Development of an Integrated Flood Risk Management Model for the Panchganga River Basin, Kolhapur District

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Abstract: The Kolhapur district in Maharashtra, on the banks of the Panchganga river, which is prone to frequent flooding such as 2019 and 2021. The region's topography, heavy monsoonal rainfall and poorly managed urban growth are significant factors that increase flood risks. The study aims to support flood resilience through developing a framework for flood management. The main parameters, that trigger flooding such as rainfall, slope, land use, elevation, runoff, flood depth and population density, are investigated. A Digital Elevation Model (DEM) is created with QGIS to perform topographic and hydrological analysis through spatial data processing. The HEC-RAS program is used to simulate the behaviour of rivers and to define flood risk zones. Some of the recommendations put forward are based on the principle of integrated river basin management, spatial restructuring, early warning systems and community resilience. The measures are intended to minimize the impact of flooding and facilitate sustainable regional planning. The study offers a repeatable approach to the districts susceptible to floods in India.
Keywords: Kolhapur, Flood Management, Panchganga River

Introduction

Water Flooding is one of the most common and worst hydrometeorological hazards that may cause significant loss of life, property and infrastructure. Flood prone areas like Kolhapur (Maharashtra) in India are becoming more vulnerable because of the increasing chances of extreme rainfall events, mismanagement of dams and its structures, encroachments, and an unregulated approach to land use. The Panchganga River that passes through Kolhapur is a river that has a history of flooding its banks, especially in 2005, 2019 and 2021. The problem of flooding on the river Panchganga has been a frequent and serious event in Kolhapur District especially during monsoon season. The critical flood incidents in the district in 2005, 2019 and 2021 highlighted the weaknesses in the district's disaster preparedness and urban planning (Chaphalkar & Tiwari, 2021).

Some of the important factors are encroachments on floodplains, unplanned urban expansion, deforestation in catchment areas, and outdated drainage system (Gavhane and Raut, 2020; Deshmukh et al., 2021). The topography and river confluence of Kolhapur make it susceptible to floods, and poor land utilization and lack of coordination among the authorities make the situation worse (Tiwari & Kumar, 2021). The use of the GIS and Remote Sensing (RS) techniques to analyze flood prone zone and to improve the management of the floods is evident in the use of model AHP and Morphometric analysis in Kolhapur as well as the entire Panchganga basin (Gavali & Pawar, 2020; Bhagat et al., 2021; Golekar & Kulkarni, 2021). The tools help to develop flood hazard maps and define vulnerable communities from a scientific perspective and provide the basis for interventions.

Indian Meteorological Department (IMD) states that the number of heavy rainfall days is gradually increasing in Western Ghats in the river basin such as Panchganga. Kamble et al. (2020) reported that more than 200 villages in Kolhapur were flooded in 2019 and more than 2.5 lakh people were affected. The disaster underscored the need for better flood infrastructure, and for integrated flood resilience planning. Along with geospatial technologies, NbS and integrated watershed management are also new, sustainable and resilient approaches towards flood mitigation (Kumar et al., 2020; Sharma et al., 2020).

Improvements to wetlands, afforestation and sustainable farming in the basin can help retain excess rainfall and minimize runoff. Community based preparedness, early warning and engagement of local stakeholders have been found effective in strengthening resilience particularly in semi urban and rural areas of Kolhapur (Chavan & Kanase, 2020; Patil et al., 2020). Some studies have suggested Integrated River Basin Management (IRBM) as a comprehensive approach to coordinate the planning of both the upstream and the downstream areas of the river, addressing both the environmental, social and economic aspects (Jadhav et al., 2020; Shinde et al., 2021). The aim of the present study is to develop a holistic flood resilience management plan for Panchganga River region using the geospatial data, community feedback and policy frameworks. The results will be used to design future initiatives to reduce the risk of flooding and to improve disaster management in Kolhapur District (Deshmukh et al., 2026).

This paper examines an interdisciplinary strategy where the spatial analysis and GIS, hydrological modelling and

HEC-RAS, and the extreme value statistics and Gumbel distribution are integrated. It offers a framework for local government, disaster management authorities and planners to adopt in order to reduce exposure and vulnerability in the Panchganga basin from flooding (Deshmukh et al., 2026). This paper attempts to address vulnerabilities of the Panchganga River Basin, analyze the current flood management system in Kolhapur and suggest a comprehensive and sustainable approach to make the river basin more flood resilient. The result is to assist urban planners, engineers and policy makers in designing a good flood mitigation framework.

Study Area: Panchganga River Basin

The source of Panchganga river is Prayag Sangam in Kolhapur district of Maharashtra at 16°44′4″N 74°10′33″E. It is created by the confluence of five rivers, namely Kasari, Kumbhi, Tulsi, Bhogavati and Saraswati and is 80.7 km long before it joins the Krishna River.

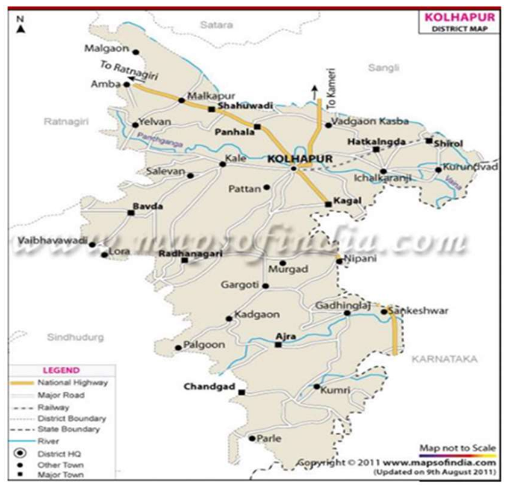


Fig. 1 Kolhapur Map (Source - www.mapsofindia.com)

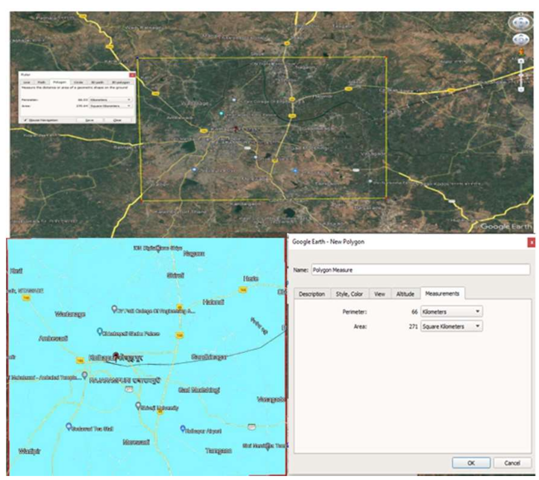


Fig. 2 Selected Study Area (Source - Google Earth)

Research Methodology

The research methodology of this paper starts with identifying and selecting the key risk parameters that affect flood occurrences in the Kolhapur region, especially along the Panchganga River.

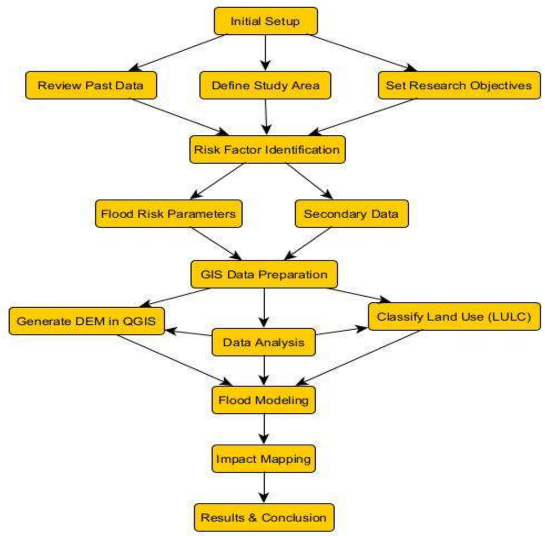


Fig. 3 Research Methodology for the study

The parameters include meteorological, hydrological, topographical and socio-economic variables like rainfall intensity, soil parameters, slope gradient, downstream obstructions, land use/land cover (LULC), nearness to river, elevation, surface runoff, flood depth and velocity, stream density and depth, population distribution, critical infrastructure and crop type. These variables are gathered from different national databases, remotely sensed imagery and the available literature for a comprehensive knowledge of the flood prone dynamics in the region (Deshmukh et al., 2026).

The methodology after data collection, is the spatial data processing using Quantum geographic information system (QGIS), to produce Digital elevation model (DEM) as the basis of terrain and watershed analysis. These are then used in a river hydraulics model using the Hydrologic Engineering Center River Analysis System (HEC-RAS) to simulate flood events under various scenarios. This helps to produce flood risk maps to identify areas that are vulnerable to flooding. Furthermore, Gumbel’s statistical approach is used for analysing flood frequency and making forecasts, yielding probabilistic estimates of extreme flooding occurrences (Deshmukh et al., 2026). This is a holistic approach that can be used to create detailed flood models and flood risk maps, and help to develop suitable flood management and mitigation plans for the area.

Data Collection

Primary and secondary sources were used to collect data for this study to determine flood vulnerability along the Panchganga River in Kolhapur district. The study area was initially marked using Google Earth, this gave spatial orientation and area of square kilometres was estimated. The Maharashtra Water Resources Department, Maharashtra (Mahahp, Pune Division) was used to obtain rainfall data to help understand the precipitation patterns that influence flood risks. Also, 20-years of maximum data for the daily and annual discharges were acquired from the Terwad discharge station under the Central Water Commission (CWC) in Pune. These are the data sets used to analyse hydrological parameters that are critical for flood modelling.

Topographic and land use analysis was facilitated by obtaining Digital Elevation Model (DEM) and land use/landcover data from USGS Earth Explorer from SRTM imagery and satellite bands. With these spatial data it was possible to create accurate terrain profiles, slope measurements and drainage data in QGIS. A computer modeling program called HEC-RAS (Hydrologic Engineering Center River Analysis System) was used to model flood depth and flood velocity data. The combination of these tools enabled to assess the hydrological behaviour, to prepare spatial flood impact maps and to generate flood forecasts for the study area.

In QGIS the study area was delineated to estimate the catchment size. Then slope and drainage density were derived from the DEM and river network data. LULC (land use and land cover) maps were developed to assess urbanisation and land transformation trends impacting flood risk. Based on discharge data and terrain inputs, the flood simulation was carried out using HEC-RAS software for the 2019 10-day flood event, to model the depth and velocity of flooding. Rainfall distribution was computed in QGIS, using the method of Polygon developed by Thyssen. Precipitation modelling and hydraulic parameters were combined in HEC-RAS to create flood risk zones. Moreover, Gumbel's distribution method was used to estimate flood recurrence intervals for the coming 100 years to assist in flood resilience planning for the long-term along the Panchganga river.

Data Analysis

The below GIS Map is a visual representation of the Panchganga River network and its basin in Kolhapur District. It overlays layers such as topography (contours), rivers and place names, giving it a spatial context. This Visual

Tool is critical to understanding flood patterns and creating successful flood resilience strategies. The map is probably used to create hydrological modelling and risk assessment in the paper.

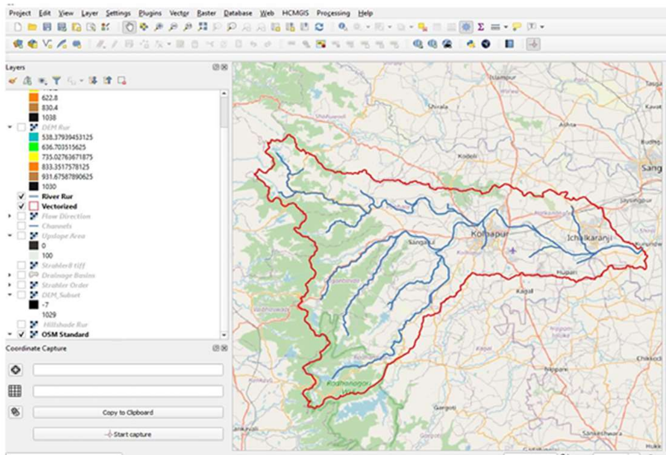


Fig. 4 GIS map with the river for present study

The map below is a crucial visualization that was created using methodology. It is a direct representation of the modelling of hydrology and hydraulics done with HEC-RAS, based in the Digital Elevation Model (DEM) and other spatial data that was processed in QGIS. It is evident that this map is able to clearly indicate the flood-prone areas in Kolhapur District in addition to clearly showing the different flood depths. The map visually shows the spatial distribution of flood depths, providing a tangible result of the analysis and demonstrating the severity and extent of flood risk throughout the district. This map helps to visually confirm the main conclusions of the study regarding flood vulnerability and gives a clear basis for informed spatial planning and the proposed management measures.

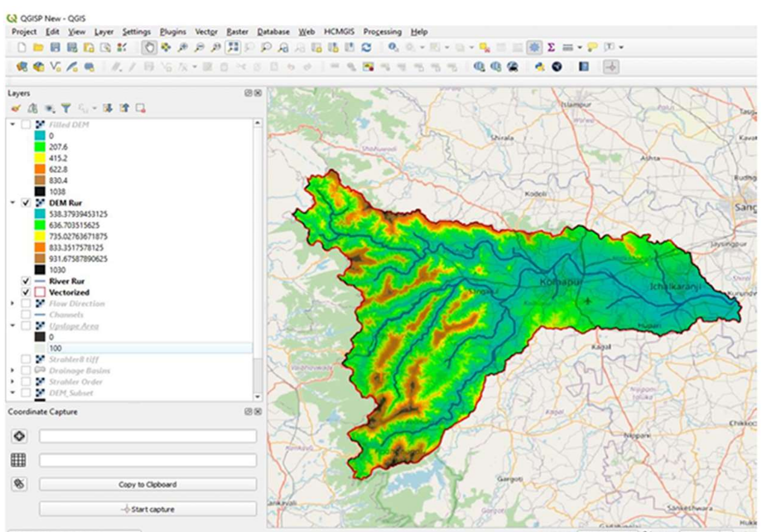
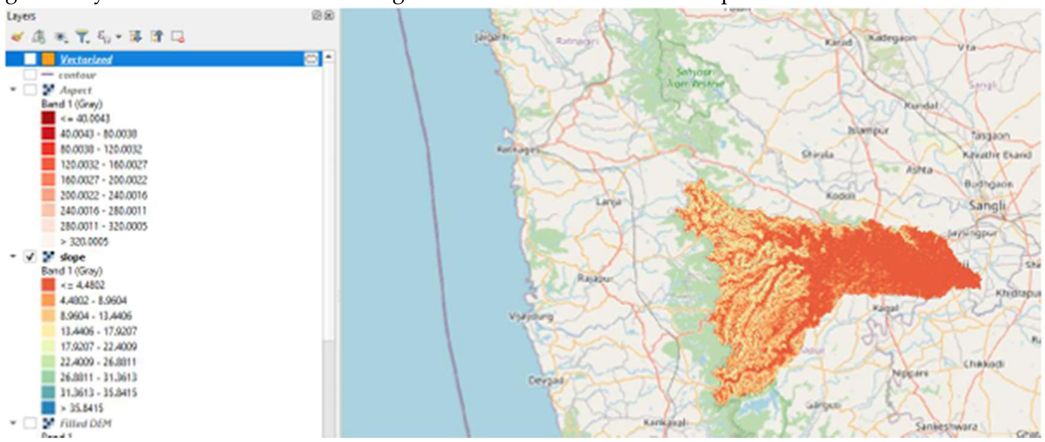


Fig. 5 Digital Elevation Model (DEM)

Identification and determination of parameters that can cause flooding. In analysing flood vulnerability, several key risk parameters are crucial. The magnitude of a flood is directly related to rainfall, with heavy or prolonged rainfall, that exceeds the infiltration capability of the soil, producing high surface runoff and rapid rise in river levels. This runoff is effected by the slope of the surface, the longer and steeper the slope the greater the velocity of the runoff and the more runoff which will occur. Land Use/Land Cover (LULC) significantly affects flood frequency and intensity, with urbanisation and deforestation causing water to run faster and in larger volumes, thus increasing the risk of flood damage; and with good land-use planning, flood damage can be reduced. The ratio of the total length of the streams in the basin to the area of the basin is called the drainage density. The higher the drainage density the more effective the drainage from the basin and the more rapid the surface runoff and discharge



through the stream. Finally, Flood Depth and Flood Velocity are direct measures of flood severity, increasing width, depth and velocity in the river as discharge increases, and ultimately leading to channel overflow and widespread flooding.

Fig. 6 DEM Map - Slope

The above map displays the slope of the terrain, derived from the DEM, which is critical for understanding runoff velocity and water accumulation patterns.

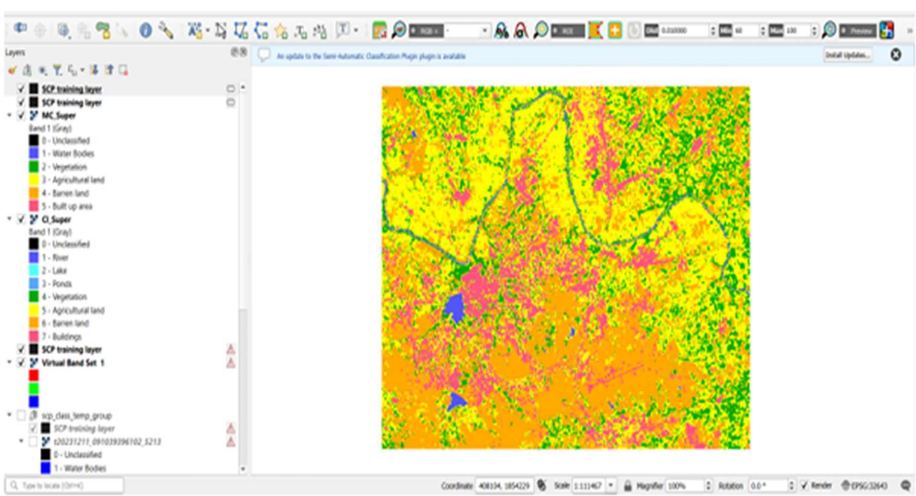
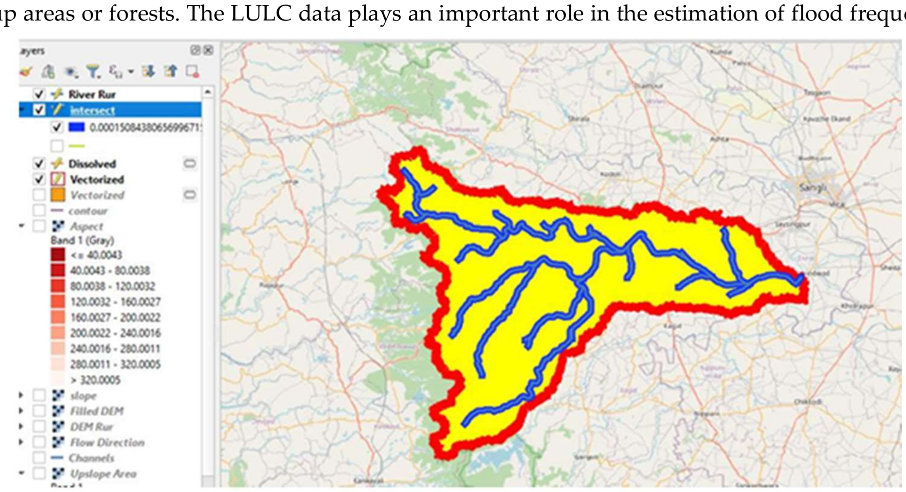


Fig. 7 DEM Map – Land Cover

The above map is the Land Use/Land Cover (LULC) classification, which is a way of categorizing the surface types, such as built-up areas or forests. The LULC data plays an important role in the estimation of flood frequency and



magnitude and in developing sustainable land use practices to minimize the effects of flooding.

Fig. 8 DEM Map – Drainage Density

The above map is a representation of the drainage network in the Panchganga River basin with the yellow area marking the Panchganga River basin boundary and the blue lines carefully delineating the main river and its many tributaries. This full system is important for calculating drainage density, a hydrological parameter that is the length of all the streams in a basin divided by the area of the basin. The higher the drainage density, represented by the more closely spaced blue lines, the more efficient and rapid the removal of surface runoff from the basin, thus directly affecting flood characteristics in the basin during precipitation events. The Hydraulic Modelling and Flood Delineation using HEC-RAS software. The use of the Hydraulic Modelling and Flood Delineation software HEC-RAS. This study's management approach was enhanced by the use of the HEC-RAS program to model river behaviour and delineate flood risk areas. Two sample models were created to simulate flood events and to understand the inundation pattern along the Panchganga River.

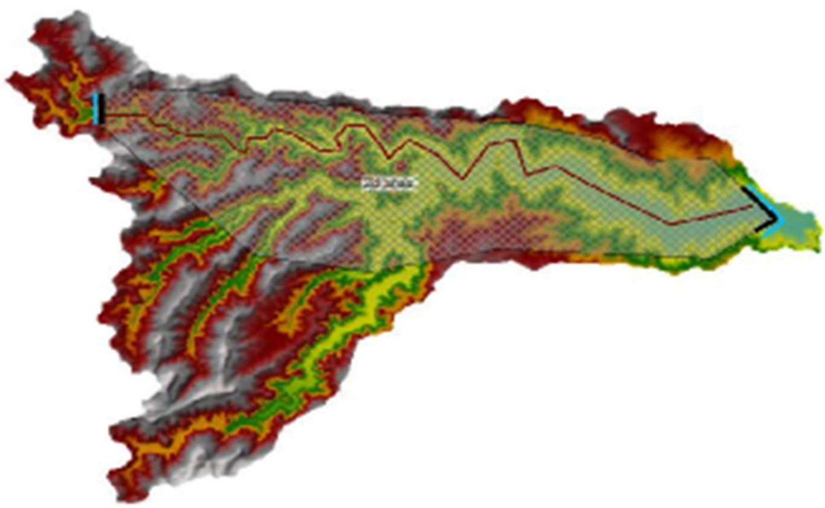


Fig. 9 2D Area and Channel (Sample Model 1)

The above fig. shows the initial configuration of a river reach in the HEC-RAS modelling environment on top of the Digital Elevation Model (DEM) of the Panchganga River basin. This visualization shows the elevation or profile of the river along the specified section (shown in red) of the river channel. The different shades of the terrain indicate its topography, an essential detail for water flow simulation. This figure shows how the geometry of the river and the elevation of the basin are integrated – a fundamental step needed to define the hydraulic characteristics of the river channel and floodplain. The blue sections at the upstream and downstream boundaries may be boundary conditions or specific cross-sections within the model.
The output and summary for an unsteady flow simulation done in HEC-RAS version 6.4.1 are shown in above fig. The upper part shows the "Finished Computation" window that contains information about the simulation run, such as computation messages and a summary of the unsteady input. This encompasses important parameters such as "Overall Volume Accounting Error" which reflects the model's accuracy and stability. The bottom of the figure shows the simulated flood inundation area as computed (as a visual representation). The different shades of blue and green over the terrain represent flood inundation zones, and the different shades may be flood depths dependent (as a function of the HEC-RAS model). This number directly supports the study's "delineation of flood risk areas," and offers significant knowledge about the spatial scale and nature of flood events.

Discussion

The HEC-RAS program was used to model the river behaviour and establish flood risk areas. Two sample models were developed to simulate flood events and to understand inundation pattern along the Panchganga river.
The geometric setup within HEC-RAS is shown in figure 11 with a defined 2D flow area (in teal) and the integrated river channel (in red) on top of the DEM. This setup is necessary to simulate the complex propagation of flood water throughout the floodplain, showing the spatial input that is needed for the hydraulic model.

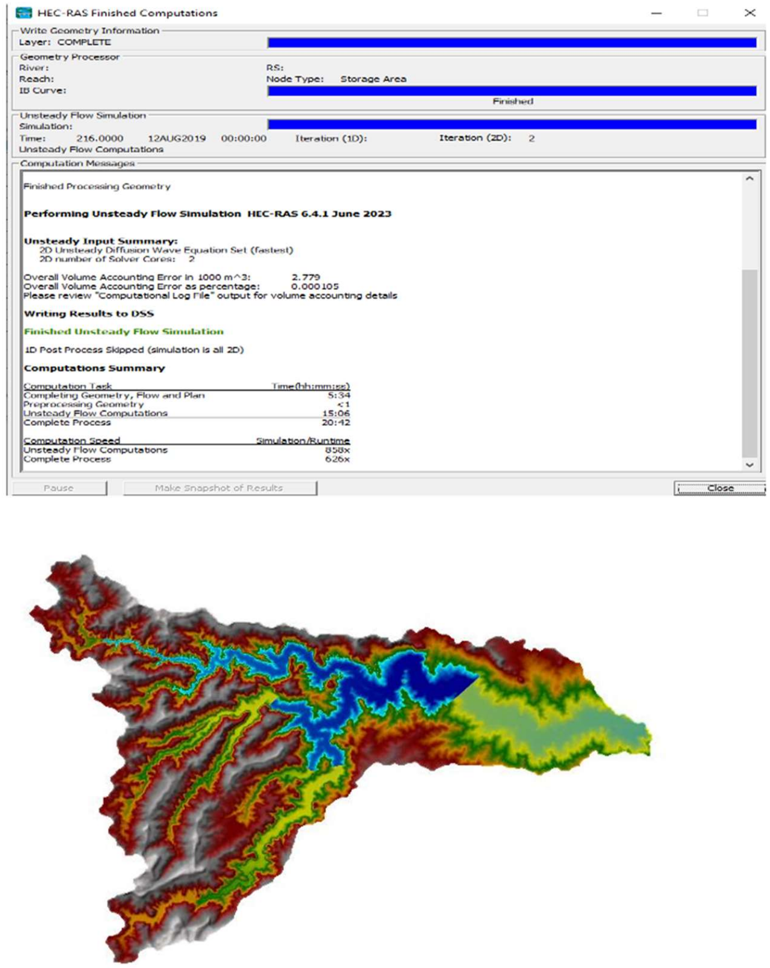


Fig. 10 HEC-RAS model for Panchganga River

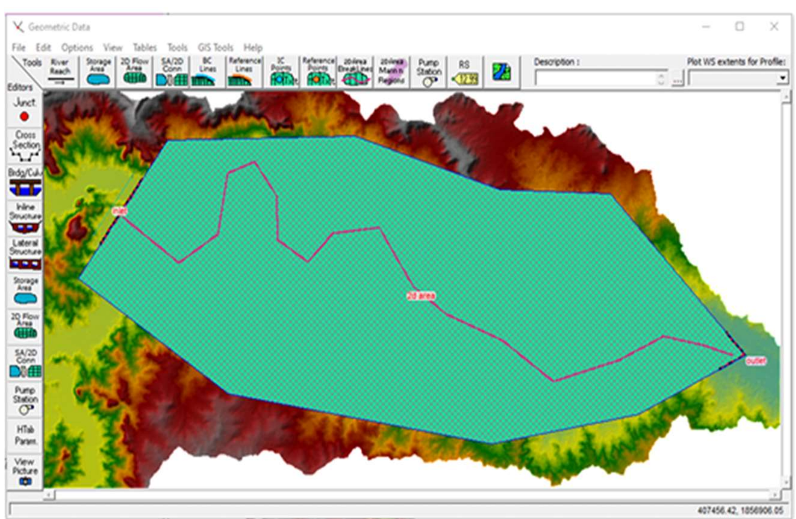


Fig. 11 2D Area and Channel (Sample Model 2)

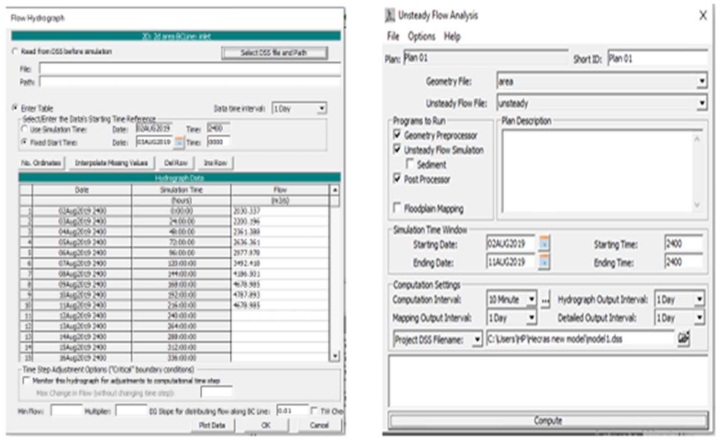


Fig. 12 Unsteady Flow Analysis

An unsteady flow analysis can be performed in HEC-RAS using input parameters and settings as shown in Figure 12. This interface shows crucial details such as simulation time windows, computation intervals, and output settings, all vital for conducting robust hydraulic simulations. This figure shows the technical set up supporting the flood modelling.

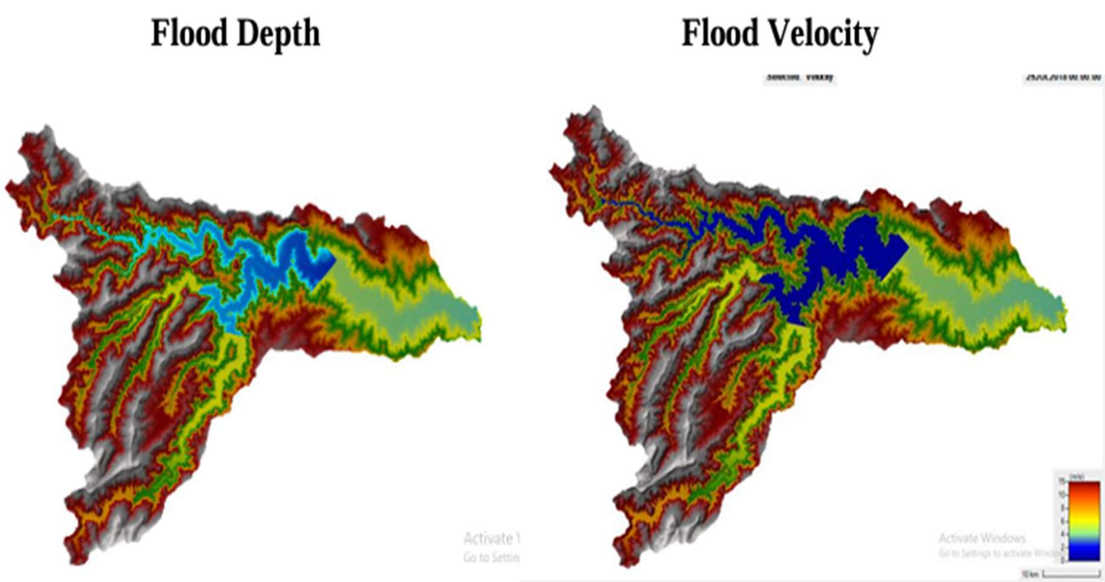


Fig. 13 Flood Depth & Flood Velocity

The main results of the HEC-RAS hydraulic modelling are shown in Figure 13: maps showing Flood Depth and Flood Velocity throughout the simulated floodplain. Left map is different level of inundation, right map is the speed of inundating water. The maps will help identify high-risk areas, assess potential damage, and develop targeted flood management and warning programs.

Conclusion

In Kolhapur District, an area that is becoming more and more susceptible to frequent and severe floods, this study successfully offers a structured management method to improve flood resilience along the Panchganga River. A combination of hydraulic simulations in the program HEC-RAS and geospatial analysis in the program QGIS proved to be effective to map the high risk flood zones and to predict the flood behaviour in extreme situations, based on modelling and evaluation of the most important flood-inducing factors such as drainage density, topography, land use, rainfall intensity and runoff. By using Gumbel's method, the predictive capacity was further enhanced by predicting the flood magnitude for different return periods. This multi-disciplinary approach provides a scalable framework that can be used for various other river basins with flood risk in addition to helping in the data-driven planning and preparedness of Kolhapur. The findings provide local governments, urban planners and disaster management agencies with practical guidance in strengthening early warning systems, implementing targeted mitigation strategies, and fostering disaster risk informed and sustainable development along the Panchganga River. The results of the geospatial analysis and hydraulic modelling highlight the importance of taking proactive measures for flood management in the region. The produced DEM and the resulting HEC-RAS flood simulations have been used to identify vulnerable areas, to understand the effects of existing infrastructure on flood dynamics and to scientifically base decision-making. This holistic solution enables the identification of possible mitigation measures such as planned and targeted placement of flood control structures, optimisation of land use planning and implementation of suitable early warning systems. Additionally, the approach used in this study clearly shows the potential of using open source GIS software, such as QGIS, and hydraulic software that are widely available, such as HEC-RAS, to solve the complex issues of water resource management. These tools are easily accessible, affordable and replicable and can be adapted to other riverine systems in other areas that are at risk of flooding. Finally, this study offers a solid basis to improve flood resilience for the Panchganga River. The overall combination of QGIS and HEC-RAS is a comprehensive tool set to comprehend flood dynamics, assess vulnerability, and assess the effectiveness of potential management interventions. The information obtained from this study is essential for the policymakers, disaster management organisations and local communities in Kolhapur District to formulate and implement sustainable solutions to reduce the effect of future flood events and create a resilient future for the district. Further studies may involve applying climate change scenarios to the hydraulic models and examining or discussing the socio-economic impacts of the proposed management plan to provide a more comprehensive understanding and implementation plan.

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