is the stage hydrograph value input to the model.

Discharge, water level, and area of cross-section are stated at nodes of grid and  $S_o$ ,  $S_f$ ,  $S_e$  i.e. bed slope, friction slope and energy line slope are stated at reaches.

Space derivatives of the Saint-Venant equations are:

$$\frac{\partial Q}{\partial x} = \theta \frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x_{i+1/2}} + (1 - \theta) \frac{Q_{i+1}^j - Q_i^j}{\Delta x_{i+1/2}} \quad (3)$$

$$\frac{\partial h}{\partial x} = \theta \frac{h_{i+1}^{j+1} - h_i^{j+1}}{\Delta x_{i+1/2}} + (1 - \theta) \frac{h_{i+1}^j - h_i^j}{\Delta x_{i+1/2}} \quad (4)$$

$$\frac{\partial \left( \frac{\beta Q^2}{A} \right)}{\partial x} = \theta \frac{\frac{\beta Q^2}{A}_{i+1}^{j+1} - \frac{\beta Q^2}{A}_i^{j+1}}{\Delta x_{i+1/2}} + (1 - \theta) \frac{\frac{\beta Q^2}{A}_{i+1}^j - \frac{\beta Q^2}{A}_i^j}{\Delta x_{i+1/2}} \quad (5)$$

Time derivatives of the Saint-Venant equations are:

$$\frac{\partial A}{\partial t} = 0.5 \frac{A_{i+1}^{j+1} - A_{i+1}^j}{\Delta t^j} + 0.5 \frac{A_i^{j+1} - A_i^j}{\Delta t^j} \quad (6)$$

$$\frac{\partial Q}{\partial t} = 0.5 \frac{Q_{i+1}^{j+1} - Q_{i+1}^j}{\Delta t^j} + 0.5 \frac{Q_i^{j+1} - Q_i^j}{\Delta t^j} \quad (7)$$

Other factors,  $A$ ,  $Sf$ ,  $q$  are approximated as follows:

$$q = \theta q_{i+1/2}^{j+1} + (1 - \theta) q_{i+1/2}^j \quad (8)$$

$$Sf = Sf q_{i+1/2}^{j+1} + (1 - \theta) Sf_{i+1/2}^j \quad (9)$$

$$A = \theta A_i^{-j+1} + (1 - \theta) A_i^{-j} \quad (10)$$

Substituting all values into the continuity equation yields,

$$0.5 \frac{A_{i+1}^{j+1} - A_{i+1}^j}{\Delta t^j} + 0.5 \frac{A_i^{j+1} - A_i^j}{\Delta t^j} + \theta \frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x_{i+1/2}} + (1 - \theta) \frac{Q_{i+1}^j - Q_i^j}{\Delta x_{i+1/2}} - q_{i+1/2}^{j+1} + (1 - \theta) q_{i+1/2}^j = 0$$

Putting all values into the momentum equation yields,

$$0.5 \frac{Q_{i+1}^{j+1} - Q_{i+1}^j}{\Delta t^j} + 0.5 \frac{Q_i^{j+1} - Q_i^j}{\Delta t^j} + \theta \frac{\frac{\beta Q^2}{A}_{i+1}^{j+1} - \frac{\beta Q^2}{A}_i^{j+1}}{\Delta x_{i+1/2}} + (1 - \theta) \frac{\frac{\beta Q^2}{A}_{i+1}^j - \frac{\beta Q^2}{A}_i^j}{\Delta x_{i+1/2}} + g * (\theta A_i^{-j+1} + (1 - \theta) A_i^{-j}) \left[ \theta \frac{h_{i+1}^{j+1} - h_i^{j+1}}{\Delta x_{i+1/2}} + (1 - \theta) \frac{h_{i+1}^j - h_i^j}{\Delta x_{i+1/2}} + Sf q_{i+1/2}^{j+1} + (1 - \theta) Sf_{i+1/2}^j \right] = 0$$

These equations are solved by the Newton-Raphson iterative technique to calculate water level and discharge at  $(j+1)^{\text{th}}$  timeline at nodes  $(i)$  and  $(i+1)$ .

#### 4. Methodology adopted

A hypothetical, rectangular river section was established, assuming a width of 800 m, an average longitudinal bed slope of 0.0005, and Manning's roughness coefficient of bed slope changing with time and distance.

The study area is strategically important, and the upper Bhima River basin catchment (45,678 km<sup>2</sup>) is one of the important tributaries of the Krishna River in the upstream part of the basin in western Maharashtra state in India. The catchment is located between 16.5°-19.5° latitude and 73.0°-76.5° longitude. The elevation ranges from 414 m in the east to 1,458 m in the western Ghat mountains; 95% of the catchment is below 800 m and relatively flat. The location of Bhima basin in Pune is shown in Figure 2.

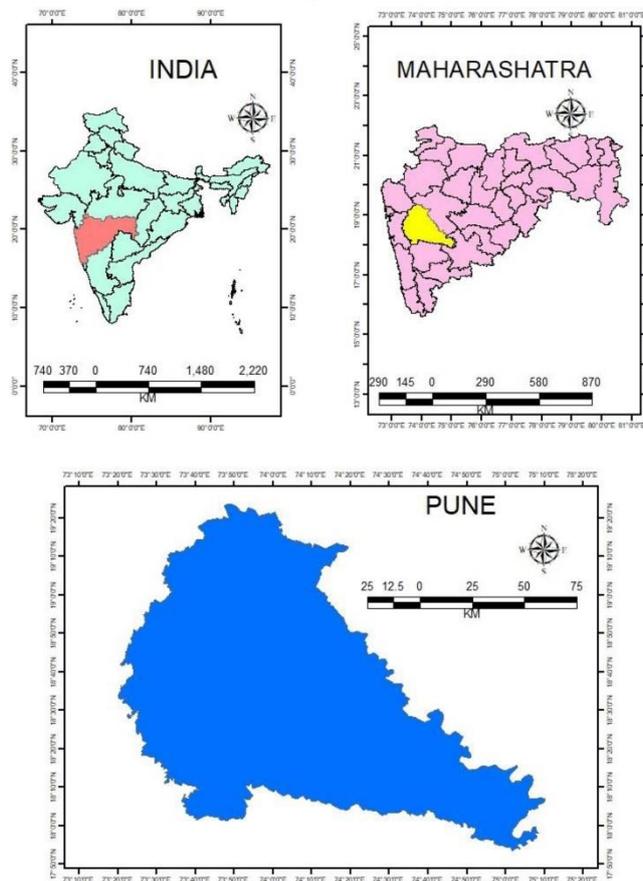


Fig. 2. Location of study area.

The Hydrologic Engineering Center's River Analysis System (HEC-RAS, V. 5.0.7) developed by the USACE is generally used for the study of flood analysis of numerous return periods. 1-D HEC-RAS hydrodynamic modeling is an applicable tool for deriving 1-D river hydraulic parameters including total discharge, water surface elevations (WSE), energy gradient elevation (EG), energy gradient slope, velocity, flow area, and Froude number at different channel sections, which help for better analysis. The applica-

tions are specifically planned for flood plain management and flood-insurance studies to estimate flood-way interruption and to reproduce estimated flood inundation in the study area. HEC-RAS demands a number of input variables for hydraulic analysis of the stream channel geometry and water flow. These parameters are used to create a series of cross-sections along the stream. In each cross-section, the locations of the stream banks are identified and used to divide the cross-section into segments of left floodway, main channel, and right floodway. At every cross-section various input parameters are used to define elevation, shape, and relative position at a river station number, including lateral and elevation coordinates for all terrain points, left and right bank locations, downstream reach lengths between the left floodplain, stream center-line, and right floodplain of every adjacent cross-section, and Manning's roughness coefficients for left, main channel, and right floodplains. Further, geometric descriptions of any hydraulic structures, such as bridges, culverts, and weirs for current study in flood modeling data for flood events of 2005 and 2017 were considered. A Bhima River stretch 67 of km with 595 cross-sections, each approximately 800 m long, was modeled. The primary data required for this modeling was collected from the Water Resource Department (WRD), Pune, Government of Maharashtra, National Hydrology Project (NHP)<sup>1</sup>, Nasik Maharashtra, and Central Water Commission (CWC) water books. Manning's roughness coefficients were selected according to Central Water Commission (CWC) guidelines; bank stations were marked with the help of RAS-Mapper and ArcGIS world imagery. Reach length data was also collected from WRD<sup>2</sup> at Pune in Maharashtra. River geometry was created as shown in Figure 3.

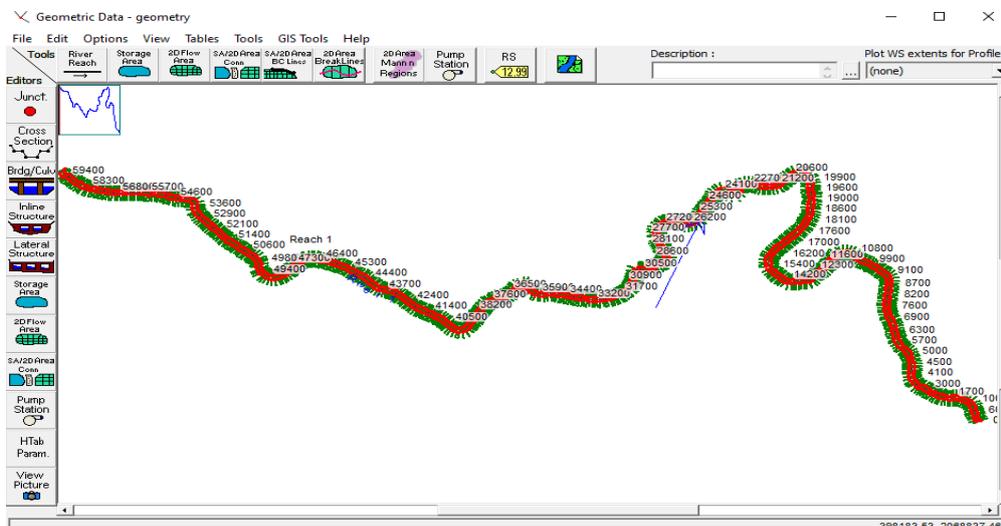


Fig. 3. Geometry of Bhima River.

Manning's coefficient reach lengths and bank stations were also used for each cross-section as shown in Figure 4. For hydrodynamic flow analysis, stage hydrographs for the period of July and August 2005 were used as downstream boundary conditions, and the flow hydrograph for the same period was used as the upstream boundary condition.

<sup>1</sup> <https://www.mahahp.gov.in/HDUG>

<sup>2</sup> <https://wrд.maharashtra.gov.in>

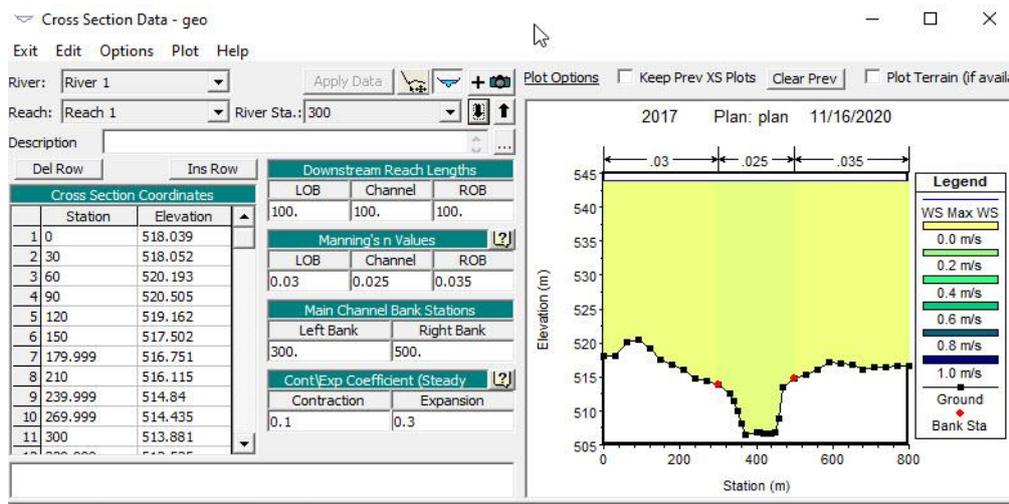


Fig. 4. Cross-section details of the Bhima River channel.

The flow data, and flow category with regime conditions are used to build up the model for the desired outcomes. The methodology followed is expressed in a flow chart (Figure 5).

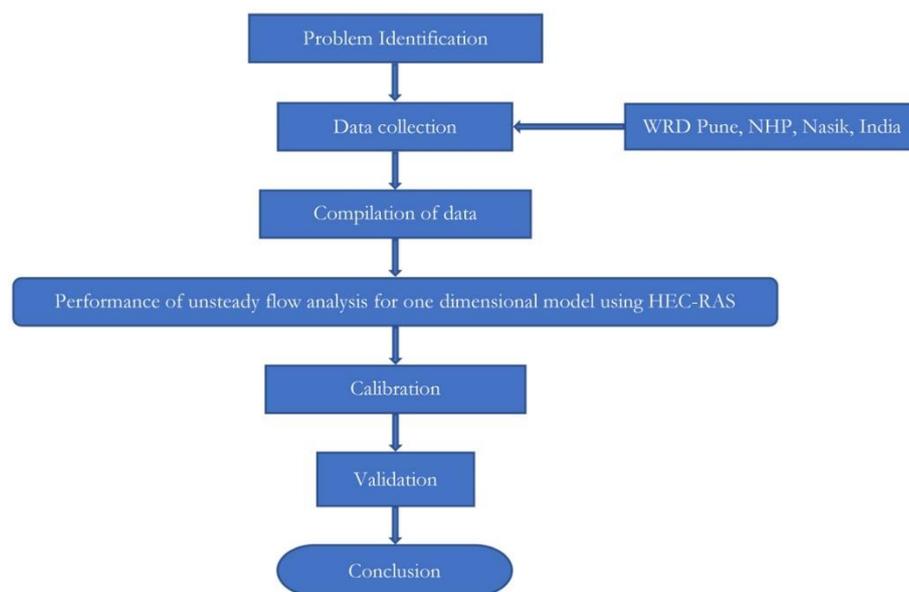


Fig. 5. Flowchart of methodology.

## 5. Data availability

Table 1 below gives the details of data types and sources of data used in this research paper on hydrodynamic flow modeling and the effect of roughness on river stage forecasting.

Table 1. Data type and source of data.

DATA TYPE	SOURCE
Flood hydrographs	1. National Hydrology Project (NHP), Nasik Maharashtra, India. 2. Central Water Commission (CWC) water books, India.
River Geometry data	Water Resource Department (WRD), Pune, Government of Maharashtra, India.

## 6. Hydrodynamic model calibration

Calibration is the adjustment of a model's parameters so that it reproduces observed data to an acceptable accuracy. Roughness coefficients, i. e. Manning's roughness coefficient ( $n$ ) in this case, are among the main variables used in calibrating a hydraulic model. It is known that for a free-flowing river, roughness decreases with increased stage, and flow. However, if the banks of a river are rougher than the channel bottom, then the composite value of the roughness coefficient ( $n$ ) will increase with increased stage. Deposits and debris can also play an important role in the roughness. When Manning's  $n$  is increased in a particular area, then stage will increase locally, the peak discharge will decrease (attenuate) as the flood wave moves downstream, and the travel time will increase. The hydrodynamic model is calibrated using the flow hydrograph for the period of 20 July 2005 to 8 August 2005 as the upstream boundary condition and the stage hydrograph from 20 July 2005 to 8 August 2005 as the downstream boundary condition. Flow data from 2005 has been used for calibration of Manning's roughness coefficient ' $n$ ' at a time step of 24 hours. The flow and stage have been simulated using the daily hydrograph for two months from 20 July to 8 August 2005. Calibrations have been done using Manning's roughness coefficient for values ranging from 0.015 to 0.040. Subsequently, final control parameters obtained from calibration have been used for validation in the Bhima River basin. Manning's roughness coefficient ( $n$ ) was fixed as 0.025 for the main channel, 0.03 for the left floodplain, and 0.035 for the right floodplain. The comparison of observed and simulated stage hydrograph at Phulgaon gauging station (Latitude:  $18^{\circ}40'01''$ , Longitude:  $74^{\circ}00'08''$ )<sup>3</sup>, using the specified values of  $n$ , are shown in Figure 6.



Fig. 6. Calibrated water level profiles (stages) at Phulgaon gauging station (from 20 July 2005 to 8 August 2005).

## 7. Hydrodynamic flow validation

Model validation involves testing of a model with observed field data. This data set is an independent source for channel flow, distinct from the data used to calibrate the model. The calibrated hydraulic model has been used to validate the flow for the year 2017<sup>4</sup>. The comparison of observed and simulated flow hydrographs at Phulgaon gauging station in the basin is shown in Figure 7.

<sup>3</sup> <http://cwc.gov.in/sites>

<sup>4</sup> <http://cwc.gov.in/water-year-book>

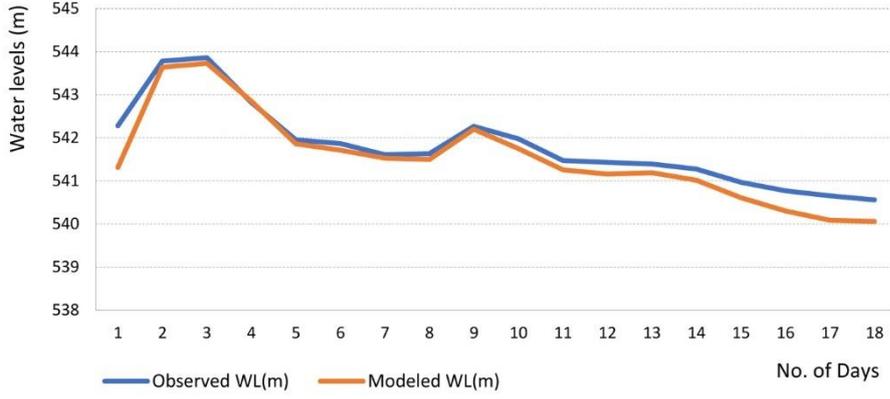


Fig. 7. Validation water level profiles (stages) at Phulgaon gauging station (from 20 July 2005 to 8 August 2005).

## 8. Model performance evaluation

Performance of the hydraulic simulation model has been evaluated using the statistical performance indicators coefficient of determination ( $R^2$ ) (Equation 11) and root mean square error (RMSE) (Equation 12). The  $R^2$  statistic describes the degree of agreement between simulated and measured water levels in the analysis.  $R^2$  ranges from 0 to 1, with higher values indicating less error variance; typically values greater than 0.5 are considered acceptable in flow modeling (Legates, McCabe 1999; Moriasi et al. 2007).

$$R^2 = 1 - \frac{\text{sum of squares of errors (SSE)}}{\text{total sum of squares (SST)}}$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (11)$$

where  $y_i$  – actual/observed data at  $i^{\text{th}}$  value;  $\hat{y}_i$  – simulated result at  $i^{\text{th}}$  value;  $n$  – total number of data;  $\bar{y}$  – mean value of  $n$  data.

The root-mean-square deviation (RMSD) or root-mean-square error (RMSE) is a commonly used to express the quantity of the differences between values predicted by a model and the values observed.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (X_i - \bar{X}_i)^2}{N}} \quad (12)$$

where:  $i^{\text{th}}$  variable,  $N$  – number of data points;  $X_i$  – observed values;  $\bar{X}_i$  – simulated values.

In calibration of the model, the coefficient of determination  $R^2$  and lowest root mean square error (RMSE) were 0.9568 (Fig. 8) and 0.3099, respectively, which indicate that the simulated river stages are close to the observed stages.

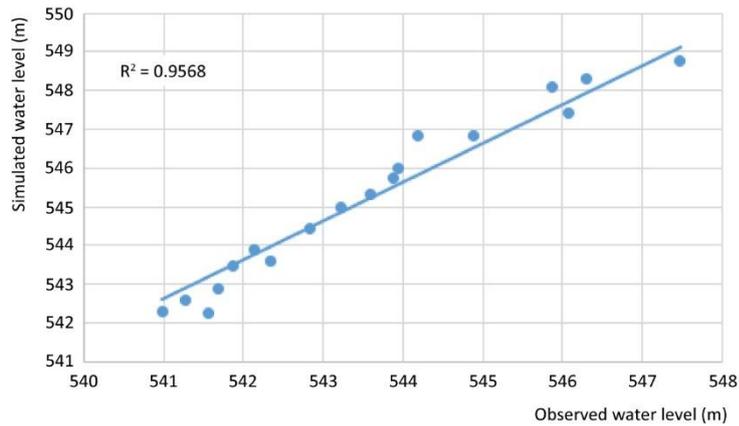


Fig. 8. Simulated river stages versus observed river stages.

## 9. Concluding remarks

This paper discusses 1-D hydrodynamic modeling developed using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) and a geographical information system. The model is calibrated for the Phulgaon gauging station using the flow hydrograph during 20 July 2005 to 8 August 2005. Calibrations and validations for various values of Manning's roughness coefficient ( $n$ ) were done, and observed and simulated water levels were compared. Values of  $n = 0.025$  for the main channel, 0.03 for the left floodplain and 0.035 for the right floodplain gave optimum results for simulated water levels. The hydrodynamic flow model validation has the highest  $R^2$  and lowest RMSE. These statistics indicated that the simulated values of water levels are in close agreement with the observed value of water levels. hydrodynamic flow modelling of the Bhima River basin in India using HEC-RAS demonstrates satisfactory validity for the selected values of  $n$ .

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## References

- Ahmad B., Hassan Z.A., 2011, Flood map of Tupai River using combined 1D and 2D modelling, [in:] 3<sup>rd</sup> International Conference on Managing Rivers in the 21<sup>st</sup> Century: Sustainable Solutions for Global Crisis of Flooding, Pollution and Water Scarcity, 491-496, available online at [http://redac.eng.usm.my/html/publish/2011\\_33.pdf](http://redac.eng.usm.my/html/publish/2011_33.pdf) (data access 16.07.2021).
- Hicks F., Peacock T., 2005, Suitability of HEC-RAS for flood forecasting, Canadian Water Resources Journal, 30 (2), 159-174, DOI:10.4296/cwrj3002159.
- Horritt M.S., Bates P.D., 2002, Evaluation of 1D and 2D numerical models for predicting river flood inundation, Journal of Hydrology, 268 (1-4), 87-99, DOI: 10.1016/S0022-1694(02)00121-X
- Khattak M.S., Anwar F., Saeed T.U., Sharif M., Sheraz K., Ahmed A., 2016, Floodplain mapping using HEC-RAS and ArcGIS: a case study of Kabul River, Arabian Journal for Science and Engineering, 41, 1375-1390, DOI: 10.1007/s13369-015-1915-3.

- Kvoc'ka D., Falconer R.A., Bray M., 2015, Appropriate model use for predicting elevations and inundation extent for extreme flood events, *Natural Hazards*, 79, 1791-1808, DOI: 10.1007/s11069-015-1926-0.
- Legates D.R., McCabe Jr. G.J., 1999, Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation, *Water Resources Research*, 35 (1), 233-241, DOI: 10.1029/1998WR900018.
- Moriassi D.N., Arnold J.G., Van Liew M.W., Bingner R.L., Harmel R.D., Veith T.L., 2007, Model evaluation guidelines for systematic quantification of accuracy in watershed simulation, *Transactions of the ASABE*, 50 (3), 885-900, DOI: 10.13031/2013.23153.
- Sahoo S.N., Sreeja P., 2015, Development of flood inundation maps and quantification of flood risk in an urban catchment of Brahmaputra River, *Journal of Risk and Uncertainty in Engineering Systems. Part A: Civil Engineering*, 3 (1), DOI: 10.1061/AJRUA6.0000822.
- Salajeghah A., Bakhshaei M., Chavoshi S., Keshtkar A.A., Najafi Hajivar M., 2009, Floodplain mapping using HEC-RAS and GIS in semi-arid regions of Iran, *DESERT*, 14 (1), 83-93, DOI: 10.22059/JDESERT.2010.21750.
- Timbadiya P.V., Patel P.L., Porey P.D., 2012, HEC-RAS based hydrodynamic model in prediction of stages of lower Tapi River, *ISH Journal of Hydraulic Engineering*, 17 (2), 110-117, DOI: 10.1080/09715010.2011.10515050.
- US Army Corps of Engineers, 2016, Hydrologic Engineering Requirements for Reservoirs, EM 1110-2-1420, available online at [https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/EM\\_1110-2-1420.pdf?ver=CjRXa4pEi5SXva0UuneAZQ%3d%3d](https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/EM_1110-2-1420.pdf?ver=CjRXa4pEi5SXva0UuneAZQ%3d%3d) (data access 16.07.2021).
- Vozinaki A.-E.K., Morianou G.G., Alexakis D.D., Tsanis I.K., 2016, Comparing 1D and combined 1D/2D hydraulic simulations using high resolution topographic data a case study of the Koiliaris basin, Greece, *Hydrological Sciences Journal*, 62 (4), 642-646, DOI: 10.1080/02626667.2016.1255746.
- Yang J., Townsend R.D., Daneshfar B., 2006, Applying the HEC-RAS model and GIS techniques in floodplain delineation, *Canadian Journal of Civil Engineering*, 33, 19-28, DOI: 10.1139/105-102.
- Yerramilli S., 2012, A hybrid approach of integrating HEC-RAS and GIS towards the identification and assessment of flood risk vulnerability in the city of Jackson, MS, *American Journal of Geographic Information System*, 1 (1), 7-16, DOI: 10.5923/j.ajgis.20120101.02.