



Real-time flood forecasting using an integrated hydrologic and hydraulic model for the Vamsadhara and Nagavali basins, Eastern India

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Abstract

Due to recent rainfall extremes and tropical cyclones that form over the Bay of Bengal during the pre- and post-monsoon seasons, the Nagavali and Vamsadhara basins in India experience frequent floods, causing significant loss of human life and damage to agricultural lands and infrastructure. This study provides an integrated hydrologic and hydraulic modeling system that is based on the Soil and Water Assessment Tool model and the 2-Dimensional Hydrological Engineering Centre-River Analysis System, which simulates floods using Global Forecasting System rainfall forecasts with a 48-h lead time. The integrated model was used to simulate the streamflow, flood area extent, and depth for the historical flood events (i.e., 1991–2018) with peak discharges of 1200 m³/s in the Nagavali basin and 1360 m³/s in the Vamsadhara basin. The integrated model predicted flood inundation depths that were in good agreement with observed inundation depths provided by the Central Water Commission. The inundation maps generated by the integrated modeling system with a 48-h lead time for tropical cyclone Titli demonstrated an accuracy of more than 75%. The insights gained from this study will help the public and government agencies make better decisions and deal with floods.

Keywords Floods · Flood inundation area and depth · Lead time · SWAT · HEC-RAS · GFS · Integrated model

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1 Introduction

The intensity and frequency of precipitation extremes have changed as a result of climate change, which has a significant impact on human life and infrastructure, particularly by contributing to floods (Ali et al. 2019; Guhathakurta et al. 2011; Luo et al. 2018; Sridhar et al. 2019; Moustakis et al. 2021). Extreme precipitation is expected to become more common in the Indian subcontinent as the climate warms (Asghar et al. 2019; Mishra et al. 2018; Nanditha and Mishra 2021). Recent studies by Bisht et al. 2018; Dash et al. 2009; Deshpande et al. 2016; Dubey and Sharma 2018; Goswami et al. 2006; Guhathakurta et al. 2011; Jain et al. 2017; Krishnamurthy et al. 2009 reported a significant increase in extreme precipitation events on a national and regional scale. Flooding is becoming more common in India as extreme weather events become more common, accounting for half of all natural disasters (Patankar 2020). According to flood statistics from the Government of India, the flood-affected area in India has increased from 25 million hectares (Mha) in 1952 to 40 Mha in 1980 and 49.8 Mha in 2011 (Bhanduri 2019). Between 1953 and 2011, floods claimed 1,653 lives per year on average and caused 36.12 billion USD in economic losses, including house, public property, and crop damage, according to government records (Joshi 2020). Flood damage is caused by a number of factors, including rapid population growth, rapid urbanization, increased development and other activities in flood plains, snowmelt anomalies, and global warming (Hillard et al. 2003; Leon et al. 2014; Bhatt et al. 2017; Sridhar et al. 2021).

Structural flood protection measures such as dams, levees, embankments, and flood walls emphasize modifying a flood characteristic to reduce peak evaluations and spatial extent (Sudheer et al. 2019). However, these measures will not completely eliminate the risk due to the difficulty in building larger structures to handle extremely low probability events (Perumal et al. 2011). As a result, experts have advocated for a shift away from structural flood protection measures and toward non-structural flood protection measures that reduce flood exposure (Jain et al. 2018). Flood forecasting is an important non-structural measure for preventing flood damage and reducing flood-related deaths and it is only beneficial if accurate forecasts are made with sufficient lead time (Hillard et al. 2003; Nanditha and Mishra 2021).

The Central Water Commission (CWC) is the nodal agency in India for providing deterministic flood forecasts based on observed precipitation and streamflow across the major rivers and their tributaries. Currently, CWC provides flood warnings at 324 stations, including 128 reservoir inflow forecasts and 196 water level forecasts (CWC 2020). In addition to the CWC forecasts, researchers have used several hydrologic models to predict streamflow across various river basins (Kumar et al. 2015; Nanda et al. 2019, 2016; Perumal et al. 2011, 2007; Shah and Mishra 2016; Tiwari and Chatterjee 2011; Sridhar et al. 2013). The majority of these studies produced inflow estimates at specified locations along the river for real-time reservoir operations. During the extreme weather events, local agencies use the CWC water level forecasts to issue early warnings and plan rescue operations (Harsha 2020). However, water level estimates at a point were inconsistent and sparse over large areas, resulting in uncertainty in estimating flood inundation area and flood depth, making rescue operations difficult for local agencies. This is especially true following the recent floods in Assam, Tripura, Karnataka, Tamil Nadu, and Kerala (CWC-FRMD 2020). Local administrations can make better decisions and be better prepared if they have flood forecasts with inundation areas rather than deterministic flood forecasts. Countries such as the United States, the European Union and Japan have already shifted their focus to flood

forecasting and inundation areas (Harsha 2020). In India, public and government officials have limited information about the extent and depth of flood inundation. As a result, there is a need for integrated hydrologic and hydraulic models to be developed with enough lead time to provide flood forecasts as well as inundation extent and depth.

From the literature, it has been observed that numerous hydrologic models such as SWAT (Soil and Water Assessment Tool) (Arnold et al. 2012), HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System) (Sahu et al. 2023), VIC (Variable Infiltration Capacity) (Liang et al. 1994; Hillard et al. 2003; Hoekema et al. 2013; Sridhar et al. 2021), HBV (Hydrologiska Byråns Vattenbalansavdelning) (Devia et al. 2015), TOPMODEL (TOPographic MODEL) (Beven and Kirkby 1979), HSPF (Hydrological Simulation Program-FORTRAN) (Li et al. 2012), DHSVM (Distributed Hydrology-Soil-Vegetation Model) (Wigmosta et al. 1994), MIKE SHE (MIKE by DHI Surface Water Hydrology) (Ma et al. 2016), WBNM (Water Balance Model) (Kemp and Daniell 2020), PRMS (Precipitation-Runoff Modeling System) (Dhami and Pandey 2013), and MACHBV (McMaster University Hydrologiska Byrans Vattenbalansavdelning) (Machado et al. 2015) are used for streamflow simulations worldwide.

Our earlier studies have implemented the SWAT model in India (Nageswara Reddy et al. 2022; Jayanthi et al. 2022; Ramabrahmam et al. 2021), Southeast Asia (Kang et al. 2021; Sridhar et al. 2019) and the U.S. (Sehgal and Sridhar 2019; Thilakarathne et al. 2018; Sehgal et al. 2018; Leon et al. 2014) and we developed reliable baseline parameters and model customization techniques from these efforts. HEC-HMS is another widely used hydrologic model employed for water resources management, flood forecasting, and reservoir operations and includes specialized modules for different hydrologic processes (Sahu et al. 2023). TOPMODEL is mainly designed to focus on topographic control, and its representation of subsurface flow makes it a valuable tool for analyzing hydrological processes in a watershed. However, it has limited applicability in flat or arid regions and requires high-resolution topographic data for better representation (Beven and Kirkby 1979). HSPF is a powerful tool for simulating hydrological and water quality processes in watersheds. It captures the interactions between land use, hydrological processes, and pollutant transport, allowing for comprehensive analysis and management of water resources and pollution control strategies. However, extensive calibration is required (Li et al. 2012). DHSVM's distributed nature and ability to capture spatial variability of hydrological processes make it valuable for simulating water and energy movement in complex landscapes. It provides insights into watershed-scale hydrological processes and supports decision-making in water resources management and land use planning. However, it is computationally intensive and has limitations in representing groundwater processes (Wigmosta et al. 1994). MIKE SHE's integrated approach, combining surface water and groundwater modeling, makes it a powerful tool for studying and managing water resources holistically. It enables a comprehensive analysis of the hydrological cycle and its impacts on water availability and quality. However, it is a complex model with a specialized software and a steeper learning curve (Ma et al. 2016). WBNM serves as a valuable tool for understanding overall water dynamics and assessing the sustainability of water resources in a given area. It quantifies water inputs, outputs, and storage, aiding decision-making related to water management, planning, and policy development. However, it may not capture complex hydrologic processes due to limitations in process representation (Kemp and Daniell 2020). PRMS offers a flexible and comprehensive framework for simulating hydrological processes within a watershed. By considering spatial and temporal variability of watershed characteristics, it enables detailed analyses of water availability, runoff generation, and streamflow dynamics. Its applications contribute to informed decision-making and sustainable water

resources management. However, extensive calibration is required for accurate representation (Dhami and Pandey 2013).

From the literature, it has been observed that numerous hydraulic models such as HEC-RAS (Hydrologic Engineering Centers River Analysis System) (Brunner 2016), SWMM (Storm Water Management Model) (McDonnell et al. 2020), MIKE URBAN (DHI Urban Water Modeling Software) (DHI 2023), InfoWorks ICM (Integrated Catchment Modeling) (Sidek et al. 2021), InfoWorks CS (Collection System Modeling) (Chan et al. 2002), XP-SWMM (eXtended Period Simulation SWMM) (SWMSP 2023), MOUSE (Modular Urban Stormwater Environment) (Haris et al. 2016), and TUFLOW (Two-Dimensional Unsteady FLOW) (Huxley 2004) are used for surface and subsurface water modeling.

Among all the hydraulic models, HEC-RAS is one of the most widely used models, supporting both steady and unsteady flow simulations with its 1D, 2D, and combined 1D and 2D capabilities (Brunner 2016). SWMM is specifically designed for stormwater management and drainage modeling. It handles runoff modeling, pollutant transport, and water quality analysis and supports various stormwater control measures. However, the model requires detailed input data for calibration and has limited capabilities in other aspects of hydraulic modeling (McDonnell et al. 2020). MIKE URBAN software is mainly used for urban water modeling. It integrates water distribution, wastewater collection, and urban drainage systems and supports simulation of all components of the urban water cycle (DHI 2023). InfoWorks ICM has the capability to integrate surface and subsurface flow modeling, supports 1D and 2D modeling of urban drainage and river systems, and provides advanced tools for water quality analysis and real-time control. It is suitable for integrated catchment analysis and flood modeling. However, the model is commercial software, and the setup and calibration of the model are complex (Sidek et al. 2021). InfoWorks CS is primarily designed for wastewater collection (Chan et al. 2002). XP-SWMM is designed for long-term simulations and is suitable for supply and demand analysis (SWMSP 2023). MOUSE is a specialized software for urban stormwater modeling and management (Haris et al. 2016). TUFLOW is a 2D modeling software for surface water flow and floodplain inundation. It provides high-resolution simulations for complex hydraulic scenarios and is suitable for flood modeling, coastal engineering, and river system analysis. However, TUFLOW is commercial software that requires expertise in modeling and significant computational resources (Huxley 2004). Similar to hydrologic models, hydraulic models also have their own pros and cons. In the present study, the HEC-RAS model was chosen for flood inundation modeling due to its comprehensive hydraulic analysis capabilities, data compatibility and GIS integration, 1D, 2D, and combined 1D-2D modeling capabilities, tools for designing bridges and culverts, and integration with other software tools.

Integrating hydrologic and hydraulic models can be a powerful method of modeling extreme hydro-meteorological events using current computing resources (Leon et al. 2014; Sridhar et al. 2019). Bonnifait et al. (2009) coupled n-TOPMODEL hydrologic model with a CARIMA one-dimensional hydraulic model to reconstruct a flood event in the Gard region of France in 2002 for post-event surveys. They suggested that the coupled model was useful for critical analysis and extrapolation of discharge rating curves. Schumann et al. (2013) integrated the VIC model with LISFLOOD-FP for flood inundation forecasting over the Lower Zambezi River in Africa. The model simulated inundation extent showed an agreement of 86% when compared with the observed flood map. Grimaldi et al. (2013) proposed a hydrologic and hydraulic model for a small and ungauged watershed using the WFIUH hydrologic model and the FLO-2D hydraulic model. For peak flow estimation, the model was tested using an event-based approach, a semi-continuous approach, and a fully continuous approach. They found that the fully continuous approach accurately predicted peak flows when compared

to observed flows. Nam et al. (2014) integrated the super-tank hydrologic model with the one-dimensional HEC-RAS model to study the Vu Gia-Thu Bon River in central Vietnam. The model predicted flood inundation depth and extent agreed well with field observations. Nguyen et al. (2015, 2016) developed HiResFlood-UCI, an integrated hydrologic and hydraulic model for flash flood modeling at decameter resolution by combining the NWS's hydrologic model (HL-RDHM) with the hydraulic model (BreZo). The model was able to produce spatially distributed, high-resolution flow information while maintaining hydrograph quality. Mai and De Smedt (2017) linked the WetSpa and HEC-RAS models for flood prediction in Vietnam. Hydrographs were accurately predicted, with Nash–Sutcliffe efficiencies greater than 0.8. In particular, the time of concentration and flow volumes of peak flows were well predicted. They suggested that the model is suitable for predicting inundation and assessing flood risks. Duvvuri (2019), Loi et al. (2019), and Sholichin and Qadri (2020) integrated the SWAT model with HEC-RAS to identify inundation areas in various basins around the world, and the integrated model was able to predict flood inundation areas.

SWAT and other hydraulic models like LISFLOOD-FP and HEC-RAS have been integrated to improve the coupling between hydrological and hydraulic processes (Duvvuri 2019; Loi et al. 2019; Rajib et al. 2016; Sholichin and Qadri 2020). HEC-RAS is one of the most comprehensive and efficient event-based model, capable of better predicting flood inundation extent and inundation depth (Nguyen et al. 2015; Zeiger and Hubbart 2021). Given the complementary strengths of SWAT and HEC-RAS, an integrated modeling approach that accounts for watershed losses and generates event-based 2-D state and velocity response to effective rainfall can be implemented.

Both the Nagavali and Vamsadhara basins experience frequent floods due to heavy rainfall in the monsoon season, as well as during the pre- and post-monsoon periods caused by tropical cyclones originating from low-pressure depressions in the Bay of Bengal (BoB) (Rao et al. 2020a, b). Setti et al. (2018) reported an increase in annual average rainfall of 100 mm over the previous two decades. The uplands of these basins are hilly, resulting in frequent flooding of low-lying areas due to extreme rainfall events. Over the last few decades, the frequency of prolonged floods has increased, causing severe damage to crops, life, and property in both basins' delta regions (DC 2017). According to the Andhra Pradesh State Disaster Management Authority (APSDMA), the Nagavali basin experienced more than 12 flood events, while the Vamsadhara basin experienced nine flood events (APSDMA 2017). Authorities frequently struggle to evacuate villagers during floods due to a lack of a weather and flood forecasting system in the area. Even though studies on streamflow forecasting and flood inundation modeling across the globe are numerous but only a few studies have been conducted on the flood-prone Nagavali and Vamsadhara river basins. If information on floods and flood inundation extents is made public, people and government agencies will be able to deal with floods more effectively. As a result, the current study aims to develop an integrated hydrologic and hydraulic model over the Nagavali and Vamsadhara river basins using the SWAT and HEC-RAS models to forecast streamflow, flood area extent, and flood depth. The following sections present the study area, data used, methodology, and results.

2 Study area

Nagavali and Vamsadhara are the two-interstate eastern flowing rivers in the peninsular India (Fig. 1). Both rivers originate in southern Odisha and flow into the BoB in north-east Andhra Pradesh, India. The Nagavali and Vamsadhara rivers are 256 and 254 km

long, respectively, with catchment areas of 9510 and 10,830 sq.km. Annual rainfall ranges between 1200 and 1400 mm in both basins, with average minimum and maximum temperatures of 8 °C and 43 °C, respectively. The Nagavali basin has elevations ranging from 0 to 1634 m, while the Vamsadhara basin has elevations ranging from 0 to 1505 m. Low-lying areas in both basins are frequently flooded as a result of heavy rainfall during the monsoon season and tropical cyclones during the pre- and post-monsoon seasons. Flooding occurs more than twice a year in nearly 107 villages in the Nagavali basin and 124 villages in the Vamsadhara basin (Iqbal and Yarrakula 2020).

3 Data used

The input data of the hydrologic and hydraulic models include hydro-meteorological data, soil data, land use and land cover (LULC), and Digital Elevation Model (DEM) (Table 1). The majority of the spatial, rainfall and temperature data used in the analysis were freely available to the public. The observed streamflow and water levels were collected from Mahanadi & Eastern Rivers Organization (M&ERO), CWC, Bhubaneswar, India. The data used in the current analysis are described in detail in the following sections.

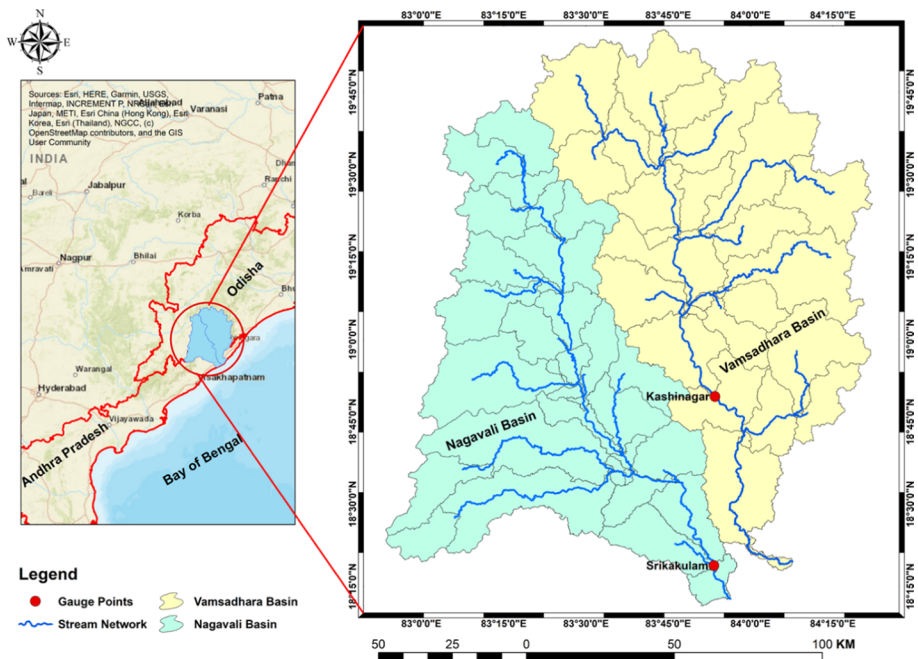


Fig. 1 Geographical location map of the Nagavali and Vamsadhara river basins in Eastern India along with the stream network, SWAT simulated sub-basins and observed gauge locations

Table 1 Input datasets used for the development of an integrated hydrologic and hydraulic model

Dataset	Spatial resolution	Web source
Observed rainfall	0.25° × 0.25°	https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html
Observed temperature	1° × 1°	
Hydrologic data	–	Mahanadi & Eastern Rivers Organization (M&ERO), Bhubaneswar
Forecasted rainfall and temperature	0.25° × 0.25°	https://rda.ucar.edu/datasets/ds084.1/
SRTM DEM	30 m × 30 m	https://earthexplorer.usgs.gov/
Land use/land cover (LULC)	1:2,50,000	https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php
Soil data	1 km × 1 km	https://www.isric.org/explore/soil-geographic-databases

3.1 Spatial data

The spatial data used in this study include DEM, LULC and a soil map. The Shuttle Radar Topography Mission (SRTM) 30 m DEM was obtained from the US Geological Survey (USGS) earth explorer (SRTM, 2013). LULC data for both basins were obtained from Bhuvan, National Remote Sensing Center, at a scale of 1:2,50,000 (Bhuvan-NRSC). There are 14 land cover patterns identified in both basins, such as built-up land, current fallow, deciduous forest, the scrub forest, double-crop, evergreen forest, kharif crop (July–October), rabi crop (October–March), zaid crop (March–June), plantation, shifting cultivation, wasteland, and waterbodies. The spatial plots of DEM and LULC maps of both basins are presented in Fig. 2. Soil classification map was obtained from the International Soil Reference and Information Centre (ISRIC) soil data site (Nachtergaele et al. 2009). There are five types of soil textures in both basins including loam, sandy loam, sandy clayey loam, and clayey soils. The upper portion of the Nagavali basin has mostly sandy clayey soils, whereas the downstream portion has loam soil. The soils in the Vamsadhara basin, on the other hand, are loam.

3.2 Hydro-meteorological data

Hydro-meteorological data include rainfall, temperature, and streamflow. The primary inputs for the hydrological model setup are daily rainfall and temperature records. The India Meteorological Department (IMD) provided daily rainfall (0.25° × 0.25°) and temperature (1° × 1°) records for a 29-year period (i.e., 1986–2014). The Nagavali and Vamsadhara basins received an average annual rainfall of 1243 mm and 1298 mm, respectively, over the course of 29 years. The maximum temperature ranged between 20 and 43 °C and the minimum temperature ranged between 8 and 30 °C in both the basins.

The gauge data over a period of more than 25 years for both basins were obtained from M&ERO. Observed streamflow and water level data are provided by gauge stations at Srikakulam in the Nagavali basin and Gunupur, Kashinagar in the Vamsadhara basin. The hydrological model was calibrated and validated using observed streamflow at Srikakulam and Kashinagar in the Nagavali and Vamsadhara basins, respectively. Water levels at Srikakulam were used to calibrate the hydraulic model in the Nagavali basin, while water levels at Kashinagar were utilized to calibrate in the Vamsadhara basin.

3.3 GFS forecasted data

The National Center for Environmental Prediction's (NCEP) Global Forecast System (GFS) is a medium-range hydrostatic Numerical Weather Prediction (NWP) model. It gives deterministic and probabilistic weather guidance in GRIB2 format for the next 16 days. Weather forecasts from the GFS model were available from June 2015. From the NCAR Research Data Archive, GFS forecasts were downloaded at a resolution of $0.25^\circ \times 0.25^\circ$. The detailed explanation about the evaluation of GFS rainfall forecasts over Nagavali and Vamsadhara basins can be found at Rao et al. (2022).

4 Methodology

Figure 3 depicts the detailed framework of the forecasting methodology used in this study. In the present study, the SWAT model was chosen for streamflow simulations due to its comprehensive watershed analysis, ability to assess land use and climate change, capability to analyze water quantity and quality, provision of a decision support system, user-friendly interface, and wide applicability. First, the SWAT model was set up using the daily time series data from the IMD gridded rainfall, maximum and minimum temperatures for both the Nagavali and Vamsadhara basins. After model calibration and validation, the bias corrected GFS rainfall forecasts were used in the SWAT model to forecast the streamflow with lead time. Once the SWAT model simulation was completed, HEC-RAS 2D model was set up with the SWAT simulated discharge as the upstream boundary condition to determine

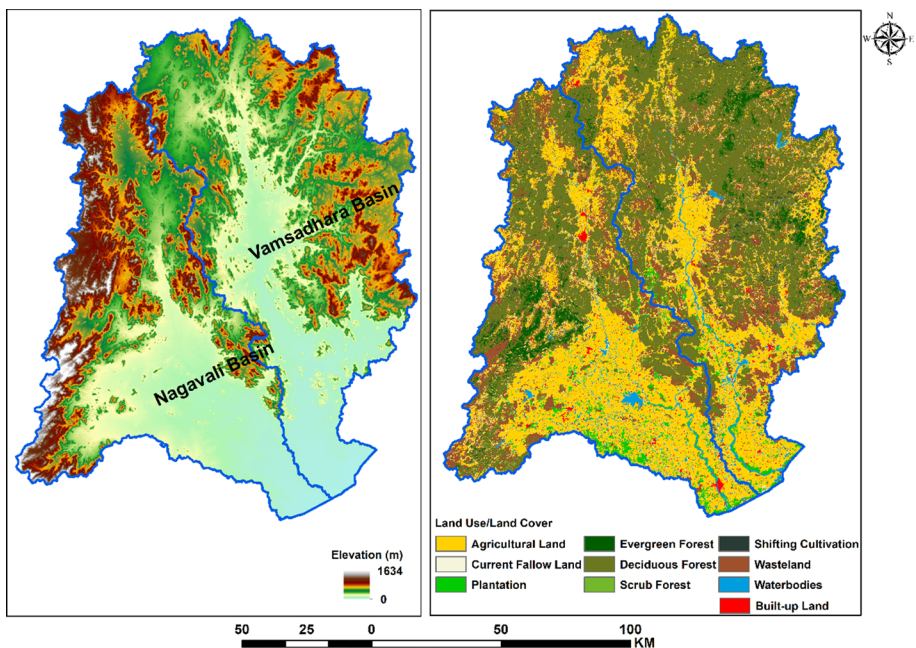


Fig. 2 Spatial maps of Digital Elevation Model (DEM) from SRTM and Land Use Land Cover from Bhuvan—NRSC for both the Nagavali and Vamsadhara Basins

the flood inundation extent and depth in both basins. The detailed explanation about the SWAT and HEC-RAS model setup is provided in the following sections.

4.1 SWAT model set-up

SWAT is a physically based semi-distributed watershed-scale hydrological model developed by USDA's Agricultural Research Service (ARS). The model is designed to predict the impact of land management practices on hydrology, sediment and contaminant transport in large and complex catchments at the hydrological response unit (HRU) level. Initially, to build the SWAT model, DEM, LULC and soil data were projected into common projection as WGS 1984 UTM 44N. The Nagavali river basin is delineated into 34 sub-basins and 2153 hydrological response units (HRUs) and the Vamsadhara river basin is delineated into 30 sub-basins and 2183 HRUs based on the homogeneity of soil, LULC, slope and 100 hectares (Ha) of threshold area (Fig. 1). The Natural Resources Conservation Service (NRCS) curve number method (USDA-NRCS, 2004) was used to simulate daily runoff by the SWAT model. Observed daily streamflow was used to calibrate and validate the simulated streamflow. The SWAT model performance is evaluated by using the coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), and percent bias ($PBIAS$). The values of R^2 are ranged between 0 and 1 (0 indicates no correlation between observed and simulated streamflow and 1 indicates the perfect correlation between them). The values of NSE ranged between $-\infty$ and 1 and they provide a measure of how well the simulated output matches the observed data along a 1:1 line. The optimal value for $PBIAS$ is 0, a positive value represents the model underestimation, while a negative value represents the model overestimation. The model performance is considered satisfactory if the NSE is greater than 0.6 and $PBIAS$ is within $\pm 25\%$ (Moriassi et al. 2007). The mathematical expressions for R^2 , $PBIAS$, and NSE are provided in the supplementary material.

4.2 HEC-RAS model set-up

Flood inundation extent and depth were predicted for the Nagavali and Vamsadhara basins using the 2-dimensional HEC-RAS model developed by the U.S. Army Corps of Engineers, with unsteady flow and the diffusive wave equations (Brunner 2016). The user can perform one-dimensional (1-D), two-dimensional (2-D), as well as coupled 1-D and 2-D hydraulic calculations with the model. Using 2-D unsteady modeling, the river and its floodplain can be discretized into a group of computational cells. The computational cells store information about the elevation as well as roughness values at that specific location. The model calculates the water surface elevation (WSE) at the center of the cell at each time step using a finite volume approach.

The terrain for the HEC-RAS 2D model in both the Nagavali and Vamsadhara basins was developed using SRTM DEM with a resolution of 30 m. The 2-D flow area is marked by a polygon, which specifies the extent of the area in which the 2-D flow calculation can be performed in lateral and longitudinal directions, assuming velocity in the z-direction is negligible. Based on the 2-D flow area, a 2-D computational mesh was defined with cell spacing of 100 m \times 100 m, yielding 95,735 and 77,322 computational cells in the Nagavali and Vamsadhara basins, respectively. During the generation of the 2-D computational mesh, the cell size was selected based on the computational time step and model stability. The SWAT simulated discharge was applied to the upstream boundary conditions at three different locations in the Nagavali basin and two

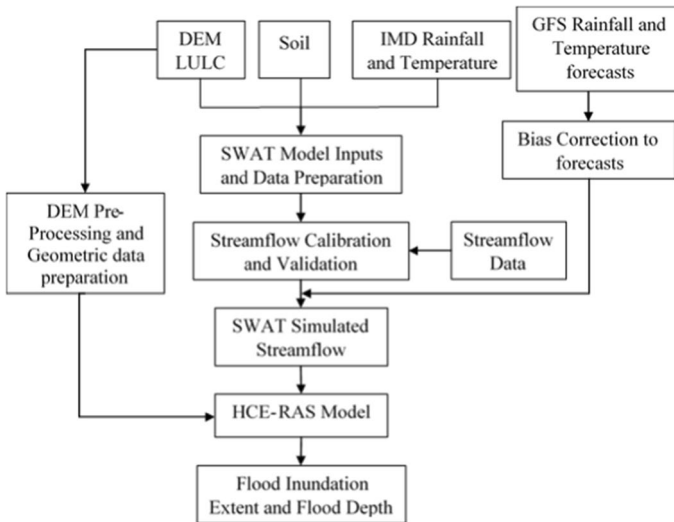


Fig. 3 Flowchart showing the process involved in the present study

different locations in the Vamsadhara basin, with a calculated energy slope of 0.001816 and 0.001327, respectively. The downstream boundary condition in both basins was set to normal depth. The roughness values were assigned to the 2-D computational mesh in both basins using the NRSC LULC map. Banklines were established at every 10 km interval in both basins to extract depth information. Figure 4 illustrates a schematic representation of the HEC-RAS 2D model setup for the Nagavali and Vamsadhara basins.

4.3 Integrated SWAT and HEC-RAS model

The calibrated and validated SWAT model was used to generate the discharge hydrograph, which was then linked with the HEC-RAS 2D model to generate the flood inundation extent and depth. The SWAT model simulates discharge when it receives input parameters such as rainfall and temperature. The HEC-RAS model subsequently assimilated the simulated discharge as upstream boundary conditions in both basins to generate the flood inundation extent and depth.

4.4 Flood frequency analysis

The National Disaster Management Authority (NDMA) recommended a discharge threshold of 1500 m³/s for modeling flood events in the Nagavali and Vamsadhara basins in its hazard assessment report for Andhra Pradesh and Odisha states (RMSI 2015). A study by Thameemul Hajaj et al. (2019) found that the Nagavali basin has been flooded more than nine times since 1990. It suggests that flood events with discharges of less than 1500 m³/s caused the floods in the basin. As a result, in the present analysis, a flood frequency analysis has been performed instead of considering the NDMA's recommended threshold for flood modeling. Flood frequency analysis uses annual maximum

discharge collected at gauge stations to provide information on both the magnitude and frequency of floods. In the present study, stationary and nonstationary flood frequency analysis was conducted to estimate the flood peaks for different return periods of 2, 5, 10, 25, 50, and 100 years in the Nagavali and Vamsadhara basins.

Stationary flood frequency analysis assumes consistent flood data characteristics over time, using historical records to estimate statistical distribution parameters (e.g., Gumbel, Log-normal). It predicts future flood magnitudes and frequencies, mainly in areas with stable hydrological conditions and homogenous historical data. It proves particularly useful for evaluating flood risk in areas with long-term data records and consistent climate and land use patterns. Nonstationary flood frequency analysis acknowledges the potential changes in flood data properties over time, considering factors like climate change, land use alterations, and watershed modifications. It aims to capture evolving flood patterns by allowing statistical parameters to vary with time or other factors. This approach often integrates additional variables, such as rainfall patterns, temperature trends, or land use data, to account for changing hydrological conditions. By employing techniques like time series analysis, trend analysis, or regression models, nonstationary approaches can detect and quantify changes in flood characteristics, leading to more accurate flood frequency estimates (Machado et al. 2015). The detailed explanation about the methodology followed in the present study for flood frequency analysis is given in Yang et al. 2019.

In both the stationary and nonstationary analyses, four 2-parameter distributions, namely Log-Pearson Type-III, Log-Normal, Weibull, and Gumbel, were used to estimate the peak discharges (Yang et al. 2019). The parameters of the distributions were estimated by maximum likelihood estimation method. Two open source R programming-based packages, namely “extremes” (Gilleland 2020; Gilleland and Katz 2016)

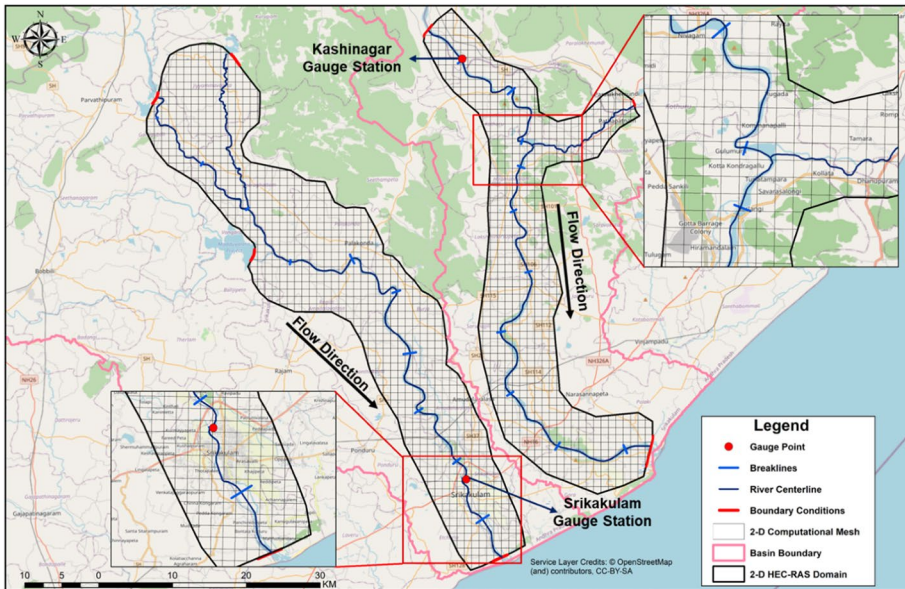


Fig. 4. 2-D HEC-RAS model setup for the Nagavali and Vamsadhara basins. The boundary conditions are indicated as red lines, and the flow direction is indicated by an arrow

and “gamlss” (Rigby et al. 2005), were used to perform stationary and nonstationary analysis. Under the stationary assumption, the best fit distribution was selected based on the Akaike Information Criterion (AIC) value. Compared with the other distributions, Log-Pearson Type-III provided the lowest AIC of 459 in the Nagavali basin and 741 in the Vamsadhara basin. Under the nonstationary assumption, six different cases were created for each distribution, with the scale and location parameters changing over time (Table 2). The Log-Pearson Type-III distribution performed the best for the nonstationary analysis. The residuals for the Log-Pearson Type-III distribution are presented in Table 3. All six models have the same mean and variance in both basins. The M3 and M4 models have the lowest AIC values, while M3 has the lowest kurtosis value in the Vamsadhara basin when compared to M4. Therefore, the M3 model was chosen to calculate peak discharges under nonstationary conditions. The estimated peak discharges for the basins based on the stationary and nonstationary analyses are presented in Table 4. From the statistics, it was found that the peak discharges estimated by the non-stationary method at various return periods were less than the peak discharges estimated by the stationary method. The difference in peak discharge estimates from stationary and non-stationary techniques was relatively small during short return periods and increased with return period length. The fact that only time was considered as a covariate in calculating return periods may explain the smaller difference between peak discharges calculated using stationary and non-stationary methods. This may be due to that only time was considered as covariate in the calculation of design floods. Flood events with discharges greater than or equal to the 2-year return period discharge calculated using the nonstationary method were considered for flood simulation in this study.

4.5 Model calibration and validation

4.5.1 SWAT model calibration and sensitivity analysis

The SUFI-2 algorithm in the SWAT-CUP was used for calibration, validation, and sensitivity analysis. The observed streamflow from Srikakulam and Kashinagar stations was used to calibrate and validate the SWAT model on daily basis over the Nagavali and Vamsadhara basins, respectively. The model was run for a total of 29 years, from 1986 to 2014. Of those 29 years, the first 5 years (1986–1990) were considered as a warm-up period, the next 15 years (1991–2005) were considered for calibration, and the last 9 years (2006–2014) were considered for validation. A total of 17 parameters were considered during the calibration. Sensitivity analysis was conducted to identify the most sensitive parameters using the P value. Among those parameters, Manning’s n value for the main channel (CH_N2), curve number (CN2), groundwater revap coefficient (GW_REVAP), effective hydraulic conductivity in main channel alluvium (CH_K2), deep aquifer percolation fraction (RCHRG_DP), effective hydraulic conductivity in tributary channel alluvium (CH_K1), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), and Manning’s n value for the tributary channels (CH_N1) were the most sensitive parameters for streamflow simulations in the Nagavali basin. Whereas, in the Vamsadhara basin, CN2, CH_K1, CH_N1, CH_N2, and GW_Delay were the most sensitive parameters for streamflow simulations. The calibrated parameters and their fitted values for the Nagavali and Vamsadhara basins are shown in Table 5. A more in-depth explanation about SWAT applications and

Table 2 Location and scale parameters with time (*t*) in nonstationary analysis

Models	Location	Scale
M1		$\mu = \mu_0 + \mu_1 * t$ $\sigma = \text{Constant}$
M2	$\mu = \mu_0 + \mu_1 * t$	$\sigma = \sigma_0 + \sigma_1 * t$
M3		$\mu = \mu_0 + \mu_1 * t + \mu_2 * t^2$ $\sigma = \text{Constant}$
M4	$\mu = \mu_0 + \mu_1 * t + \mu_2 * t^2$	$\sigma = \sigma_0 + \sigma_1 * t$
M5		$\mu = \mu_0 + \mu_1 * t + \mu_2 * t^2 + \mu_3 * t^3$ $\sigma = \sigma_0 + \sigma_1 * t$
M6	$\mu = \mu_0 + \mu_1 * t + \mu_2 * t^2 + \mu_3 * t^3$	$\sigma = \sigma_0 + \sigma_1 * t + \sigma_2 * t^2$

calibration of parameters can be found in published literature including Jin and Sridhar 2012; Sehgal et al. 2018; Stratton et al. 2009; Sehgal and Sridhar 2018.

4.5.2 HEC-RAS model evaluation

Two approaches were used to validate the flood inundation maps generated by the HEC-RAS model. In the first approach, the simulated depths for historical events were compared with observed water levels at the Srikakulam and Kashinagar gauge stations in the Nagavali and Vamsadhara basins, respectively. In the second approach, the inundation maps generated by the HEC-RAS model for Titli cyclone over the Vamsadhara basin using SWAT simulated discharge from IMD rainfall and GFS forecasts were validated against the flood inundation map provided by the Bhuvan-NRSC. Based on overlapping areas between the inundation map generated by the model and the inundation map provided by NRSC, the performance of the HEC-RAS model was assessed (Tamiru and Dinka 2021). The intersection tool was used to get the percentage of overlapping area between the NRSC flood inundation maps and the HEC-RAS model.

5 Results and discussion

The SWAT model was used in this study to estimate streamflow’s in both the Nagavali and Vamsadhara basins. The estimated streamflow was calibrated and validated using SUFI-2 algorithm in SWAT-CUP. The SWAT model evaluation includes a sensitivity analysis to identify the parameters for streamflow simulations. The simulated streamflow from the SWAT model was given as input to the HEC-RAS model to predict flood inundation extent and flood depth. The following sections provide a detailed explanation of the results.

5.1 SWAT simulated streamflow

The calibration and validation results showed good agreement between the observed and simulated streamflow and are presented in Table 6. During the calibration and validation periods, the NSE values for daily streamflow at Srikakulam gauge station in the Nagavali basin were 0.59 and 0.57, respectively, and 0.64 and 0.59 at Kashinagar gauge station in the Vamsadhara basin. The PBIAS values during the calibration period were 0.8% in the Nagavali basin and 6.5% in the Vamsadhara basin. The PBIAS values during the validation period were 7% and 11% over the Nagavali and Vamsadhara basins, respectively. From the

Table 3 Residuals of Log-Pearson Type-III distribution over the Nagavali and Vamsadhara basins

Model	Nagavali Basin					Vamsadhara Basin				
	AIC	Mean	Variance	Coefficient of Skewness	Coefficient of Kurtosis	AIC	Mean	Variance	Coefficient of Skewness	Coefficient of Kurtosis
M1	459.357	0	1.03	0.975	0.897	741.090	0.0	1.02	0.081	-0.886
M2	457.801	0	1.03	0.815	0.625	742.419	0.0	1.02	0.171	-1.148
M3	453.050	0	1.03	0.739	0.912	741.005	0.0	1.02	0.080	-0.765
M4	453.050	0	1.03	0.739	0.912	741.005	0.0	1.02	0.080	-1.148
M5	459.357	0	1.03	0.975	0.897	741.090	0.0	1.02	0.082	-0.886
M6	456.668	0	1.03	0.604	0.274	742.646	0.0	1.02	0.270	-1.272

Table 4 Estimated maximum discharge over the Nagavali and Vamsadhara River with different return periods using Log-Pearson Type-III distribution

Return period (T years)	Peak discharge (m ³ /s)			
	Nagavali River		Vamsadhara River	
	Stationary	Nonstationary	Stationary	Nonstationary
2	1223	1200	1365	1360
5	1948	1877	2634	2596
10	2650	2490	3841	3774
25	3750	3443	5960	5837
50	4770	4252	8110	7916
100	5989	5195	10,900	10,605

Table 5 SWAT model calibrated parameters range and fitted values over the Nagavali and Vamsadhara basins

S.no	Parameter name	Minimum value	Maximum value	Fitted value	
				Nagavali Basin	Vamsadhara Basin
1	R_CN2.mgt	-0.1	0.1	-0.04	-0.088
2	V_ALPHA_BF.gw	0.3	1	0.99	0.479
3	A_GW_DELAY.gw	-30	90	45.60	-23.2
4	A_GWQMN.gw	-1000	1000	-873.33	713.33
5	V_GW_REVAP.gw	0.02	0.2	0.05	0.093
6	A_REVAPMN.gw	-750	750	-77.50	-375.50
7	V_ALPHA_BF_D.gw	0	1	0.64	0.723
8	A_RCHRG_DP.gw	-0.05	0.05	0.04	0.035
9	R_SOL_AWC.sol	-0.05	0.05	-0.01	-0.029
10	V_ESCO.hru	0.3	0.6	0.41	0.439
11	V_LAT_TTIME.hru	0	120	94.00	12.4
12	V_SLSOIL.hru	0	120	14.80	27.6
13	V_CANMX.hru	0	20	1.27	2.20
14	V_CH_N2.rte	0.01	0.15	0.07	0.055
15	V_CH_K2.rte	0	100	69.67	53.00
16	V_CH_K1.sub	0	100	43.00	84.33
17	V_CH_N1.sub	0.01	15	0.10	0.143

PBIAS values, it is observed that the SWAT model underestimated the streamflow during the calibration and validation period in both basins.

The underestimation of streamflow by the SWAT model can be attributed to various factors, including precipitation, surface runoff, water yield, lateral runoff, and evapotranspiration. The majority of the catchment area in both basins is covered by forest and agricultural land, leading to a significant impact of evapotranspiration on the water resources of both basins. The presence of abundant plant growth, humidity, and wind velocities in both basins during the monsoon and post-monsoon seasons results in higher rates of evapotranspiration. In the dry months, the monthly evapotranspiration is estimated to exceed the total precipitation for both river basins. This is possible because evapotranspiration is a

continuous process that occurs at different rates throughout the day and night, independent of precipitation, and utilizes water from the near-surface soil moisture. The depth of the plant root, which allows it to extract water from deeper soil layers, affects the rate of evapotranspiration. Due to its ability to account for changes in soil moisture content, the SWAT model is a continuous model that easily incorporates the soil moisture content from the previous day. As a result, total precipitation in a given month may be lower than the total evapotranspiration during dry months, which leads to underestimation of streamflow in both basins (Nagireddy et al. 2022a, b).

The observed versus simulated streamflow during the calibration and validation period at Srikakulam and Kashinagar stations in the Nagavali and Vamsadhara basins, respectively, is presented in Figs. 5 and 6. During the calibration and validation period, the time series plot of simulated streamflow reflected the precipitation patterns over the Nagavali and Vamsadhara basins and matched with the observed streamflow. In the Nagavali and Vamsadhara basins, the monsoon season produced the most streamflow (i.e., from June to September). In the Nagavali basin, the SWAT model overestimated the streamflow flow from 2004 to 2009. The overestimation of streamflow in the Nagavali basin may be attributed to uncertainty in gridded products caused by inhomogeneity's in observation practices and irregular distribution of observation stations (Rao et al. 2020a). The observed rainfall data utilized in the current study are IMD gridded data with a resolution of $0.25^\circ \times 0.25^\circ$. This gridded rainfall dataset was generated by incorporating rainfall observations from 6995 rain gauge stations across India. Although the gridded dataset was developed with utmost care, the results of individual stations may be affected by the inhomogeneities in the underlying time series data that were not detected. Additionally, the irregular spatial distribution of rain gauge stations across the Nagavali and Vamsadhara basins could be another potential factor contributing to the underestimation of streamflow (Klein Tank et al. 2006; Pai et al. 2014). Suitability of rainfall data products for the hydrological analysis of these study areas may also play an important role (Reddy et al. 2022; Tan et al. 2021).

Streamflow in both basins has been increasing since 1991. The annual average streamflow has increased at a rate of $14 \text{ m}^3/\text{s}$ in the Nagavali basin and $16 \text{ m}^3/\text{s}$ in the Vamsadhara basin. According to the observed flow data, the average annual flow in the Nagavali basin is $83.52 \text{ m}^3/\text{s}$ and in the Vamsadhara basin it is $88.72 \text{ m}^3/\text{s}$. A highest peak flow of $5624.74 \text{ m}^3/\text{s}$ was recorded in the Nagavali basin on August 04, 2006, while $7321.54 \text{ m}^3/\text{s}$ was recorded in the Vamsadhara basin on October 07, 2007. The peak flow recorded in the Vamsadhara basin on October 07, 2007, could have been caused by measurement error or spurious data, as there is no scientific evidence of heavy rainfall or a cyclone passing over the basin at that time. The Vamsadhara basin received secondary peak of $4250 \text{ m}^3/\text{s}$ on September 07, 2014. According to SWAT simulated streamflow, the average annual flow in the Nagavali basin is $79.71 \text{ m}^3/\text{s}$ and $72.50 \text{ m}^3/\text{s}$ in the Vamsadhara basin. The highest peak flow evidenced in the simulated streamflow was $6753 \text{ m}^3/\text{s}$ on August 04,

Table 6 Statistics for the calibration and validation of daily streamflow over the Nagavali and Vamsadhara basins

River Basin	Gauging station	Calibration				Validation			
		Period	R^2	NSE	$PBIAS$	Period	R^2	NSE	$PBIAS$
Nagavali	Srikakulam	1991–2005	0.59	0.59	0.8	2006–2014	0.58	0.57	7
Vamsadhara	Kashinagar	1991–2005	0.66	0.64	6.5	2006–2014	0.60	0.59	11

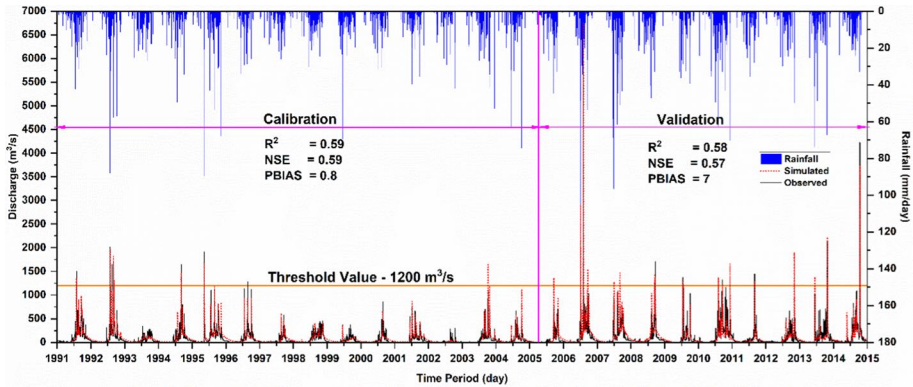


Fig. 5 Observed and simulated streamflow in the Nagavali basin at Srikakulam gauge station

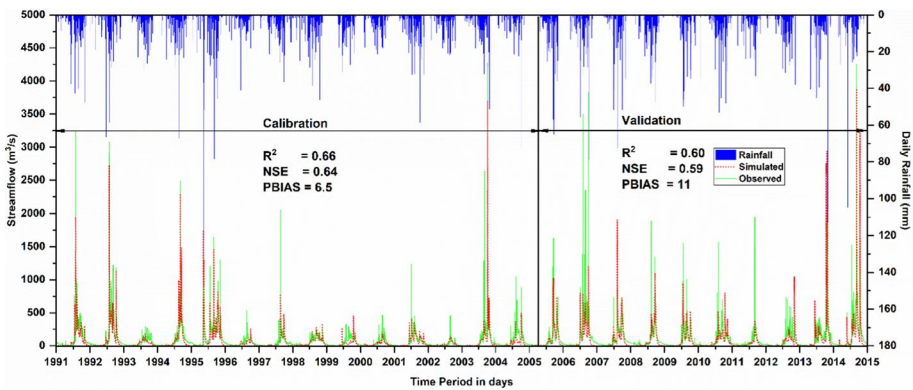


Fig. 6 Observed and simulated streamflow in the Vamsadhara basin at Kashinagar gauge station

2006, in the Nagavali basin and 3884 m³/s on September 07, 2014, in the Vamsadhara basin. The SWAT simulated peak flows that were in good agreement with the observed flow. The maximum annual discharge in the Nagavali basin was 2070 billion cubic meters (BCM) in 2010, while the maximum annual discharge in the Vamsadhara basin was 2295 BCM in 2006. Both basins had minimal annual discharges of 212 and 252 BCM in 2002, respectively.

5.2 Flood inundation maps of the historical flood events

The Nagavali and Vamsadhara basins are frequently flooded as a result of heavy rainfall during the monsoon season and tropical cyclones during the pre- and post-monsoon seasons. Based on the 2-year return period peak discharge (1200 m³/s in the Nagavali basin and 1360 m³/s in the Vamsadhara basin), Nagavali basin was flooded 16 times, while the Vamsadhara basin was flooded 9 times between 1991 and 2014. In the Nagavali basin, 11 flood events occurred during the monsoon season, four during the post-monsoon season,

and the rest during the pre-monsoon season. In the Vamsadhara basin, six events occurred during the monsoon season and the rest during the post-monsoon season. The flood inundation maps for historical events from 1991 to 2014 were generated using the HEC-RAS model and discharge hydrographs generated by the SWAT model. Figures 7 and 8 show flood inundation maps for historical events in the Nagavali basin, while Fig. 9 shows flood inundation maps in the Vamsadhara basin.

Based on historical flood events, the flood inundation area in the Nagavali basin has varied from 182 to 229 sq.km, with a minimum inundation area in 1992 and a maximum inundation area in 2006. The flood inundation area predicted by the integrated hydrologic and hydraulic model over the Nagavali basin for different flood events is in good agreement with Iqbal and Yarrakula (2020). Floods have affected over 115 villages across 10 Mandals, namely Vangara, Veeraghattam, Regidi, Palakonda, Burja, Santhakaviti, Ponduru, Amadalavalasa, Etcherla and Srikakulam rural in the Srikakulam district, Andhra Pradesh, have been affected due to floods. In the Vamsadhara basin, the flood inundation area was varied from 245 to 309 sq.km, with a minimum inundation area in 1995 and a maximum inundation area in 2003. In the years 1994 and 2013, the Vamsadhara basin received streamflow over 1000 m³/s for more than three consecutive days, resulting in an increase in the inundation area despite a lower peak discharge when compared to previous flood events. More than 139 villages across 11 Mandals, namely Bhamini, Kotturu, Hiramandalam, Jalumuru, L N Peta, Sarubujjili, Narasannapeta, Polaki, Amadalavalasa, Srikakulam rural and Gara, have been affected. Floods threaten, an average area of 220 sq. km and at least 1 lakh people in 115 villages in the Nagavali basin, and an area of 272 sq.km and 1.25 lakh people in 135 villages in the Vamsadhara basin. Figure 10 shows the geographical locations of the villages in both basins that are prone to flooding.

5.3 Validation of flood inundation depth

The flood inundation depth predicted by the HEC-RAS 2D model was compared to data from gauge stations in the Nagavali and Vamsadhara basins at Srikakulam and Kashinagar. A graphical representation of observed vs simulated flood depths is shown in Figs. 11 and 12. The inundation depths provided by the HEC-RAS 2D model in both the basins were clearly in good agreement with the observed depths. Flood inundation depths predicted by the model ranged from 2.70 to 4.51 and 2.28 to 3.77 m for Nagavali and Vamsadhara basins, respectively. In contrast, the observed inundation depths in the respective basins varied from 2.55 to 6.05 and 2.16 to 3.65 m, respectively. Except for two floods in the Nagavali basin in August 2006 and October 2014, the HEC-RAS 2D model overestimated inundation depths in both basins. Aside from those two flood events, the difference in observed and simulated depths in the Nagavali basin ranged from 0.04 to 0.20 m, and in the Vamsadhara basin ranged from 0.04 to 0.29 m. The flood inundation depth was underestimated by 1.58 m and 0.32 m, respectively, for the flood events in August 2006 and October 2014.

5.4 Flood inundation modeling of tropical cyclone Titli

Tropical Cyclone Titli was a powerful cyclonic storm that hit the Vamsadhara basin in October 2018. According to state government records, the basin received 426 mm and

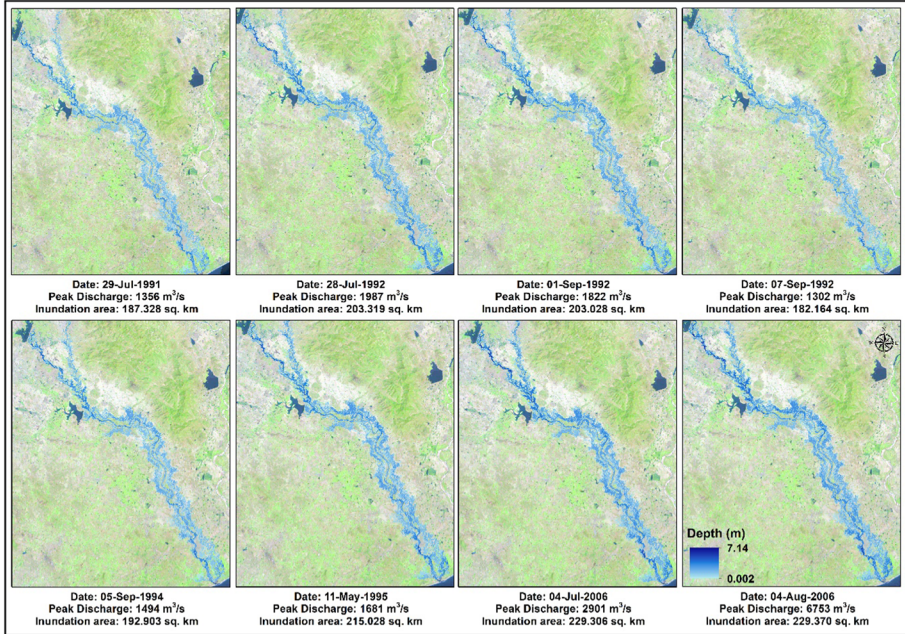


Fig. 7 Flood inundation maps generated by HEC-RAS model using SWAT simulated discharge as upstream boundary from 1991 to 2006 over the Nagavali basin

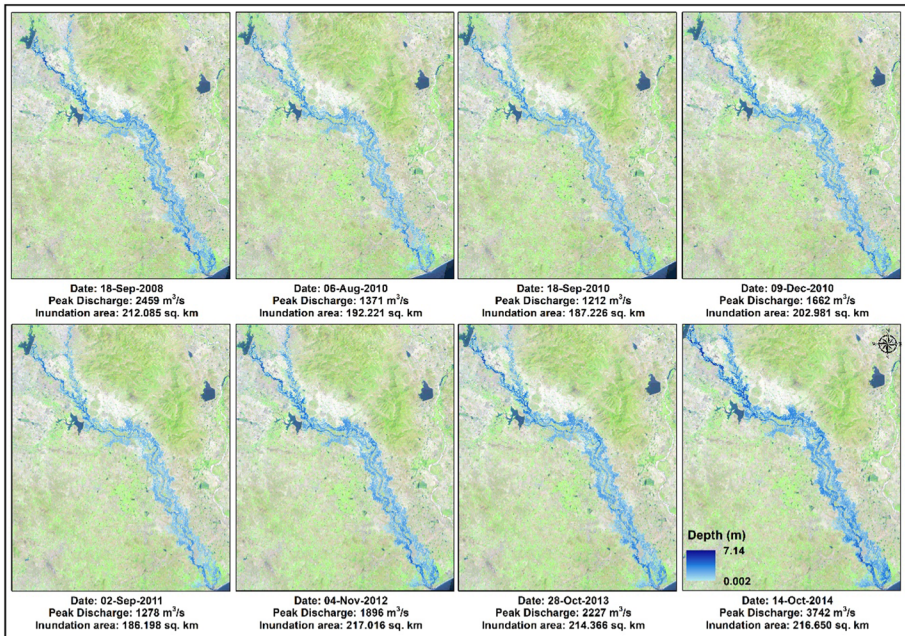


Fig. 8 Flood inundation maps generated by HEC-RAS model using SWAT simulated discharge as upstream boundary from 2008 to 2014 over the Nagavali basin

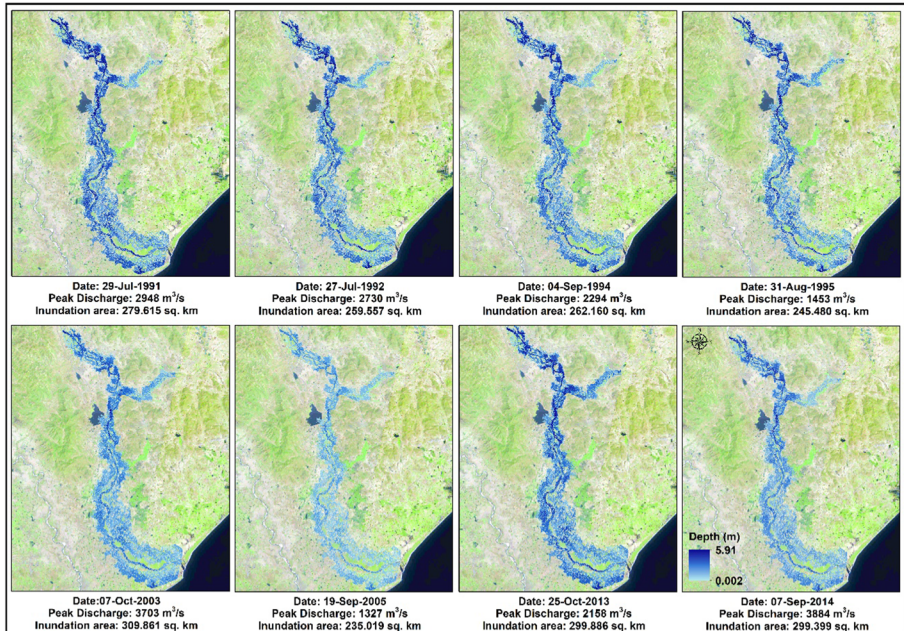


Fig. 9 Flood inundation maps generated by HEC-RAS model using SWAT simulated discharge as upstream boundary from 1991 to 2014 over the Vamsadhara basin

352 mm of rainfall on October 11th, 2018, at the Booravilli and Kanchili_ARG gauge stations, respectively, and 153 mm at Sarubujjili and Levidi gauge stations on October 12th, 2018, resulting in an increase in water levels and floods in the basin on October 13th, 2018. Flooding from cyclone Titli affected nearly 25,000 families in over 200 villages, and the agricultural and horticultural crops in the Vamsadhara basin were damaged for over 3600 crores of Indian rupees (GOI-UNDP 2018; TNIE 2018).

The SWAT model, which had been calibrated and validated, was used to estimate streamflow for the Titli cyclone, which hit the Vamsadhara basin from October 8th to October 12th, 2018. The basin experienced heavy rainfall on 11th and 12th October. According to IMD gridded data, the basin received 148 mm of rainfall on October 11th and 133 mm on October 12th. On October 11th, the GFS model forecasted rainfall of 186 mm, 131 mm, 107 mm, 70 mm, and 50 mm from day-1 to day-5. The streamflow for the Titli cyclone was simulated using observed rainfall and bias corrected GFS rainfall forecasts. Peak discharges simulated by the SWAT model were 4332 m³/s, 2281 m³/s, 2661 m³/s, 1536 m³/s, 1090 m³/s, and 700 m³/s for observed rainfall and GFS 1-day to 5-day forecasts. The SWAT simulated streamflow revealed that the GFS 1-day and 2-day streamflows are in good agreement with the observed streamflow. The streamflow simulated by the SWAT model using 3-day to 5-day GFS forecasts was less than half of the observed streamflow. The underestimation of streamflow using 3-day to 5-day forecasts was mainly due to variations in rainfall intensity. For further analysis, GFS 1-day and 2-day forecasts were considered. The hydrograph for the observed and simulated discharge based on IMD rainfall and the GFS 1-day and 2-day forecast is presented in Fig. 13.

The simulated discharges from the SWAT model were used as an upstream boundary condition in the HEC-RAS 2D model to generate inundation maps during the Titli Cyclone

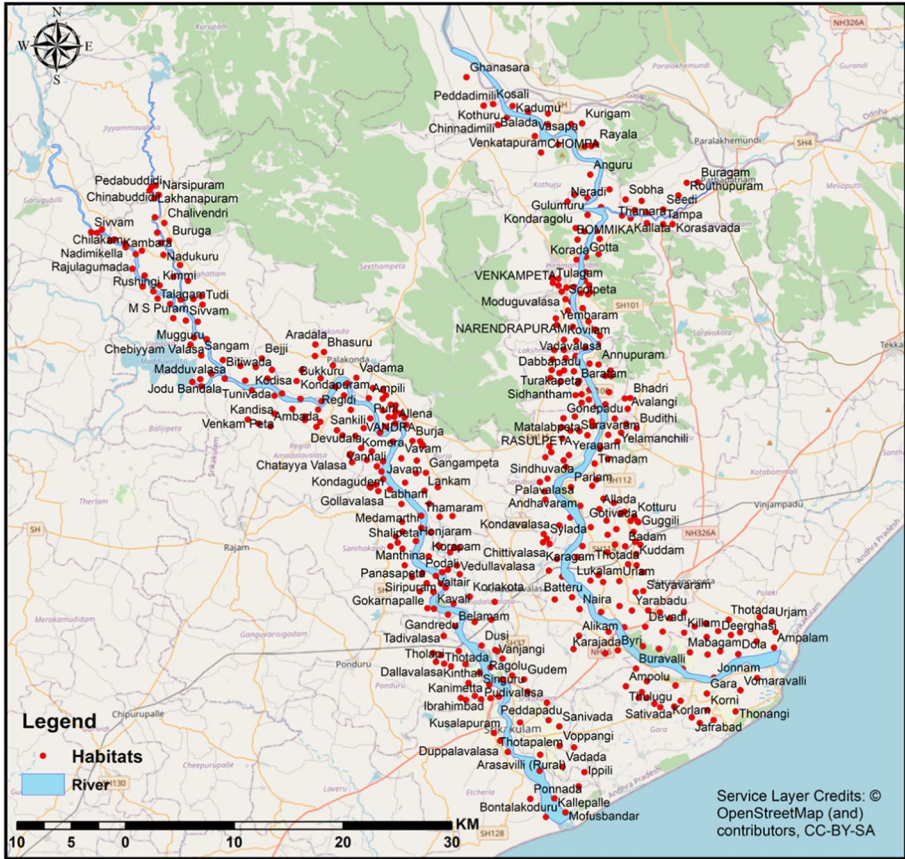


Fig. 10 Geographical location of the Habitats vulnerable to flooding in the Nagavali and Vamsadhara basins

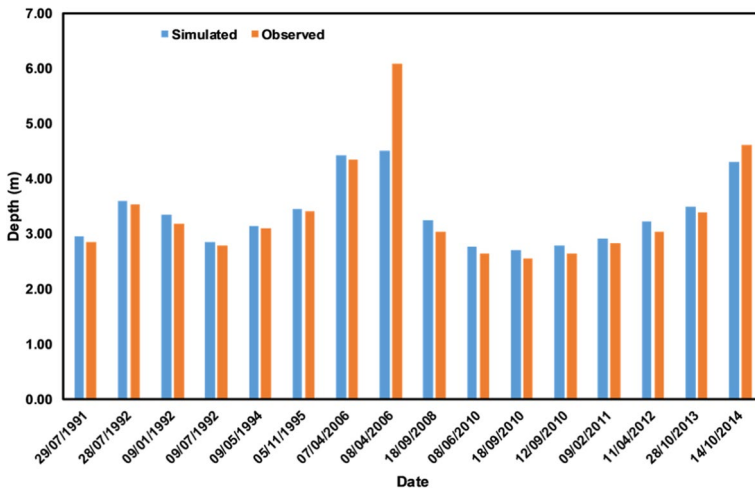


Fig. 11 Observed versus simulated flood inundation depths at Srikukulam gauge station in the Nagavali basin for the historical flood events from 1991 to 2018

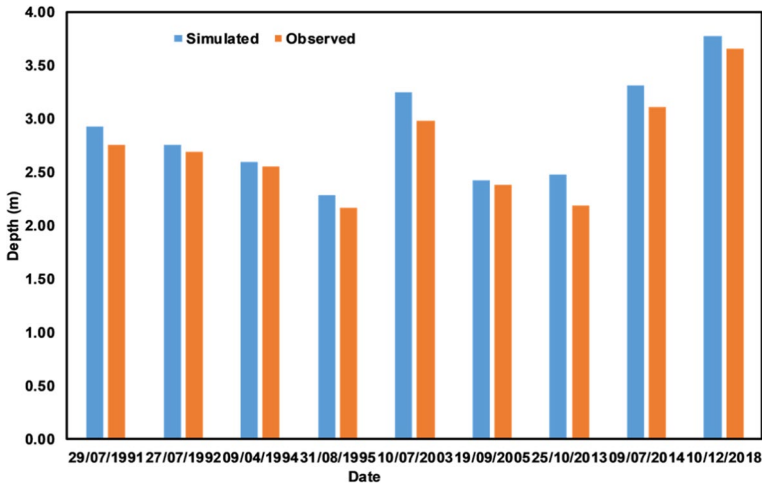


Fig. 12 Observed versus simulated flood inundation depths at Kashinagar gauge station in the Vamsadhara basin for the historical flood events from 1991 to 2018

(Fig. 14). From the observed gauge data and SWAT simulated discharge (IMD, GFS 1-day and 2-day) for the Titli cyclone, the inundation area was 307.027, 311.601, 302.076, and 290.674 sq.km, with peak discharges of 3362, 4332, 2884, and 2661 m³/s. The flood inundation maps generated by the HEC-RAS 2D model were validated with the Bhuvan-NRSC flood inundation map. The inundation maps were evaluated based on the overlapping area.

The intersection tool was used to calculate the area that overlapped between the observed and simulated inundation maps (Tamiru and Dinka 2021). From the calculated overlapping areas, it was found that the HEC-RAS 2D model was able to predict at least 75% of the inundation area when compared to Bhuvan-NRSC data. From the simulated flood inundation maps, it was observed that more than 150 villages were affected, and an area of 177 sq.km of crops (agriculture and horticulture) were damaged in the Vamsadhara basin. The areas of crops affected by the cyclone were in good agreement with observed statistics (Sphere-India 2018).

The inundation depth from the HEC-RAS model was further compared with the observed depth. When the SWAT model simulated discharge using IMD rainfall was given as the upstream boundary condition, the HEC-RAS 2D model overestimated the inundation depth by 0.12 m. Whereas for other simulations, using observed gauge data and SWAT simulated discharge with GFS 1-day and 2-day rainfall forecasts, the HEC-RAS 2D model underestimated inundation depth by 0.38, 0.46, and 0.53 m, respectively. The overestimation and underestimation of flood inundation depths for the tropical cyclone Titli may be attributed to the variations in peak discharges. The results showed that by using GFS 2-day rainfall forecasts, the developed integrated hydrologic and hydraulic model was able to predict runoff, flood inundation extent and inundation depth with a 2-day lead time.

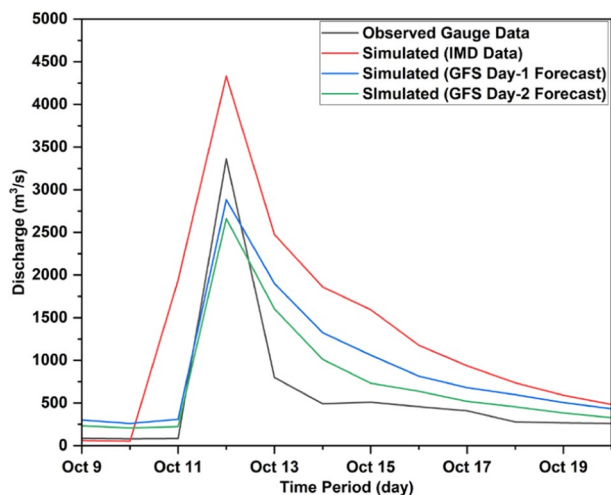
Although the integrated hydrologic and hydraulic model is able to provide flood inundation maps with a 2-day lead time, the model still has some uncertainties. The SWAT model has been calibrated and validated in both basins using observed streamflow values provided by CWC. Extensive care was taken during the setup of the SWAT model, considering reservoirs, dams, and other water bodies present in both river basins. Therefore, the uncertainty caused by the SWAT model for streamflow simulation has

been minimized. Similarly, extensive care was taken in setting up the HEC-RAS model in both Nagavali and Vamsadhara basins. However, the validation of flood inundation maps provided by the HEC-RAS model was limited to one flood event in the Vamsadhara basin, and no validation was performed in the Nagavali basin due to the lack of observed data. Additionally, the severity of the floods depends on land use and land cover (LULC) changes and soil moisture variations. Therefore, the dynamic changes in LULC and soil moisture also introduce some uncertainty in the prediction of flood inundation maps.

6 Conclusions

Floods are most dangerous in the Nagavali and Vamsadhara basins. Flooding occurs frequently in the basins during the monsoon and post-monsoon seasons, causing significant damage to humans and agriculture. In the present study, an integrated hydrologic and hydraulic model capable of providing flood forecasts was developed using SWAT and HEC-RAS 2D models. When the model was applied to both basins, it was found that when compared to Bhuvan-NRSC data, the integrated model was able to predict at least 75 percent of the inundation area with acceptable accuracy in terms of flood inundation depth. Although the flood inundation map generated by the integrated model was verified for a single event, the model was able to provide flood forecasts with a lead time of 48 h, which is crucial for government agencies issuing early warnings to the public during the flood events and evacuating the people from vulnerable areas. The framework presented in this study is useful for developing real-time flood forecasts as well as developing a web-based framework for disseminating flood inundation information. We are working to improve the model forecasts with a lead time of 120 h by ensemble weather forecasts from multiple numerical weather prediction models. The developed model must be continuously maintained by incorporating changes in land use land cover and other hydraulic structures, so that the model will be always up-to-date and reliable during the floods.

Fig. 13 Hydrograph for the observed and simulated discharge based on IMD rainfall and the GFS 1-day and 2-day forecast of Titli cyclone in the Vamsadhara basin in 2018



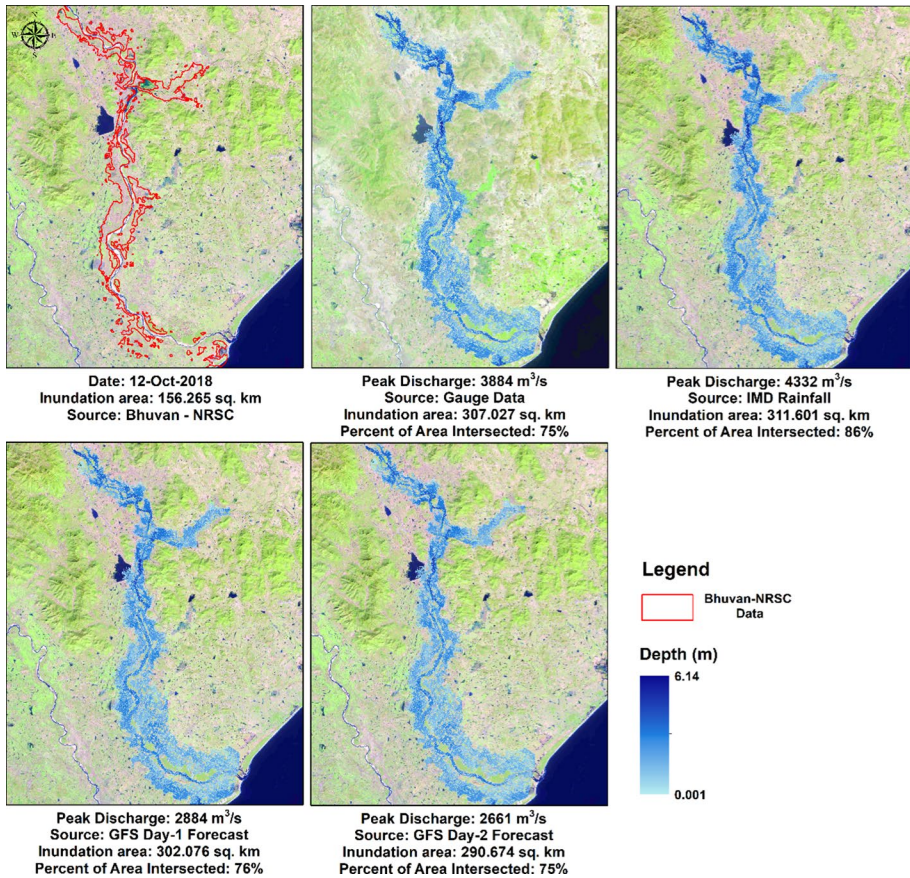


Fig. 14 Flood inundation maps for the tropical cyclone Titli: **a** Flood inundation map provided by Bhuvan—NRSC. **b** Flood inundation map generated by 2-D HEC-RAS model using observed discharge data, **c** Flood inundation map generated by 2-D HEC-RAS model by giving SWAT simulated discharge using IMD rainfall as upstream boundary condition, **e** Flood inundation map generated by 2-D HEC-RAS model by giving SWAT simulated discharge using GFS day-1 rainfall forecast as upstream boundary condition, **f** Flood inundation map generated by 2-D HEC-RAS model by giving SWAT simulated discharge using GFS day-2 rainfall forecast as upstream boundary condition

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Data availability Data available from the corresponding author upon request.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical statement The submitted work is original and it not published elsewhere in any form or language (partially or in full). It is not submitted to any other journal for simultaneous consideration. Results are presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation. Proper acknowledgements to other works are given wherever it is appropriate.

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