Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 22 | No. 2 | pp. 977-983 | 2023

Original Research Paper | https://doi.org/10.46488/NEPT.2023.v22i02.042 | Open Access Journal

Extreme Flood Calibration and Simulation Using a 2D Hydrodynamic Model Under a Multipurpose Reservoir

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 16-07-2022
Revised: 08-12-2022
Accepted: 22-12-2022

Key Words:
Hydrodynamic model
Calibration
Simulation
Flood hydrograph
Validation
HEC-RAS

ABSTRACT

Extreme floods have become common in Asian cities, with recent increases in urbanization and extreme rainfall driving increasingly severe and frequent events. Understanding the flood dynamic is essential for developing strategies to reduce risk and damage, thus ensuring the city's protection. Channel roughness is a sensitive parameter in developing a hydraulic model for flood forecasting and flood inundation mapping. A High-resolution 2D HEC-RAS model was used to simulate the flood events of 1994, 1998, 2002, 2006, and 2015. The calibrated model, in terms of channel roughness, has been used to simulate the flood for the year 2006 in the river. The performance of the calibrated HEC-RAS-based model has been accessed by capturing the flood peaks of observed and simulated floods and computation of root mean squared error (RMSE) for the intermediated gauging stations on the lower Tapi River. Results revealed that there is good agreement between simulated and observed floods.

INTRODUCTION

India has witnessed rapid growth in its population in the past 50 years, which has put pressure on the country's water resources (Ahmed et al. 2013, Liu et al. 2019). This stress is further increased by global warming impacts, including increased precipitation, storm intensity, and rising seawater levels in coastal and low-lying areas, which are responsible for pluvial and urban flooding (Rangari et al. 2019). Because of changing climatic conditions, the chances of flooding in the cities on the river's banks and in coastal areas have increased dramatically. Floods are one of the primary reasons for the loss of life and property due to their devastating effects. It affects the emotional, social as well as economic life of the people who are affected by it. Flooding is a natural disaster, but its behavior changes due to human intervention in flood plains and catchments, such as the construction of bridges, roads, and houses, consequently increasing the risk and losses to properties and life (Timbadiya et al. 2011). Thus, there is an urgent need to predict the water level along the river accurately. Hence, reliable hydraulic models are required for the same.

A simulation is a primary tool for proper reservoir planning and management by assessing various scenarios for different operating conditions (Koutsoyiannis & Economou 2003). Simulation modeling is often used to examine and evaluate the performance of complex water resource systems. Simulation models may be deterministic or stochastic. The simulation model may be time-sequenced or event-sequenced. In a time-sequenced model, the properties of the system, such as inflow, storage, releases, deficits, and surplus, are examined at a fixed time interval, viz. seasonally, monthly, ten-daily, weekly, daily, or hourly basis. In event-sequenced simulation models, the event is fixed, viz., the number of times droughts or floods occurred. Wurbs (1993) presented various computer models developed for evaluating reservoir operations and emphasized that the model selection and analysis approach for a particular application depends on the characteristics of the application, the extent of ease provided by alternate models, and the preference of the analyst. With advancements in computer technology, various hydraulic models (1D and 2D) have been developed for flood forecasting and flood inundation mapping.

Predicting stage and discharge in the river is considered the flood warning parameter in any river across the globe (Quirogaa et al. 2016). Generally, levels are predicted along the river, and inflows are predicted for reservoirs.

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Apart from that, insurance studies and the development of risk map predictions of water levels are essential for effectively managing future flooding. Thus, estimating water levels in flood plains is of prime importance. Stages in the stream and their corresponding value of discharges and several other parameters are reliant on the roughness of the channel. Hence, the prediction of channel roughness also plays a significant role in studying open channel flow, especially in hydraulic modeling (Bhandari et al. 2017). The channel roughness is not a constant parameter, and it varies along the river depending upon variation in channel characteristics.

For example, the flood in 2006 alone caused direct damage to the nation's US $ 4200 million, and the whole city remained submerged for more than two days (Thakar 2007). Thus, there is an urgent requirement for a hydrodynamic model which should predict the flood levels considering the release from the Ukai dam in the lower part of the Tapi River for flood forecasting and planning safety measures in and around Surat city. Accordingly, channel roughness for the lower Tapi River (Ukai dam to Hope Bridge) has been calibrated using stream flow data of the past floods, i.e., 1994, 1998, 2002, 2006, and 2015 flood data.

MATERIALS AND METHODS

The Study Area

The Tapi River flows east to west in central India, between the Godavari and Narmada rivers. It is one of the major rivers of peninsular India, having a length of about 725 km. Tapi River originates at a place known as Multai in the Betul district of Madhya Pradesh state, having an elevation of about 753 m. For the initial 282 km, the river flows through Madhya Pradesh, in which the path of 54 km is the borderline area next to Maharashtra State. It rises in the eastern Satpura Range of Southern Madhya Pradesh and flows westward to the Nimar region of Madhya Pradesh, having historical importance. Tapi River flows in Maharashtra before entering Gujarat. After traveling the length of 214 km in Gujarat, the Tapi river finally joins the Arabian Sea in the Gulf of Cambay after crossing Surat city.

The Tapi River basin has a total area of 65,145 km^2. The basin lies in the states of Maharashtra (51,504 km^2), Madhya Pradesh (9,804 km^2), and Gujarat (3,837 km^2). The entire Tapi Basin can be divided into three sub-basins: Upper Tapi Basin from the origin up to Hathnur, having an area of 29 430 km^2, the Middle Tapi Basin from Hathnur to Sarangkheda gauging site, having an area of 31861 km^2 and the Lower Tapi Basin from Ukai Dam up to the Arabian Sea having an area of 3854 km^2.

Surat city is in the Lower Tapi basin. Low banks and many rapids characterize the Tapi River after the Kakrapar Weir. The Tapi passes through small towns like Kathor and Mandvi. There are large chances of occurrence of flood due to the low banks beyond the Kakrapar Weir. The Tapi River is braided in some portions, and the river has very rocky strata at places like Veratha Village, Khanjroli, and Bodhan. Lower Tapi, as the study area, is shown below in Fig 1. There are 14 major tributaries to the Tapi River, having a length of more than 50 km. On the left bank are ten important tributaries, and on the right bank are four tributaries.

Data Sources for the Present Study

The required data is collected from various agencies to carry out the present study, as described below.

Landsat Images

Earth-Explorer (http://earthexplorer.usgs.gov) provides

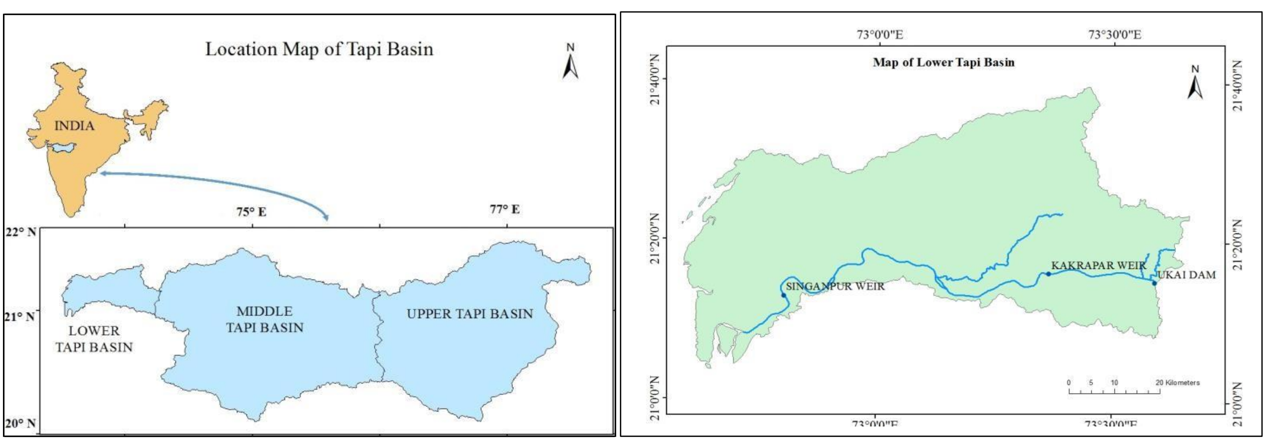


Fig 1: Index map of lower Tapi Basin.

online search, display browsing, data export, and downloading data from the U.S. Geological Survey (USGS) archives. And Landsat 8 images for the study period were obtained from the above-mentioned website.

Digital Elevation Model

The present study downloaded DEMs from USGS Earth Explorer (http://earthexplorer.usgs.gov). Among the available DEM in USGS, the most accurate one is SRTM (Shuttle Radar Topography Mission) 1 arc second (30m), and hence it is used.

Hydraulic Data

Hourly outflow data from Ukai Dam and the consecutive levels from the Kakrapar weir and Causeway weir were collected from the flood control cell, Surat Irrigation Circle, Surat, and hourly levels of the Ghala gauging stations were collected from CWC for 1994, 1998, 2002, 2006 and 2015 flood data.

Methodology

The present study demonstrates the calibration of Manning's roughness coefficient, 'n.' It uses the same in the simulation of future floods in the lower Tapi River from the Ukai dam to the Hope bridge using 2D hydrologic modeling. 2D hydrodynamic modeling of rivers becomes easy due to readily available software such as HEC-RAS, Flow 3D, etc.

The 2D hydrodynamic model was developed by using a 30 m resolution DEM. For all the cross-sections, Manning's n value was assigned. A Weir of a height of 4.75 m was created at the causeway location. Flow hydrograph was given as the boundary condition from the upstream, and the model was simulated. For different n values model was calibrated.

RESULTS AND DISCUSSION

Hydro-Dynamic Model Calibration

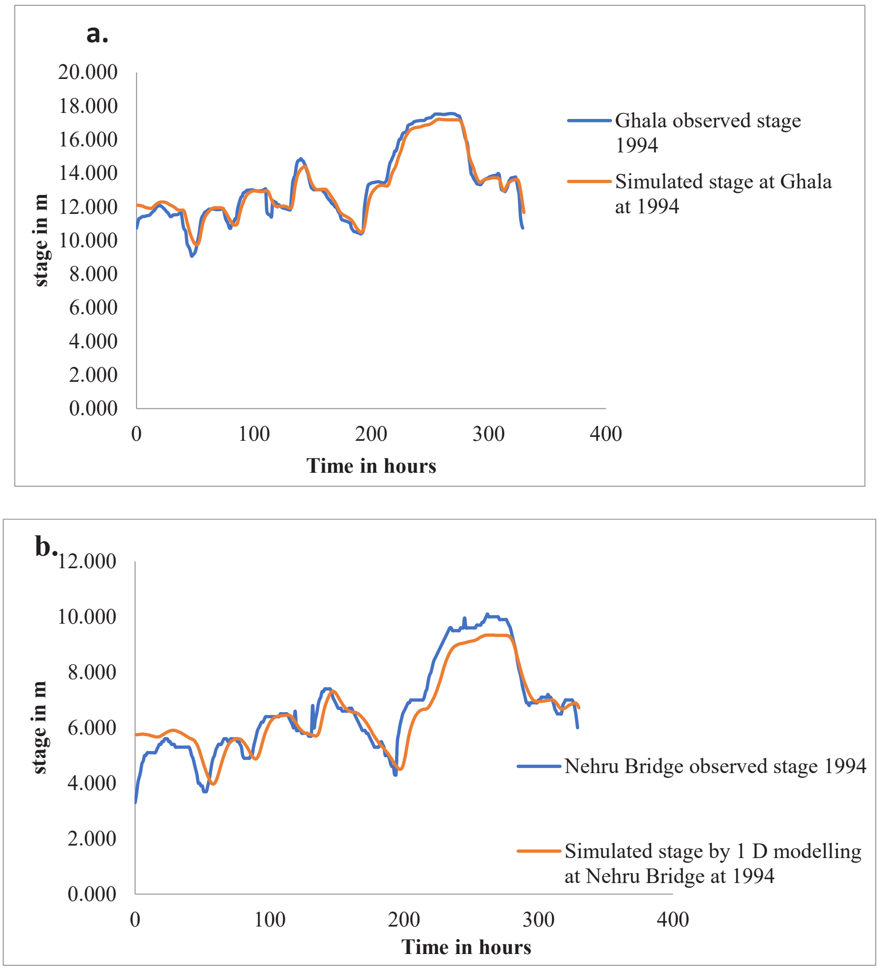


Fig. 2: Observed and simulated stages hydrograph of 1994 using HEC-RAS 2D modeling at a) Ghala; b) Nehru Bridge.

Table 1 (a): Calibration table for the 2 D model for the year 1994 flood.

Manning's 'n' value	RMSE		
	Kakrapar weir	Nehru Bridge	Ghala
0.015	2.9	1.1	1.8
0.02	0.29	0.71	1.6
0.025	0.27	0.9	1.78
0.03	0.21	1.2	2.4
0.035	0.20	0.7	1.9

Table 1 (b): Calibration table for the 2 D model for the year 1998 flood.

2 D Model performance table for 1994 flood with n = 0.035			
Parameters	R^2	RMSE	SE
Ghala	0.9741	0.017631	4.524833
Nehru Bridge	0.8897	0.586411	0.111394

Using the measured water surface elevation data, the HEC-RAS model is calibrated against Manning's roughness coefficient (n-value). An n-value is first estimated based on the previous Studies on the Tapi River (Timbadiya et al. 2011) and in consultation with textbook guidelines. Using this as a starting point, the n-value progressively changes until an optimization parameter. The model was calibrated based on the coefficient of correlation and RMSE. The

Table 2: Model performance for 1998 and 2002 at Ghala and Nehru Bridge.

Model Performance Table		
Parameters		Coefficient of Correlation r^2
		2 D Modeling
Ghala	1998	0.8967
	2002	0.9591
Nehru	1998	0.9607
	2002	0.8952

correlation coefficient was maximized to optimize the results and get the best n value. Fig. 2 a & b show the calibration and stage results of the HEC-RAS 2D model for the Ghala and Nehru Bridge, respectively. From Fig 2 a & b, it can be seen that there is a good prediction from the model for Manning's value of 0.027 on banks and 0.035 in the river. Table 1 (a and b) shows the calibration results for the 2D model for the year 1994 and 1998 flood events, respectively.

Table 1 (a and b) shows that the calibrated Manning's n value of 0.035 for the flood plain is in good agreement with the observed stage at both gauging sites.

HEC RAS 2D models were simulated for three years at two gauging sites. From the figures, it can be seen that there is a very close simulation obtained from 2D hydrodynamic

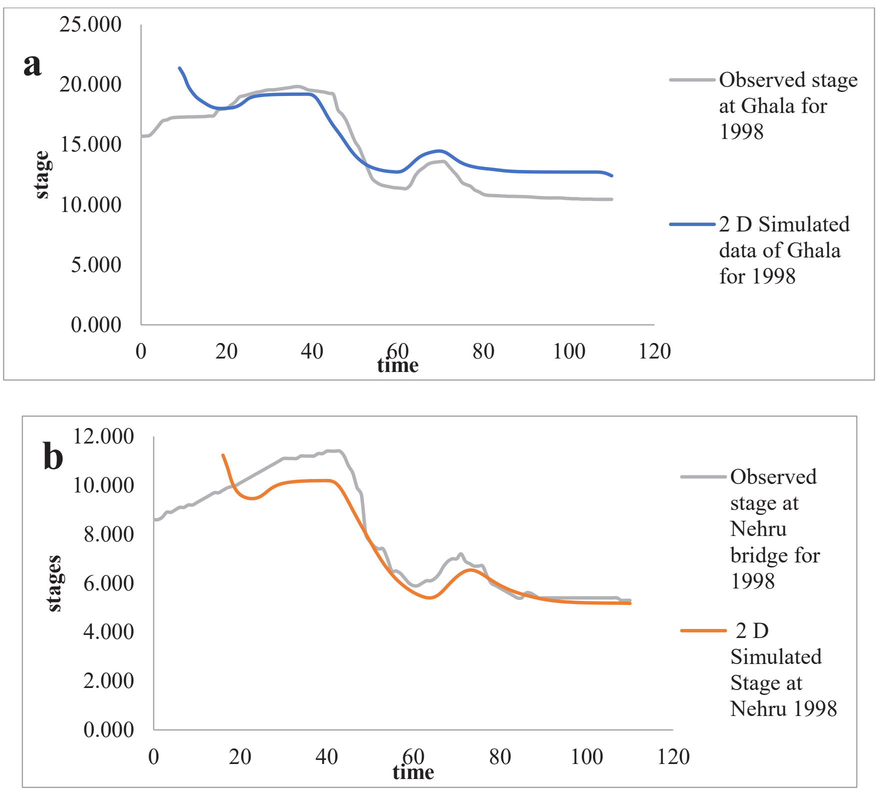
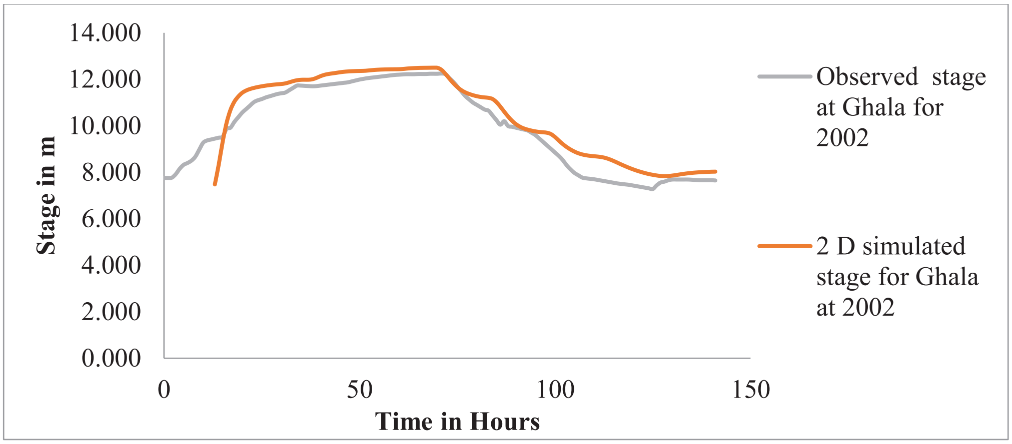


Fig. 3: Observed and simulated Stage of 2D for 1998 at a) Ghala; b) Nehru Bridge.



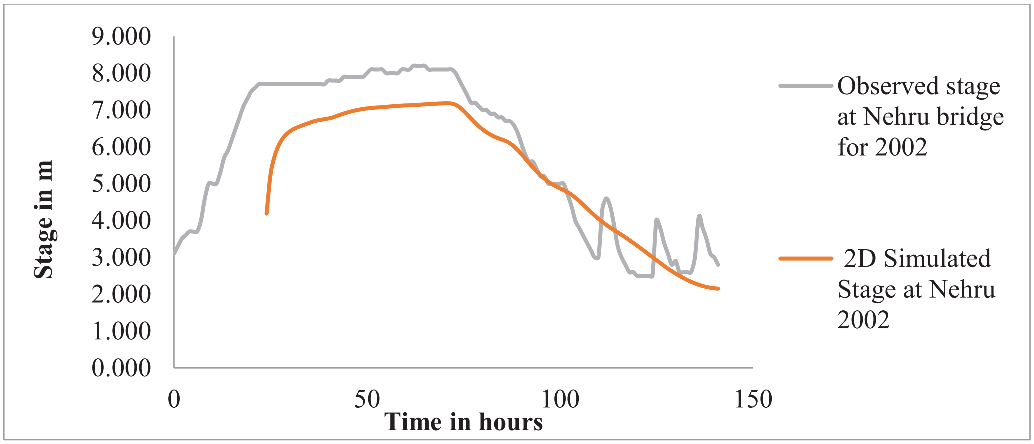


Fig. 4: Observed and simulated Stage for 2D for 2002 at a) Ghala b); Nehru Bridge.

models. The 2D model prediction always has a better correlation coefficient between observed and predicted stages for all the gauging sites, as shown in Table 2.

Fig. 3 (a & b) and Fig. 4 (a & b) show the predicted and observed stages for the two different years for 2D models at Ghala and Nehru Station for 1998 and 2002, respectively. From Fig. 3 (a & b) and Fig. 4 (a & b), there is a good prediction of stages at both the gauging sites for 1998 and 2002, respectively.

Calibration Result OF HEC-RAS 2D Model for Extreme Flood

The maximum water level obtained for different locations, known as the distributed water level outside the river, is obtained with the help of surveys. These levels are compared with the simulated levels with the help of HEC-RAS 2D. The model was calibrated for the year 2006. Around 15 to 20 levels are taken from each zone of the city, and the city is divided into 7 zones. Initially, the model was made with the help of 12 m × 12 m mesh, and the stability condition was satisfied by giving the time step of 30 seconds. The initial values of manning's roughness value were assumed to be 0.2, 0.03, 0.035, 0.04, and 0.1 for Urban, Agriculture, water, barren land, and forest, respectively. After simulation, levels obtained at different locations are shown in Table 3. Fig. 5 shows the flood inundation map for the study area under the year 2006 flood event. In this case Coefficient of correlation between observed and predicted levels was 0.62, as shown in Fig. 6. From Fig. 6, it can be seen that the entire Surat

Table 3: Simulated and measured levels for the year 2006 flood.

Location	Measured Level	Simulated Level
Akruthi Bungalow	1.850	1.244
Valentine cinemas	1.246	1.515
Sarojini Naidu Udhyan	2.121	1.87
Bakipark Society	2.345	3.0
Rambay Palace	3.600	3.855
Raghkul Palace	3.600	3.655
Silk Plaza	2.750	1.3

city was under flood. And almost all the roads were flooded except in the southwest area, where some roads can be seen as not flooded.

Table 3 shows that simulated levels are close to the observed levels for the flood that happened in the year 2006. For Rambay Palace and Raghkul Palace, the levels simulated were very close.

From Fig. 6, it can be seen that there is a good correlation between observed and simulated water levels for the selected locations.

Validation Result of HEC-RAS 2D Model

HEC-RAS 2D model is calibrated by changing Manning's roughness coefficient (n) for different classes to observe the water levels. When the simulated and observed water levels matched, those values of Manning's n for the five land use classes were fixed. By considering the calibrated Manning's roughness coefficient, the 2015 extreme event was considered for validation. In addition, the hydrologic response of the catchment for release from the Ukai Dam was considered. Inlet boundary condition was defined as the discharge obtained from the extreme event and routed hydrograph of the release at the Ghala gauging station. The downstream boundary condition was defined as the causeway water level. The obtained flood map for 2015 is shown below in Fig 7.

It is evident from Fig. 8 that for 2015, the area of inundation is found to be less, and the nearer portion of the Lower Tapi underwent flooding to a lesser extent. The level obtained at the Causeway, Nehru Bridge, and Ghala gauging stations were 1.7 m, 6.05 m, and 6.8 m, respectively.

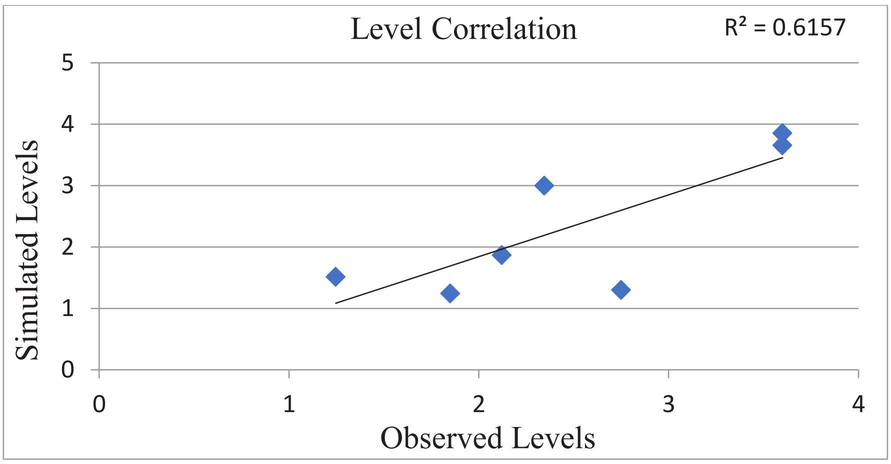


Fig 6: Correlation between observed and simulated water levels for the flood of the year 2006.

Fig 7: Flood Inundation map for predicted image for the year 2015.

Measured levels at the Causeway, Nehru Bridge, and Ghala gauging station were 1.8 m, 5.95 m, and 6.6 m, respectively. The obtained results show close agreement between observed and simulated water levels. This shows the satisfactory model performance for the given set of conditions.

CONCLUSIONS

The developed HEC-RAS 2D model is calibrated for the extreme event of the 2006 flood, and the water levels obtained are compared with the measured water levels. The Manning's roughness coefficient (n) obtained from the HEC-RAS 2D model during the calibration period as the flood period of 2006 estimated the values as 0.025 for urban, 0.035 for water and barren land, 0.1 for agriculture and 0.12 for the forest, which may be useful in estimating the future flood peaks. The correlation between observed and simulated water levels for the selected locations is found to be 0.61, which indicates that the model is performing well. HEC-RAS 2D model is validated using the releases from the Ukai Dam for 2015 and validated for the same year. Simulated levels at Causeway, Nehru Bridge, and Ghala gauging station are 1.7 m, 6.05 m, and 6.8 m, respectively. Measured levels at the Causeway, Nehru Bridge, and Ghala gauging station are 1.8 m, 5.905 m, and 6.6 m, respectively. This shows the model is performing well for the given set of conditions.

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