One-dimensional hydrodynamic modelling of flooding and stage hydrographs in the lower Tapi River in India

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The present study addresses the simulation of floods for the years 2003 and 2006 and the development of stage–discharge relationship along the lower Tapi River in India. The river network and cross-sections, for the present study, were extracted from the field-surveyed contours of the Tapi River. Using the aforesaid geometry and hydrological data, supplied by the stakeholders, the MIKE 11 hydrodynamic model was calibrated for the 1998 flood using releases from the Ukai Dam (flood hydrograph) and the tidal water level in the Arabian Sea as the upstream and downstream boundary conditions respectively. The calibrated model was validated using low- and high-flood data of the years 2003 and 2006 respectively. The time series of the simulated flood levels were compared with the corresponding observed values at four intermediate gauging stations: Kakrapar Weir, Mandavi Bridge, Ghala village and the Surat city (Nehru Bridge). The model performance was also evaluated using the standard performance index (i.e. root mean square error) and was found to be reasonably satisfactory for such a data-scarce region. The rating curves (i.e. stage–discharge relationship) were also developed from the aforesaid calibrated model which would be useful in flood forecasting and development of flood protection measures along the lower Tapi River.

Keywords: Flood forecasting, flood protection measures, hydrodynamic modelling, rating curve, stage–discharge relationship.

FLOODS are one of the major causes of the loss of life and property and have an adverse effect on the economy across the globe. The prediction of river stages plays a vital role in the structural and non-structural measures of flood management. The predictions are also useful to prepare the flood maps in river floodplains[1]. With rapid advancement in computational technology and research in numerical techniques, various one-dimensional (1D) hydrodynamic models, based on hydraulic routing, have been developed, calibrated, validated and successfully applied for flood forecasting and inundation mapping. Hydrodynamic models that reproduce the hydraulic behaviour of river channels have been proven to be effective tools in floodplain management[2]. The flood water levels along the 79 km long Kalu River in Sri Lanka were simulated using the 1D HEC-RAS hydrodynamic model to prepare the people to survive during floods with minimum damages[3]. The urban flash flood in 2001 in Gdańsk, Poland was simulated using a 1D model for the operation of storm gates under different conditions; and technical solutions were proposed to mitigate the consequences of similar floods[4]. Pramanik *et al.*[5] developed a 1D model of the Brahmani River in India using field-surveyed and DEM-extracted data and the MIKE 11 hydrodynamic (HD) module. Vijay *et al.*[6] used RiverCAD[7] to simulate and visualize flood flows for a 23 km stretch in the Yamuna floodplain of the Delhi region. The basic concepts of MIKE 11 HD module and its usefulness have been described in various studies[1,8,9].

Surat is one of the highly urbanized cities of India and is situated on the tail portion of the Tapi River. Historical records indicate that large floods on the Tapi River have occurred in 1727, 1776, 1782, 1829, 1837, 1872, 1944, 1959, 1968, 1970, 1994, 1998 and 2006. The flood during 1968, before construction of the Ukai Dam, with a peak discharge of 42,500 $m^3 s^{-1}$, was the largest in the last century. The average annual flood, with a recurrence interval of 2.33 years, on the Tapi (at Ukai) is 14,323 $m^3 s^{-1}$ (ref. 10). The flood in 2006 alone had caused damage totalling US$ 4200 million and a loss of about 150 human lives[11]. Almost 80% of the area of Surat city was flooded in 2006, with a peak discharge of approximately 25,780 $m^3 s^{-1}$ from the Ukai Dam. The flow capacity of the Tapi River has been reduced in Surat city due to rapid urbanizations/industrialization and severe encroachment of the floodplain. For example, a discharge of merely 25,780 $m^3 s^{-1}$ during the flood in 2006 had attained a level of 12.5 m at the Nehru Bridge in Surat city compared to the level of 12.9 m attained by the historically maximum flood of discharge 42,500 $m^3 s^{-1}$ in 1968.

The modelling of floods in the lower Tapi River is essential to implement structural (i.e. levee along the banks) and non-structural measures for flood control. Considering the availability of data from the stakeholders and the challenge ahead for management of floods in the lower Tapi River, a 1D hydrodynamic model (MIKE 11)

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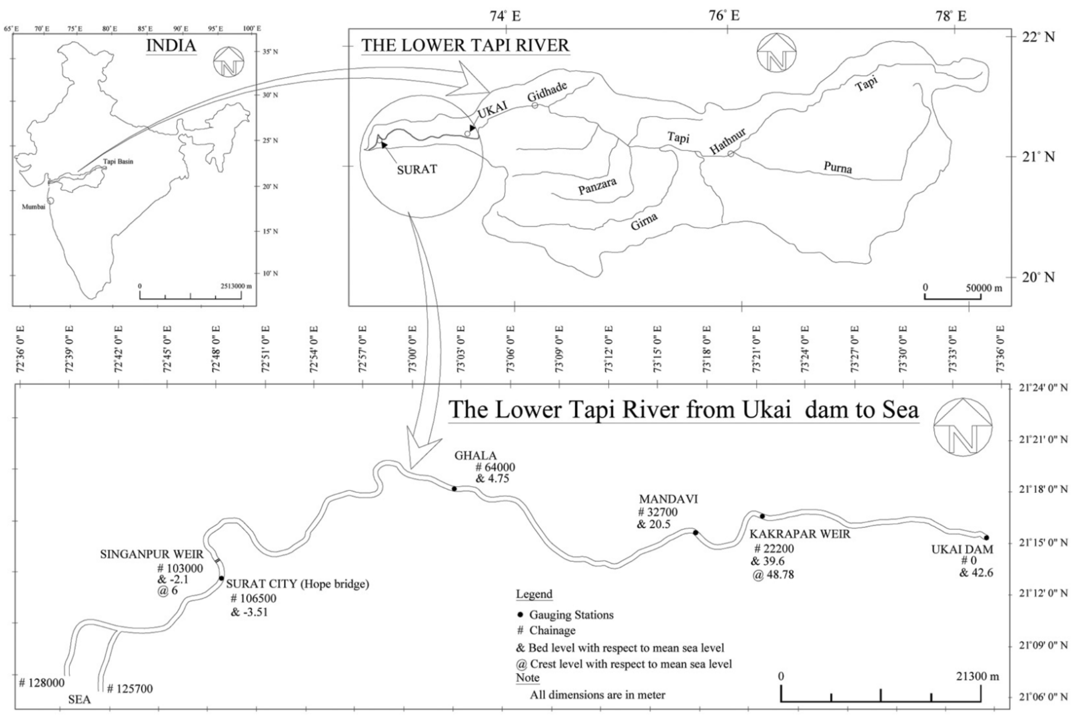

Figure 1. Map of the Tapi Basin, including the study reach in the lower Tapi River[18].

was used to simulate the floods during 1998, 2003 and 2006 for calibration and validation.

Study area and data collection

Description of the study reach

The Tapi River is the second largest west-flowing river and the sixth largest in the Indian Peninsula. It originates from Multai in Betul district in Madhya Pradesh at an elevation of 752 m, having a length of 724 km, and falls into the Arabian Sea slightly beyond Surat city limits. Majority of the higher order tributaries, such as Panzara, Purna and Girna join the Tapi River from the south (Figure 1). The total drainage area of the Tapi River is 65,145 km^2, out of which 9,804 km^2, 51,504 km^2 and 3,837 km^2 lie in the Madhya Pradesh, Maharashtra and Gujarat respectively. The basin is elongated in shape, with a maximum length (i.e. 687 km) from east to west and maximum width (210 km) from north to south. The average channel gradient of the Tapi River is 0.001 (ref. 11). Figure 1 shows the map of the Tapi Basin and the study reach along with the chainages and bed levels with respect to the mean sea level. Surat city is located in the delta region of the Tapi River and has a history of frequent flooding. The Tapi Basin is divided in three sub-basins, namely the upper Tapi Basin (up to Hathnur), the middle Tapi Basin (from Hathnur to Gighade) and the lower Tapi Basin (from Gighade to the sea)[12]. Over 90% of the total rainfall arrives during the summer monsoon (i.e. June–October) season in the basin, and the flow is negligible in the remainder of the year. The basin falls within the zone of severe rainstorms. The flood-producing heavy rainfall spells, generally lasting 1–2 days in duration, have been observed in the basin in the recent past with a maximum 24 h heavy rainfall ranging from 86 to 459 mm.

The length of the present study reach is 128 km, lying in the part of the lower Tapi River extending from the Ukai Dam (zero chainage) to the sea mouth. The Kakrapar Weir, an ogee-shaped structure (with a crest elevation of 48.78 m and a coefficient of Weir of 1.881) and the Singanpur Weir, a broad crested shape structure (with a crest elevation of 6 m and coefficient of Weir 1.666), are the two control structures located at the chainages of 22.2 km and 103.03 km respectively, in the study reach[11]. Near the Ghala Gauging Station, significant sand mining activities have occurred due to the large demand for sand in the urban area of Surat city. Further, contribution from lateral inflow is negligible from the Ukai Dam to Surat city, as no major tributary enters into the study reach. According to Kale[13], peninsular rivers are more stable and less unpredictable, mainly due to the low channel gradient and bed shear stress with low erosive power. Accordingly, the transport of sediments has not been included in the simulation of flood in the present study. Further, available sediment data were not sufficient to include the effect of sediment transport in the foregoing study.

Geometric and hydrologic data collection

The Surat Municipal Corporation (SMC) provided the geometric data of the study reach in the form of a contour map and the cross-sections at several locations in the study reach were extracted from the same. Detailed configuration of the Singanpur and Kakrapar Weirs was collected from the SMC and the Surat Irrigation Circle (SIC) respectively. The SIC also provided hourly data of the outflow and stages for the Ukai Dam (zero chainage) and the Kakrapar Weir for the floods during 1998, 2003 and 2006. The State Water Data Centre (SWDC)–Gandhinagar, Government of Gujarat has provided hourly water levels at the Mandavi Bridge (chainage 32.7 km) for the aforesaid period. The data for the Ghala Gauging Station (chainage 64 km) and Surat city (i.e. Nehru Bridge; chainage 106.5 km) were obtained from the Central Water Commission (CWC). The hourly tidal levels at the sea mouth were observed by the SIC from 6 December 2009 to 5 January 2010, which includes both the spring and neap tides. The hourly tidal levels, so collected from the SIC corresponding to the spring tide, were used in simulating the flood because the durations of flooding for 2006 and the spring tide were synchronized with each other.

Hydrodynamic modelling

Hydrodynamic modelling of the river required river network, cross-sections, hydrodynamic parameters and boundary conditions. A brief description of the numerical scheme, river network, boundary conditions, calibration and validation of the model is included below.

Numerical scheme

MIKE 11 HD, developed by Danish Hydraulic Institute[14], is a one-dimensional, unsteady, non-uniform flow simulation model that solves the 1D hyperbolic dynamic Saint–Venant equations[1,15] using an implicit six-point Abbott–Ionescu finite difference scheme. The scheme uses a staggered grid solution of the finite difference equations using a double-sweep algorithm. The computational scheme is applicable for vertically homogenous flow conditions extending from steep river flows to tidal estuaries. Additionally, the module can consider both subcritical and supercritical flow conditions in an open channel.

River network scheme

In this study, the river network was entered into a HD model for the lower Tapi River (0–128 km), including the Hazira Branch (118.3–128 km) and the two weirs at Kakrapar and Singanpur, as shown in Figure 1. The stage and discharge of the lower Tapi River are influenced by the tidal level, and the effect is propagated up to the Singanpur Weir under normal flow condition because the crest level of the Weir is higher than the maximum tidal level in the sea. However, the tidal effects may even be anticipated upstream of the Weir for the floods, wherein the Weir becomes submerged. Figure 2 depicts the left bank, right bank and thalweg line elevations along the chainages of the lower Tapi River.

MIKE 11 treats the domain as a series of cross-sections perpendicular to the flow direction. The lower Tapi River (i.e. the study reach) was surveyed and the river cross-sections were collected during 2007. A total of 190 cross-sections among those surveyed have been used for the present study. The cross-sections at Ukai Dam, 43 m upstream of the Kakrapar Weir, 115 m downstream of the Mandavi Bridge, and Ghala village, 203 m upstream of the Singanpur Weir and 108 m downstream of the Nehru Bridge (Surat city) are shown in Figure 3. From the figure, the width (i.e. distance from left to right bank) of the river is observed to increase as it moves from the hilly terrain (near Ukai Dam) to the plain area (near Nehru Bridge).

Boundary conditions

The monthly tidal cycle was observed at the sea mouth during 6 December 2009 to 5 January 2010 by the SIC to predict the possible tidal conditions during floods (viz. for the present study, the 2003 and 2006 floods) under consideration by synchronizing the hourly flood time series with that of the said observation, and noting the relevant tidal levels. Thus, the hourly discharge hydrograph at Ukai Dam and the hourly time series of the tidal levels during the flood have been considered as the upstream and downstream boundary conditions respectively, for the foregoing 1D hydrodynamic modelling.

Hydrodynamic parameters

The lower Tapi River is a tail part of the river and passes the releases from Ukai Dam into the Arabian Sea. The average bed slope and distance between the gauging stations in the lower Tapi River, included in the foregoing model, are listed in Table 1.

From the table it is apparent that the river, in general, has small slopes and, therefore, higher-order, fully dynamic wave equations are appropriate to simulate the flood flow in the study reach. The values of Δx and Δt have been chosen appropriately to make the computation stable by keeping the Courant number less than unity.

Calibration of model

Unsteady flow models must be calibrated and verified. The calibration and verification processes require two

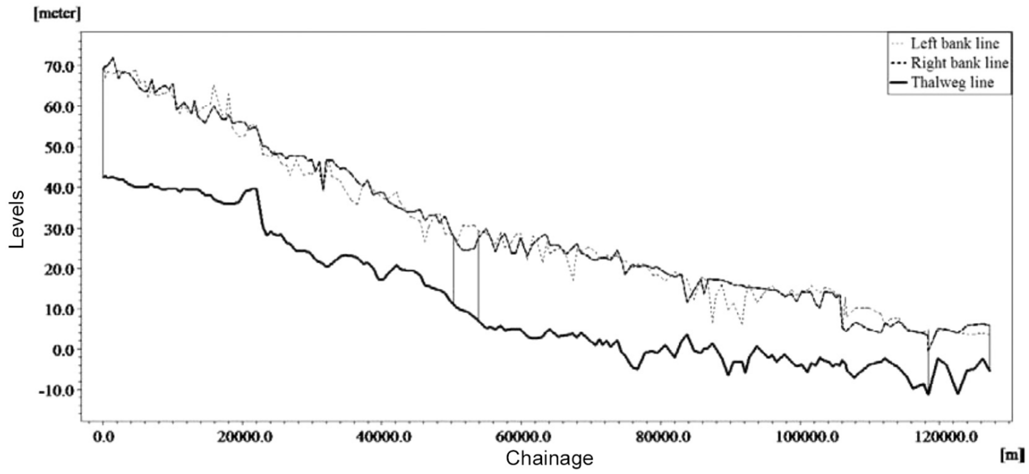

Figure 2. Profile of the left bank, right bank and thalweg lines of the lower Tapi River.

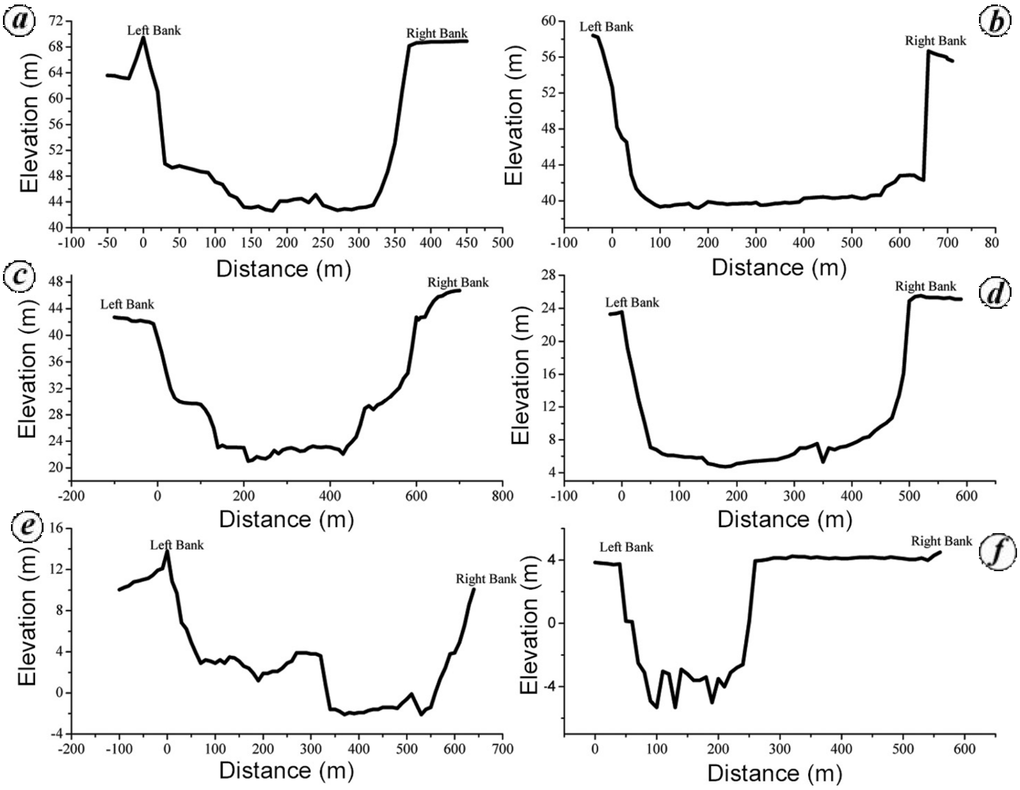

Figure 3. Cross-sections of the lower Tapi River: ***a***, Ukai Dam; ***b***, Kakrapar Weir; ***c***, Mandavi Bridge; ***d***, Ghala village; ***e***, Singanpur Weir; ***f***, Nehru Bridge (Surat city).

Table 1. Average bed slope of the lower Tapi River

Station	Thalweg line distance (m)	Bed slope
Ukai to Kakrapar Weir	22,200	0.00014
Kakrapar Weir to Mandavi	10,500	0.00175
Mandavi to Ghala	31,300	0.00051
Ghala to Singanpur Weir	39,000	0.00016
Singanpur Weir to Nehru Bridge	3,500	0.00042
Nehru Bridge to Sea	21,000	0.00002

independent and statistically reliable sets of data. One dataset is used to establish the optimum values of the 'free' coefficients, and the second dataset is used to verify (i.e. for validation) the calibrated model[16]. The channel roughness coefficient (i.e. Manning's n ($m^{1/3}$ s^{-1})) for the range of flows associated with the previously observed floods was selected using a trial-and-error method to obtain the best comparison between the observed and simulated flow parameters. The range of channel

Table 2. Root mean square error (m) in the calibration and validation of the one-dimensional model

Simulation	Year		Stream gauging stations: Kakrapar Weir	Mandavi Bridge	Ghala	Nehru Bridge (Surat city)
Calibration	1998	$n = 0.015$	1.1584	3.0484	3.2250	3.0230
		$n = 0.020$	1.1605	2.3122	2.3061	2.0629
		$n = 0.025$	1.1643	2.0326	1.6120	1.4589
		$n = 0.030$	1.1643	2.1216	1.3805	1.3292
		$n = 0.035$	1.1732	2.4736	1.8112	1.5990
Validation	2003		0.2137	0.5750	1.9740	0.9610
	2006		1.1592	0.8527	2.1947	0.7469

roughness values selected during the trails was based on the conditions of the channel[15,16]. The flood in 1998 (with a peak discharge of 19,815 $m^3 s^{-1}$) of duration from 15 September 1998 at 12 noon to 18 September 1998 at 12 noon (i.e. a total of 73 h) was simulated for different values of Manning's roughness coefficient n, and root mean square error (RMSE) at different gauging stations was compared (Table 2). From Table 2, it can be qualitatively seen that the simulated result of flood stage are in better agreement with the observed stages for a channel roughness (i.e. Manning's n) of 0.03. Accordingly, Manning's $n = 0.03$ has been considered for further simulations of flooding in the present study.

Validation

The calibrated hydrodynamic model, as described above, has been validated for the floods during 2003 (peak discharge flow, 1943 $m^3 s^{-1}$) and 2006. The floods occurring during 29 August 2003 at 00:00:00 h to 1 September 2003 at 00:00:00 h (i.e. a total of 73 h) and 6 August 2006 at 6:00:00 h to 11 August 2006 at 00:00:00 h (i.e. total of 115 h) were selected as the simulation periods for the 2003 and 2006 floods respectively, to capture the flood peak that had occurred in the aforesaid periods. As the purpose of this study was to simulate the stages and discharges at different locations along the lower Tapi River, the simulated river stages were compared with the observed river stages to measure the performance of the model graphically and using a standard performance index (i.e. RMSE).

The time series of the simulated and the observed flood levels is shown in Figure 4 for different gauging stations along the lower Tapi River. Further, the maximum observed levels available at other stations (viz. Kadod–Kosadi Culvert at 42.4 km, Kathor Bridge at 77.25 km, Nana Varachha Bridge at 87.05 km, Amroli Bridge at 93.14 km and Singanpur Weir at 103.03 km) were also compared with the maximum simulated levels for the 2006 flood (Figure 5).

In general, from Figures 4 and 5 it can be seen that the simulated results are systematically higher than the observed flood levels at different gauging stations. The same hypothesis is supported by Figure 6, which shows the scatter plots of the observed and simulated water levels in a time interval of 1 h for a period of 115 h from 6 August 2006 at 6:00:00 h to 11 August 2006 at 00:00:00 h.

A 1D model creates a vertical wall-type situation on either bank as the water level exceeds the bank level[14], and the entire flow domain remains concentrated within both banks. Thus, the consistent overestimation by the 1D calibrated model may be ascribed to the fact that it may not provide accurate results as the water starts spilling from either bank of the river into the plain area and flow starts behaving in a two-dimensional manner.

Model performance assessment

The RMSE between the observed and the simulated water levels of the Kakrapar Weir, Mandavi Bridge, Ghala village and Nehru Bridge (Surat city) stations for the 2003 and 2006 floods are shown in Table 2. The simulated results invariably provide better performance for the gauging stations located in the upper part (i.e. Kakrapar Weir and Mandavi Bridge) of the lower Tapi River for both the floods. The simulated results for the Nehru Bridge station may be more sensitive to the accuracy of the sea tidal levels, being closer to the downstream boundary. The accuracy of the simulated values at Nehru Bridge cannot be compared with the same degree of confidence as the downstream boundary condition (i.e. the tidal level), based on the observations during 6 December 2009 to 5 January 2010 at the sea, and may also exhibit small variations from the tidal levels present during the 2003 and 2006 floods. Regarding the simulation of the entire flood duration (w.r.t. RMSE), from Table 2, it is apparent that the in-bank flood (i.e. 2003 flood) is better simulated than the higher over-bank flood (2006 flood) due to the limitation of the 1D model in simulating over-bank flow situations. Furthermore, simulated values at the Ghala station exhibit maximum departure from the corresponding observed values. This difference might have been caused by the effect of the sand mining

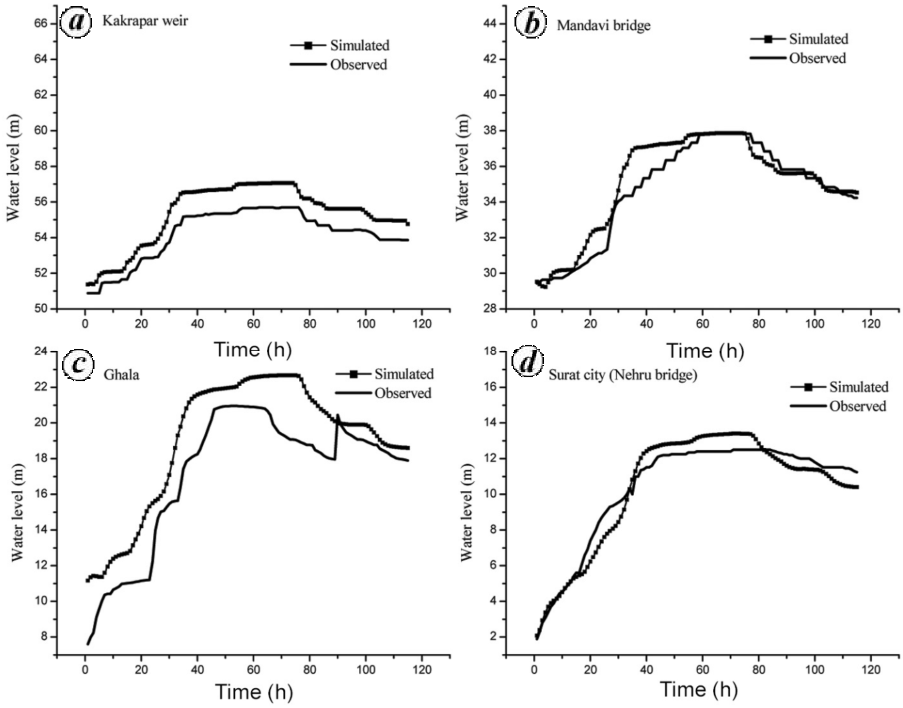

Figure 4. Comparison of the observed and simulated stage hydrographs: ***a***, Kakrapar Weir; ***b***, Mandavi Bridge; ***c***, Ghala village; ***d***, Surat city (Nehru Bridge).

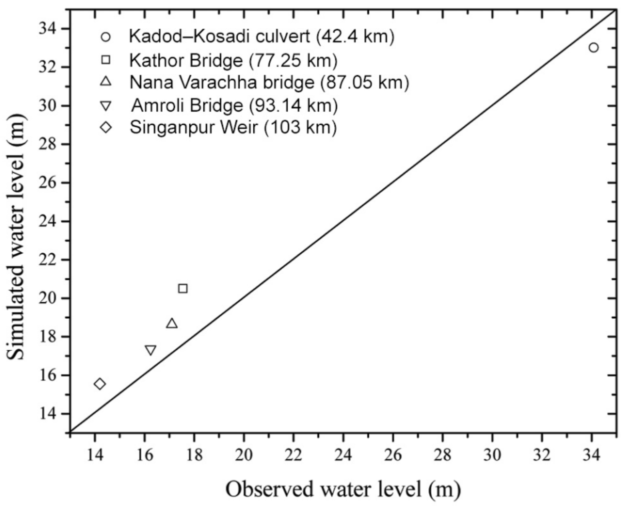

Figure 5. Comparison between the observed and simulated highest water levels.

operations on the observed values in the vicinity of Ghala station.

The simulated results from the foregoing 1D model may be suited to the conditions when the vertical wall-type situation exists on both the banks[14]. The situation analysed in the present study would, ideally, represent the case when levees are present on either bank of the river. Thus, these results (i.e. simulated flood levels) may be useful in designing the levees in the plain area for protecting the city from floods in the future.

Prediction of the rating curves in the lower Tapi River

Various hydraulic properties of the flow, including the water surface slope, energy slope, flow velocity, Froude number and bed shear stress were generated through simulation of the flood in 2006 along the river reach (Table 3). These computed hydraulic parameters demonstrate the capability of the model, which may be useful in assessing the morphological behaviour of the water flow during a flood.

The levels with respect to the mean sea level are marked at the different gauging stations and control structures along the lower Tapi River. Accordingly, the discharge and water level (i.e. stage) have been considered as dependent and independent variables respectively, in the development of the rating curves through the hydrodynamic simulation performed in the present study.

Mosley and McKerchar[17] presented the general form of the rating curve equation as

$$Q = C(h - a)^N, \tag{1}$$

where Q is the discharge ($m^3 s^{-1}$), C and N are constants, h is the stage (in m) and a is the stage at which the discharge is zero. The rating curves were derived using the log–log regression relationships for the simulated values at Kakrapar Weir, Mandavi Bridge, Ghala village, Singanpur Weir and Nehru Bridge (Surat city). The computed rating curves at the aforesaid stations are shown

Table 3. Hydraulic properties of the lower Tapi River for the flood during 2006

Station	Velocity (m/s)	Froude no.	Energy-level slope (10^{-4})	Water-level slope (10^{-4})	Bed shear stress (N/m^2)
	Maximum				
Kakrapar Weir	3.10	0.29	2.4	2.6	33.97
Mandavi Bridge	3.28	0.33	2.1	9.8	50.26
Ghala	3.42	0.28	3.2	4.9	41.39
Singanpur Weir	3.05	0.26	2.2	3.4	28.49
Surat city (Nehru Bridge)	2.22	0.47	4.4	4.7	47.81

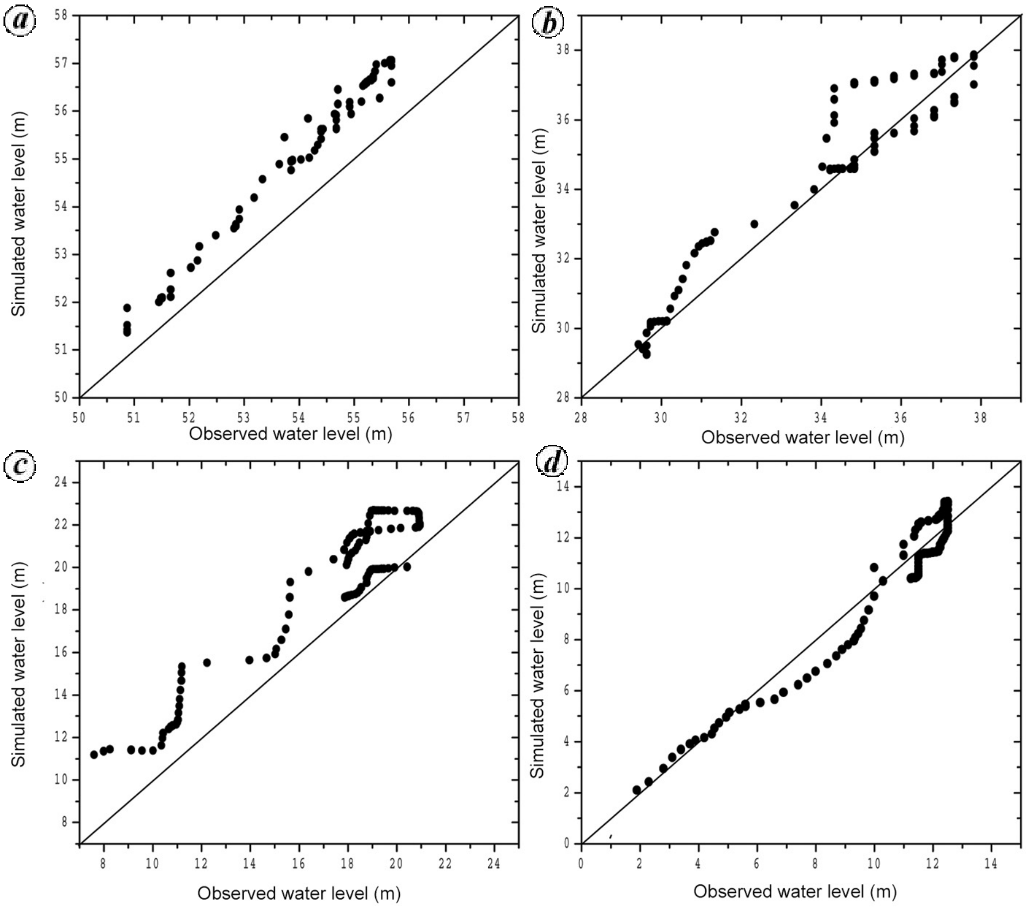

Figure 6. Comparison of scatter plots of the observed and simulated hourly water level: ***a***, Kakrapar Weir; ***b***, Mandavi Bridge; ***c***, Ghala village; ***d***, Surat city (Nehru Bridge).

graphically in Figure 7. The right/left-bank levels and the riverbed level from mean sea level at which the discharge is zero (a in eq. (1)), at the respective locations can be determined from Figure 3. It may be seen that at Nehru Bridge (Surat city) gauging station, the bed level is lower than the mean seal level. The rating curves can similarly be prepared at any chosen station along the study reach.

The rating curves thus developed, may be useful for the computation of the water level at any of the other locations in the lower Tapi River for discharges of different magnitudes. In addition to the use of the rating curve for the levee design, it can also be utilized for river-front development and design of the side-channel structures. The rating curves can also be used to develop flood inundation maps (although the simulated inundation extent may be on the higher side), which may be helpful in managing floods in an effective manner. Due to the lack of availability of the data for past floods, the present study could only use two flood events (of 2003 and 2006) for model validation. The stage prediction, through the simulation of floods, can be improved further using the data from several past floods in the model calibration and

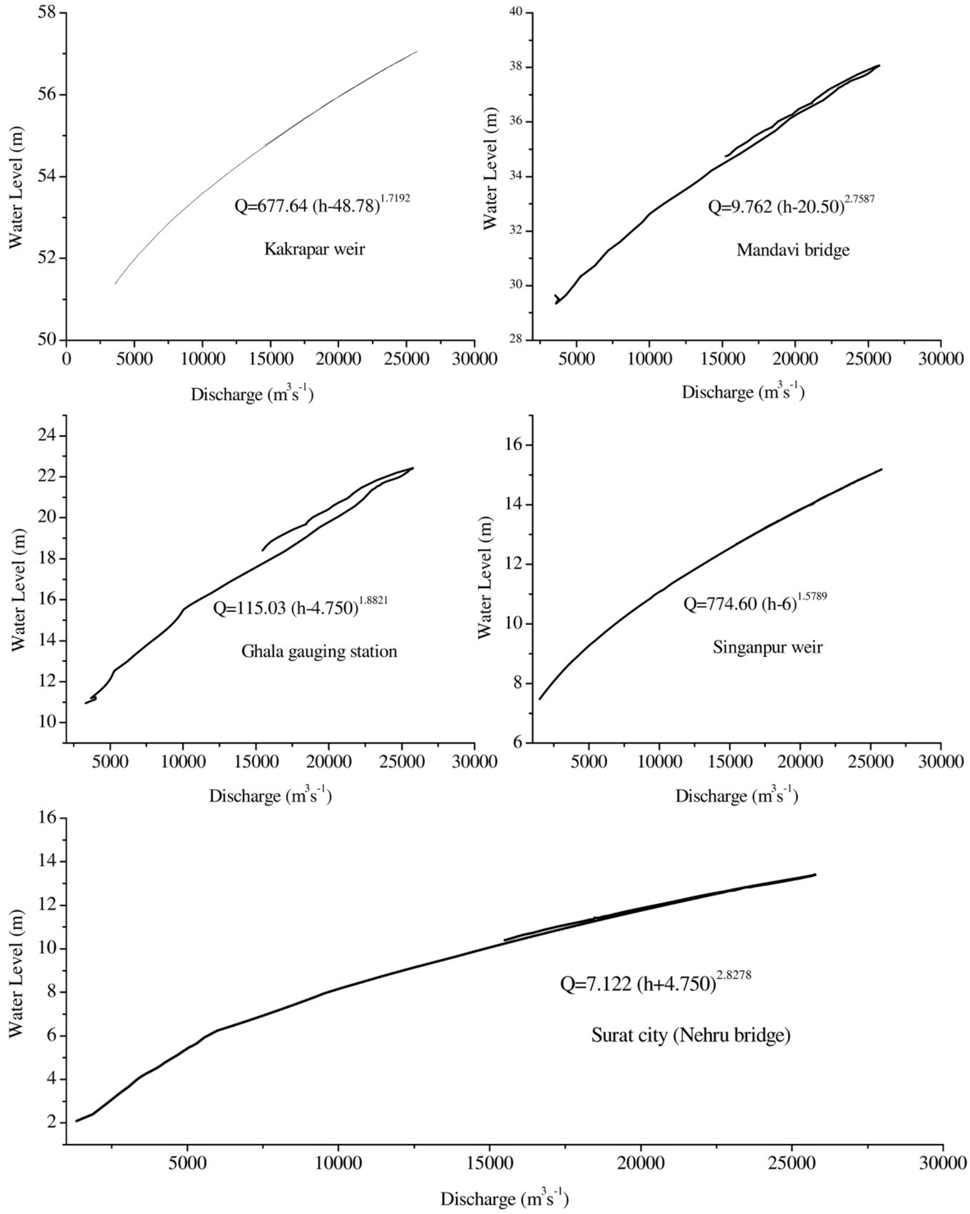

Figure 7. Rating curve (Q–h relationship) along the lower Tapi River.

by studying the characteristics of the stage–discharge relationships along the river.

Conclusion

Simulation of the floods during 2003 and 2006 was performed using MIKE 11 HD, and the results were validated for different gauging stations along the lower Tapi River. Based on the hydraulic analyses of the river, the following conclusions can be drawn:

(a) The complete geometry of the study reach was developed using the MIKE 11 model and precisely surveyed cross-sections. The resistance coefficient (i.e. Manning's *n*) was calibrated for the study reach for the flood in 1998, which led to the recommended value of 0.03 for future simulations.

(b) The calibrated 1D model was used to simulate the floods during 2003 and 2006. The in-bank river flood (for the year 2003) is better simulated than the over-bank flood (for the year 2006) because the 1D model introduces errors as soon as water starts spilling onto either of the banks. As the 1D models are computationally more efficient, the calibrated model in the present study represents an efficient tool for flood forecasting and management.

(c) The simulated levels of the lower Tapi River are consistently higher than the observed flood levels for the year 2006. This overestimation may be ascribed to the fact that, at higher discharge levels, the water starts to spill over either of the banks as the flow becomes two-dimensional in nature.

(d) The hydraulic parameters of the lower Tapi River were computed through a 1D hydrodynamic model and, subsequently, the rating curves were computed along the river. These may be helpful in designing flood protection measures and development of flood inundation map of the lower Tapi River. The accuracy of the developed stage–discharge curves would have improved, had the data of several floods been considered in their development. Thus, the predictions from such rating curves will be more conservative.

(e) The simulation results based on the hydrodynamic modelling can be improved by using a two-dimensional model, particularly in the plain areas of the lower Tapi River. The results of the model can be further improved by giving due consideration to sediment transport in the river during a flood.

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ACKNOWLEDGEMENTS. We thank the All India Council for Technical Education, Ministry of Human Resource Development, Government of India for providing support through the Nationally Coordinated Project on the 'Development of Water Resources and Flood Management Centre at SVNIT–Surat'. We also thank the Central Water Commission, Ministry of Water Resources, Government of India; the Surat Irrigation Circle; the State Water Data Centre (SWDC) of Narmada; Water Resources, Water Supply and Kalpsar Department, Ministry of Water Resources, Government of Gujarat and the Surat Municipal Corporation for providing hydrologic and topographic data, and the anonymous reviewers for their useful comments.

Received 10 October 2013; revised accepted 14 December 2013