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Hydrodynamic Flood Inundation Modelling And Risk Assessment In The Upper Banas River Basin, Gujarat

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Abstract
In recent years, severe flooding has occurred in several parts of India, including Gujarat, where heavy rainfall caused extensive damage to houses, vehicles, and livestock. These events highlight the urgent need for effective flood risk management and mitigation strategies. Flood modelling plays a vital role in understanding flood behavior and supporting decision-making. The objective of this study is to evaluate the effectiveness of HEC-RAS 5.0.7 and HEC-RAS 6.0 for one-dimensional (1D) and two-dimensional (2D) flood modelling in the upper Banas River basin. A flood map was generated for the extreme flood event that occurred between 22 and 24 July 2017 and compared with observed data obtained from the State Water Data Centre (SWDC), Central Water Commission (CWC), and Shuttle Radar Topography Mission (SRTM DEM, 30 m resolution) satellite imagery. Rainfall analysis was also carried out as part of this assessment. The model outputs, including flood depth, water surface elevation (WSE), and velocity, were spatially mapped and analyzed for the duration of the event. Cross-section elevations at various locations were validated against CWC data for pre- and post-monsoon seasons. Model calibration was performed using CWC, SWDC, and site-specific observations at the dam location, ensuring reliability of the results.
Keywords: *HEC-RAS, Geo-Informatics System, Hydrodynamic Modelling*

Highlights:
- **Inadequate Infrastructure Capacity:** Existing flood management structures, such as the Dantiwada Dam, were insufficient to handle extreme inflows.
- **Need for Improved Flood Modeling and Early Warning:** The results show that hydrodynamic simulations integrated with GIS can provide reliable flood forecasts, which must be operationalized in real-time disaster management.
- **Community-Level Preparedness:** The spatial maps clearly identify vulnerable zones, providing a basis for land-use planning, relocation strategies, and targeted flood mitigation measures.

1. INTRODUCTION

Floods are among the most widespread and devastating natural hazards, responsible for significant economic losses, environmental degradation, and human casualties worldwide. Globally, more than 1.6 billion people have been affected by floods over the past two decades, with the Asia-Pacific region being disproportionately impacted (UNDRR, 2020). Flood disasters arise from multiple drivers, including extreme rainfall events, overflowing rivers, snowmelt exacerbated by climate warming, dam breaches, and sudden cloudbursts that trigger flash flooding (Alfieri et al., 2017; Kundzewicz et al., 2019; Kapadia et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) highlights that intensification of the global hydrological cycle due to climate change is likely to increase both the frequency and magnitude of flooding events in the future (IPCC, 2021). Particularly in developing countries, floods have been identified as one of the leading causes of disaster-related mortality and economic damage, underscoring the urgent need for integrated flood risk management and mitigation measures (Hirabayashi et al., 2013; Guha-Sapir et al., 2016; Gohil et al., 2024).

In India, floods represent one of the most recurrent natural hazards, with nearly 12% of the total land area, equivalent to 40 million hectares, prone to recurrent flooding (CWC, 2018). The monsoon system, spanning from June to October, is the dominant hydrological driver, often bringing intense precipitation that overwhelms river systems, reservoirs, and drainage networks (Mishra and Herath, 2015; Baudhanwala et al., 2024). Approximately 75% of India's annual rainfall occurs during the monsoon season, and its variability across space and time plays a pivotal role in shaping the flood hazard profile of the country

(Goswami et al., 2006; Rajeevan et al., 2008; Mehta et al., 2023). Large-scale floods are frequently observed in major river basins such as the Ganges, Brahmaputra, and Mahanadi, leading to widespread inundation, displacement, and infrastructural losses (Jain et al., 2007; Chatterjee and Ghosh, 2010; Mehta et al., 2022). According to the National Disaster Management Authority (NDMA, 2019), floods in India affect on average 30 million people annually, resulting in billions of dollars in economic damage.

Within India, the western state of Gujarat has emerged as one of the region's most vulnerable to floods, particularly during monsoon seasons when cyclonic disturbances from the Arabian Sea combine with heavy rainfall to generate high-intensity flood events (Patel and Gundaliya, 2016; Mehta et al., 2019; Mangukiya et al., 2022). Gujarat's physiographic diversity, comprising coastal zones, river basins, and arid plains, makes it especially susceptible to both riverine floods and flash floods (Chowdhury et al., 2015; Patel et al., 2018). Banaskantha district in northern Gujarat is particularly vulnerable due to its location in the downstream reaches of the West Banas River, where monsoon-induced flash floods are recurrent hazards. Low-lying areas and villages along the Banas River and its tributaries face repeated inundation, resulting in substantial agricultural damage, livelihood disruption, and displacement (Pandya et al., 2019; Mehta et al., 2013).

The Banas River itself originates from the Aravalli ranges in Rajasthan, traverses through the Banaskantha district of Gujarat, and ultimately flows towards the Rann of Kutch. Despite being a seasonal river that tends to dry up during the summer months, the Banas exhibits erratic behavior during monsoon periods. Heavy rainfall in its catchments often leads to the river breaching its banks, submerging adjoining agricultural lands, and inundating settlements (Gamit et al., 2018). The catastrophic flood of July 2017 exemplified this hazard. Triggered by extreme rainfall in the upper catchments, the river overflowed into large stretches of Banaskantha, submerging villages, destroying croplands, and causing significant infrastructure damage (Shah and Patel, 2018). National Disaster Response Force (NDRF) units and local authorities carried out emergency evacuations and relief operations, yet the event highlighted systemic gaps in early warning, infrastructure preparedness, and community resilience. Such floods emphasize the urgency of developing robust flood forecasting and risk management strategies, especially in regions characterized by complex river–floodplain dynamics and high exposure.

Flood modeling and risk mapping have become essential tools in addressing such challenges. Hydrodynamic and hydrologic models allow researchers and policymakers to simulate river behavior, predict flood inundation extents, and develop hazard maps to guide mitigation measures (Teng et al., 2017). Among these, the Hydrologic Engineering Center's River Analysis System (HEC-RAS), developed by the U.S. Army Corps of Engineers, is widely recognized for its versatility in simulating one-dimensional (1D) and two-dimensional (2D) river hydraulics, flood extents, water surface profiles, and floodplain interactions (Brunner, 2016). HEC-RAS supports unsteady flow simulations and has been increasingly coupled with Geographic Information Systems (GIS) to produce flood hazard and risk maps for vulnerable areas (Horritt and Bates, 2002; Merwade et al., 2008).

Globally, HEC-RAS has been applied in diverse contexts to evaluate flood dynamics. For instance, Peker et al. (2024) applied an integrated HEC-RAS–HEC-HMS–GIS framework in Türkiye's Göksu River Basin to generate flood hazard maps under varying rainfall scenarios. Similarly, Zischg et al. (2018) applied 2D HEC-RAS modeling for flash flood hazard mapping in Alpine catchments, demonstrating its accuracy in representing flow velocities and inundation depths. In Southeast Asia, Thol et al. (2016) successfully applied HEC-RAS for flood prediction in the Mekong Delta, with model calibration showing close agreement with observed flood extents. These international applications confirm the model's global relevance for both flood hazard assessment and disaster risk reduction strategies.

In India, applications of HEC-RAS have expanded in recent years. Patel and Gundaliya (2016) employed HEC-RAS integrated with GIS to prepare flood hazard maps for Surat city along the Tapi River, demonstrating the model's effectiveness in delineating vulnerable zones. Pathan, Vadher, and Agnihotri (2017) applied GIS-based preprocessing with HEC-GeoRAS to analyze inundation scenarios in the Purna River basin. Similarly, Patel, Dhruvesh, and Prakash (2016) utilized HEC-RAS for flood modeling along the Shetrunji River, recommending embankment height increases and slope protection to reduce flooding. In Banaskantha itself, preliminary applications of HEC-RAS have shown its capability in simulating monsoon-driven floods and evaluating the performance of protective infrastructure such as embankments and dams (Patel, 2019). These studies collectively highlight the growing adoption of HEC-

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RAS as a critical tool for river basin flood risk analysis in India. Recent advances in HEC-RAS, especially version 5, allow two-dimensional floodplain modeling, improving accuracy in representing flood propagation and interaction with floodplain topography (Brunner, 2016). Studies by Papaioannou et al. (2016) and Horritt et al. (2010) have shown that 2D modeling can better capture localized inundation dynamics, which are especially relevant for flash flood-prone basins such as Banaskantha. Moreover, the integration of HEC-RAS with hydrologic models like HEC-HMS and with remote sensing data has expanded its utility in scenario-based flood risk assessments under changing climate and land use conditions (Lai et al., 2016).

Despite these advances, challenges remain in applying flood models in India's smaller catchments and flash flood-prone basins, where limited gauging data, irregular rainfall patterns, and complex terrain create uncertainties (Mishra and Herath, 2015). In Banaskantha, these challenges are amplified due to the river's seasonal behavior, rapid runoff from upstream catchments, and the socio-economic vulnerability of downstream communities. This makes the region an important case study for advancing flood risk modeling through integrated hydrodynamic tools such as HEC-RAS.

The objective and purpose of this study are to comprehensively evaluate the flood dynamics of the Banas River and its tributaries within the Banaskantha region of Gujarat through the application of the HEC-RAS hydrodynamic modeling framework. By simulating extreme monsoon-induced rainfall events, the study seeks to generate precise flood inundation maps, quantify flood depths, flow velocities, and water surface elevations, and delineate spatial extents of inundation under varying hydrological scenarios. These outputs will serve not only to reconstruct the catastrophic flood event of 2017 but also to provide predictive insights into potential future flood hazards. The integrated modeling approach will inform evidence-based flood risk management strategies tailored to the local context, enhance the effectiveness of early warning systems, and support decision-making for infrastructure planning, river embankment design, and land-use regulation in vulnerable floodplain areas. Ultimately, the purpose of the study is to build scientific knowledge that strengthens community resilience, minimizes socio-economic losses, and contributes to sustainable floodplain management in the Banaskantha district, thereby addressing one of Gujarat's most pressing climate-related challenges.

2. Study Area

The Banaskantha district (24°10′23″N, 72°25′53″E) lies in the northeastern part of Gujarat, India, and derives its name from the West Banas River, which traverses the region. The river originates in the Aravalli hills near Mount Abu and flows through a valley before entering the plains of Gujarat, eventually draining toward the Rann of Kutch. Characterized as a seasonal river, the West Banas typically desiccates during the hot summer months; however, it remains an important water source for irrigation during the monsoon and post-monsoon periods. Banaskantha district is situated in the downstream stretch of this river system, making it particularly vulnerable to fluctuations in discharge and flood hazards during high rainfall events (Figure 1).

The monsoon season in Gujarat usually begins in mid-June, bringing substantial precipitation that recharges river flow and agricultural fields. The catchment of the West Banas River encompasses an area of about 1,876 km², while the total watershed spans approximately 3,995 km². Of the total river length, nearly 50 km lies in Rajasthan, with the remaining course flowing across Gujarat before dissipating into the saline wetlands of the Rann. The hydrological and geomorphological characteristics of this basin, coupled with its dependence on seasonal rainfall, make it a critical region for hydrological studies, water resource planning, and flood risk assessment (Figure 2).

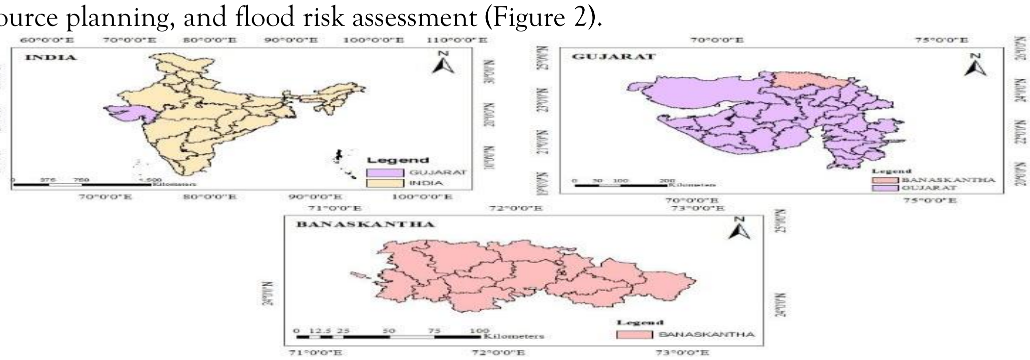

Figure 1. Location map of the study area.

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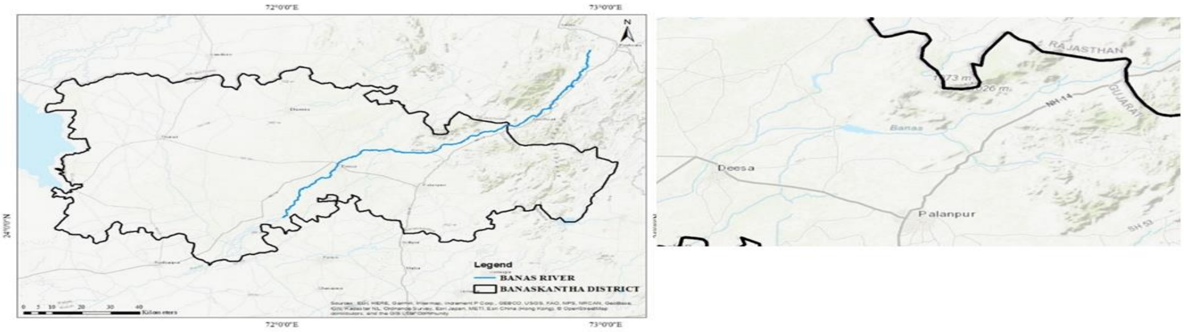

Figure 2. Location map of the Banas River with Banaskantha District (study area), Gujarat.

3. MATERIALS AND METHODS

3.1 Data Collection

Rainfall and discharge data were obtained from the State Water Data Centre (SWDC), Gandhinagar, and the Central Water Commission (CWC) for the Banaskantha region during the 2017 flood event. Rainfall was recorded at several gauging stations, including Umbari, Tharad, Shihori, Panthawada, Dantiwada, Chandisar, Bhilda, Bhabhar, Sarotra, Abu Road, and Amirgadh (Figure 3). During the critical period between 21 July 2017 and 26 July 2017, the observed rainfall reached 41.73 mm at Amirgadh, 45.09 mm at Chandisar, and 25 mm at Umbari, contributing to a cumulative total of 617 mm across Banaskantha (Figure 4).

Figure 3. Location of Station Gauge of Banaskantha (Source: State Water Data Centre).

Discharge records were also obtained and compared between the SWDC and the Dantiwada Dam station on the Banas River. The mean discharge was estimated at 1,063.17 m³/s from SWDC records and 880.32 m³/s from dam measurements (Figures 6 and 7). These datasets, along with Digital Elevation Models (DEMs) and river cross-section surveys, provided the necessary inputs for hydraulic modeling (Table 1).

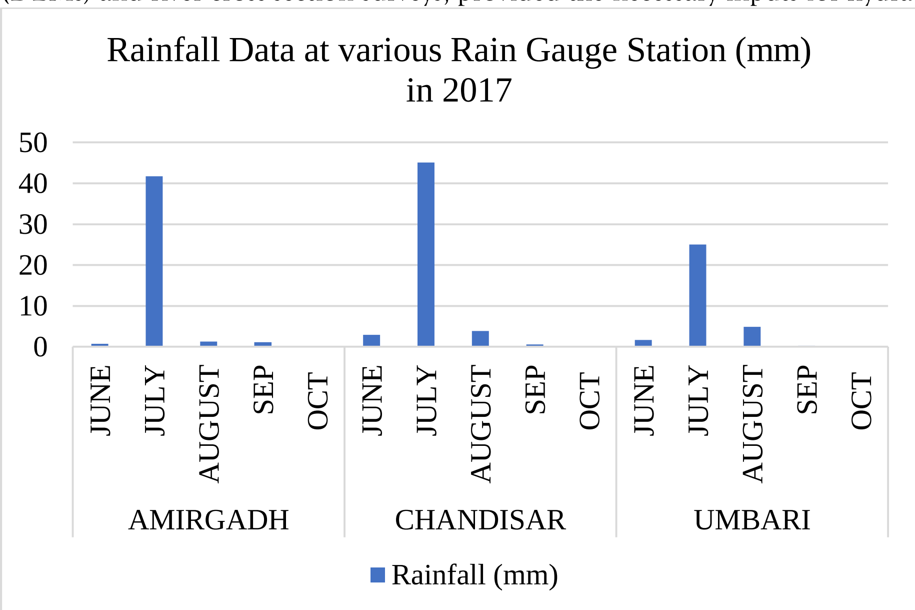

Figure 4. Monthly Rainfall (mm) at Rain Gauge Station Amirgadh, Chandisar, and Umbari in the year 2017 (source: SWDC)

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Table 1. Datasets and their respective sources used in this study.

Sr. No.	Data	Sources
1	30 m SRTM DEM data	Earth Explorer, Bhuvan
2	Rainfall and Discharge Data	State Water Data Centre (SWDC), Central Water Commission (CWC)

3.2 Digital Elevation Model and Pre-processing

Topographic data were derived from 30 m spatial resolution Shuttle Radar Topography Mission (SRTM) DEMs, obtained from the USGS Earth Explorer and ISRO's Bhuvan platform. These datasets were used for terrain delineation, catchment analysis, and the extraction of river profiles necessary for hydraulic simulations (Figure 5). The use of DEM data in flood modeling has been well established in hydrodynamic studies, as it supports accurate floodplain characterization (Hawker et al., 2018).

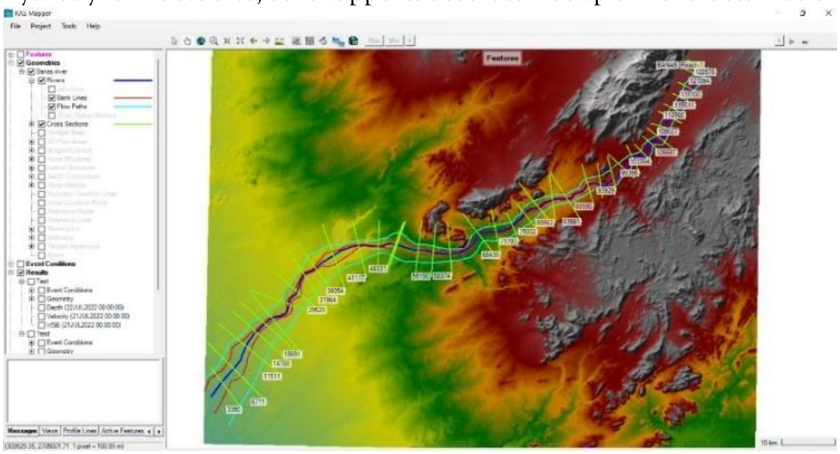

Figure 5. Geometrics and River Cross Section.

3.3 Hydraulic Model Setup

Hydrodynamic modeling was carried out using HEC-RAS (Hydrologic Engineering Center's River Analysis System), a widely adopted tool for flood modeling and river hydraulics (Brunner, 2016; Patel et al., 2020). The overall modeling procedure is illustrated in the flow chart (Figure 6). The model setup included defining the river geometry, reach alignment, bank lines, flow paths, and cross sections, which were digitized and imported into RAS Mapper (Figure 7). Cross-section data for the Upper Banas River Basin were supplemented by field surveys conducted by the Central Water Commission (CWC).

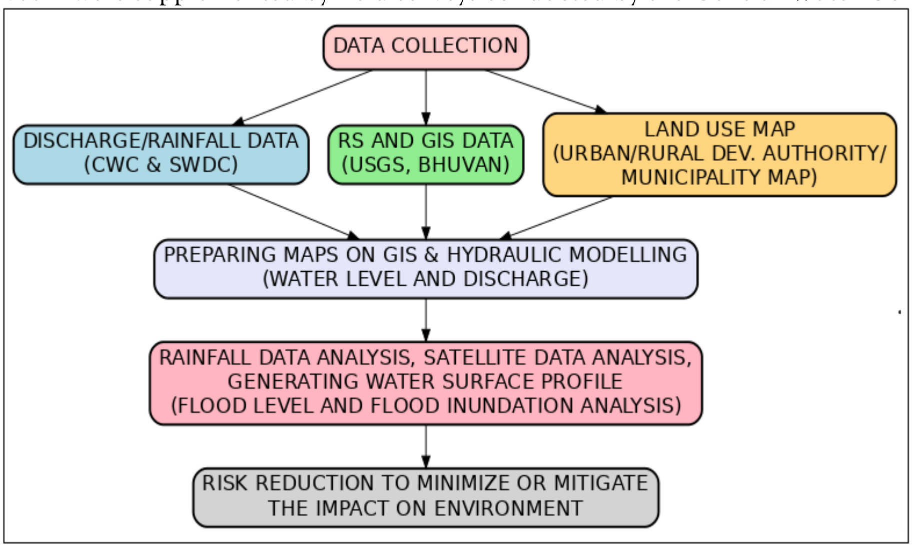

Figure 6. Flowchart of Hydraulic Modeling.

The floodplain was divided into three flow compartments: the left overbank (LOB), main channel, and right overbank (ROB), according to natural drainage directions. Manning's roughness coefficient (n) was assigned as 0.03 for LOB and ROB, while the main channel was assigned a slightly higher value of 0.035

to reflect differences in land use, vegetation cover, and slope characteristics. Such Manning's n values are consistent with previous studies of Indian river basins (Chow, 1959; Pathan et al., 2019).

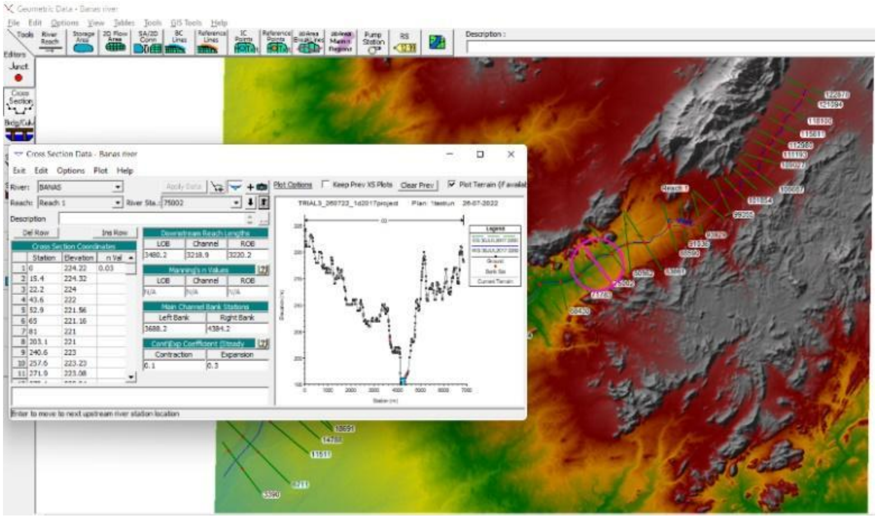

Figure 7. Added Geometrics in RAS Mapper, i.e, River, Reach, Bank Line, Flow Path, Cross Section.

3.4 Model Inputs and Calibration

The peak discharge values of 2017 were incorporated as unsteady flow inputs to evaluate river hydraulics and flood dynamics. Boundary conditions were defined using discharge hydrographs from SWDC and Dantiwada Dam. The HEC-RAS model was then calibrated against observed river stage and discharge to validate the accuracy of simulated water levels and flows. Similar calibration approaches have been applied in flood studies across India and globally, showing that HEC-RAS simulations provide reliable outputs when supported with field data (Patel et al., 2020; Thol et al., 2021; Pandya et al., 2022).

3.5 Model Simulation and Outputs

The unsteady flow analysis was performed to obtain outputs including water surface elevation (WSE), flood depth**,** velocity distribution, and flood extent along the Banas River. The successful simulation produced output hydrographs and flood profiles. Three-dimensional visualization of the river channel and inundation was generated through an x–y–z perspective plot (Figure 8). Furthermore, the simulated stage and flow hydrographs demonstrated temporal variations in water levels and discharge across key river sections (Figure 9).

The cross-sectional data of the Upper Banas River Basin collected by CWC were compared with the modeled outputs of HEC-RAS for validation. Representative cross-sections from locations such as Sarotra and Chitrasani confirmed that the modeled results closely matched observed profiles, ensuring reliability in predicting flood behavior under future rainfall and discharge scenarios.

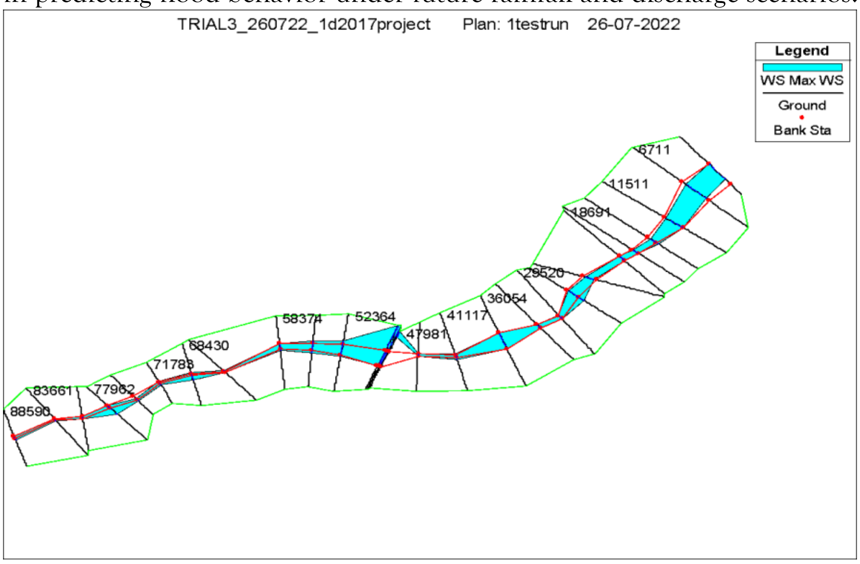

Figure 8. X-Y-Z perspective plot.

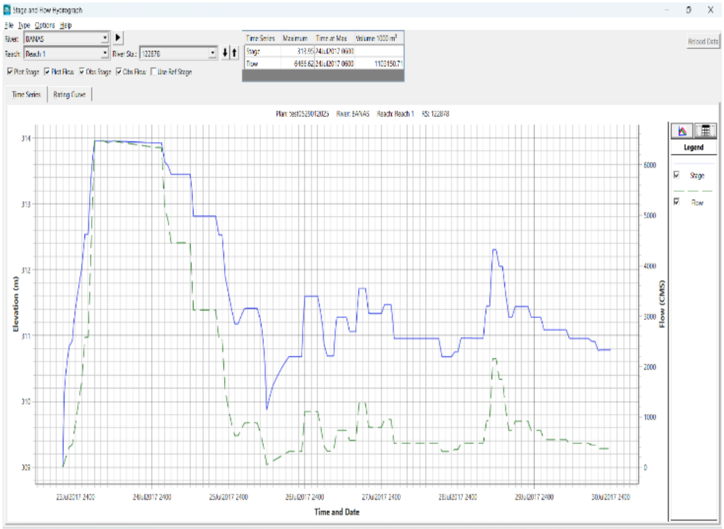

Figure 9. Stage and flow Hydrograph.

4. RESULTS AND DISCUSSIONS

4.1 Simulation of the 2017 Banas River Flood Event

The 1D HEC-RAS model was applied to simulate the major flood event of July 2017 in the Banas River basin. The outputs were generated at a 30-minute time interval for the period from 24 July 2017 to 25 July 2017, capturing the dynamics of flood propagation. The simulated results indicate that the flood event initiated at 11:00 h on 24 July 2017, when the river discharge reached 3,500 m^3/s, marking the onset of inundation. The affected upstream villages included Ranawas, Vadvas, Varnia, Malivas, and Chekhala, while downstream villages such as Rampura and Arniwada also experienced severe submergence.

4.2 Flood Inundation Analysis

The flood extent during the peak event is illustrated in Figure 10, which presents the inundation map corresponding to the discharge of 6,438 m^3/s at 23:00 h on 24 July 2017. The inundation analysis shows a boundary length of approximately 609,803.01 m, with a total inundated area of 73.03 km^2. This large-scale flooding submerged both agricultural and residential zones, highlighting the spatial vulnerability of low-lying regions along the Banas River. Furthermore, Figure 11 identifies the specific upstream villages that were inundated, corroborating field observations reported during the disaster.

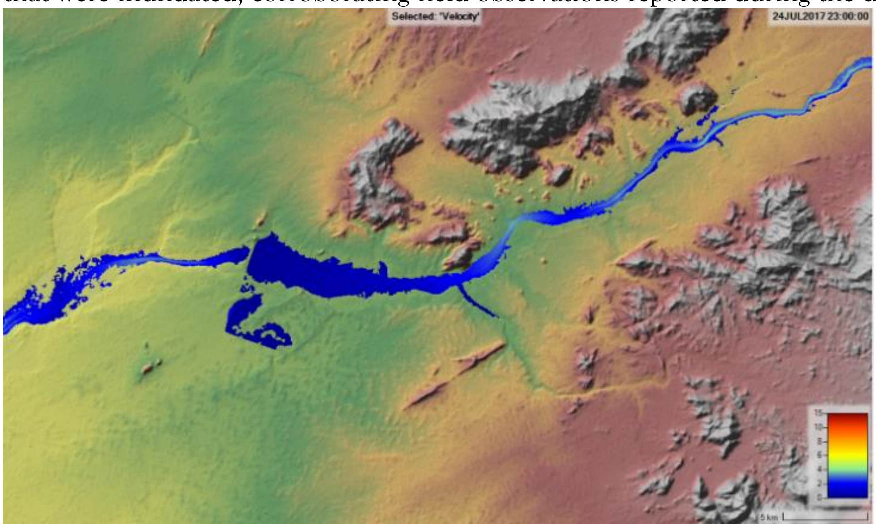

Figure 10. Flood inundation map of 24 July 2017, 23:00 Banas Discharge 6438 m^3/s.

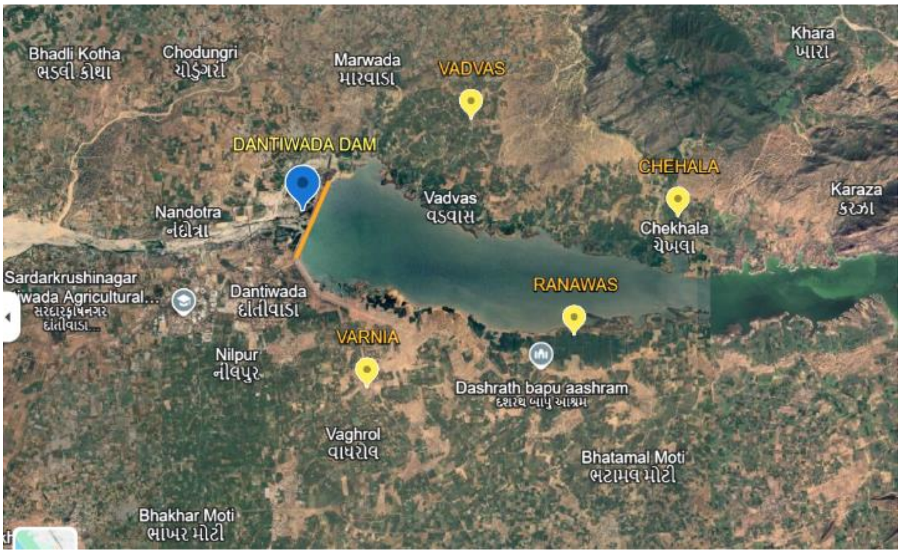

Figure 11. Upstream Submerged villages in the flood event of 2017.

4.3 Hydrodynamic Parameters of Flooding

To better understand the hydraulic behaviour of the flood event, the HEC-RAS results were integrated into ArcGIS to produce spatial maps of flood depth, velocity, water surface elevation, and inundation boundaries.

1. Flood Depth: Between 21 August and 24 August 2017, water depths increased progressively, reaching peak levels that remained stable for several hours. The depth variations confirm the high storage capacity of floodplains, where waterlogging persisted even after peak discharge receded (Figure 12).

2. Velocity Distribution: The velocity maps highlight high-energy zones concentrated along the main river channel, with reduced velocities in adjoining floodplain areas. This variation is critical for understanding sediment transport and potential erosion during extreme floods (Figure 13).

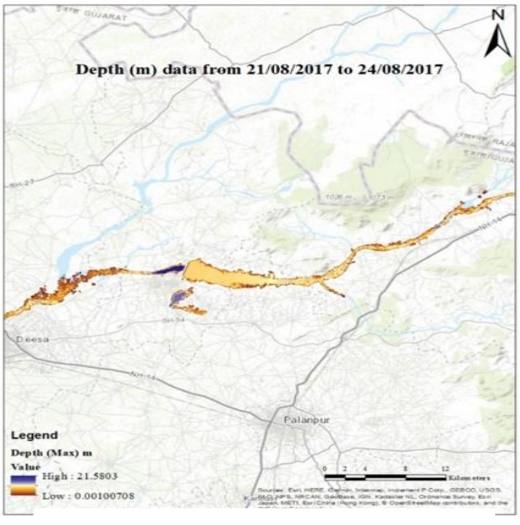

Figure SEQ Figure * ARABIC 12. Depth (m) data from 21/08/2017 to 24/08/2017

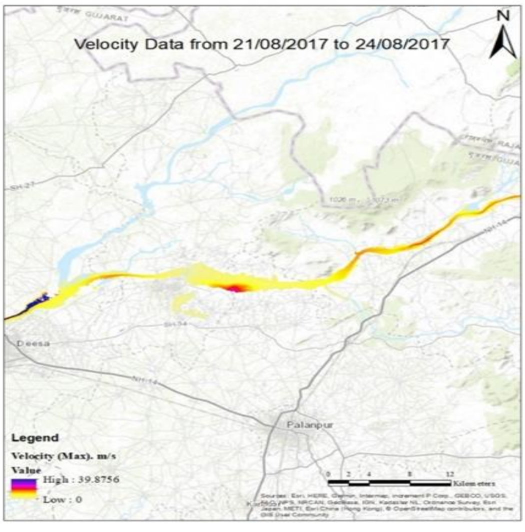

Figure SEQ Figure * ARABIC 13. Velocity (m) data from 21/08/2017 to 24/08/2017

3. Water Surface Elevation: The longitudinal water surface profile showed significant fluctuations, with elevated levels corresponding to peak discharge conditions. These variations are consistent with the overflow experienced at the Dantiwada Dam reservoir, where storage exceeded safe thresholds (Figure 14).

4. Flood Inundation Boundary: The delineation of the inundation boundary provides an accurate representation of the spatial extent of flooding across the basin. The results demonstrate the connectivity between upstream flood surges and downstream overflows, establishing the cascading flood risk from the upper Banas basin to low-lying settlements (Figure 15). However, the extreme inflows from the upper Banas basin during this event led to overtopping at the Dantiwada Dam, aggravating flooding in the

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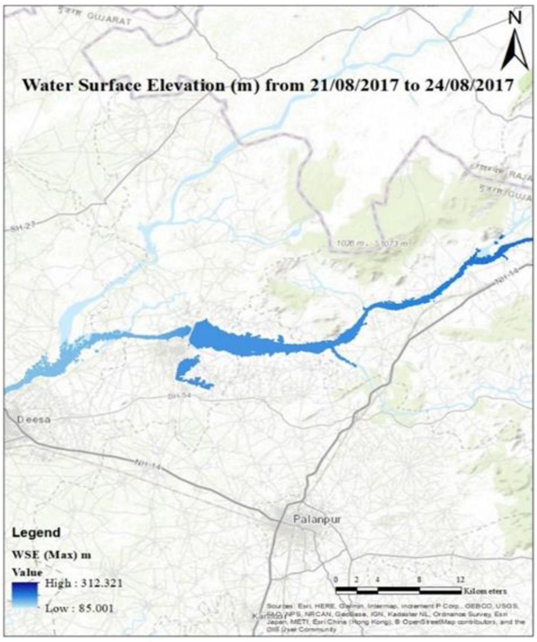
downstream reaches. The event emphasizes the vulnerability of existing infrastructure to high-magnitude floods and underscores the need for enhanced reservoir operation strategies and early-warning mechanisms.



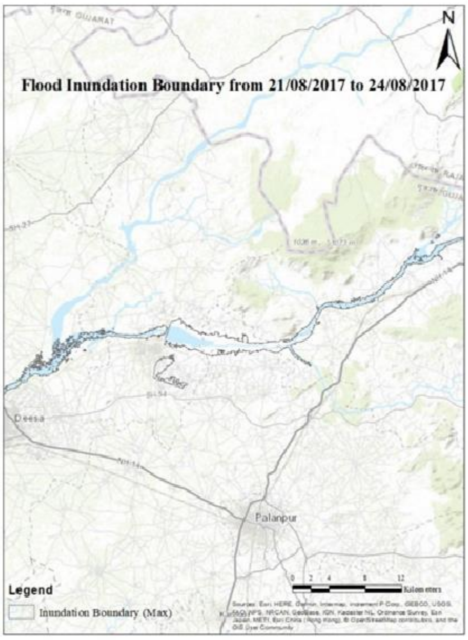


Figure SEQ Figure * ARABIC 14. Water surface elevation (m) from 21/08/2017 to 24/08/2017

Figure SEQ Figure * ARABIC 15. Flood Inundation boundary (m) from 21/08/2017 to 24/08/2017

5. CONCLUSIONS

The flood modeling results of the 2017 Banas River event provide critical insights into the dynamics of an extreme hydrological disaster in Banaskantha district, Gujarat. The HEC-RAS simulation effectively captured the temporal variation of discharge, depth, velocity, and water surface elevation, with outputs highlighting the rapid escalation of flooding from an initial discharge of 3,500 m^3/s to a peak of 6,438 m^3/s within a few hours. The analysis revealed that approximately 73.03 km^2 of land was inundated, affecting multiple upstream and downstream villages, while the overtopping of the Dantiwada dam reservoir amplified downstream hazards. Depth and velocity distributions confirmed that the areas of maximum inundation coincided with zones of high hydraulic energy, increasing the risk of erosion, structural damage, and community displacement. The integrated use of HEC-RAS and ArcGIS proved instrumental in producing reliable inundation maps, identifying flood-prone zones, and providing critical datasets for disaster preparedness and mitigation strategies. The findings reinforce the importance of hydrodynamic modeling in flood-prone basins and underline the necessity of developing resilient infrastructure, robust embankments, and effective early warning systems. Furthermore, the study highlights the urgent need for proactive land-use planning and community-based disaster risk reduction measures to reduce the vulnerability of Banaskantha district to future flood events.

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