Exploring River's Flood Dynamics: Integrating HEC-RAS 1-D Modelling and Geospatial Techniques for the Karjan River in Gujarat's Narmada Basin, India

ABSTRACT

Floods rank among the most devastating natural disasters, causing extensive damage to property and severe impacts on communities. Effective management and mitigation of flood risks necessitate reliable data regarding flood depth, discharge, and extent. The Karjan River Basin's low-lying regions experienced significant flooding in 2020. This research utilizes the latest new HEC-RAS version for one-dimensional hydrodynamic flood modelling for the Karjan River in low-lying areas and the merging point of the Karjan River Basin in Narmada River, emphasizing geospatial techniques. The study showcases the analytical process of the new HEC-RAS v6 in spatial analysis. River features like bank lines and cross-sections were derived from ALOS Palsar for flood modeling. An unsteady flow simulation was conducted to model water dynamics, yielding water depth results viewable in the HEC-RAS geospatial RAS mapper. Flood depth maps created for 2020 reveal that areas low lying area i.e. Dhamncha, bhadam, Juna Rundh and surrounding area near the merging point of Karjan River are prone to floods when river discharge surpasses 8836 cubic meters per second. Model accuracy was verified by comparing simulated outcomes with historical data from the mentioned events, demonstrating the model's precision and reliability.

***Keywords**: Flood assessment, Geospatial Techniques, HEC-RAS, Karjan River, River Dynamics*

1. INTRODUCTION

India faces significant challenges with floods, influenced by its diverse climate and rainfall patterns. The country's geographical diversity and monsoon-dependent climate make it highly susceptible to extreme weather events. Some areas experience severe flooding, while others suffer from drought (Chandole et al., 2024; Meena & Jha, 2022; Mondal & Mujumdar, 2012; Pal et al., 2022; Ramkar & Yadav, 2018; Sharma et al., 2024). The interplay of these extreme events poses significant threats to both the environment and the socio-economic fabric of the nation. Climate change has exacerbated these floods, particularly in India's drier regions(ASCE, 2018; Padikkal et al.,2020; Joshy et al., 2022 Mangukiya & Andharia, 2024; Mehta et al., 2023; Trivedi et al., 2023), leading to more frequent and severe flood events. Floods are among the world's most frequent and damaging natural disasters, and their occurrence and intensity are expected to increase due to climate change (Samarasinghe et al., n.d.). To address these issues, experts use various tools to assess flood risks, identify flood-prone areas, and develop strategies to reduce potential damage.

From 1901 to 2020, heavy rainfall events tripled in northern and central India, likely due to warming in the Arabian Sea. As floods become more frequent, new approaches are needed. These may include improving water management structures, implementing early warning systems, smart land-use planning, working with natural water management, preparing communities, and setting aside funds for disasters (Mangukiya & Sharma, 2022; Mitsopoulos et al., 2022; Šakić Trogrlić et al., 2022; Sättele et al., 2016). Researchers gather data from various sources, including detailed elevation maps and on-site surveys, to create accurate flood models and validate their findings. Satellite imagery has proven useful in assessing flood risk (Haq et al., 2012). Patel and Dholakia (2010) proposed remote sensing and GIS techniques to identify flood plains areas in Surat. Similar techniques have been applied in other countries to develop flood mitigation plans (Mangukiya & Yadav, 2021; Trambadia et al., 2022; Wang et al., 2002) and assess coastal vulnerabilities (Malik & Abdalla, 2016). Wetlands play an important role in managing floods, and studies have shown how remote sensing and geographical information systems can help protect these areas (Deb & Talukdar, 2010). Researchers have also used various tools to map flood-prone areas in different parts of India (Kumar et al., 2017; NDMA, 2017; Samanta et al., 2018).

Factors like industrial development, cyclones, and urban growth contribute to flooding in regions like northern Australia while combining flood risk management with mapping systems has shown promise in mitigating impacts (Zerger & Wealands, 2004) . Studies have addressed flood risks in diverse areas, from typhoon-prone Korea (Wang et al., 2002) to coastal regions threatened by sea-level rise (Malik & Abdalla, 2016) . Following a catastrophic flood in Surat in 2006, researchers created detailed flood maps of low-lying areas (D. P. Patel & Srivastava, 2014), while similar predictive modeling was conducted for Navsari city (Pathan & Agnihotri, 2020). These studies collectively demonstrate how modern technology and mapping techniques can enhance flood prediction and preparation, potentially reducing damage and saving lives in vulnerable communities.

Flooding in the Karjan River has been a concern, particularly during heavy rainfall and other events due to overflowing conditions of the Narmada River which leads to flood-like conditions in the low-lying areas of the Karjan River. events highlight the challenges faced by communities in managing water levels and mitigating flood risks. This study has taken a significant step in this direction by river dynamics, flood flow multiple inflows, and single outflow conditions. The lower Narmada basin encompasses rivers such as Ashvin, Kim, and Heran, small tributaries, and major tributaries like Karjan and Orsang extending downstream to the Gulf of Cambay and covering the Bharuch and Narmada districts. Flooding in the Karjan River is often caused by heavy rainfall, leading to waterlogging in various areas and rivers overflowing their banks. This study aims to demonstrate the application of the new HEC-RAS version 6.0 (Hydrological Engineering Central Analysis System) to a one-dimensional hydrodynamic flood model. This study focuses on the extraction of water geometry data from ALOS PALSAR DEM (Digital Elevation Model) using the RAS Mapper geospatial tool available in HEC-RAS, demonstrating the use of geospatial methods in flood production. The simulation results show the water depth at each turn during floods. This approach can be a useful tool for disaster management authorities for flood forecasting and flood-warning during future flood emergencies. This study highlights the importance of continuous research and innovation in flood management for the safety and well-being of communities in flood-prone areas.

2. METHODOLOGY

2.1 Study Area

The Karjan River Basin is one of the sub-basins of the Lower Narmada Basin which is the main focus of this study. Narmada River Basin is subdivided into subbasins: Sukhi, Rami, and Karjan. The Karjan River, a significant tributary of the Narmada River, originates from the Mandvi hills near Bilwan, located in the Trappean highlands. It flows predominantly northward for approximately 90 km, passing through the hilly terrain of Mosda-Sagbara and Dediyapada uplands. The river's journey through these highlands is characterized by its meandering path until it reaches the alluvial plains near Jitnagar. Eventually, it converges with the Narmada River at Mota Bhilwada. The Tarav and Daman Khadi are notable right-bank tributaries that join the Karjan River in its upper reaches, enhancing its flow and hydrological significance in the region. Together with one of its tributaries, the Terav, it forms a "winding valley" in the faulted ridges and valleys of the Deccan Trap terrain south of the Narmada. Karjan River starts from Bardipada, which is closer to the Tapti River than Narmada, and its course in its first part consists of faults and cracks. However, it has a valley before emerging as a plain in the north. The Karjan Dam, an important structure within this basin, is located at approximately 22.504°N latitude and 73.405°E longitude. The right bank of the Karjan Reservoir was under consideration of this research (Fig.1).

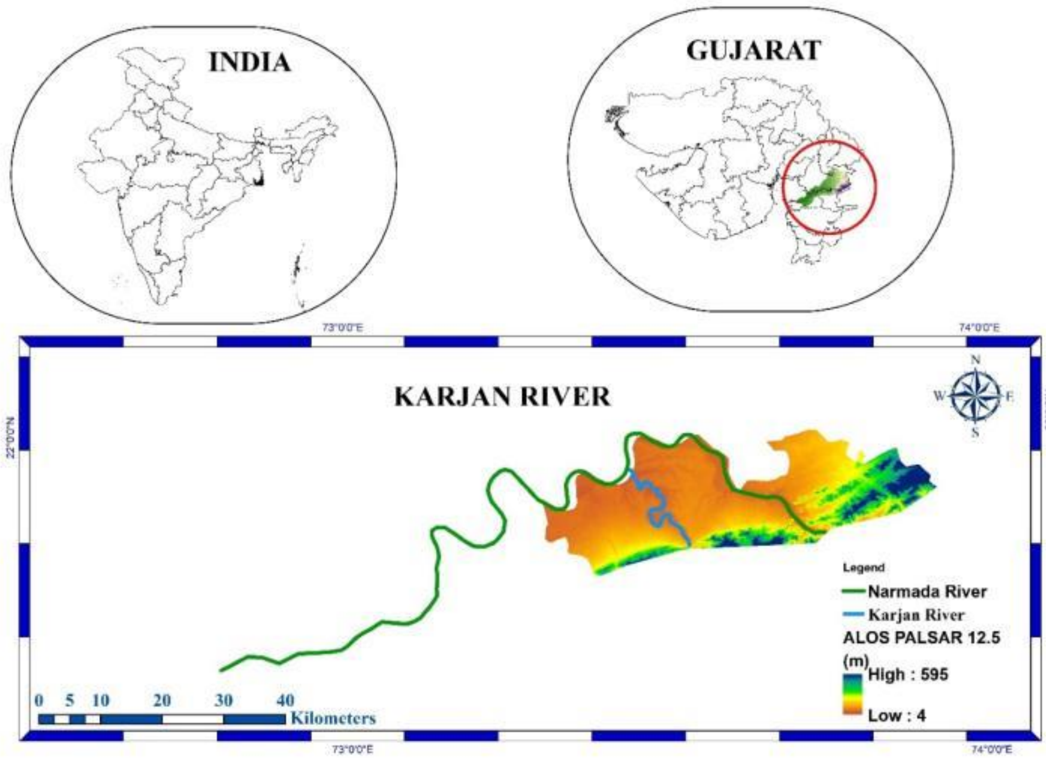


Fig. 1 Study area of Karjan River Basin

DATA COLLECTION

The data for the hydrodynamic models were meticulously sourced from a variety of open-access websites and administrative authorities. The ALOS PALSAR DEM, renowned for its high accuracy and detailed surface information, was obtained from the Alaska portal. With a spatial resolution of 12.5 meters, this Digital Elevation Model (DEM) leverages L-band synthetic aperture radar to penetrate through vegetation and provide precise ground elevation data. This makes it particularly useful for flood modeling in regions characterized by dense vegetation or complex terrain. An analysis of the research region, supplemented by Google Maps, underscores the significant impact of floods in the lower region. A site visit is planned to verify ground features and conduct a bank discharge survey to investigate the area's flooding. This survey is pivotal for validating the 1D hydraulic model results, as it confirms that the river has enough water up to the validation point to cause flooding.

Stage-discharge information for the Karjan Dam was collected from SSNNL (Sardar Sarovar Narmada Nigam Limited). Historical flood data for the study area was collected from various official publications by the SANDARP (South Asian Networks on Dams, Rivers, and People), the Central Water Commission, India (CWC), and SSNNL authorities in Gandhinagar, Gujarat. The amalgamation of these data sources ensures a comprehensive understanding of the flood dynamics in the sub-basins of the Lower Narmada Basin Named as Karjan River Basin. Table 1 summarizes the relevant facts and data needed for the analysis.

Table 1 Data Acquisition table for modelling

Data types	Details	Data Source	Use of Data	Data Frequency
Digital elevation models	ALOS Palsar (12.5 m)	Japan Aerospace Exploration Agency (JAXA)	Terrain Model	-
Topographical drawings	1:50,000 scale	Survey of India	River reach generation	-
Stream gauge data	Karjan Dam	SSNNL	Model input variable	Daily
Water surface level data	Rajpipla Bridge	SSNNL	Manning roughness coefficient, validation	Daily

Methods

The HEC RAS 1-D hydrodynamic model, which uses mapping methods, is a fast and accurate way to figure out how depth of the water will be in different places during a flood. This process of making a flood map has two parts: first, we organize the data with a mapping tool, and then the HEC RAS program is used to predict the flood. There's a chart (Figure 2) that shows the steps of this method. In this connection, a model was developed with the river stage and cross-section analysis in order to overbank discharge of the river throughout the meeting point in the Narmada River. Discharge data on a daily basis from Karjan dam as upstream boundary conditions and validation site Rajpipla designated as downstream boundary conditions as normal depth. River geometry was created with cross-section spacing of 200m each and 2000m wide.

Initially, ALOS Palsar has a resolution of 12.5 m and is available for free download from the Japan Aerospace Exploration Agency (JAXA) (https://search.asf.alaska.edu/). Then, DEM data was converted into DTM (Digital Terrain Model) by adding DEM data to the RAS Mapper a GIS tool of HEC-RAS (Hydrological Engineering Center-River Analysis System). Additionally, georeferenced projection data was placed in the same window installed in the work area. River centerlines, shorelines, flowlines, and section lines were digitized on a HEC-RAS plotter as shown in Figures 3 and 4. The oceanic portion of the research area was captured in HEC-RAS. This study also suffers the lack of ground surveyed cross sections of the river stretch. In this context, the DEM generated cross sections are used for the study purpose. The data processing window is presented in Figure 5 Station gain data obtained on CS-11800, CS-7200, CS-5400, and CS-2400 are shown in Figures 6a, b, c, and d, the sub-area after the measurement station. The middle river is shown in blue, and the crossing line is shown in green; The Google Maps satellite image is overlaid on top of the terrain map as a base map. A regular survey was conducted on the Karjan River in 2020, with the maximum flow rate upper limit being 5437 m^3/s and the slope lower limit being 0.00195 (Patel et al. et al. 2020). In semi-arid regions, the Manning-n value is 0.03.

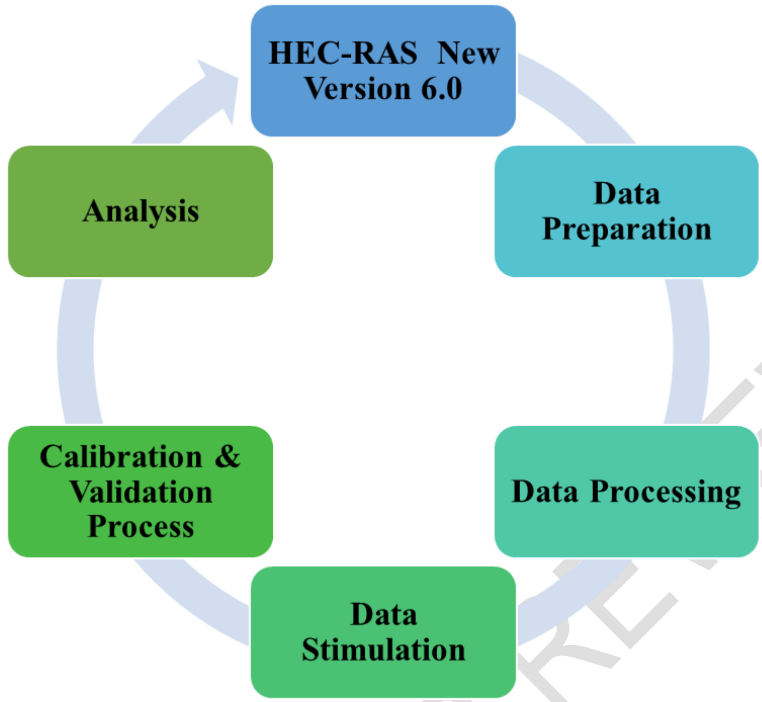
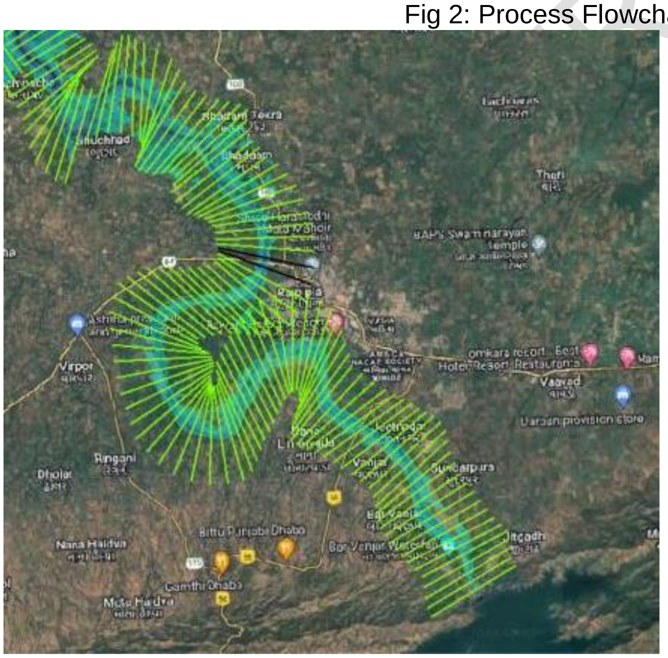


Fig 2: Process Flowchart



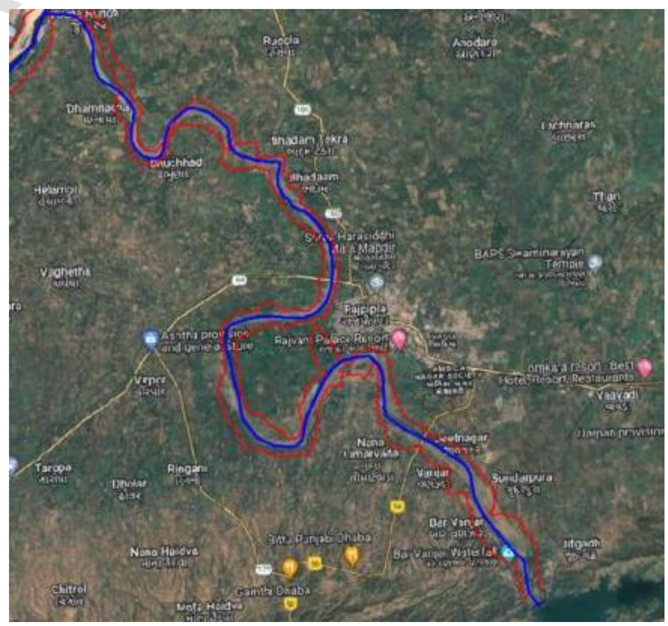


Fig 3. Cross sections of river

Fig 4. River Bank line in Karjan River

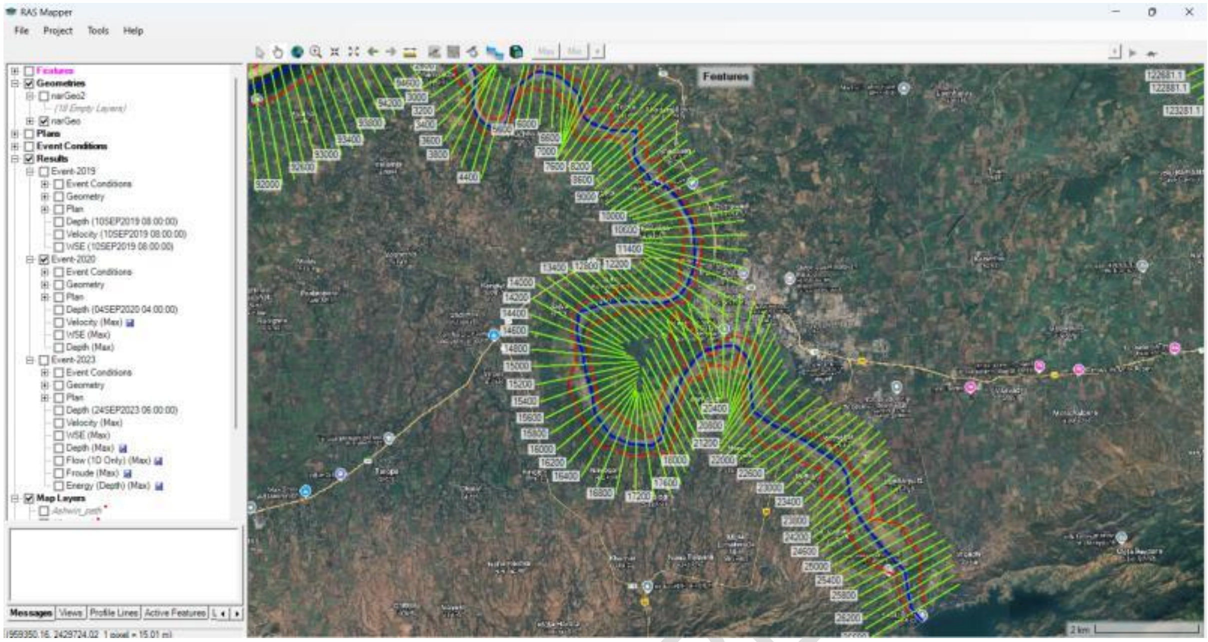


Fig 5 Screenshot of RAS Mapper editor

3. RESULTS:

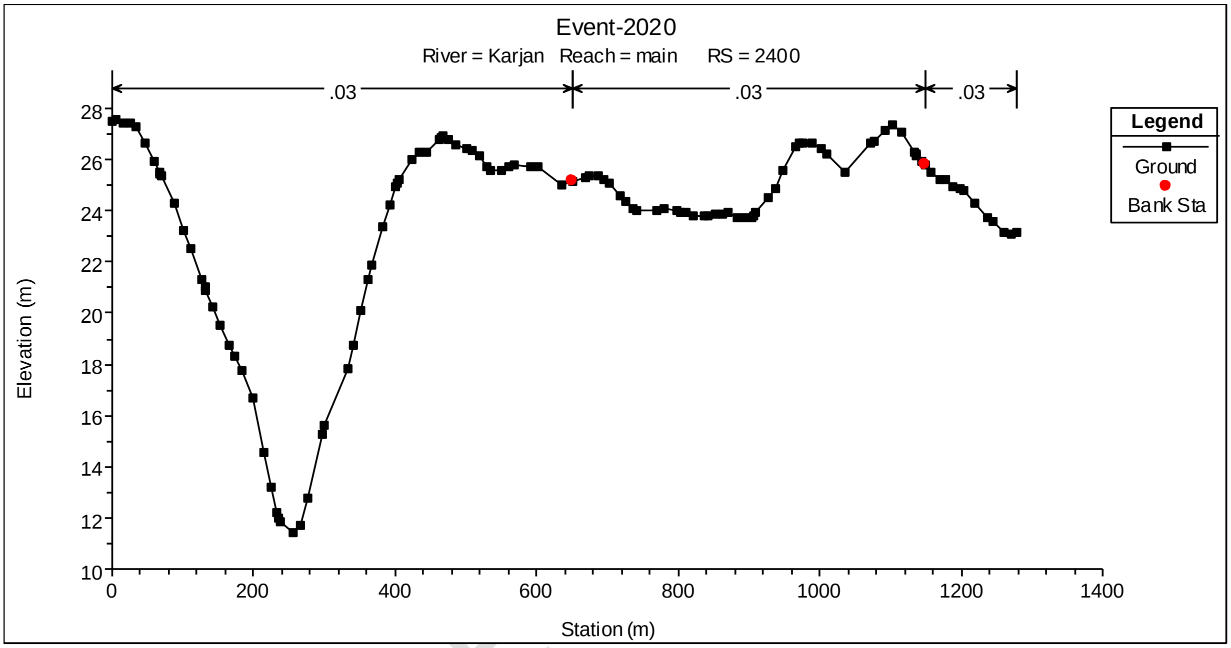
Calibration

At the Rajpipla gauging station, the peak depth was measured in a Single-year event, and due to insufficient data, only a random trial was made to match the observed depth with the actual depth. Perform instability tests on simulation models. The results obtained in this study are the water depth corresponding to the discharge of 31844.50 m^3/s from the Narmada Dam for the year 2020. The simulation results are less affected by floods due to the height of section no. 11400 at maximum discharge and the bridge location. There is also a section number. 7200, 5400, and 2800 are close to Dhamncha, bhadam, and Juna Rundh areas located at the confluence of Karjan and Narmada rivers, which are prone to floods, as shown in Figures 6a, b, c, d. Changes in water depth at different points are shown in Figure 7 (a, b, c, d).

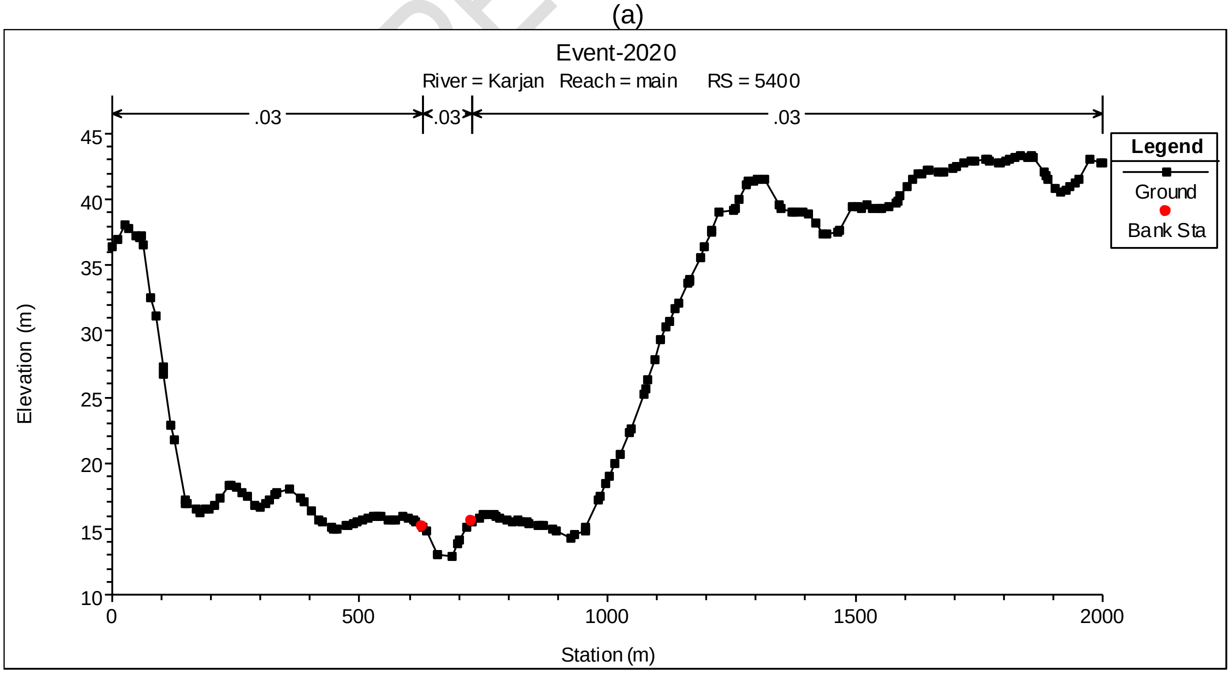
Table 2 Calibrated Water Depth (m) at Rajpipla Gauging Site

Date	Simulated Depth	Actual Depth	Difference in depth
21/08/2020	3.44	6.71	3.27
22/08/2020	3.28	6.38	3.1
23/08/2020	3.28	6.53	3.25
24/08/2020	5.06	7.01	1.95
25/08/2020	3.37	6.61	3.24
26/08/2020	3.05	6.34	3.29
27/08/2020	3.05	6.33	3.28
28/08/2020	3.31	6.29	2.98
29/08/2020	3.08	6.22	3.14
30/08/2020	3.68	6.75	3.07
31/08/2020	4.27	7.45	3.18
01/09/2020	5.35	7.51	2.16
02/09/2020	4.12	6.65	2.53
03/09/2020	3.53	6.11	2.58

04/09/2020	3.05	6.05	3
05/09/2020	3.05	6.01	2.96
06/09/2020	3.06	5.98	2.92
07/09/2020	3.05	6.02	2.97
08/09/2020	3.06	6.01	2.95
09/09/2020	3.05	5.97	2.92
10/09/2020	3.06	5.97	2.91



(a)



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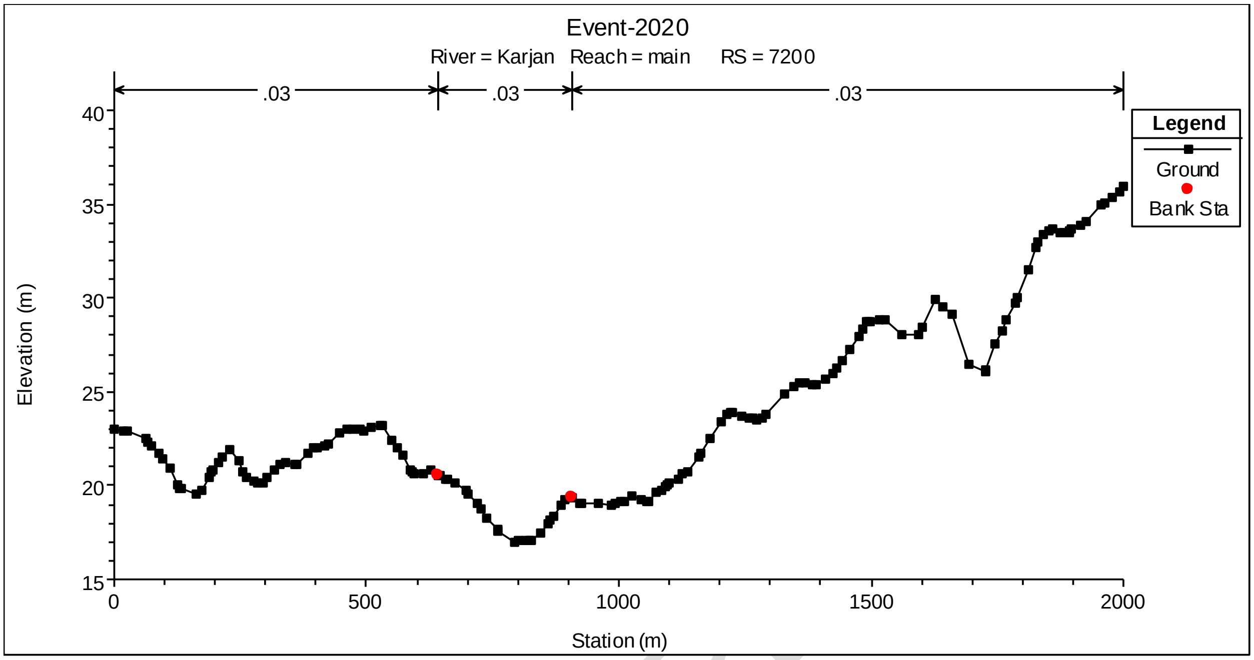

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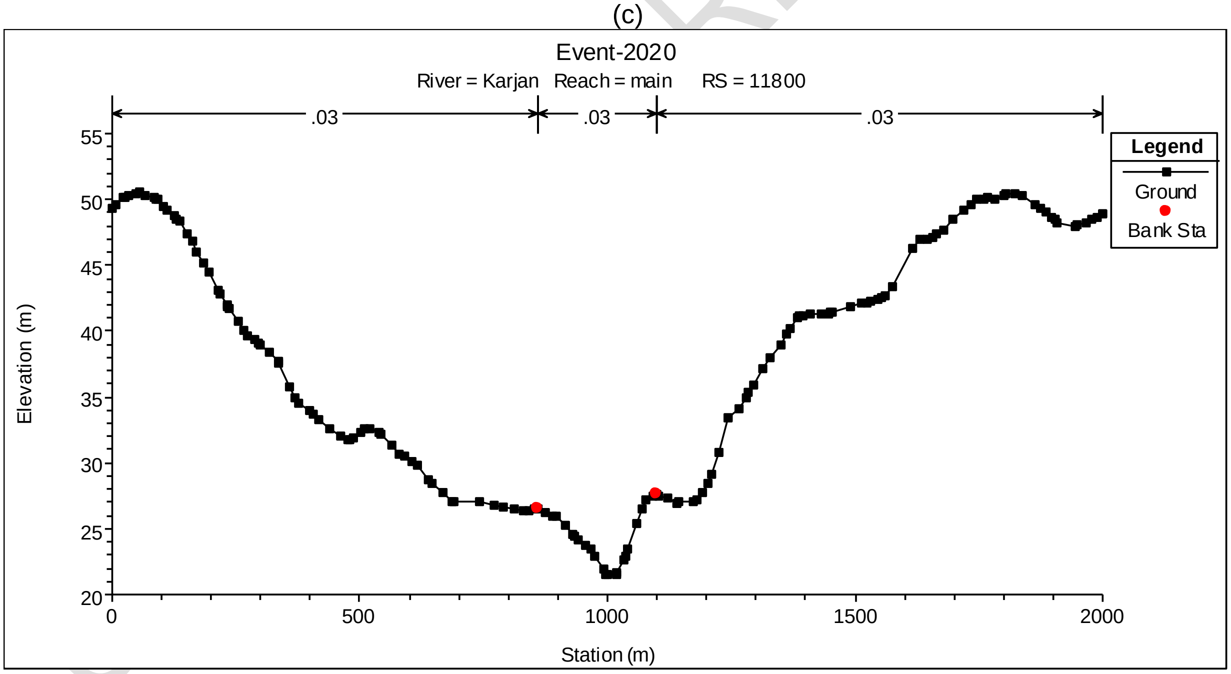
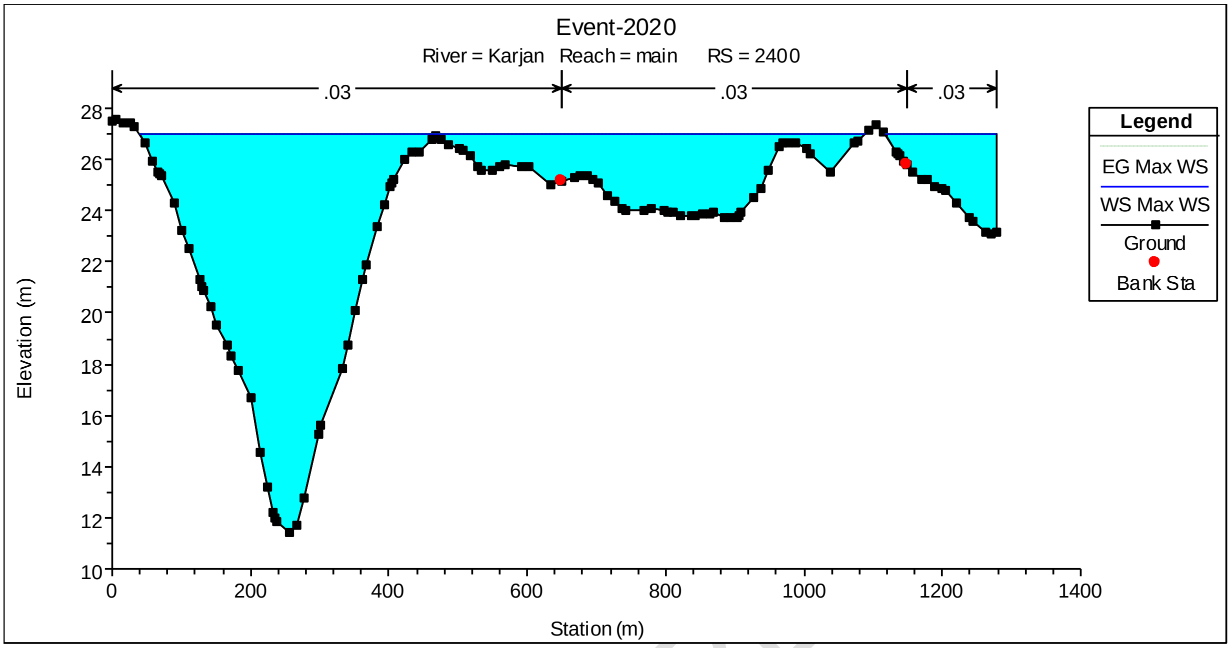


(d)

Fig 6(a, b, c & d): Station-elevation data of extracted cross-sections in HEC-RAS geometric data editor window


Event-2020
River = Karjan Reach = main RS = 2400
.03
.03
.03
Legend
EG Max WS
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Elevation (m)
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28
26
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22
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400
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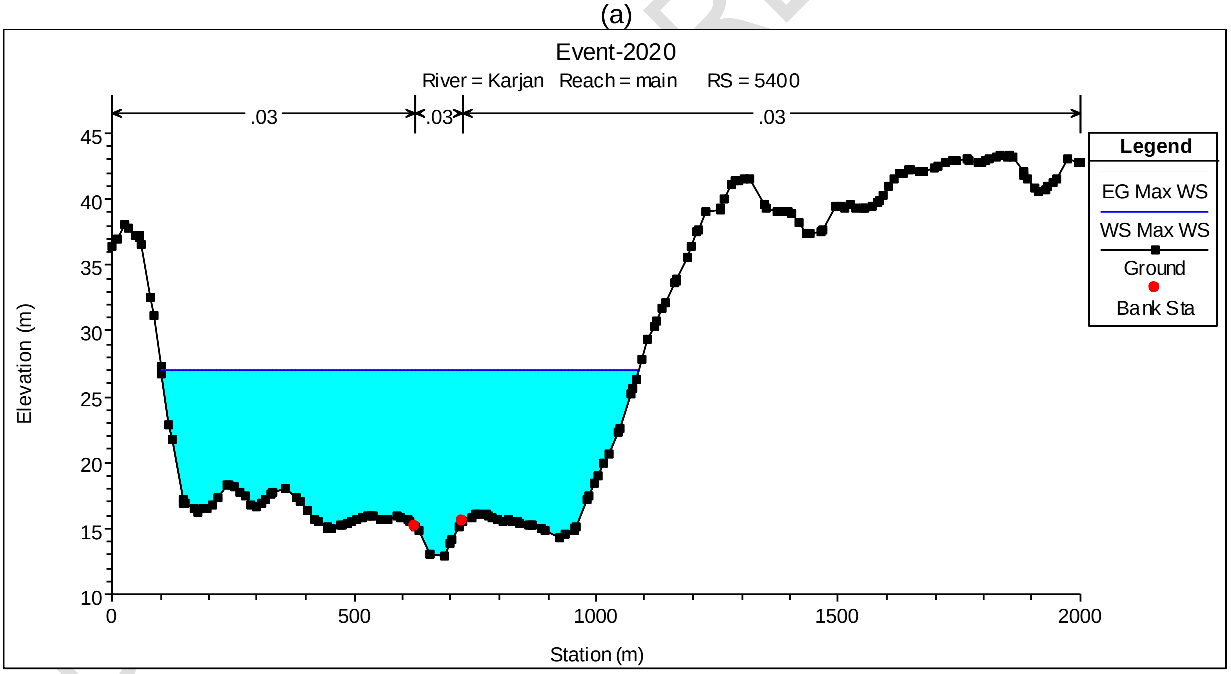
1000
1200
1400

(a)


Event-2020
River = Karjan Reach = main RS = 5400
.03
.03
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Legend
EG Max WS
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Ground
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Elevation (m)
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25
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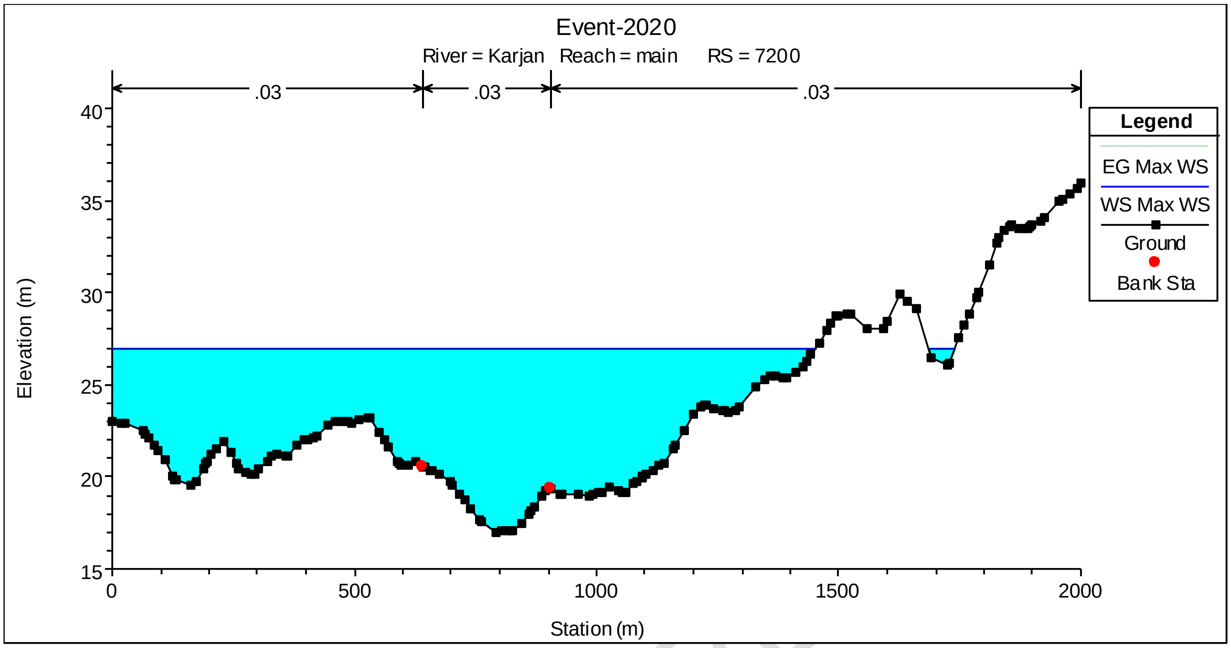
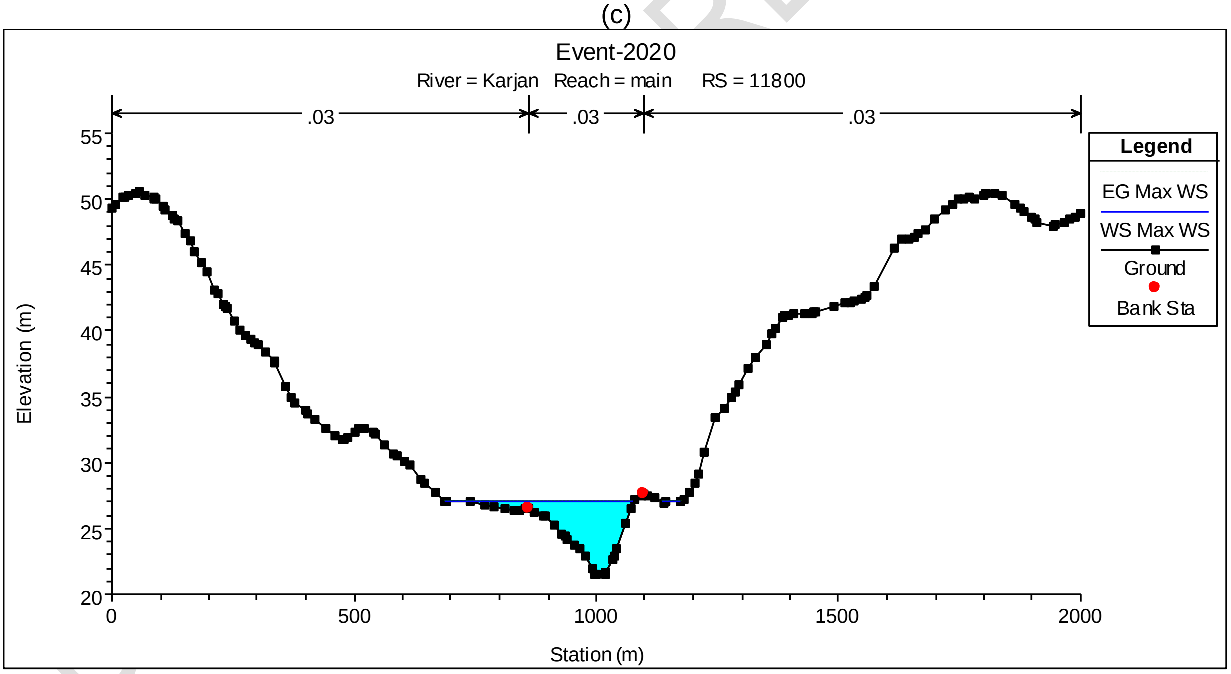
(B)



(c)



(d)

Fig 7(a, b, c &d): Water Surface Profile at Various Locations

Validation

The verification was done using observation data from the Rajpipla Bridge gauging station near Rajpipla town. Due to the scarcity of data, the data obtained from a measurement site can only be used to validate the simulation presented in HEC-RAS. Water depth data 2020 is used to check the consistency of the simulation model. A comparison of the simulated data with the measured data of Rajpipla station is shown in Table 2. Future flood forecasting and this model can be used in situations where information is scarce. The current study is limited to one-sided modeling and only floods observed in the channel. Diffusion analysis was not taken into account in this study. The method of using two-dimensional flood quantity for flood analysis will provide authorities with better information on flood prevention. An example of a two-dimensional hydrodynamic model and continuous analysis has been made for the Karjan River region. Flooding was observed in low-lying areas of the city area of Nandod, Bhadam, Juna Rundh, Dhanpor, and Dhamancha in the Karjan River basin. Therefore, the HEC-RAS 2-D model needs to be simulated as a normal flood problem in the Karjan River, especially during heavy rainfall and other events that cause flood-like conditions in the low-lying areas due to overflow of the Narmada River in the region along the Karjan River.

Simulated Flood Map

The 2020 flood event Simulated Karjan river basin is shown in Fig. 8, with a corresponding flow of 31844.5 m^3/s from Sardar Sarovar Dam. The simulated flood map shows the changes in water depth along the channel in color, dark blue indicates deeper water and light blue indicates deeper water. Figure 8 depicts that the impact of floods in the lower reaches of the Karjan River (Juna Rundh, Dhamancha, and Dhanpore) in the Karjan Basin during the 2020 event was very high with a correlation of 1158.35 m^3/s and equal to 31844.5 m^3/s from Narmada Dam. The major cause of this flood in the Karjan River basin's low-lying area is due to high discharge from the Narmada River.

Fig 8. Stimulated Flood Map

Discussion

This research demonstrates the capabilities of the latest HEC-RAS version, which includes integrated mapping tools for more efficient river data collection. The process combines ARC-GIS software with the HEC-GeoRAS in the old version now RAS Mapper add-on, now streamlined within RAS Mapper. This integration allows for more accurate river modeling while reducing initial setup time.

High-resolution ALOS Palsar satellite images were used to map the river's geometry. The study analyzed water flow patterns during the 2020 flood event. Results identified specific low-lying areas along the Karjan River that experienced flooding(Bhargav et al., 2024; Farooq et al., 2019; Trivedi et al., 2023). Figure 8 presents a flood depth map, while Figure 7

compares model predictions with actual water depths, validating the model's accuracy. Figure 8 illustrates water levels at various cross-sections along the river, derived from satellite imagery analysis. The study revealed that flood impacts varied across different river sections(Pandya & Patel, 2024; M. Patel & Parekh, 2024; Pathan & Agnihotri, 2021). Table 2 compares predicted water depths with actual measurements, demonstrating the value and effectiveness of combining HEC-RAS with mapping techniques and difference in simulated and observed flood stage data is might be due to cumulative flood flow inundation simultaneously at the site. However, depth predictions showed some discrepancies due to limitations in the Digital Elevation Model (DEM) profile(Adesina et al., 2022; Jena et al., 2016; Masood & Takeuchi, 2012; Pramanik et al., 2010; Wang et al., 2002).
Factors affecting water level measurements can include instrument precision issues, improper gauge placement, or environmental elements i.e. debris (Md Ali et al., 2015; Orlyankin & Aleshina, 2020; Saini & Barik, 2024). To address these challenges in the flat terrain, high-resolution DEMs created using Unmanned Aerial Vehicle (UAVs) were employed (Şerban et al., 2016).

4. CONCLUSION

The study focused on applying the latest version of HEC-RAS v 6.0, coupled with geospatial techniques, to the Karjan River Basin in Gujarat, India. During monsoons and heavy rainfall, areas like Bhadam, Juna Rundh, Dhanpor, and Dhamancha experience flooding, exacerbated by high discharge rates from the Narmada Dam. The GIS capabilities of HEC-RAS v 6 were validated by extracting river geometry data from the ALOS Palsar DEM (12.5 m). A 1-D hydrodynamic simulation, using unsteady flow analysis, was executed in HEC-RAS. Simulated results for the 2020 flood events were visualized in the RAS Mapper window, closely aligning with observed data. This approach demonstrates that geospatial methods, combined with HEC-RAS, provide an accurate and reliable method for one-dimensional hydrodynamic flood modeling of the Karjan River. Our future work aims to extend this analysis to a two-dimensional modeling approach, covering the entire Karjan River stretch in the lower Narmada Basin, enhancing our understanding of flood parameters for effective mitigation strategies.

Data Availability

The datasets used during this study are available at the Alaska Satellite Facility website (https://asf.alaska.edu/). Other datasets can be obtained from the relevant authorities as per their policies.

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