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RESEARCH ARTICLE

Floodplain Mapping Using Hydraulic Simulation and Geographic Information System

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Abstract

Objectives- A flood is a strangely high stage in a river generally, the level at which the river overflows its banks inundates the adjacent area. Flood occurs due to intense rainfall, dense population, industrialization, illegal settlement along riverbanks, bank erosion, high tide, and urbanization, and it causes harmful damage to human beings and properties. It can be taken care of by adopting flood risk measures. One of the measures is the development of flood inundation maps. Hence in the current study, flood inundation maps are developed with the integration of GIS and HEC-RAS along the Bhīma River reach in Maharashtra, India. **Methods:** In this study, using the series of annual peak discharges, flood flows were estimated for different recurrence intervals. Inundated areas marked along the Bhīma River represent peak flows of 25 years and 100 years return periods using HEC-RAS, ArcGIS handling of spatial data, and HEC-GEORAS for the interfacing between HEC-RAS and ArcGIS. Simulation for 2, 5, 10, 25, 50, and 100-year return periods is done, and inundation maps have been developed for the 100-years reoccurrence interval. **Findings:**The analysis on the left and right banks has been done using water surface elevations generated from the HEC-RAS model. The significant findings revealed that the left bank representing the east side of the river is more vulnerable to water spills than the right bank representing the west side of the river. The flooded areas along the Bhīma River are 32.4 km^2 and 43.82 km^2 for 25-year and 100-year reoccurrence intervals, respectively. Generally, this study revealed that urban and agricultural areas downstream of river reach are more susceptible to flooding. **Novelty:** The developed inundation map will help the local authority in effective decision-making and disaster management in flooding situations, especially on the left bank side of Bhīma River. Obtained water surface elevations and flood inundation depths can help to decide the necessity of structural measures that can reduce the deteriorating effects of flooding

Keywords: Inundation map; flood frequency; DEM; Sensitivity analysis; Return Period; HEC-RAS

1 Introduction

Floods are the most common natural hazard on earth and are the natural phenomenon of extreme weather conditions, often violent. With an increased population growth along with global warming and climate change, a disaster like flooding worsened yearly. Fighting natural disasters like flooding can be possible with comprehensive risk analysis[(1)]. Flood event in a particular area also depends upon nature and the amount of vegetation on land and around riverbanks, the river's nature and slopes, and downstream water levels[(2)]. Flood mitigation measures have a massive impact on assessing flood risk that depends upon reliable and accurate simulation of hydrologic and hydraulic processes resulting in efficient flood forecasting and warning system. As a non-structural method to mitigate the effect of floods, many mathematical models have been introduced worldwide to provide cost-effective, reliable, and crucial mechanisms for flood alertness, control of damage, and managing of flood disasters by using an early warning system. Accurate and reliable simulation using HEC-RAS can prove an effective method for developing flood forecasting and warning system[(3)].

One of the flood mitigation measures is the development of Flood Inundation Mapping [FIM]; an inundation can be defined as a spread out of an expanse of water that submerges the land, it occurs when channel capacity fulfills, and water flows out of the channel. Flood inundation simulation simulates severe flood events, developing hazard maps, and risk mitigation measures worldwide are discussed[(4)]. The development of the hydrodynamic model to assess flood hazards and vulnerability can be an effective measure to reduce the risk of damages due to flooding. Simulating flood events and spatially depicting the degree of exposure of the regions towards hazards in terms of inundation extent, water levels, and depths is done by the authors[(5)].

A vital tool for flood monitoring is the HEC-RAS software, and remote sensing (RS) technology, in combination with geographic information systems (GIS), is used for developing Flood Inundation Mapping [FIM][(6)]. Geographic Information System (GIS) is an influential and valuable tool that allows the spatial analysis of results obtained by hydraulic modeling, such as from the HEC-RAS/HEC-Geo-RAS software[(7)]. GIS-based flood characterization methodology demonstrated practical and rapid identification of the flood-prone area in an urban area[(8)]. Flooding characteristics are studied in the flood plain of the Tikurwha river catchment using two-dimensional (2D) hydrodynamic modeling.

The flood inundation map of the flood-prone areas is carried out using HEC-RAS 2D models with the incorporation of Arc-GIS tools[(9)]. From the literature reviewed, it is concluded that the development of Flood Inundation Mapping [FIM] is an effective measure of flood mitigation using HEC-RAS and GIS. However, no significant attempt has been observed in the literature to check the vulnerability of riverbanks separately in a flooding scenario. This vulnerability assessment can help make immediate and effective decisions in flooding situations to safeguard the resources. Simulation model sensitivity is also not noted well in the past studies. Hence the current study, Flood Inundation Mapping [FIM] for a 100-year return period, has been developed. Also, the vulnerability of the left-over and right-over banks is attempted separately by identifying the number of cross-sections under water after the hydrologic simulation. The sensitivity of the simulation model has been verified for Manning's roughness coefficient.

2 Material and Methods

Bhīma is a significant tributary of the Krishna River and one of the two major rivers of Maharashtra state, with the other being the Godavari. Bhīma originates at Bhīma-Shankar in the Sahyadri Ghats at the elevation of MSL 700m. The banks of Bhīma are densely populated and form fertile agricultural areas. The river is prone to frequent flooding due to the heavy monsoon season. Figure 1 shows the study area and Bhīma basin in the western part of Maharashtra between 17^0 53' N to 19^0 24' N latitude and 73^0 20' E to 75^0 18' E longitude. Figure 2 (a) shows the study area's Data Elevation Model (DEM).

2.1 Land Use Land Cover

Land use Land cover (LULC) has primary importance along with other spatial databases like soil type, lithology, hydrology soil group in assessing flood risk[(10)]. Image classification is carried out on satellite images of 2018 to develop the LULC map of the study area, as shown in Figure 2 (b). Maximum-likelihood-based supervised classification constitutes preprocessing and post-processing techniques for preparing a reliable LULC map[(11)(12)]. A maximum likelihood algorithm is used for classification in this study. This classification is based on training samples created by the training sample manager. Land use/land cover shows the forest, urban, agricultural land, bare land, and water bodies. A higher percentage of the agricultural land is cultivated with sugarcane. Visual interpretation by including a base map in ArcGIS is done to avoid misclassification and improve the map's accuracy.

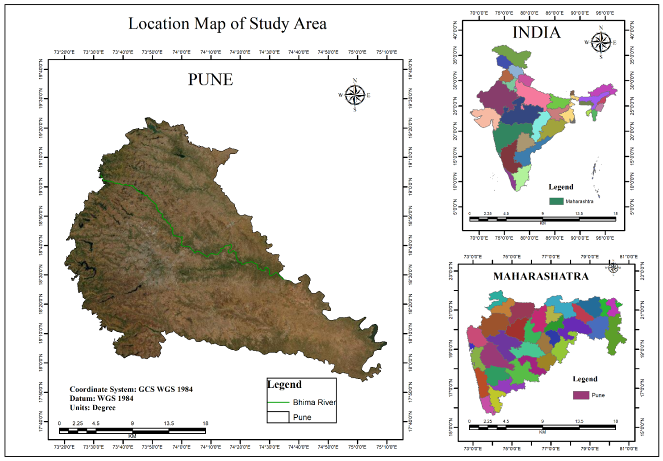

Fig 1. Location map of study area

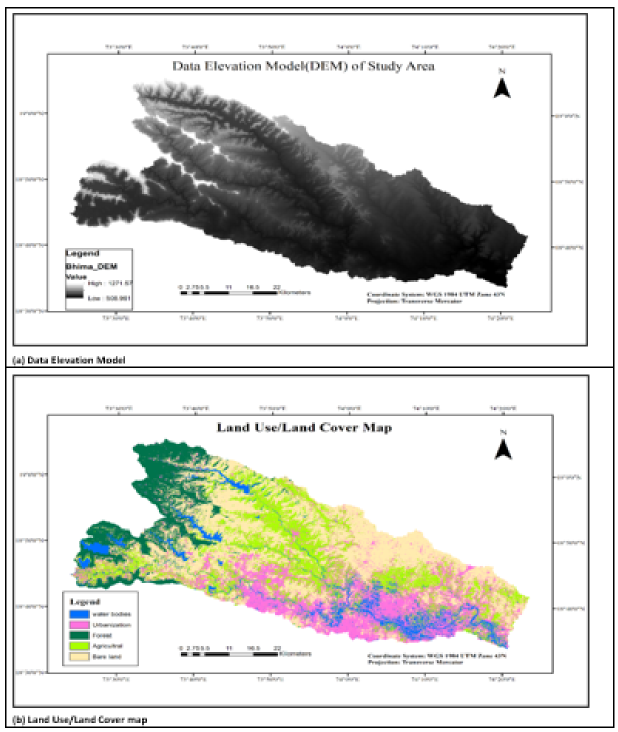

Fig 2. Data Elevation Model and Land use Land Cover map

2.2 Methodology

The digital elevation model (DEM) and runoff excess quantity plots have been evaluated using ArcGIS with an extension of HEC-GEO-RAS. The digital elevation model (DEM) is a raster dataset that gives information about the topography. It is constructed using data obtained from remote sensing techniques and sometimes data gathered from land surveying. The accuracy of the Digital elevation model (DEM) plays a vital role in flood simulation and floodplain mapping[13].

The HEC-GEORAS is a spatial extension of ArcGIS to develop geospatial data to be used in HEC-RAS. This extension works as an interface to transfer data between ArcGIS and HEC-RAS. HEC-RAS is a river modeling computer program used for the simulation of hydraulics of water flow in natural rivers as well as other channels. HEC-RAS is a proven efficient tool for analyzing flood models and inundation maps[6]. Shuttle Radar Topography Mission (SRTM) 30m x 30m data elevation model, rainfall data, and land use/land cover are used for floodplain mapping. The process can be divided into three steps- Pre-processing, processing, and post-processing.

In the current study, the Bhīma River reach under study was defined. In preprocessing phase consisting of the preparation of model input, geometry data is done with the help of HEC-GEO-RAS in ArcGIS. The high-resolution elevation data DEM is converted to a triangular irregular network (TIN) elevation model. This TIN model is in the raster format in ArcGIS. The quality of the TIN model is based on its cell size or resolution. For more accurate analysis smaller cell size is preferred because the smaller the cell size more excellent the resolution resulting in high accuracy. The current study uses a resolution of 30 m x 30m shuttle radar topography mission (SRTM) DEM of Bhīma River. The HEC-GEORAS extension obtains the required features like stream center-line, bank stations, and cross-sections. In the processing phase, the geometry attributes created with HEC-GEORAS are imported into HEC-RAS, and analysis has been carried out. In the post-processing phase, the outputs of the HEC-RAS model are imported in ArcGIS, and water surface TIN was created for a 100-year profile based on water surface elevation (WSE). The conceptual framework of the methodology adopted is shown in Figure 3.

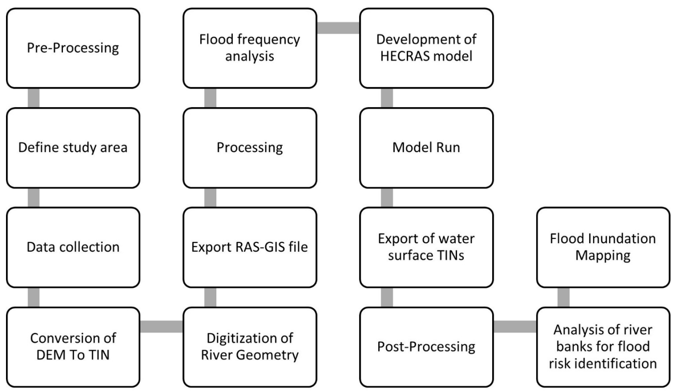

Fig 3. Conceptual framework of Methodology

2.2.1 Flood frequency analysis

The flood frequency analysis plays a vital role in the case of stream/river hydrology. Past flood event records need to be evaluated to check their future occurrences. Flood problems can be quantitively and qualitatively assessed by estimating the frequencies of the flood[14].

In the frequency of a hydrologic event, the annual peak flow value is the probability that a value will be equaled or exceeded in any year. The flood frequency analysis is one of the significant studies of river hydrology conducted based on maximum instantaneous flow[15]. Gumbel distribution (Generalized Extreme Value Distribution Type-I)-Gumbel distribution is the most extensively used probability distribution function(pdf) for extreme values in hydrologic and meteorological studies for predicting flood peaks and maximum rainfalls. Gumbel distribution is used for predicting floods, earthquakes, and other natural hazards[14]; in this method, the variate X_T is a flood peak discharge or maximum rainfall with a recurrence interval T given by

X_T = mean +K*std. deviation.

Flood frequency analysis is done based on maximum flood discharge recorded at Phulgaon, Maharashtra, India gauging station between 1992 to 2018 for 5, 10-, 25-, 50- and 100-year return period using Gumbel Distribution (EV1).

2.2.2 Development of flood inundation mapping

Shuttle radar topography mission (SRTM) DEM coupled with Sentinel-1 Synthetic Aperture Radar data is used to prepare flood hazard layers in terms of the probability of flood inundation in the GIS platform[16]. The high-resolution DEM is converted to the TIN model for flood inundation mapping. River geometry containing river cross-sections, stream center lines, bank lines, and flow lines are extracted from this TIN. These features are created as a 3D spatial polyline served as RAS themes. Manning's roughness coefficients are taken from the LULC map for every cross-section. After creating a river analysis system (RAS) file is imported to HEC-RAS as an input file through HEC-GEO-RAS. The RAS-GIS file to be created needs complied data from the 3D stream center line and 3D cross-section line that was written to the RAS-GIS export file. This RAS-GIS export file contains whole geometry data of river cross-sections, stream center line, bank lines, flow lines, downstream reach lengths, bank stations, river, reach names, river stations numbers, main channel, left-over bank, right-over bank, X and Y coordinates of river cross-sections.

In HEC-RAS, three specific parameters must be needed. The first one is stream geometry, the second is flow data, and the third one is the Model plan. The stream geometry data is in the RAS-GIS file. For the analysis, additional parameters like Manning's roughness coefficients which are taken from the LULC map for every cross-section, channel contraction, and expansion coefficients, are required. After putting all geometry data, steady flow data is given to the model, and finally, by assigning the Model plan, the model has been given a run. The model outputs are then imported back to GIS for the development of flood inundation mapping.

2.3 Analysis of Right and Left Bank of Floodplain

Simulation for one-dimensional flow under steady conditions has been performed for possible discharge of return periods of 5, 10, 25, 50, and 100 years. The discharge evaluated for various return periods using the Gumbel flood frequency method has been used to simulate steady HEC-RAS model. The maximum water surface elevation for each profile has been simulated, and maximum water surface elevation of 25-year and 100-year return periods have been plotted against elevations of the right bank and left bank. Figure 4 (a) and Figure 4(b) shows it to check for overflowing of water from either bank respectively. It helps to compare the vulnerability of both banks.

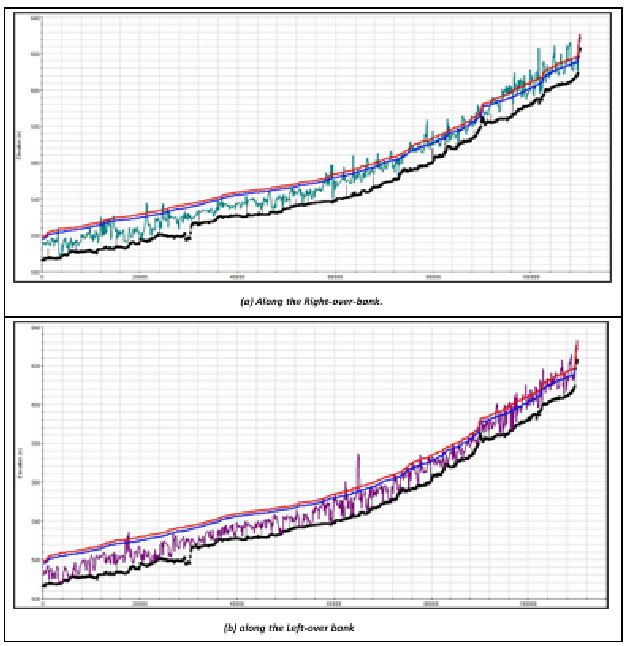

Fig 4. Water Surface Elevations

2.4 Sensitivity analysis

The sensitivity analysis for a model shows how stable the model is. Sensitivity can be checked by outputs developed by a model corresponding to change in the input variables, and it can be plotted to give the best fit of the model. Sensitivity is the rate of variation in one parameter regarding change in another parameter. It is a mathematical tool for the developing, calibrating, and validating a hydraulic model**.** The sensitivity of the HEC-RAS model can be checked for roughness, cross-section spacing, and data elevation model resolution.

The primary response parameters to be used to quantify the sensitivity of the one-dimensional flow model are Manning's coefficient and cross-section spacing [17]. Both parameters are essential in the modeling of geometry data. The process includes keeping all model input parameters constant, excluding the analysed parameter. Changes in modelled and simulated are observed to quantify the model's sensitivity and changes in manning's values and cross-section spacing. In the current study sensitivity of Manning's roughness coefficient has been checked. For sensitivity simulations, all boundary conditions are kept constant for supercritical flow. The sensitivity analysis has done for the 25-year return period and 100-year return period. Variations in roughness coefficient n value are varied by +- 20% from its base value to determine the model's sensitivity. The base value for Manning's coefficient is taken as 0.020 for the right and left floodplain and the main channel.

3 Results and Discussion

The hydraulic simulation model and geographic information system are highly effective for floodplain mapping. Sustainable and economic development of the wider geographic area is achieved through a systematic approach to floodplain management. The present research aims to develop flood inundation maps on the left and right bank of Bhīma River in Maharashtra state, India, and it includes integrating GIS and HEC- RAS tools.

3.1 Flood Frequency Analysis Results

The reoccurrence interval of hydrologic data is estimated to match the number of stimulating actions to their frequency of existence over the use of probability circulations [14].Flood frequency analysis considering extreme flow recorded at Phulgaon gauging station from the years 1992 to 2018 and return period of 5, 10, 25, 50 and 100 year and using Gumbel Distribution and the peak discharge has been observed to be varying from 2085 cum/sec (5 years return period) to 4626 cum/sec. (100 years return period) as given in Table 1.

Table 1. Peak discharges (cum/sec) and flood frequencies using the Gumbel method

Return Period (year)	5	10	25	50	100
Mean (Xm)	1290.87	1290.87	1290.87	1290.87	1290.87
Stand Deviation (Sy)	894.51	894.51	894.51	894.51	894.51
Frequency Factor (K_T)	0.89	1.57	2.44	3.08	3.72
Skewness (Cs)	0.73	0.73	0.73	0.73	0.73
Yn	0.53	0.53	0.53	0.53	0.53
Sn	1.09	1.09	1.09	1.09	1.09
Peak Discharge (X_T)(m^3/s)	2085	2700	3477	4053	4626

3.2 Flood inundation mapping

Geometry data with the main channel is shown in Figure 5 (a). The left and right bank of the river was modified using the cross-section editor, as shown in Figure 5(b) in HEC-RAS, and it leads to more accurate geometry. The steady flow analysis was done for routing of discharging capacity of 2085 m^3/s, 2700 m^3/s, 3477 m^3/s, 4053 m^3/s, and 4626 m^3/s of flows.

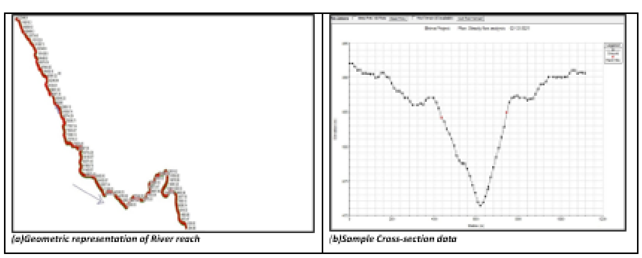

Fig 5. Geometric representation and Sample Cross-section data imported from HEC-RAS

The parameters used are river station (RS), station-elevation data, stream center-line locations of the left and suitable bank stations, downstream reach lengths, expansion, contraction coefficients, Manning's roughness coefficients, and details of hydraulic structures. The cross-sections are perpendicular to the river line and must be stretched to ensure all the flood water is occupied within the cross-sectional area. Accuracy in geometry and flow controls increases the model's efficiency. The floodplain mapping is done with the help of georeferenced shapefiles in ArcGIS. The elimination of errors can be done efficiently in ArcGIS while importing the outputs of the simulations. Floodplain was then delineated for different recurrence intervals. Water surface TIN was obtained for a 100-year return period in post-processing, as shown in Figure 6, and then it is used for floodplain mapping. Flood inundation of a 100-year return period is designated, and flood inundation depths are mapped for carrying out flood inundation depth analysis. The simulated floodplain area was estimated at around 82.2 Km^2. Inundation areas for 25-year return period are 30.8 Km^2 (37.46 %) and for 100-year return period are 41.65 Km^2 (50.66%).

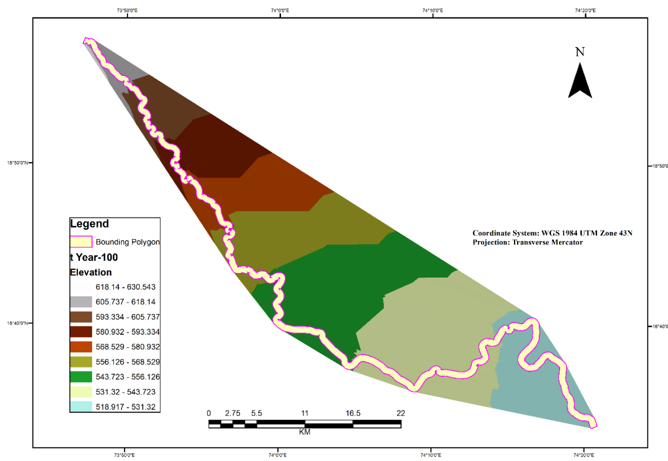

Fig 6. Water Surface TIN generated after post-processing

The flood inundation depth map (refer to Figure 7) for river reach under study has been designed for the 100 years return period. Flood inundation depth varies from 0 to 5.6 m and it is classified into five classes i) 0 to 0.3 m, ii) 0.3 to 0.9 m, iii) 0.9 to 1.2 m, iv) 1.2 to 3.6 m, v) 3.6 to 5.6 meters. The flood inundation depth classification shows that 17 % to 23% of the total flooded area has been inundated by water depth varying from 3.6 m to 5.6 m, 1 % to 3.5% of the area inundated by water depth less than 0.3.m for 25-yr return period and 100-yr return period respectively.

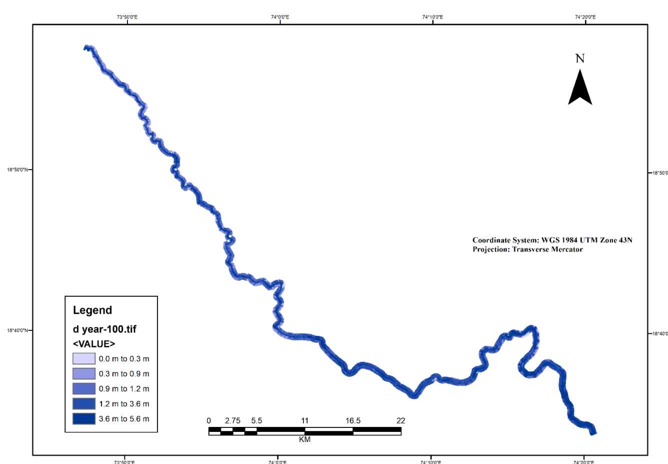

Fig 7. Flood Inundation depth map for 100-yearreturn period

3.2 Right and Left Bank Analysis for Floodplain Zoning

Figure 4(a) and (b) show maximum water surface elevation corresponding to the left and the right bank, giving the possibility of water getting spilled over from the left or right banks.

It has been observed that the left bank representing the east side of the river is more vulnerable to water spills than the right bank representing the west side of the river. The probability of the number of cross sections on both sides of banks has been estimated to check the vulnerable zone for high water levels for different return periods along the study reach.

It is noticed that the left bank number of cross-sections overtopped is 849 (77%) of total cross-sections for 25- the year return period, and for the 100-year return period number of cross-section overtopped are 995 in number (90%) of total cross-sections.

In the case of the right-over bank, the number of cross-sections overtopped for a 25-year return period is 712, which is 64% of total cross-sections. For a 100-year return period, the number of cross-sections overtopped is 893 which is 81% of total cross-sections.

The probable peak discharge for return periods of 25 and 100 years is estimated from Gumbel frequency distribution, and it has been simulated under steady conditions. Maximum water surface levels have been compared for the elevations of both the left (east) and right (west) banks of Bhīma River for all cross sections. The cross sections having elevation lesser than relative water surface elevation on the corresponding bank have been considered unsafe, and these will have the probability of water spill. The percentage of cross-section prone to spilling of water during high discharge on the left bank is 77 % and for the right bank is 64 % for 25-year return period while for 100-year return periods it has come out as 90% On the left bank and 81 % on the right bank. For all the return periods, it has been observed that the left bank of the Bhīma River is more prone to water spills due to higher water levels in the river than the right bank.

3.3 Sensitivity Analysis Results

Sensitivity analysis was performed keeping Manning's roughness (Range 0.02 to 0.045) as a variable, and its effect has been observed on the other parameters; this shows changes in response parameters like average velocity, Froude number, hydraulic depth, and water surface elevations. Manning's roughness sensitivity analysis results are summarized in Table 2, respectively (the -ve sign indicates a decrease in values, and the +ve sign indicates an increase in values).

Table 2. Effect of Manning's coefficient on average velocity and Froude number Water surface elevation and Hydraulic Depth

Manning's Roughnes Coefficient			**Change in average velocity (%) (-ve)**		**Change in Froude number (%) (-ve)**		**Change in Water surface elevation (WSE)(%) (+ve)**		**Change in Hydraulic Depth (%) (+ve)**	
Left Flood Plain	Central Channel	Right Flood Plain	25-yr	100-yr	25-yr	100-yr	25-yr	100-yr	25-yr	100-yr
0.025	0.02	0.025	10.5	12.2	13.2	20	10.4	12.7	4.20	4.38
0.03	0.025	0.03	12.5	15.7	15	21.8	13.8	15.48	5.30	5.38
0.035	0.03	0.035	14.23	19.5	18.6	22.5	15.6	17.5	6.48	6.2
0.04	0.035	0.04	17.5	22.40	23.2	30.2	19.7	21.8	7.68	8.4
0.045	0.035	0.045	19.75	23.61	25	32.57	21	23	8.65	9.61

From the sensitivity analyses, it has been observed that the response parameters established projected guiding changes in ranged from +- 8 to 33% approximately. The rate of change of Manning's roughness coefficient considering 25 years of return period increases from 0.02 to 0.045. The average velocity and average Froude number decreased by -19.75% (i.e., from 4.47 m/s to 2.32 m/s) and -25% (i.e., from 0.96 to 0.43), respectively, while the average water surface elevation (WSE) increase by 21% (i.e., from 549.46 m to 551.78 m), and hydraulic depth increases by 8.65% (i.e., from 1.62 to 2.71m).

The rate of change of Manning's roughness coefficient considering 100 years of return period increases from 0.02 to 0.045. The average velocity and average Froude number decreased by -23.61% (i.e., from 5.46 m/s to 3.24 m/s) and -25% (i.e., from 0.85 to 0.43), respectively. In comparison, the average water surface elevation (WSE) increases by 23% (i.e., from 551.72 m to 553.93 m), and hydraulic depth increases by 8.65% (i.e., from 2.47 to 3.81 m).

The Sensitivity analysis indicates that the model is performing appropriately. As the roughness parameter increased, there was a decrease in Froude Number, average total velocity, and increased hydraulic depth and water surface elevation.

4 Conclusion

Integrating a hydraulic simulation model and geographic information system is a general and trustworthy approach for floodplain mapping, and it is used in the Bhima River basin in this paper. This approach can be helpful to the decision-makers in catchment management in various scenarios like flooding, catchment degradation, erosion, and landslips. It is further helpful in the sustainable and economic development of the wider geographic area by providing systematic and consistent information applicable to the catchment. The current study aimed to develop flood inundation maps on the left and right banks of Bhīma River, including integration of GIS and HEC-RAS tool along Bhima River, reach located in the Maharashtra state of India. The digital elevation model (DEM) of Bhīma River is used to develop the geometric data and delineation of floodplain maps using the HEC-GEORAS tool. Flood frequency analysis for the Bhima River basin using Gumbel Probability distribution indicates flood magnitudes of 2085 m^3/s, 2700 m^3/s, 3477 m^3/s, 4053 m^3/s, 4626 m^3/s for the return periods of 2, 5, 10, 25, 50, and 100 years respectively.

It is observed that around 30.8 Km^2 (37.46 %) and 41.65 Km^2 (50.66%) area gets inundated for the 25 years and 100-year return period, respectively. The flood inundation depth classification reveals that around 17 % to 23% of the total flooded area may get inundated due to water depth of 3.6 m to 5.6 m, and around 1 % to 3.5% area may get inundated by water depth of less than 0.3.m for the return period of 25-yrs and 100-yrs respectively.

In case of analysis of water surface elevations, the possibility of a percentage of cross-section prone to spilling of water during high discharge on the left bank may be around 77 % and around 64 % on the right bank for the return period of 25 years. Similarly, it may be around 90 % on the left bank and 81 % on the right bank for the 100 years return period. It has been observed that the left bank of the Bhīma River is more prone to water spills due to higher river water levels than the right bank.

The sensitivity analysis with the variations in roughness coefficient (n) ranging from +20% to -20% from its base value recommends that the model is working suitably as the roughness parameter was increased for a 25-year return period from 0.02 to 0.045; Froude Number decreases - by 25% (i.e., from 0.96 to 0.43), and the average total velocity decreases by -19.75% (i.e., from 4.47m/s to 2.32 m/s) and increases in hydraulic depth 8.65% (i.e., from 1.62 to 2.71m).and water surface elevation increases by 21% (i.e. from 549.46 m to 551.78 m), also for 100-year return period the roughness parameter was increased for 25-year return period 0.02 to 0.045 Froude Number decreases -25% (i.e., from 0.85 to 0.43) and average total velocity decreases by -23.61% (i.e., from 5.46 m/s to 3.24 m/s) and increases in hydraulic depth by 8.65% (i.e., from 2.47 to 3.81 m) and water surface elevation increases by 23% (i.e from 551.72 m to 553.93 m). The simulation model developed in this paper has shown effectiveness in floodplain mapping.

5 Acknowledgement

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References

1) Aydin MC, Birincioğlu ES. Flood risk analysis using gis-based analytical hierarchy process: a case study of Bitlis Province. *Applied Water Science*. 2022;12(6):1–10. Available from: https://doi.org/10.1007/s13201-022-01655-x.
2) Nigusse AG, Adhanom OG. Flood Hazard and Flood Risk Vulnerability Mapping Using Geo-Spatial and MCDA around Adigrat, Tigray Region, Northern Ethiopia. *Momona Ethiopian Journal of Science*. 2019;11(1):90–90. Available from: https://doi.org/10.4314/mejs.v11i1.6.
3) Loi NK, Liem ND, Tu LH, Hong NT, Truong CD, Tram VNQ, et al. Automated procedure of real-time flood forecasting in Vu Gia – Thu Bon river basin, Vietnam by integrating SWAT and HEC-RAS models. *Journal of Water and Climate Change*. 2019;10(3):535–545. Available from: https://doi.org/10.2166/wcc.2018.015.
4) Surwase T, Manjusree P, Prakash S, Kuntla S. Development of algorithms for evaluating performance of flood simulation models with satellite-derived flood. *H2Open Journal*. 2020;3(1):222–235. Available from: https://doi.org/10.2166/h2oj.2020.117.
5) Madhuri R, Raja YSLS, Raju KS, Punith BS, Manoj K. Urban flood risk analysis of buildings using HEC-RAS 2D in climate change framework. *H2Open Journal*. 2021;4(1):262–275. Available from: https://doi.org/10.2166/h2oj.2021.111.
6) Singh SK, Kanga S, Đurin B, Kranjčić N, Chaurasia R, Markovinović D. Flood risk modeling using HEC-RAS and geospatial techniques. *E-Zbornik, Elektron Zb Rad Građevinskog Fak*. 2021;11:20–36. Available from: https://doi.org/10.47960/2232-9080.2021.22.11.20.
7) Leal M, Reis E, Santos PP. Exploring spatial relationships between stream channel features, water depths and flow velocities during flash floods using HEC-GeoRAS and Geographic Information Systems. *Journal of Geographical Sciences*. 2022;32(4):757–782. Available from: https://doi.org/10.1007/s11442-022-1971-z.
8) Zhou Q, Su J, Arnbjerg-Nielsen K, Ren Y, Luo J, Ye Z, et al. A GIS-Based Hydrological Modeling Approach for Rapid Urban Flood Hazard Assessment. *Water*. 2021;13(11):1483–1483. Available from: https://doi.org/10.3390/w13111483.
9) Adane A, Abate B. River Modeling for Flood Inundation Map Predictions Using 2D-Hec-Ras Hydraulic Modeling With Integration of Gis. *ASEAN Engineering Journal*. 2022;12(1):9–15. Available from: https://doi.org/10.11113/aej.v12.16483.
10) Kocsis I, Ştefan Bilaşco, Irimuş IAA, Dohotar V, Rusu R, Roşca S. Flash Flood Vulnerability Mapping Based on FFPI Using GIS Spatial Analysis Case Study: Valea Rea Catchment Area, Romania. *Sensors*. 2022;22(9):3573–3573. Available from: https://doi.org/10.3390/s22093573.
11) Dash P, Sar J. Identification and validation of potential flood hazard area using <scp>GIS</scp> -based multi-criteria analysis and satellite data-derived water index. *Journal of Flood Risk Management*. 2020;13(3):1–14. Available from: https://doi.org/10.1111/jfr3.12620.
12) Nsangou D, Kpoumié A, Mfonka Z, Ngouh AN, Fossi DH, Jourdan C, et al. Urban flood susceptibility modelling using AHP and GIS approach: case of the Mfoundi watershed at Yaoundé in the South-Cameroon plateau. *Scientific African*. 2022;15:e01043–e01043. Available from: https://doi.org/10.1016/j.sciaf.2021.e01043.
13) Puno GR, Puno R, Maghuyop IV. Flood hazard simulation and mapping using digital elevation models with different resolutions. *Glob J Environ Sci Manag*. 2022;8(3):339–52. Available from: https://doi.org/10.22034/gjesm.2022.03.04.

14) Samantaray S, Sahoo A. Estimation of flood frequency using statistical method: Mahanadi River basin, India. *H2Open Journal*. 2020;3(1):189–207. Available from: https://doi.org/10.2166/h2oj.2020.004.
15) Coronado-Hernández ÓE, Merlano-Sabalza E, Díaz-Vergara Z, Coronado-Hernández JR. Selection of Hydrological Probability Distributions for Extreme Rainfall Events in the Regions of Colombia. *Water*. 2020;12(5):1397–1397. Available from: https://doi.org/10.3390/W12051397.
16) George SL, Kantamaneni K, Prasad KA, Shekhar S, Panneer S, Rice L, et al. A Multi-Data Geospatial Approach for Understanding Flood Risk in the Coastal Plains of Tamil Nadu, India. *Earth*. 2022;3(1):383–400. Available from: https://doi.org/10.3390/earth3010023.
17) Vojtek M, Petroselli A, Vojteková J, Asgharinia S. Flood inundation mapping in small and ungauged basins: sensitivity analysis using the EBA4SUB and HEC-RAS modeling approach. *Hydrology Research*. 2019;50(4):1002–1019. Available from: https://doi.org/10.2166/nh.2019.163.