



# Application of latest HEC-RAS version 6 for 2D hydrodynamic modeling through GIS framework: a case study from coastal urban floodplain in India

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## Abstract

Hydrodynamic models play an important role in efficient flood management by identifying flood risk zones. The present study is carried out using GIS-integrated 2D hydrodynamic modeling to appraise the flood event of the year 2006 and find inundation in the low-lying regions of Surat city. In this study, terrain data of Surat city and Lower Tapi Basin obtained from Shuttle Radar Topographic Mission (SRTM) 30 m digital elevation model (DEM) and flood data of 2006 were used to develop a 2D hydrodynamic model in HEC-RAS-v6.1. The discharge from the Ukai Dam during the flood event and the normal depth at downstream are considered as upstream and downstream boundary conditions, respectively, to simulate the model under unsteady flow condition. The simulated flood showed satisfactory performance when compared with the observed flood level map of the flood event prepared by Surat Municipal Corporation (SMC), with  $R^2$  value of 0.96, NSE value of 0.90, and RMSE value of 0.66 m. Additionally, the simulation yield information such as flood water depth, flow velocity, flood arrival time, and water surface elevation (WSE). The west and north zone of Surat city are topographically low-lying areas and are most vulnerable to flooding with greater flood extent, higher water depth, and longer flood duration. The decision-makers can use the simulated results to take proper decisions at the appropriate time to reduce the number of casualties and destruction of property. The study can assist in reducing the flood risks in vulnerable areas by planning and implementing appropriate flood control measures.

**Keywords** Flood inundation mapping · HEC-RAS · 2D hydrodynamic modeling · Unsteady flow analysis · Lower Tapi Basin

## Introduction

Flood occurs due to heavy rainfall or dam breach causing water to overflow the river banks and deluge the surrounding land, consequently harming the local settlements in the area (Pathan and Agnihotri 2021). As per the National Disaster Management Authority of India (NDMA 2008), a flood is the excess water inundated due to the insufficient capacity of rivers to carry a large amount of water from the upstream area within their banks following significant rainfall. Among all the catastrophic events that occur around the world, floods are the most recurrent and devastating for the social, economic, and environmental aspects of the area (Patel and Srivastava 2013). Damages due to flooding may comprise direct damage due to destruction of properties, indirect damage due to destroyed businesses and services, secondary damages due to difficulties for those who rely on

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the outcomes of the destroyed assets or resources, intangible damages such as social welfare and environmental quality, and uncertainty damages because of flooding uncertainty (Abdella and Mekuanent 2021). Human settlement, industrialization, business, framework advancement, recreational execution, loss of cultivable land, influence on drinking water, and submergence of low-lying areas are among the major consequences of flooding in coastal regions (Pathan et al. 2021). Several water infrastructures are in perilous condition due to flooding. A strategy to reduce flood levels is required to ensure the longer functioning of water infrastructures (Fadillah et al. 2020).

In a tropical country such as India, floods are the most prevalent and widespread disasters (Sahoo and Sreeja 2017). India is one of the most severely flood-affected nations in the world, being second after Bangladesh and contributing about one-fifth of the overall flood-related deaths (Patel and Dholakia 2010). From a total of 329 million hectares (Mha) of geographical area, about 40 Mha is vulnerable to floods, according to NDMA (2008). Floods in coastal urban floodplains such as Surat may be caused by several factors including increased population density, heavy rainfall, industrialization, urbanization, illegal encroachment along river banks, high tide, and bank erosion (Patel and Srivastava 2013). Flood depends on a variety of factors such as frequency, duration, propagation, depth, and rise in water level. Additionally, climate change will certainly raise the frequency and magnitude of floods (Pathan and Agnihotri 2021).

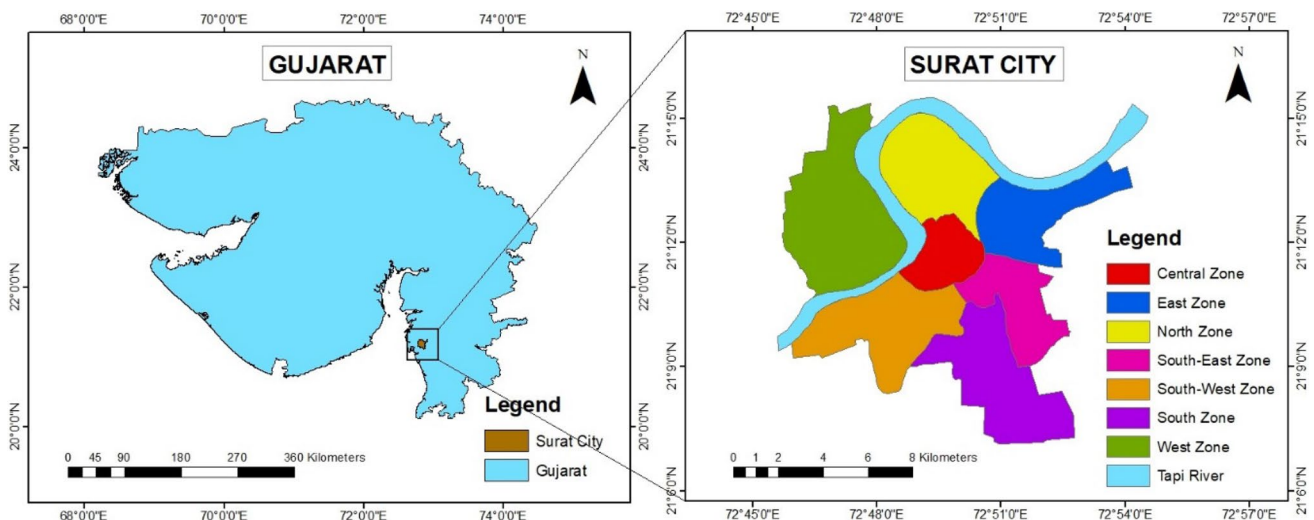
Flood management is essential for reducing life and property losses, as it is practically difficult to completely prevent urban flooding due to continuous development (Sahoo and Sreeja 2017). Flood risk assessment and management are the critical elements in recognizing present hazards and high-risk locations, and minimizing the flood risk in the future (Ranzi et al. 2011). An early warning system for flooding with both structural and non-structural measures would be extremely advantageous in preventing the loss of life and property that might result from excessive floods (Abdella and Mekuanent 2021). Determination of flood risk zones and mapping of flood inundation are the fundamental components for the formulation of flood control strategy (Sahoo and Sreeja 2017).

A geographic information system (GIS) is a significant tool for determining the flood extent and also for further analysis by producing maps that emphasize affected areas. Enhanced floodplain mapping can be achieved by incorporating all the spatial and hydrological data (Maidment and Djokic 2000). The flood extent determined by HEC-RAS model can be exported to the GIS program to validate with observed data or satellite-based flood mapping (Tegos et al. 2022), and evaluate the adequacy of the flood inundation modeling (Zin et al. 2015; Ongdas et al. 2020).

A GIS can effectively address the monitoring, mapping, and variation of flood transmission (Rahman and Thakur 2018). The surface roughness of the rivers and floodplain play an important role in the propagation of flood extent over them (Liu et al. 2019). To accurately simulate flood extent over the floodplain, Manning's roughness coefficient must be assigned correctly (Yalcin 2020).

Hydrodynamic models for one-dimensional (1D), two-dimensional (2D), and one-dimensional/two-dimensional (1D/2D) coupled hydrodynamic modeling are widely available nowadays, which enables the modeling of various flood scenarios (Quiroga et al. 2016; Shaikh et al. 2022). Examining flood events, planning for flood management, and assessing flood hazards are made easier with numerical models (Ongdas et al. 2020). Generally, they solve mathematical equations that are based on the principles of the conservation of mass and momentum to characterize the fluid motion and the dynamics of flood waves (Fassoni-Andrade et al. 2018). Hydrologic Engineering Centre's—River Analysis System (HEC-RAS) model is the most extensively used model developed by the Hydrologic Engineering Centre of the U.S. Army Corps of Engineers (USACE) in 1981. It has been developed for a variety of steady and unsteady flow computations based on 1D and 2D modeling of open channel water surface profiles. In the 1D HEC-RAS model, unsteady flow computations at the channel cross-sections are done using 1D Saint Venant Equations. While in the 2D HEC-RAS model, a computational Finite Element mesh is generated that solves the 2D Shallow Water Equations (Saint Venant Equations) or 2D Diffusion Wave Equations to examine the flood inundation map on a 2D flow area (over the river channel and the floodplain) (USACE 2016). Depending on the requirement of the study, the user can select between models with different dimensionalities (1D, 2D, 1D/2D coupled, etc.), equations (Diffusion Wave, Kinematic Wave, Muskingum, etc.), and numerical schemes (finite difference, finite volume, etc.). Although 1D modeling effectively depicts channel processes, 2D modeling would be preferable for assessing flood wave dynamics in the floodplain when the channel's capacity has been surpassed and the flow is dispersed across a wide area in the downstream topography (Patel et al. 2017; Shustikova et al. 2019; Ongdas et al. 2020). Due to its ability to produce more accurate and detailed outcomes in complex flow simulations, 2D models are often used for mapping flood extent and estimating flood risk (Teng et al. 2017; Dasallas et al. 2019).

HEC-RAS is extensively used worldwide for flood risk assessment and management. Hameed and Ali (2013) developed a model under unsteady flow condition in HEC-RAS for the Hilla river, Iraq for the prediction of appropriate Manning's  $n$  value through the calibration process. Awad (2015) developed a hydraulic model of the Al-Kahlaa



**Fig. 1** Location map of study area

River, Iraq using HEC-RAS to simulate flows and analyze several scenarios of the river system. Demir and Kisi (2016) generated flood hazard maps for floods with different return periods by employing HEC-RAS and GIS for the Mert River, Turkey. Azouagh et al. (2018) illustrated the application of the HEC-RAS model in developing floodplain maps for the Martil River in Northern Morocco. Zainalfikry et al. (2020) demonstrated the capability of HEC-RAS to simulate a 1D hydrodynamic model of the Pahang River which is the longest river in Peninsular Malaysia.

In addition, for many rivers in India, a HEC-RAS-based hydrodynamic model has been successfully developed. Parhi et al. (2012) simulated different flooding scenarios along the Mahanadi River in Odisha using HEC-RAS to calibrate Manning’s roughness coefficient. Patel et al. (2017) simulated a coupled 1D/2D hydrodynamic model for the 2006 flood event, with and without bank protection works, in low-lying regions of Surat city, Gujarat using HEC-RAS. Kumar et al. (2017) presented the adequacy of HEC-RAS model for the Yamuna River in Sangam area of Allahabad to

estimate the water surface elevation (WSE). The modeling results were examined with the actual observed data and no considerable variation was observed in the majority of cases. Nandurkar et al. (2017) presented the urban flood modeling to simulate some alarming scenarios of flood in Pune city by integrating HEC-RAS with remote sensing and GIS. Both 1D and 2D HEC-RAS hydrodynamic models were produced for the Purna River Basin in Navsari, Gujarat using a 30 m resolution DEM under unsteady flow condition to create a flood inundation map of the area (Pathan and Agnihotri 2020). They also performed 1D hydrodynamic modeling for flooding in the Purna River with particular emphasis on the geospatial approach of HEC-RAS (Pathan and Agnihotri 2021).

The capabilities of 2D HEC-RAS modeling can be applied efficiently for floodplain mapping. Many researchers have successfully developed a 2D HEC-RAS model for urban areas by utilizing DEMs of 30 m, 60 m, and 90 m resolution. Quiroga et al. (2016) simulated a flood scenario in Bolivian Amazonia using 90 m grid size SRTM DEM in the HEC-RAS-v5 and proved the applicability of

**Table 1** Details of the collected data

Sr. no.	Data	Details	Source
1	SRTM DEM	30×30 Resolution	USGS Earth Explorer ( <a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a> )
2	Projection file	UTM Zone 43 N	Spatial Reference ( <a href="https://spatialreference.org/">https://spatialreference.org/</a> )
3	Land cover map of Surat city	MODIS Land Cover—MCD12Q1 V6	USGS Earth Explorer ( <a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a> )
4	Discharge data of Ukai dam during 2006 flood	Hourly Discharge from 6th August to 12th August, 2006	Surat Irrigation Circle (SIC)
5	Observed flood level map of 2006 flood for Surat city	Observed flood level in feet	Surat Municipal Corporation (SMC)

HEC-RAS for flood studies. Thol et al. (2016) used SRTM DEM with a 30 m grid cell size to generate the HEC-RAS model for determining the flood extent of Lower Mekong River, Cambodia through steady flow analysis. The model calibration and validation indicated that the simulated and observed data were in good agreement. Rind et al. (2018) developed a two-dimensional (2D) hydrodynamic model of the Lower Indus River Basin in Pakistan using ALOS world 3D with  $30 \times 30$  m resolution to generate flood inundation maps and determine the areas that will likely experience flooding in the future.

The catastrophic flood in Surat city was caused by a peak flow of about  $25,768 \text{ m}^3/\text{s}$  discharged from Ukai Dam in the year 2006. During this disastrous flood, 75 to 77% of different zones of the city were inundated, causing the death of about 300 people and property losses of about INR 21,000 crores (Patel and Srivastava 2013). The flood event of 2006 was a major disaster in Surat due to low-lying regions in the city and inadequate flood warning information. The west zone of Surat city is a low-lying area with a steep discharge versus submergence curve, and it is at high risk of being inundated in a subsequent flood having a similar magnitude as that of the 2006 flood event. The existing levees are incapable to safeguard the city against the discharge of  $25,768 \text{ m}^3/\text{s}$  from Ukai Dam. In addition to structural measures, the development of an advanced flood forecasting and warning system is a primary concern for Surat city (Patel et al. 2017). The development of the hydrodynamic model can help in understanding, analyzing, and forecasting flood conditions and their consequences, and also provide important assistance in developing both structural and non-structural flood mitigation strategies. Therefore, the current study has been undertaken to develop a 2D hydrodynamic model using HEC-RAS in integration with GIS to appraise the flood event of 2006 in Surat city and determine the inundation in low-lying regions of the city. The most recent version of HEC-RAS with RAS Mapper is used for floodplain mapping of the city using the flood data of the year 2006.

## Study area

The location map of the study area is shown in Fig. 1. Surat city is located in Gujarat, about 19 km from the Arabian Sea and 100 km from the Ukai Dam. There are seven zones in which the city is divided, namely, central, west, east, north, south, south-east, and south-west zone. According to the zone map of the year 2006 prepared by SMC, the zone boundary of the city covers about  $126.5 \text{ km}^2$ . Surat city is

located between latitudes and longitudes of  $21^\circ 06''$  to  $21^\circ 15''$  N and  $72^\circ 45''$  to  $72^\circ 54''$  E, respectively. The city is shaped like an arc of a circle, with its walls enclosing curves that reach for nearly a mile and a quarter across the Tapi River bank (<https://www.suratmunicipal.gov.in/>). The river governs the topography which is flat in general and slopes from northeast to south-west. The weather pattern of Surat can be characterized by four seasons, i.e., summer (March to May), monsoon (June to September), autumn (October and November), and winter (December to February).

The Tapi River is 724 km long, with 214 km in the state of Gujarat, and covers an area of about  $3835 \text{ km}^2$ . The river reaches the Arabian Sea at around 19 km west of Surat (CWC 2000–2001). There are three sub-basins of the Tapi River, namely, Upper, Middle, and Lower Tapi Basin. The Lower Tapi Basin spans roughly to be 122 km, i.e., from Ukai Dam to the Arabian Sea.

Surat city has been affected by devastating floods in the years 1933, 1959, 1968, 1970, 1994, 1998, and 2006 (Patel et al. 2017). The single flood event that occurred in Surat and Hazira twin cities from 7 to 14th August 2006 is estimated to cause the death of about 300 people and property destruction of about INR 21,000 crores (Patel and Srivastava 2013). Following the 2006 flood event, the Surat Municipal Corporation and Surat Irrigation Department completed the works of embankment improvement in the city and surrounding regions. No severe flooding has occurred since 2006. Although, emergency dam releases, intense rainfall, high tides, and illegal settlement along the river bank, may increase the flood vulnerability in Surat.

## Data collection

For the development of a 2D hydrodynamic model in HEC-RAS, two prime requirements are hydrological information such as flow hydrograph and geometric information of river in the form of elevation data, Manning's roughness coefficient, normal depth at downstream, etc. From these two types of primary data, hydrological data are needed for the past events to simulate and validate the model, and geometry data are required to provide the terrain on which the flow will be simulated. The data collected for the study along with its details and source are presented in Table 1.

The first step is setting up the project spatial reference system of the study area using the projection file obtained from Spatial Reference. Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with 30 m resolution and MODIS land cover data are downloaded from USGS Earth Explorer to illustrate the magnitude and extent of the flood, and assign Manning's roughness coefficient, respectively. The hourly discharge data of the Ukai Dam for a period from 6 to 9th August 2006 is collected from Surat

Fig. 2 Outline of methodology

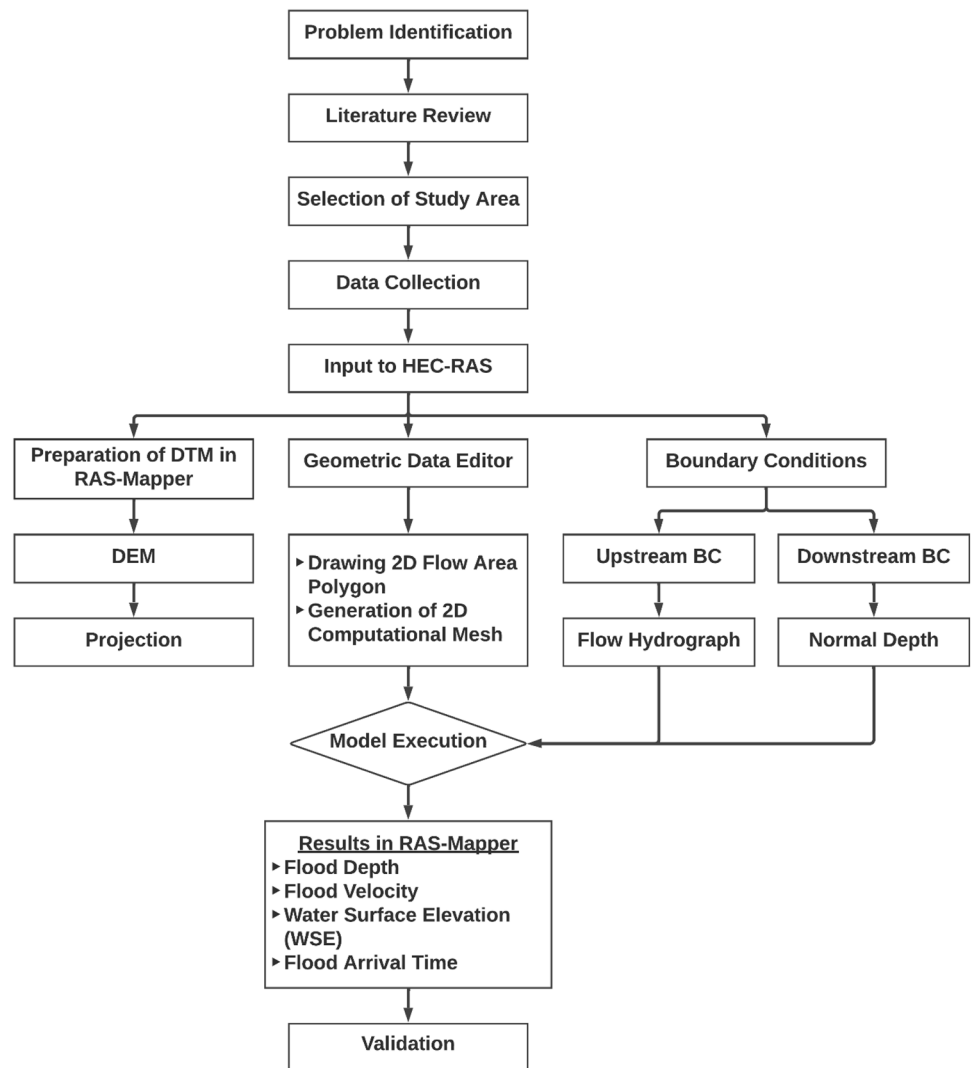


Table 2 Manning’s n corresponding to different land cover classes (Asante et al. 2008)

MCD12Q1 Value	Description	Manning’s <i>n</i>
4	Deciduous Broadleaf Forests	0.1
5	Mixed Forests	0.1
7	Open Shrublands	0.05
8	Woody Savannas	0.04
9	Savannas	0.06
10	Grasslands	0.05
11	Permanent Wetlands	0.05
12	Croplands	0.04
13	Urban and Built-up Lands	0.03
14	Cropland/Natural Vegetation Mosaics	0.035
15	Permanent Snow and Ice	0.05
16	Barren	0.03
17	Water Bodies	0.035
255	Unclassified	0.04

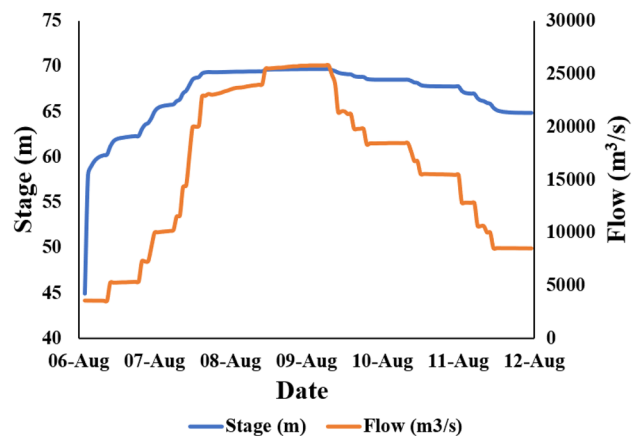


Fig. 3 Simulated stage and observed flow hydrograph from 6th August to 12th August, 2006

Irrigation Circle (SIC), and the observed flood level map is collected from Surat Municipal Corporation (SMC) for the purpose of simulation and validation of the model.

## Methodology

### Two-dimensional (2-D) hydrodynamic modeling

The new HEC-RAS version 6.1.0 developed by the USACE is used to model the flood event of 2006. It performs inundation simulation by solving shallow water equations, which depict the motion of water as depth-averaged 2D velocity and water depth in accordance with the forces of gravity and friction. These equations represent the conservation of mass (Eq. 1) and momentum (Eq. 2 and 3) in a plane (Quiroga et al. 2016; HEC-RAS 2D Manual 2021):

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0, \tag{1}$$

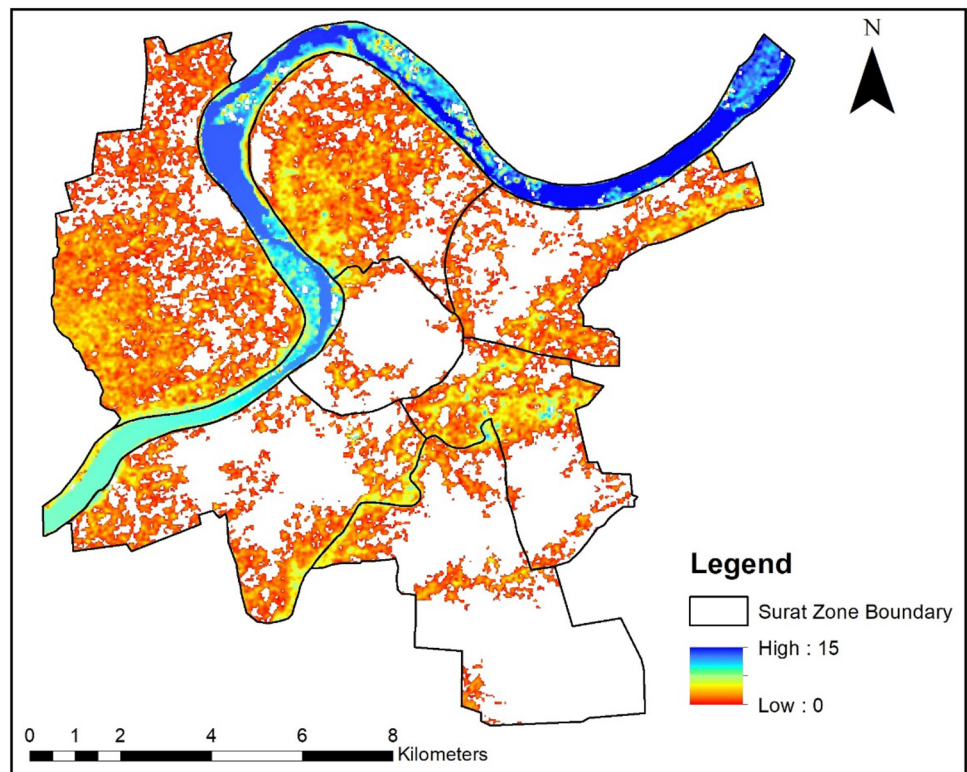
$$\begin{aligned} \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( \frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{pq}{h} \right) \\ = - \frac{n^2 pg \sqrt{p^2 + q^2}}{h^2} - gh \frac{\partial \zeta}{\partial x} + pf + \frac{\partial}{\rho \partial x} (h \tau_{xx}) - \frac{\partial}{\rho \partial y} (h \tau_{xy}), \end{aligned} \tag{2}$$

$$\begin{aligned} \frac{\partial q}{\partial t} + \frac{\partial}{\partial y} \left( \frac{q^2}{h} \right) + \frac{\partial}{\partial x} \left( \frac{pq}{h} \right) \\ = - \frac{n^2 qg \sqrt{p^2 + q^2}}{h^2} - gh \frac{\partial \zeta}{\partial y} + qf + \frac{\partial}{\rho \partial y} (h \tau_{yy}) - \frac{\partial}{\rho \partial x} (h \tau_{xy}), \end{aligned} \tag{3}$$

where  $\zeta$  is the surface elevation (m),  $p$  and  $q$  are the specific flow in the  $x$  and  $y$  directions ( $m^3/s$ ),  $h$  is the water depth (m),  $n$  is the Manning resistance,  $g$  is the acceleration due to gravity ( $m/s^2$ ),  $\rho$  is the water density ( $kg/m^3$ ),  $f$  is the Coriolis (1/s) and  $\tau_{xx}$ ,  $\tau_{yy}$  and  $\tau_{xy}$  are the components of the effective shear stress (Quiroga et al. 2016). The finite-volume method used in HEC-RAS is described as advantageous, due to its conceptual simplicity, consistency, and geometric flexibility (Teng et al. 2017). This method enables a more flexible approach to unstructured mesh and approximates the average integral on a reference volume (Patel et al. 2017).

The HEC-RAS-v6.1.0 is fully solved in this study by implementing the two-dimensional Saint–Venant equations. The outline of the methodology for two-dimensional hydrodynamic modeling using HEC-RAS is shown in Fig. 2. Digital Elevation Model (DEM) of  $30 \times 30$  m resolution obtained from USGS Earth Explorer was used as input to HEC-RAS software. The terrain is created from the Digital Elevation Model (DEM) using the Tools menu in RAS-Mapper and it is then utilized for creating the geometry of the 2D flow area of the river reach and working on the hydrodynamic properties. Manning’s roughness coefficient ‘ $n$ ’ is assigned to the 2D flow area of the river reach by

**Fig. 4** Maximum flood depth map of 2006 flood event for Surat city



**Table 3** Simulated depth and observed flood level in various zones of Surat city

Notation	Location	Zone	Latitude	Longitude	Simulated Depth (m)	Observed Flood Level (m)
A	Adajan	West	21° 11' 33" N	72° 47' 43" E	5.40	More than 3.04
B	Ved Road	North	21° 13' 39" N	72° 49' 17" E	6.46	More than 3.04
C	Nanpura	Central	21° 11' 22" N	72° 49' 03" E	1.26	0.91 to 1.52
D	Varacha	East	21° 12' 07" N	72° 52' 08" E	2.35	1.52 to 3.04
E	Parvat Patiya	South-East	21° 11' 20" N	72° 51' 52" E	1.03	Up to 0.91
F	Anuvrat Dwar	South-West	21° 09' 31" N	72° 47' 46" E	1.58	0.91 to 1.52
G	Udhna	South	21° 08' 35" N	72° 50' 38" E	0.57	-

**Fig. 5** Locations in various zones of Surat city under consideration for measuring flood depth, water surface elevation and flood arrival time

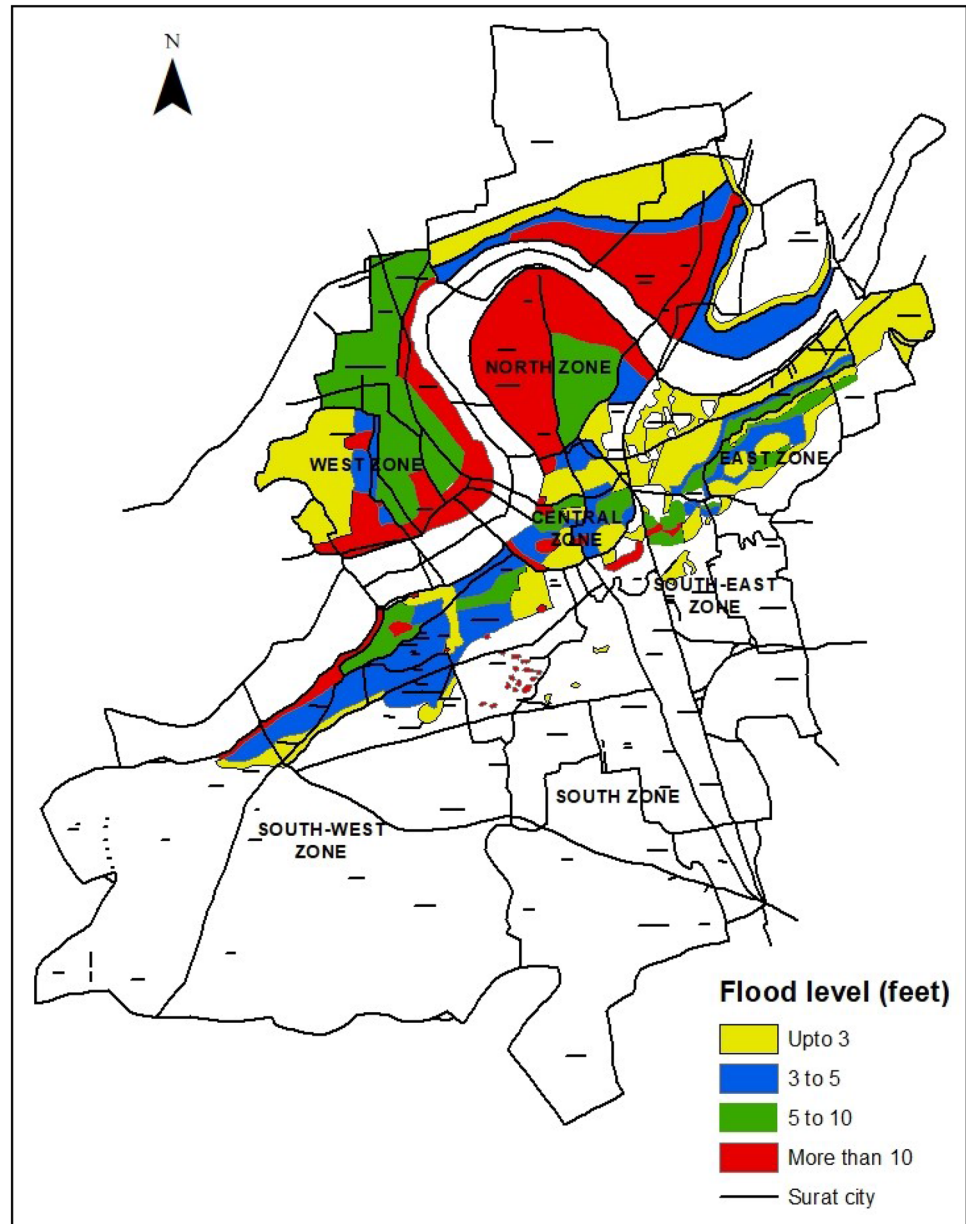
creating a land cover layer in RAS-Mapper. The assigned Manning's coefficient values corresponding to different land cover classes are indicated in Table 2.

The computational mesh is generated for the 2D flow area of Tapi River by providing a cell size of  $140\text{ m} \times 140\text{ m}$  using geometric data editor tools. Smaller cell sizes can better describe the terrain but will take longer computation time as compared to coarser resolutions, which enable faster simulations at the cost of accuracy. A total of 127,770 computational cells are generated in the 2D mesh considered for the 122 km river reach, where each cell uses the data of underlying terrain with minimal resolution loss (sub-grid model), reducing computational time. HEC-RAS produces detailed hydraulic property tables (such as elevation-area, elevation-volume relationship, etc.) for every cell and cell face. Therefore, larger cells are generated, which can use larger time steps and maintain terrain details. The flood

water can flow in any direction depending on the topography and the flow resistance determined by the land use class and corresponding Manning's value (Mihu-Pintilie et al. 2019).

For simulation of the model under unsteady flow condition, boundary conditions are provided at the upstream and downstream of the river. The flow hydrograph of the Ukai Dam during the flood event of 2006 is taken as the upstream boundary condition, whereas the normal depth is used as the downstream boundary condition. In this study, daily discharge data during the flood event of 2006 is used for the time interval from 6th August 00:00 h to 11th August 24:00 h. According to the past flood data, the most devastating flooding event occurred on 9th of August with a peak discharge of  $25,770\text{ m}^3/\text{s}$ . The hourly discharge hydrograph for the 2006 flood event used as an upstream boundary condition can be seen in Fig. 3.

**Fig. 6** Observed flood level map of 2006 flood for Surat city (Source: Surat Municipal Corporation)



The time step is determined using the Courant–Friedrichs–Lewy condition (Eqs. 4 and 5) to ensure the model stability (HEC-RAS 2D Manual 2021):

$$C = \frac{V\Delta T}{\Delta x} \leq 1.0 \quad (\text{with a max } C = 3.0), \quad (4)$$

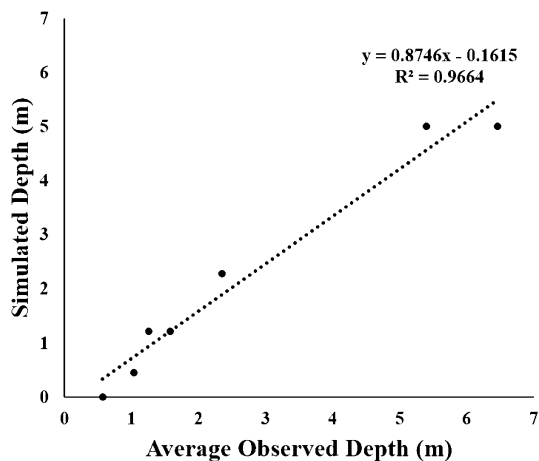
or

$$\Delta T \leq \frac{\Delta x}{V} \quad (\text{with } C = 1.0), \quad (5)$$

where  $C$  is the Courant Number,  $\Delta T$  is the computational time step (s),  $V$  is the velocity of flood wave (m/s) and  $\Delta x$  is the grid cell size (m).

The simulation starting and ending date and time are selected as per the flow hydrograph. The simulation is run for 5 s computational interval under unsteady flow condition from 6th August 02:00 h to 11th August 23:00 h and the output interval is selected as 1 h. Flood inundation maps of the flood event are obtained concerning flood depth, flood velocity, water surface elevation, and flood arrival time in RAS-Mapper. Web Imagery layers can also be imported into RAS-Mapper for enhanced visualization of the output maps.





**Fig. 7** Correlation between simulated and average observed flood depth

## Results

The flood event of the year 2006 has been modeled under unsteady condition for the period from 6th August 02 h to 11th August 23 h. Surat city was observed to be inundated maximum on 9th August. The simulated results of the two-dimensional HEC-RAS model can be visualized in RAS-Mapper in terms of maps of depth, velocity, the arrival time of flood, and water surface elevation (WSE).

The variation of flow depth and discharge with time is shown in Fig. 3. It can be seen that the stage follows the same pattern as the discharge. The depth of flow is low at the starting and then, it rises with the increase in discharge. As the discharge decreases gradually, the flow depth declines again.

### Flood depth during 2006 flood event in various zones of Surat city

Figure 4 shows the simulated flood depth map for the flood event of 2006 in Surat city. The depth of flood water is found to be maximum in the north and west zone, and minimum in the south zone. In the river channel flowing through Surat city, the depth varies between 8 and 17 m with maximum and minimum values near the east and south-west zone, respectively.

Table 3 illustrates the simulated depth of water under maximum flood extent and observed flood level, at different locations of Surat city as marked in Fig. 5. The simulated flood depth in various zones of the city was compared with the observed flood level map of 2006 flood prepared by the SMC as shown in Fig. 6. It can be seen that the Adajan region of west zone and the Ved Road region

of north zone are having the simulated depths of 5.40 and 6.46 m, respectively. Both these places come under the red color which indicates a depth of more than 10 ft (3.048 m) on the flood level map. Varacha area of the east zone is having a simulated depth of 2.35 m and falls under the green color indicating the level of 5–10 ft (1.524–3.048 m) on the flood level map. Udhna region of the south zone is having a simulated depth of 0.57 m, but no inundation is observed in this region on the flood level map. Nanpura region located in the central zone and Anuvrat Dwar region in the south-west zone are having simulated depths of 1.26 and 1.58 m, respectively, and fall under the blue color on the flood level map, which indicates the depth of 3–5 ft (0.914–1.524 m). Parvat Patiya area situated in the south-east zone is having a simulated depth of 1.03 m and falls under the yellow color which depicts the level up to 3 ft (0.914 m) on the flood level map.

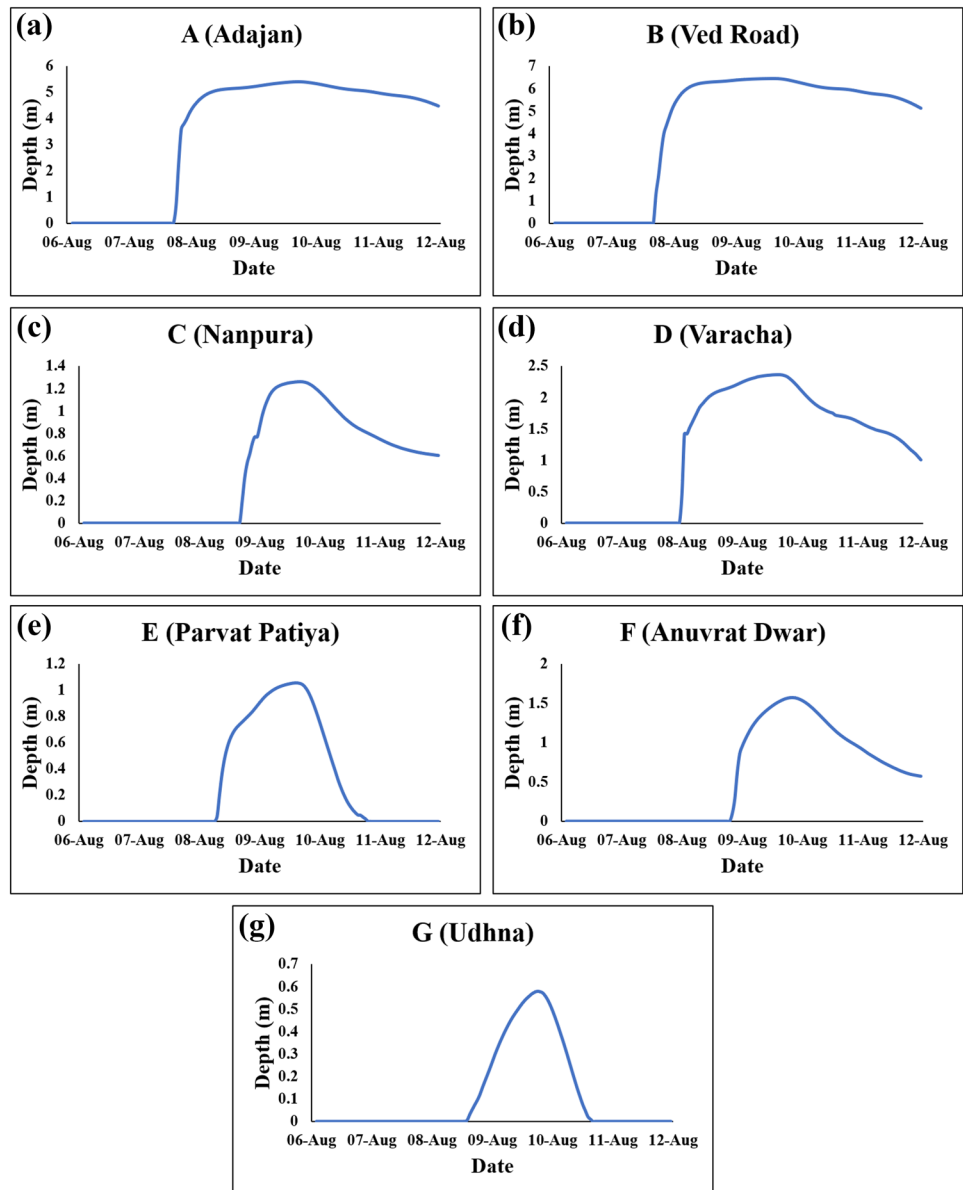
To assess the performance of HEC-RAS 2D model, the simulated flood depth in different zones of Surat was compared with the average flood level in the observed map. The model indicated the  $R^2$  value of 0.96 (Fig. 7), RMSE value of 0.66 m, and NSE value of 0.90. Hence, the results indicate a good correspondence between the observed and simulated depth. The time-series plots for the depth of flood water in various zones of Surat are shown in Fig. 8. In the majority of the zones, the depth begins to rise on 8th August and reaches its maximum value on 9th August 2006 i.e., on the day of maximum inundation.

### Flood velocity during 2006 flood event in Lower Tapi River

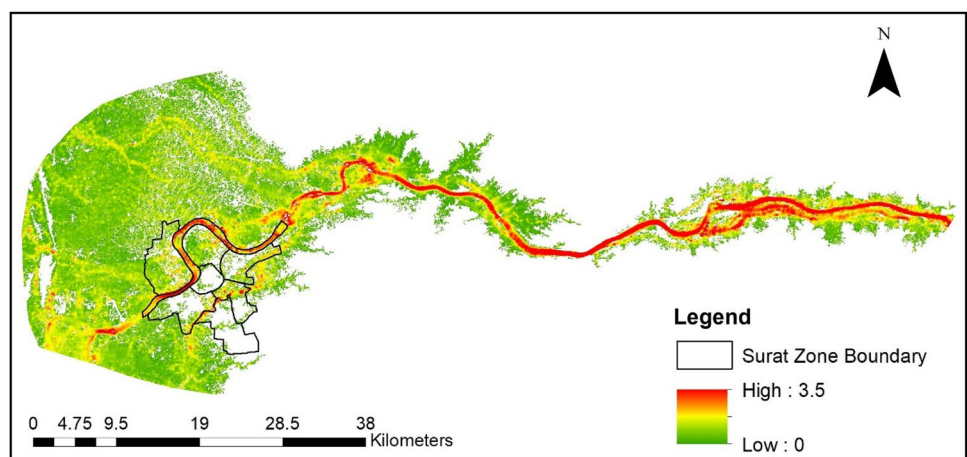
Figure 9 represents the simulated flood velocity map for the flood event of 2006 in the Lower Tapi River. The velocity of flood water in the river channel near the downstream portion of the Ukai Dam is found to be 4.5 m/s and varies between 3.5 and 4 m/s up to the Kadod region. As we move further downstream, it lies between 2.5 and 3 m/s near Surat city and near the downstream end of the river, the velocity in the channel is reduced to about 1.7 m/s.

Table 4 shows the simulated velocity of water under maximum extent, at different locations in the river channel as marked in Fig. 10. The velocity in the channel is found to be maximum at the upstream side of Surat near Kadod with a value of 4.26 m/s and minimum at the downstream side near Hazira with a value of 1.73 m/s. In the majority of the flooded areas in Surat city, the water has a velocity varying between 0 and 1 m/s. The time-series plots for the velocity of flood water in the river channel at different locations are shown in Fig. 11. The flood water is observed to have maximum velocity between 8 and 10th August 2006 at most locations in the river, except Katargam, Piplod, and Hazira.

**Fig. 8** Variation of flood depth with time from 6th August to 12th August, 2006 at **a** Adajan in west zone, **b** Ved Road in north zone, **c** Nanpura in central zone, **d** Varacha in east zone, **e** Parvat Patiya in south-east zone, **f** Anuvrat Dwar in south-west zone, and **g** Udhna in south zone



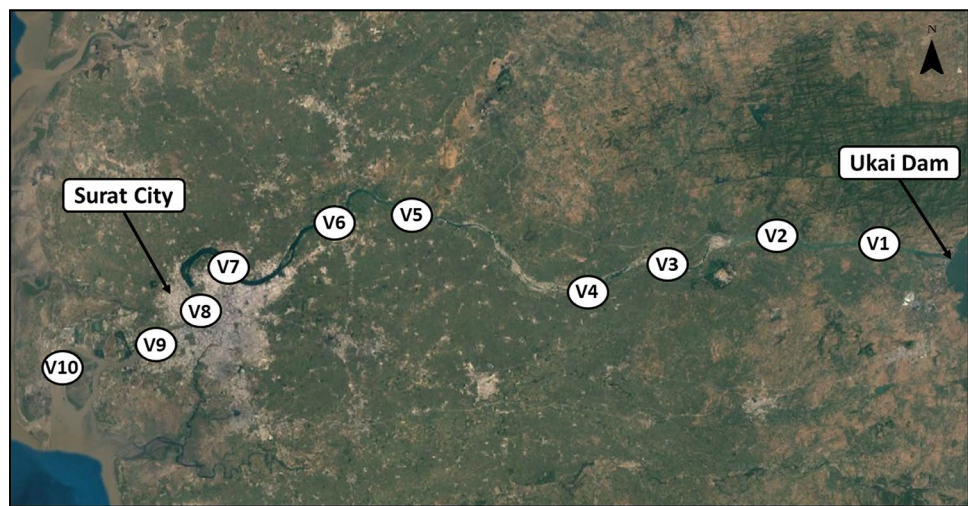
**Fig. 9** Maximum flood velocity map of 2006 flood event for Lower Tapi Basin



**Table 4** Simulated velocity of water at different locations in river channel

Notation	Location	Zone	Latitude	Longitude	Simulated Velocity (m/s)
V1	Nindvada	–	21° 16' 20" N	73° 30' 55" E	3.53
V2	Kala Vyara	–	21° 16' 41" N	73° 24' 12" E	3.70
V3	Mandvi	–	21° 14' 56" N	73° 17' 52" E	4.04
V4	Kadod	–	21° 13' 14" N	73° 13' 03" E	4.26
V5	Ghala	–	21° 17' 34" N	73° 02' 01" E	3.06
V6	Kamrej	–	21° 17' 19" N	72° 57' 36" E	2.98
V7	Katargam	North	21° 14' 00" N	72° 50' 45" E	2.67
V8	Nanpura	Central	21° 11' 22" N	72° 48' 31" E	2.56
V9	Piplod	South-West	21° 09' 35" N	72° 45' 48" E	1.85
V10	Hazira	–	21° 07' 19" N	72° 40' 00" E	1.73

**Fig. 10** Locations in the river channel under consideration for measuring flood velocity



**Water surface elevation during 2006 flood event in various zones of Surat city**

Figure 12 shows the simulated water surface elevation (WSE) map of Surat city for the flood event of 2006. The water surface elevation (WSE) is found to be maximum near the downstream portion of Ukai Dam with a value of about 70 m and reduces to 35 m near the Kadod region. Near the downstream end of the river reach, WSE varies between 7 and 8 m.

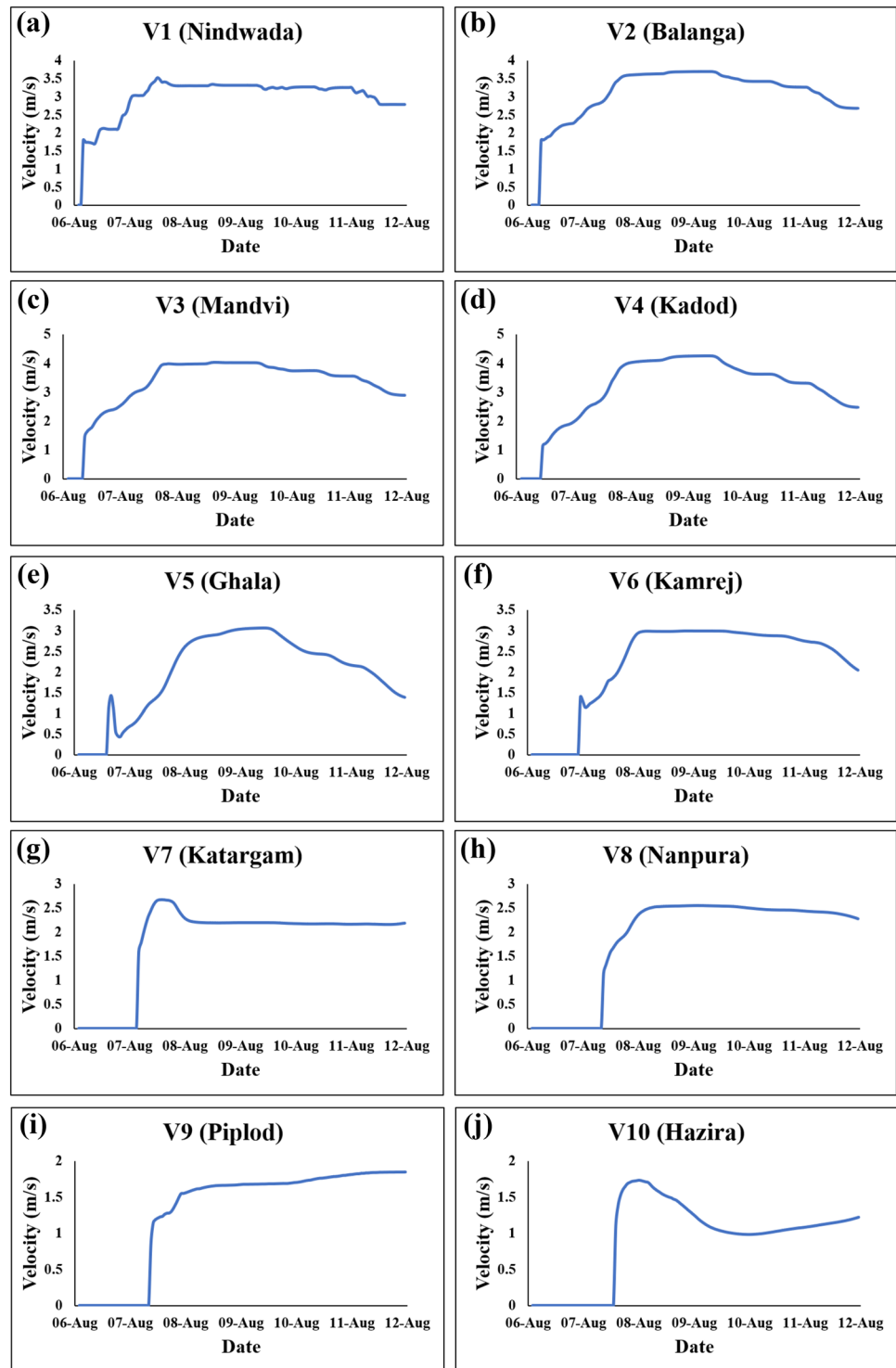
The simulated water surface elevation under maximum flood extent in various zones of Surat city is depicted in Table 5. The water surface elevation was found to be maximum in the north zone and minimum in the south-west and south zone. The time-series plots for water surface elevation at different locations are shown in Fig. 13. The water surface elevation starts to rise on 8th August and attains its maximum value on 9th August 2006 (maximum inundation), nearly in all the zones.

**Flood arrival time during 2006 flood event for various zones of Surat city**

Figure 14 represents the flood arrival map for the flood event of 2006 in Surat city, derived from the starting time of simulation i.e., 6th August 02 h and with 1 m flood inundation depth (threshold). The water reaches the river channel near Surat city within 25–30 h from the Ukai Dam.

The flood arrival time derived at 1 m flood depth at different locations of Surat city, as marked in Fig. 5, is indicated in Table 6. Water achieves 1 m depth in 40–50 h in significant parts of the west zone, whereas the north zone takes 30–40 h to get flooded up to the same depth. The east zone, south-east zone, and south-west zone get inundated in 50–60 h. The central and south zones are least affected by flooding and the arrival time for these zones is 60–70 h and 70–80 h, respectively.

**Fig. 11** Variation of flood velocity with time from 6th August to 12th August, 2006 in the river channel at **a** Nindwada, **b** Balanga, **c** Mandvi, **d** Kadod, **e** Ghala, **f** Kamrej, **g** Katargam, **h** Nanpura, **i** Piplod, and **j** Hazira

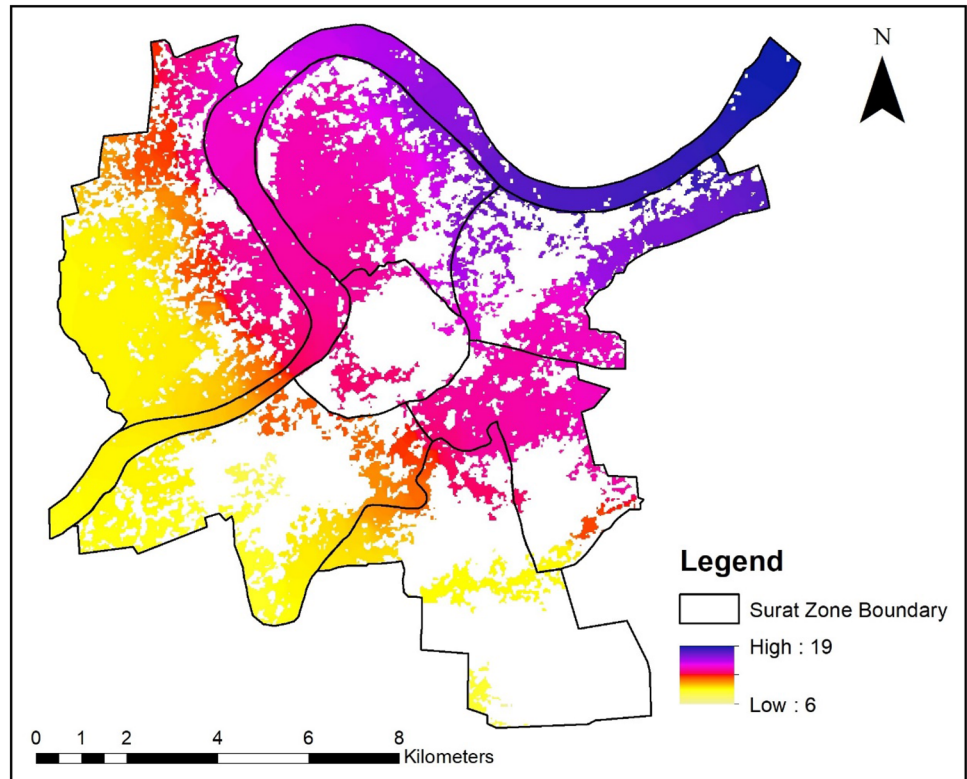


## Discussion

Coastal flooding is a severe and growing menace. Accurate coastal flood modeling poses many challenges such as representing topography and hydraulic infrastructure,

defining boundary conditions, incorporating spatially and temporally varying overtopping flows, incorporating hydrologic signals, and routing overland flows. Flood prediction has significantly improved owing to considerable

**Fig. 12** Maximum water surface elevation (WSE) map of 2006 flood event for Surat city



**Table 5** Simulated water surface elevation in various zones of Surat city

Notation	Location	Zone	Latitude	Longitude	Simulated WSE (m)
A	Adajan	West	21° 11' 33" N	72° 47' 43" E	10.54
B	Ved Road	North	21° 13' 39" N	72° 49' 17" E	14.15
C	Nanpura	Central	21° 11' 22" N	72° 49' 03" E	13.24
D	Varacha	East	21° 12' 07" N	72° 52' 08" E	13.38
E	Parvat Patiya	South-east	21° 11' 20" N	72° 51' 52" E	12.62
F	Anuvrat Dwar	South-west	21° 09' 31" N	72° 47' 46" E	9.27
G	Udhna	South	21° 08' 35" N	72° 50' 38" E	9.62

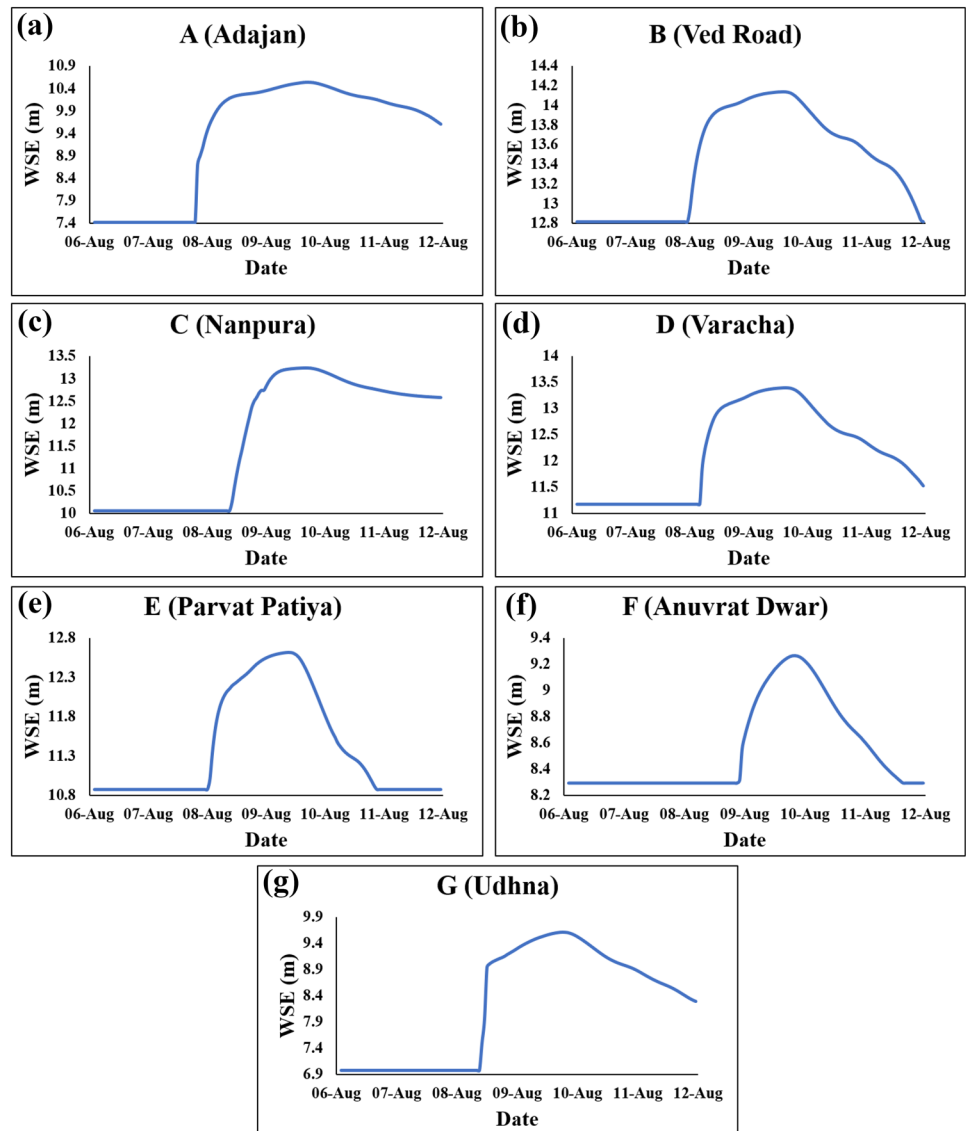
advancements in geographic data reliability, numerical modeling, and overtopping estimation (Gallien et al. 2018).

The presented approach for determining flood inundation can be an efficient tool for limiting the damage caused by floods. The developed 2D model proves to be a relevant means of investigating the depth of flood, the velocity of flood, arrival time, water surface elevation, and inundation boundary for the flood event. The performance of the model is evaluated by comparison of the flood simulation to the observed flood level map prepared by Surat Municipal Corporation. Figure 7 depicts the linear relation between the simulated flood depth and the average observed flood depth; the model closely resembles the observed flood. In addition, the model yields  $R^2$  value of 0.96, NSE value of 0.90,

and RMSE value of 0.66 m indicating that it successfully represents the flood event.

The results of the simulation demonstrate that the regions of the west and north zones are more vulnerable to flooding during peak discharge, with large flood extent and water depth. Furthermore, these zones get inundated the first, reaching a depth of 1 m in around 40 h arrival time. The major parts of the central and east zones are reasonably affected by flooding with an arrival time of 60 h. Whereas, the south, south-east and south-west zones are the least vulnerable to flooding with low water depth and long arrival time. From the simulation results, it is found that the majority of zones of the city are flooded within 60 h corresponding to a peak discharge of 25,770 m<sup>3</sup>/s. The

**Fig. 13** Variation of water surface elevation with time from 6th August to 12th August, 2006 at **a** Adajan in west zone, **b** Ved Road in north zone, **c** Nanpura in central zone, **d** Varacha in east zone, **e** Parvat Patiya in south-east zone, **f** Anuvrat Dwar in south-west zone, and **g** Udhna in south zone

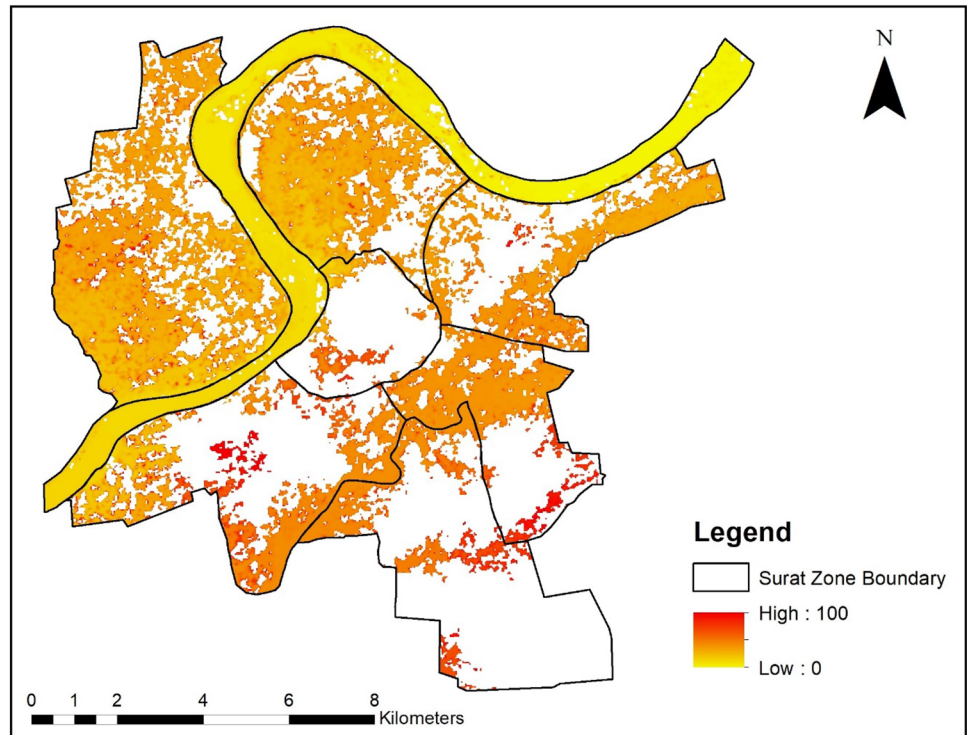


flood water velocity is examined in the river channel from the Ukai Dam to the Arabian Sea with values of 4.5 and 1.7 m/s near the dam and near the downstream end of the river, respectively. As the study area has a comparatively flat terrain, the velocity of flood water primarily lies between 0 and 1 m/s in the entire study area, indicating longer water retention and inundation period. The water surface elevation varies from 70 m just downstream of the dam to 8 m near the downstream end of the river. The research area can be highly affected by variations in velocity, depth, and water surface elevation; previous research has also corroborated this interpretation (Quiroga et al. 2016; Patel et al. 2017; Kumar et al. 2017; Rind et al. 2018; Pathan et al. 2021).

The primary limitation of the model is that it is simulated with a cell size of  $140 \times 140$  m due to unsupported computation of hydraulic property tables with smaller cell sizes for a large flow area. It is very important to assign a

suitable mesh grid size and computation time step ( $\Delta T$ ) to generate precise results with 2D flow areas (HEC-RAS 2D Manual 2021). As the simulation results are quite sensitive to DEM resolutions, hydrodynamic modeling can give more precise results by utilizing high-resolution DEM of grid interval 5 m or less in the city-level study (Shustikova et al. 2019). LU/LC is obtained from MODIS Land Cover data for the year 2006; the changes in LU/LC can significantly affect the roughness coefficient ' $n$ ' of the flow area. As a result, it will affect the flood depth, duration, velocity, and arrival time of the flood. The hydrological processes such as infiltration, evaporation, and precipitation are assumed to be insignificant in the present study, although the simulation results may be influenced by the dry soil and significant precipitation at Lower Tapi Basin. In addition, more observation data will be required to improve the accuracy

**Fig. 14** Flood arrival time map of 2006 flood event for Surat city with 1 m water depth



**Table 6** Flood arrival time in various zones of Surat city

Notation	Location	Zone	Latitude	Longitude	Arrival time (h)
A	Adajan	West	21° 11' 33" N	72° 47' 43" E	44
B	Ved Road	North	21° 13' 39" N	72° 49' 17" E	36
C	Nanpura	Central	21° 11' 22" N	72° 49' 03" E	64
D	Varacha	East	21° 12' 07" N	72° 52' 08" E	51
E	Parvat Patiya	South-east	21° 11' 20" N	72° 51' 52" E	54
F	Anuvrat Dwar	South-west	21° 09' 31" N	72° 47' 46" E	56
G	Udhna	South	21° 08' 35" N	72° 50' 38" E	75

in the assessment of flood inundation and validation of the model.

The developed methodology presents the confirmation of the applicability of HEC-RAS for flood inundation mapping. Furthermore, this approach can provide significant assistance in performing scenario-based flood assessment and evaluation for any similar case across the globe. Flood management techniques are necessary to be undertaken for the study area that can be used by the local authorities to establish an early warning system and response plan. A real-time flood mitigation strategy might be developed by analyzing the model concerning flood defense structures and river training works (Wadley et al. 2012; Abdella and Mekuanent 2021). The future scope of the study is concerned with the non-structural flood mitigation methods in the framework of multicriteria decision-making

(MCDM) approaches for the development of a flood risk map of the city and the provision of flood protection or control structures along the bank of the Tapi river. As a consequence, the property damage and loss of human lives could be reduced by minimizing the impact of flood near the floodplain of the city. In addition, dam break analysis for the Ukai Dam can be performed and the corresponding emergency action plan (EAP) can be prepared.

### Conclusion

Flood modeling enables to study, analyze and forecast flood conditions and their consequences. Identifying the risk zones is critical for recognizing flood-prone locations, and consequently improving flood risk management and disaster

preparedness. A 2D hydrodynamic model was developed using HEC-RAS in integration with GIS to analyze the flood of 2006 in Surat city. The modeling results were viewed from the output maps in HEC-RAS that were visualized on the digital terrain model (DTM) in terms of water surface elevation profile, flood arrival time, flow velocity, and depth of water. According to the results, these parameters were observed to be decreasing from upstream to downstream of the Lower Tapi Basin. Flood water depth was observed to be maximum in the north and west zones, and minimum in the south zone. The water had a velocity between 0 and 1 m/s in the major portion of flooded areas in the city. In the north zone, the water surface elevation was maximum, and in the south-west and south zones, it was minimum. The north and west zones were the first to get inundated, followed by the east, south-east, and south-west zones, and lastly, the central and south zones were flooded. The simulation showed a good correlation when comparing the simulated depth with the observed flood level map, with  $R^2$  value of 0.96, RMSE value of 0.66 m, and NSE value of 0.90. From the analysis, the north and west zones of Surat city were found considerably affected by the 2006 flood event and the flood wave may cause substantial damage to the study region. The depth of flooding determined by this research can be used to decide the maximum height of a flood protection structure in the area, which will protect it from flooding during major floods. Moreover, the study can also guide the local authorities for significant dam operation and provision of flood control measures. The flood maps can be useful for developing emergency action plans, early warning systems, ecological studies, and municipal planning in the city.

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**Availability of data and material** The data that support the findings of this study are collected from Surat Municipal Corporation (SMC), Surat Irrigation Circle (SIC), and open-source data are available in [USGS] at [https://earthexplorer.usgs.gov/].

**Code availability** The software, HEC-RAS that supports the findings of this study is openly available at [<https://www.hec.usace.army.mil/software/hec-ras/download.aspx>].

## Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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