Flood Inundation Mapping for a Kukatpally Gauged Basin Using HEC-RAS: A Case Study of Hyderabad Metropolitan Area, Telangana State, India

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Abstract. Urban flooding is a natural disaster that affects a significant portion of the world's population most frequently. Due to uncontrolled urbanization and climate change, severe floods are becoming more frequent in urban areas, and this trend is expected to continue in the upcoming years. Although preventing such events is not feasible, advancements in technology have made it possible to identify areas that are vulnerable to flooding using 2-D modeling of critical rainfall events. However, in the case of urban flood modeling it needs a lot of accurate data and is not able to predict accurate flow in the channel if this data is not available. Today world, there are a lot of commercial and open source models available for flood mapping, but these models require a wide range of data to extract good results. This study utilized a straightforward approach for analyzing integrated HEC-HMS and HEC-RAS of an extreme rainfall event that occurred on 13th October 2020 in Hyderabad, India. The study uses HEC-RAS, 2-D hydraulic model integrated with GIS, to generate flood inundation layer and risk maps for the 13th October 2020 event. The flood risk results indicate that the areas categorize the risk level as very low risk (<0.001), low risk (0.001 to 0.5) medium risk (0.5 to 1), high risk (1 to 3), and very high risk (>3) of flooding.

Keywords: 2D modeling · Flood Inundation · Flood Risk

1 Introduction

The Centre for Research on the Epidemiology of Disasters [6] stated that flood-related incidents have been the leading cause of natural disasters over the last 20 years. The world with mostly 43% of all disasters affects mainly human beings exist on the earth. Now a day's severity of floods in urban areas has increased significantly. The cities in India face a significant challenge in the form of urban flooding every year, and unfortunately, there is currently no viable solution. Major metropolitan cities such as Mumbai, Delhi, Chennai, Hyderabad, Bengaluru, and other towns and cities have experienced devastating urban floods in the last decade. Some of the most severe urban floods in the

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past decade include Chennai (2015), Srinagar (2014), Mumbai (2005), Kolkata (2013), [21], and Hyderabad (2000, 2002, 2006, 2008, 2014, 2016, and 2020) [17]. Urban flooding has been an ongoing issue for cities like Mumbai, Delhi, Chennai, and Hyderabad over the past decade. Due to urban floods, the above-mentioned cities have to get various effects namely: an infectious disease, economic losses, death of human beings, electricity, and transportation breaks [2, 24, 31]. The main causes of flooding in these cities can be traced back to several factors, including unplanned development in areas that are prone to inundation, clogging of drainage channels due to the buildup of solid waste, and changes in precipitation patterns resulting from shifts in climate conditions [7, 27, 28]. Uncontrolled urbanization can create immense pressure on land use and leads to settlements being established in low-lying areas and floodplains [26]. This increasing settlement changes flow direction and seal the natural surface features, which significantly rises runoff volume [1, 19, 20]. Most of the drainage channels in India were designed in the past to transmit rainfall intensities of 12–20 mm [18], and as a result, they become easily inundated during heavy rainfall. This causes stormwater to overflow and spread into surrounding areas, resulting in huge floods. The effect of these floods can vary depending upon the rainfall event, but due to the effect of short duration intense rainfall can lead to flooding for several days, having significant effects on society, temporarily displacing residents, damaging infrastructure, and compromising water quality [1, 25]. Recent research has pointed out that the frequency of extreme rainfall increases, and this is attributed to the changing climate [5, 15, 29]. In fact, in the last 20 years, more than 350 studies have examined the influence of climate change on over 400 extreme weather incidents [4]. While it is not possible to control the occurrence of extreme events such as floods, their potential risk, and the resultant damage can be mitigated by utilizing modern flood modeling techniques. The flood extent and inundation depth are crucial parameters for mapping flood hazards, particularly in urban areas [3]. The use of Graphical User Interfaces (GUIs) has simplified the earlier complex process of urban flood modeling, making it more accessible and producing outputs that are easily understandable [14, 22]. In addition to standard 1D/2D flood models, more advanced numerical approaches capable of generating flood extents have emerged in recent years [30]. GIS-integrated hydraulic models are capable of efficiently converting water surface elevations into flood inundation maps [9]. Topography details help in accurately transforming water surface elevations into flood inundation maps [13]. The resulting flood inundation map provides areas under high risk during the rainfall event and it also helps in issuing early warnings and provides flood relief efforts to minimize damage.

Earlier urban flood modeling studies for Hyderabad city's watershed did not consider as a gauged watershed, because lack of water level or quantity monitoring data [21]. Hence, to overcome this lack of data considered in the modeling studies, in this study real-time sensor flow observed by Osmania University has been used for actual flood prediction. This study aims to create flood risk maps for the latest 13th October 2020 extreme rainfall event for the Kukatpally zone (Zone-12) of Hyderabad, India by utilizing a 2-D model developed with HEC RAS 6.1 software.

2 Study Area

Greater Hyderabad Municipal Corporation (GHMC) divided Hyderabad's combined drainage system into 16 stormwater zones based on the topography (GHMC 2007). Among these zones, the Kukatpally zone (zone-12) located between 17°34′35.44" N and 17°24′34.03" N latitude and 78°22′ 51.34" E and 78°28′ 40.39" E longitude has been frequent flood prone and effected zone covers an area of 173.68 Sq.km was considered (Fig. 1). Zone-12 collects all the water from households and surface water generated during the monsoon was transported majorly through the open channels and disposed into the Hussain Sagar Lake. The flow monitoring sensor (Fig. 2) is installed upstream of Hussain Sagar Lake to monitor the flow fluctuations in the channel during the monsoon, non-rainy season, and its impact on surrounding areas.

2.1 Datasets Used

Carto-Digital Elevation Model (DEM) of 10m (Fig. 2) resolution was procured from National Remote Sensing Centre (NRSC), Balanagar, Hyderabad, and used to delineate the Kukatpally (zone-12) watershed of Hyderabad Metropolitan city. The satellite image of IRS Resouresat 2 LISS IV of 5.4m resolution and Soil map (1:250000) for the year 2017 used to extract the land use features and 2010 were obtained from NRSC-ISRO, Telangana State Remote Sensing Applications Centre (TRAC) respectively (Fig. 3). Hourly rainfall data from the nine automatic weather stations (AWS), viz., Balanagar, Begumpet, Jublihills, Machabollaram, Madhapur, Mithrivanam, Qutbullapur, Qutbullapur_Ghmc, and Shapurnagar were collected from Telangana State Development Planning and Society (TSDPS) for the period 13th October 2020 (Fig. 4). Hourly flow data from the ultrasonic level transmitter sensor installed upstream of Hussainsagar Lake was collected for the period of 13th October 2020.

The database generated for zone-12 using HEC-HMS 4.10 includes data from twenty-five sub-basins as presented in Table 1. The recent extreme rainfall event that hit on 13th October 2020 is used for simulation and creation of a flood risk map.

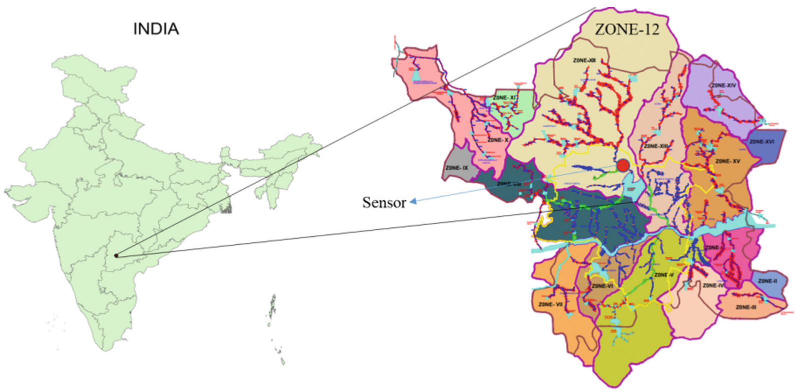


Fig. 1. Study area map

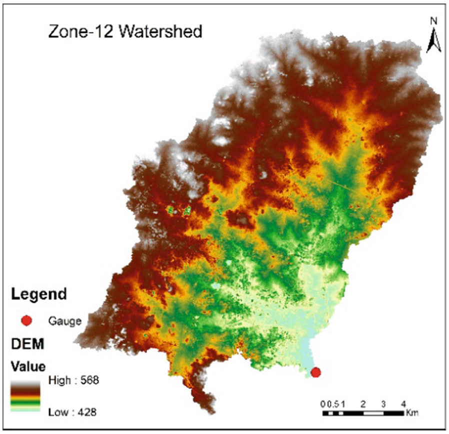
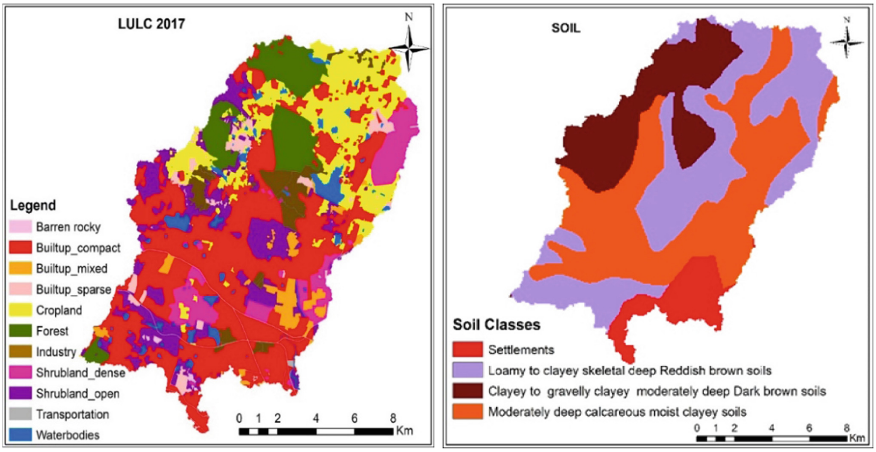


Fig. 2. CartoDEM



a) Landuse/Landcover map b) Soil map

Fig. 3. Spatial data

Parameter estimation

HEC-RAS can utilize a digital terrain model (DTM) to represent the bare ground surface. The terrain features can be extracted using DTM through the RAS mapper available in HEC-RAS by passing DEM as the input file. A cartoDEM of 10m resolution was purchased from NRSC and targeted to pass as an input file into the model for the zone-12 watershed to generate DTM.

The model consists of different parameters, such as 2-D surface roughness, boundary conditions, and flow data. Another important parameter includes Manning's roughness (n) can be assigned based on the land use classification and soil characteristics. In zone-12, sub-basin-wise Curve Number (CN) values were calculated from reclassified land

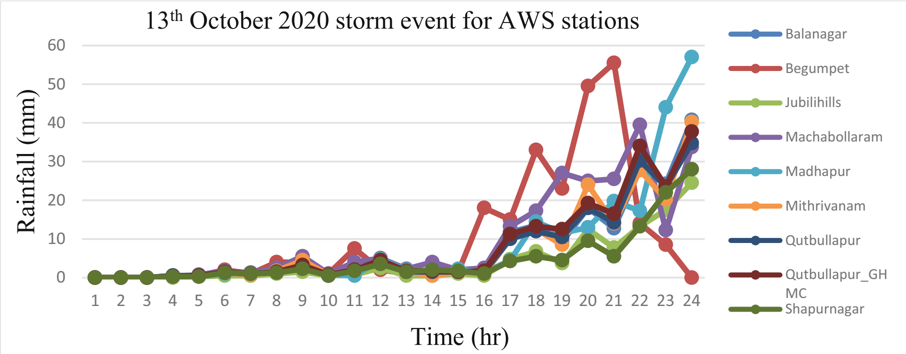


Fig. 4. Rainfall hyetograph for AWS stations of the 13th October 2020 event

use classes, as presented in Table 1. Zone-12 in Hyderabad is mostly built-up compact with loamy to clayey, clayey to gravelly, and moderately deep calcareous moist clay soil. In this study, Manning's n value of 0.025 was chosen for the entire 2-D area based on imperviousness and soil type. To run the 2-D model, it needs different boundary conditions. Depending on the availability of data, boundary conditions were assigned. This study used flood hydrographs obtained from HEC-HMS fixed to the respective sub-watershed of the 2-D flow area. The model is simulated to generate the flood inundation map with a measured flood hydrograph (Fig. 5) for the 13th October storm event, is applied as the actual boundary condition at the outlet of the watershed.

3 Methodology

Urban floods occur as a result of intense rainfall, inadequate drainage systems, or other factors such as land use changes and climate change. Urbanization can lead to the removal of vegetation and the increase in impervious surfaces, which reduces infiltration and increases runoff, exacerbating flooding. Poorly designed drainage systems can also lead to flooding, as they may not be able to handle the increased volumes of water. Urban floods can cause damage to infrastructure, homes, and businesses, and pose risks to human safety. Additionally, they can cause environmental and health problems due to the contamination of floodwater and the generation of waste. To mitigate the impact of urban floods, strategies such as green infrastructure, urban planning, and emergency preparedness measures can be implemented. In this study, presently the recent event that occurred on 13th October 2020 has been considered for simulation, and flood risk maps generation using HEC RAS 2D. Eventually, these maps will help in identifying the most critical areas, issuing warnings to the people, and helping the organizations to take administrative judgments during an emergency to prevent damages and economic losses.

The hydrological model such as HEC-HMS was used to estimate the magnitude of the torrents as well as their flow rates within the watershed. This study utilized a physically-based conceptual approach and collected data to gain more insights into the surface and topography of the watershed, as well as meteorological factors such as

Table 1. Sub-basin details

Basins	Curve Number (CN)	Basin slope (%)
Subbasin-1	85.3	0.8
Subbasin-10	88.0	0.9
Subbasin-11	90.8	0.9
Subbasin-12	88.8	0.8
Subbasin-13	91.0	1.2
Subbasin-14	92.4	1.9
Subbasin-15	91.4	0.7
Subbasin-16	92.3	0.6
Subbasin-17	91.9	0.9
Subbasin-18	89.7	1.1
Subbasin-19	91.9	0.6
Subbasin-2	90.2	0.8
Subbasin-20	91.7	0.8
Subbasin-21	92.1	0.8
Subbasin-22	90.4	0.6
Subbasin-23	88.0	1.0
Subbasin-24	92.6	0.8
Subbasin-25	89.2	2.4
Subbasin-3	83.7	0.8
Subbasin-4	88.4	0.7
Subbasin-5	87.7	0.6
Subbasin-6	81.5	0.8
Subbasin-7	90.4	0.9
Subbasin-8	90.2	0.7
Subbasin-9	89.8	0.8

rainfall and runoff. To conduct flood inundation modeling, the researchers employed the WMS model, which can seamlessly integrate with GIS, HEC-HMS, and HEC-RAS. This software can perform a wide range of operations such as basin delineation, geometric parameter calculations, cross-section extraction, floodplain delineation, and storm drain analysis. The first step in floodplain analysis involves gathering highly detailed hydrologic, hydraulic, and topographic data, from TSDPS, GHMC, and NRSC respectively. The rainfall, and discharge hydrographs, are collected from TSDPS, an Ultrasonic Level Transmitter installed by Osmania University respectively for zone-12. Subsequently, the HEC-HMS was utilized to construct an HEC-RAS flow model. The proposed methodology of phase-1 has the following steps (Fig. 6):

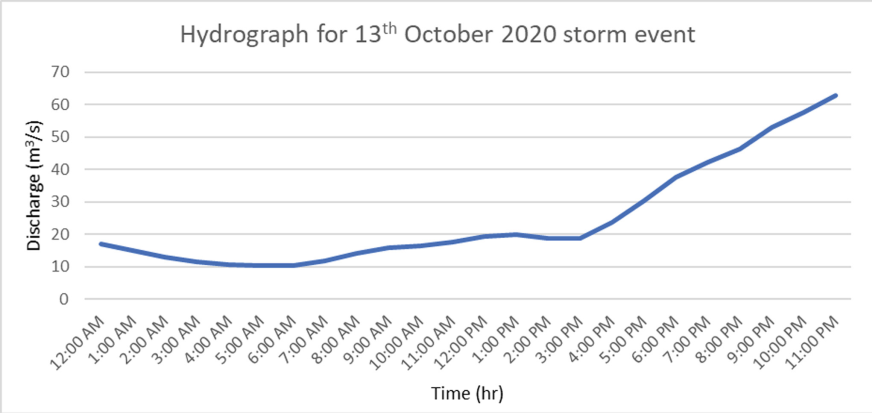


Fig. 5. Flood hydrograph at zone-12 watershed outlet

- The first step involves defining the basin delineation, stream network, topography, and geometric characteristics through digital elevation model (DEM) processing using the HEC-HMS 4.10 version.
- After this, the second step is to model the rainfall/runoff relation using the HEC-HMS model, which comprises four main steps. The first step is sub-basin delineation, followed by hydrologic parameter estimation. The third step involves setting up the basin model, meteorological model, and control specifications. Finally, calibration and validation are performed [32].

The phase-2 can be developed by importing the hydrologic modeling results obtained from HEC-HMS to be used as input data in the hydraulic model HEC-RAS. HEC-RAS 6.1 can perform 2-D flood modeling, including channel routing and flood inundation modeling (HEC-RAS 2021). The process of developing phase-2 of the HEC-RAS model is outlined in Fig. 6. The minimum data required for building a basic 2-D model are DEM and discharge data. In this study, a CartoDEM with a 10 m resolution was used (Fig. 2), processed in ArcGIS v10.1, and given as an input in ras-mapper to produce a DTM (Fig. 7a) model. Further, DTM is used to preprocess the 2-D area, compute water surface depths, and visualize the floodplain boundary. To accomplish this, the 2-D flow cover was illustrated as a polygon boundary, and a 2-D computational mesh with a resolution of 10 m x 10 m was created over the selected 2-D flow boundary (Fig. 7b). This mesh was adapted to match the 10 m resolution of the CartoDEM and covers computational grids of the 10 m x 10 m that depend on the basic terrain geometry. Finally, the resulting 2-D flood plain model that was established for the zone-12 watershed is presented in Fig. 7c.

3.1 Digital Terrain Model (DTM) Generation

DTM enhances a DEM by integrating geometric representations of natural terrain characteristics in the form of vector features, such as ridges and rivers [12]. One option for obtaining a DTM is to import a pre-existing model directly from alternate sources, or the

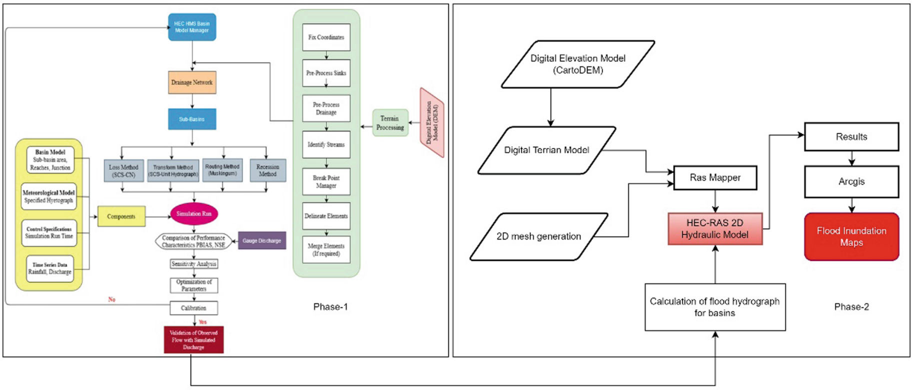


Fig. 6. Schematic flow chart for the proposed methodology

DEM file can be used as an input raster to generate a DTM. However, it's essential to use a small cell size to create the DTM as a precautionary measure, ensuring that all-terrain details are accurately considered. To create a flood inundation map, DTM needs to be interlinked with model geometry. Figure 7a depicted the generated terrain model from the 10-m DEM for the study area.

3.2 2D Flow Computations

The 2D flow cover in HEC-RAS refers to the spatial extent where 2D flow calculations take place and it is depicted using a polygon layer that covers the study region. A computational mesh consisting of 1, 50,273 cells is created with a cell spacing of 10 m within this defined 2D flow area. The use of a 10-m mesh is preferred because it matches DEM resolution and is appropriate for conducting calculations. The simulations are initiated by introducing boundary conditions in the form of time series of flood hydrographs within the 2D flow area. The 2D mesh for the 2D flow study area is generated illustrated in Fig. 7b.

3.3 2D Model Control Specifications

HEC-RAS is capable of conducting two-dimensional flow routing using either the Diffusion Wave equations (DWE) or the Shallow Water Equations (SWE) [10]. The model consists of three equation sets to determine the flow movement across the computational mesh: the original Shallow Water equations (SWE-ELM) based on the Eulerian-Lagrangian Method, a new Shallow Water equations solution (SWE-EM) based on Eulerian Method, and the Diffusion Wave equations. Although shallow water equations can simulate turbulence and Coriolis effects in the flow field, it requires higher computation power and time to complete model simulation. Furthermore, in the 2D flow type, a fine mesh is essential to address abrupt changes in the flow path in a 2-D flow field [16].

3.4 2D Mesh Boundary and Selection of Cell Size

To create a 2-D mesh, a polygon is drawn within the boundaries of the underlying terrain to define the 2-D flow area. An equal size of the hexagonal-type mesh is considered for the 2D mesh boundary with identical cell spacing. Depending on the cell size, the simulation time step, control of the model runtime, and entails accurate results. The Runtime of the model can also vary on cell size and the number of counts. It is suggested by several researchers that the mesh size should not exceed one million cells, if it exceeds this number can lead to substantial model runtime errors caused due to memory allocation issues [8, 23]. In this study, a 2D boundary consisting of 150,273 computational cells was established with a cell spacing of 10 m.

Selection of time step

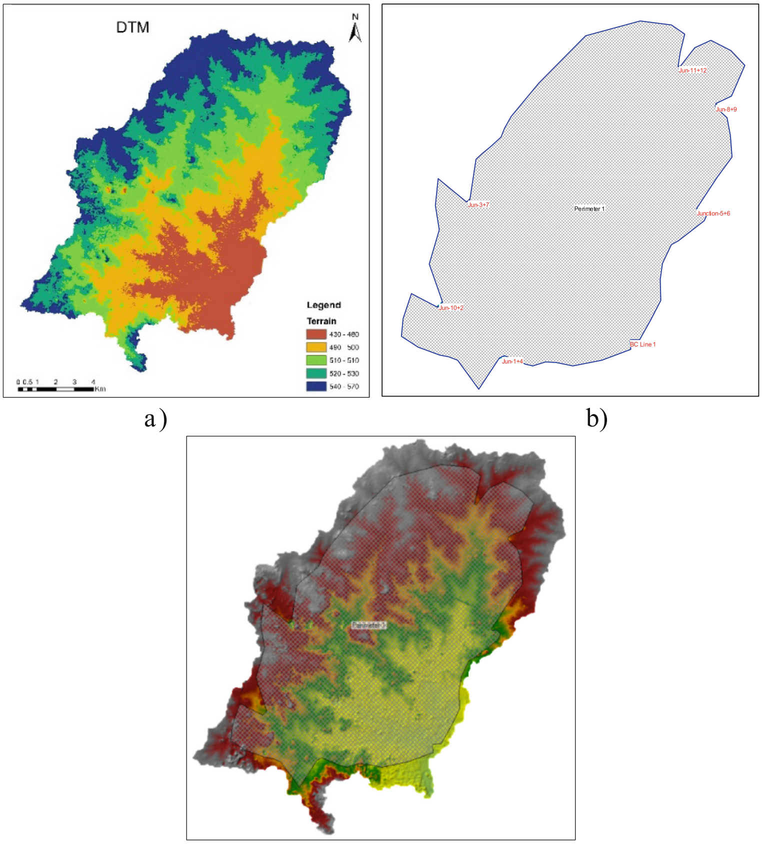
The 2D Model can produce dependable and precise outcomes even if the Courant number is as greater as 3.0 for SWE and 5.0 for Diffusion Wave equations [10]. For the computational time step (Δt) in small urban watersheds, a Courant number equal to 1.0 (for SWE) is suggested. Additionally, it is crucial to use an appropriate time step to generate constant results that can be recognized quickly. The time step should be selected as a minimum to let water drive through 2D cells [11]. The HEC-RAS model recommended using 30 s time step for 60-m cell spacing, but this size can be modified to produce good results without compromising its accuracy. To balance model strength and precision in output, it is recommended to conduct a first run with a rougher period (1–5 min). In this study, an initial time step of 1 min was used for model simulation and gradually refined by 1 s to achieve higher output accuracy without compromising model stability.

3.5 Model Simulations

The 2D model developed for the zone-12 watershed of Hyderabad city is presented in Fig. 7c. In this study, the latest flood event that occurred on 13th October 2020 was considered for model simulation and inundation mapping. The flow rates in the watershed were assessed in HEC-HMS and were assigned to HEC-RAS 2D flow area.

4 Results and Discussions

A 2-D model was constructed using HEC-RAS and is simulated for the 13th October 2020 flood event. The 2-D model used a DTM which is generated from 10 m DEM using the RAS Mapper tool. The simulation output of the model is generated with the depth of flood water inundation provided over the terrain surface. This result was then exported and further processed in ArcGIS v10.2.2 to generate food risk maps for the 13th October 2020 event based on the flood inundation layer output.



a) b)

c)

Fig.7. Ras-mapper layers a) Digital terrain model b) 2D flow area c) 2D model

4.1 Development of Flood Inundation Risk Maps

The flood inundation maps generated in the HEC-RAS model for the 13th October 2020 event are exported to ArcGIS v10.2 and further analyzed to create a flood risk map for the zone-12 watershed. The extent of inundation (in meters) during the simulation run period (13th October 2020) is used as a basis to categorize the risk level as very low risk (<0.001), low risk (0.001 to 0.5) medium risk (0.5 to 1), high risk (1 to 3), and very high risk (>3) of flooding. Figure 8 depicts the risk map derived from the latest event that occurred on 13th October 2020 extreme rainfall event.

4.2 Validation of Results

Based on the measured sensor data for the event on 13th October 2020 at the outlet of zone-12 watershed the real-time flood risk maps are generated. It is also validated with a google online survey conducted during the event.

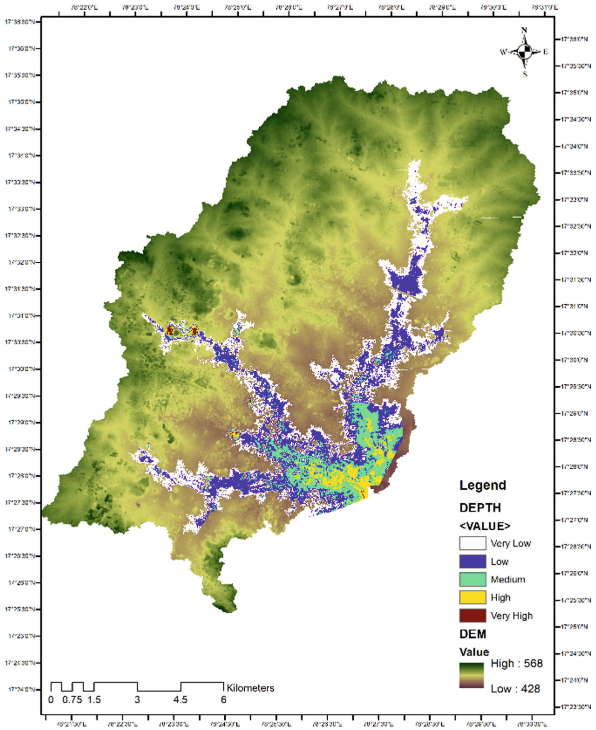


Fig. 8. Flood risk map of Zone-12 watershed

5 Conclusions

This study chose an HEC-RAS 2D hydraulic model to create flood inundation and risk maps for the zone-12 watershed of Hyderabad city during the extreme rainfall event that occurred on October 13th, 2020. The model entails most of the areas under low-lying Lakes were prone to huge flooding. Another reason for areas prone to floods under Lakes was the breaching effect. The flood risk map visualizes Pragati nagar, Dattatreya colony, and Nagarjuna colony under very high risk. The areas such as Balanagar, Shobana colony, IDA colony, Raju colony, and Vani nagar are under high risk. The areas beyond high risk are categorized as medium and beyond medium are under low and very low risk. Hence, high priority should be given to the very high-risk and high-risk zones to prevent flooding. The model yields reliable results if its terrain quality and input data are good. In this study, the high-resolution terrain feature available at NRSC and measured flow data at hourly intervals using an ultrasonic level sensor were used. Using the flood inundation maps developed with observed flow data, an early warning system can be established to alert residents of low-lying areas before extreme events occur. Additionally, integrating Automatic Weather Stations' rainfall data, flow data, and early warning systems can facilitate the adoption of relief measures.

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