



FLOOD INUNDATION MAPPING OF URBAN CATCHMENT USING HYDRO DYNAMIC MODEL

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ABSTRACT

Mitigation of urban floods and waterlogging, majorly in metropolitan cities, has drawn recent attention due to aggravated flooding in cities hindering socio-economic activities and ecology. The complexity of urban floods can be attributed due to rapid urbanization and extreme climatic events. The encroachment of water bodies and drains, unplanned construction, and destruction of natural storm conveyance need to be acknowledged to improve the drainage system to varying climatic conditions. Therefore, this study was carried out to address the inadequacy of the storm drainage network in Zone-IV GHMC (Greater Municipal Hyderabad Corporation), Hyderabad, Telangana. Environmental Protection Agency's (EPA) SWMM (Storm Water Management Model) software has been used to simulate the runoff in integration with the GIS application. Five tipping bucket rain gauges and three automatic water level recorders were installed in the pilot area for collecting the observed data. The model was simulated with different LULC periods from 1973, 1990, 2000, 2005, 2010, 2015, and 2020 and positive correlation between peak discharges, runoff coefficient, runoff depth, and percentage impervious area and find out the pilot area runoff coefficients (0.869, 0.851, 0.894, 0.903, 0.910, 0.925 and 0.956). The model simulated the runoff depth flood event for more than 100 years return period on 13 October 2020 and generated the flood inundation map using HEC RAS. Flood inundation depths are well compared with field observation marks. The dataset, the results obtained and the methodology followed in the current study can be used by urban planners to identify the potential flood risk zones and nodes and incorporate them to plan the mitigation and management strategies.

Keywords: Depth, Discharge, Flood, Network, Routing and Runoff.

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1. INTRODUCTION

Intensive climate change has aggravated the natural calamities and extreme climatic events globally. Increasing flood frequency in recent decades can be attributed due to climate change as well as growing human intervention. According to the IPCC (International Panel on Climate change) 2007, climate report, the climate simulation models predict that the average rainfall will increase by 20-30% in 60 years. Such an increase could result in urban areas suffering from an increase of up to 200% in flood risk. About one-third of the world's population was affected by floods during 1985-2003 (World Bank, 2005). India is among one of the most flood affected countries in the world (Jongmon *et al*, 2015). Assam is witnessing catastrophic flood where lakhs of people are suffering and struggling to save livelihood every year (Anon, 2022). The last two decades have seen substantial influence on the urban hydrology producing higher flood volumes for comparatively small rainfall event. The seriousness of the storm water flooding can be understood from the recent flood events in Chennai (2015), Kerala (2018), Patna (2019) and Hyderabad (2020) (Rangari 2021). Increase in building density and intense precipitation events are the driving forces that contribute to the increase in surface runoff and runoff coefficient due to storm water. Urban flooding has drawn attention due to rapid and uncontrolled urbanization. This results in overburdened drainage and unregulated construction, with no regard to the natural topography and hydro-morphology, contributes in making urban floods a man-made disaster.

Hyderabad is the emerging hub for information technology, in the state of Telangana state comprising of twelve municipalities, including GHMC (Greater Hyderabad Municipal Corporation). The rapid development in IT (information technology) sector has attracted skilled and unskilled labor to migrate from different parts of the country, further increasing the population of city (Gumma *et al* 2011; Fan *et al*, 2017). This change in land cover and land use inevitably affects the quantity of surface runoff in existing drainage system. The city has witnessed intense unprecedented flood events such as in August 2000 (241.5 mm), September 2016 and October 2020 (192 mm) (data from Indian Meteorological Department) resulting in massive destruction to life and property. The intense rainfall of October 2020 which flooded most of the Hyderabad city has drawn people's attention to mitigate the devastating floods and manage the storm water by providing enhanced drain capacity (Rangari *et al*, 2021). Storm water management is a complex task due to variation in land use, increasing population and socio-economic activities in urban areas (Choi and Ball, 2002; Hoang *et al.*, 2016). To combat the forthcoming disasters and longer sustainability, the immediate interventions are required in terms of redesigning the urban drainage system. Assessing the current and future urban drainage in coping with the increasing risk of urban floods created by regional and local factors should be the primary concerns (Vazhuthi and Kumar, 2020). Thus regulating urbanization, planning suitable and integrated flood regulating system, providing enhanced drain capacity, rejuvenating the water bodies and streams is the need of the hour to check and reduce the spatial urban flooding extent.

Flood mapping is a prominent tool to analyze inundation, flood risks zone, and vulnerability of the affected zone in order to plan reclamation strategies (Sahu *et al* 2021). Hydrologic modeling is an effective approach to assess the urban hydrology and simulate the urban storm water drainage. Several hydrological models are available for quantification of the hydrologic and hydraulic response of the urban catchment such as HEC-RAS, SWMM, and MIKE. EPA's SWMM is the rainfall-runoff model used for simulating the quality and quantity of surface runoff generated from rain catchment area (Manual, 2015). It determines the peak discharge by water balance, derived from continuity equation. Several studies have been conducted to design urban drainage using SWMM (Majeed and Chinnamma, 2021; Rangari *et al.*, 2017).

HEC-RAS is commonly used for floodplain management and flood insurance studies to evaluate inundation encroachment. It simulates one-dimensional and two-dimensional unsteady flow computation through numerical modeling (Aslam and Lasminto, 2020; Devi *et al*, 2019; Kumar *et al* 2019; Romali *et al*, 2017). Both, SWMM and HEC-RAS, use dynamic wave routing solves the complete Saint Venant equations for gradually varied, unsteady free surface flow. This routing gives the best theoretical approaches as compared with steady-state and kinematic food routing. The downside of this approach is the requirement of small time steps to maintain numerical stability.

This study is undertaken to analyze the spatial inundation in the urban catchment of GHMC (Greater Hyderabad Municipal Corporation) Zone-IV from 13th October to 14th October 2020. The downstream of the study area is adjacent to the Musi River making it susceptible to floods. Flood mapping was carried out using the hydraulic modeling through SWMM (Storm Water Management Model) for rainfall-runoff simulation and 2D mathematical modeling using HEC-RAS application. The input parameters for hydraulic modeling were determined using GIS (Geographical Information System) tool.

2. STUDY AREA

Hyderabad is sixth largest metropolitan capital situated at an elevation of 536 m above mean sea level with an average annual rainfall of 847 mm. It is located in the sub-basin Musi River which is the part of Krishna river basin, susceptible to frequent flood cycles. Historically known as Lake City, the study area comprises five major water bodies namely Saroornagar, Chandana Cherruvu, Mantralaya Cherruvu, Peddama Cherruvu and Kharmaghat. Rainfall observed on 13th October 2020 witnessed the massive destruction of property and people. The present study area is Zone-IV of GHMC (Greater Hyderabad Municipal Corporation) located in Hyderabad, Telangana, India. The location of the study area is within the outer ring road of Hyderabad is shown in figure (1) where the outlet of the area joins the Musi river. The total 49 sq.km area of watershed lies between latitudes 17° 16' and 17° 22' N and stretches between longitudes 78° 29' and 78° 33' E.

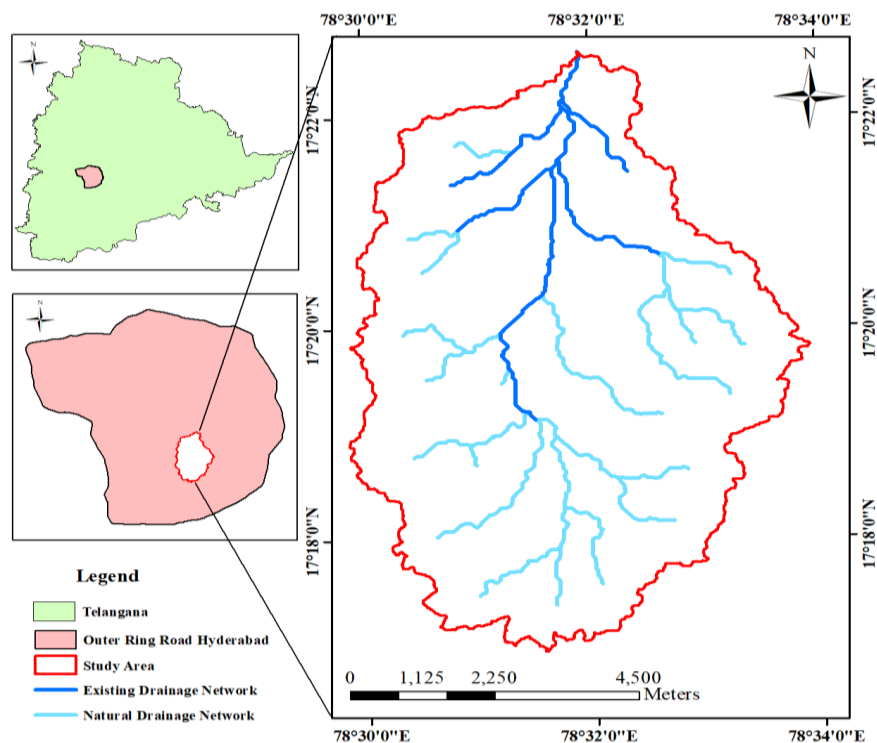


Figure 1: Location of Zone-IV GHMC Hyderabad.

3. METHODOLOGY

3.1. Data collection

The high resolution 50 cm DTM (Digital Terrain model) and Satellite images (Landsat-5 and Resourcesat-1&2) were downloaded from USGS Earth Explorer. The rainfall data was collected from Telangana State Government while toposheet from Survey of India (SOI). Drainage details for existing drainage system (type, cross sectional area and length) were collected from field inspection and GHMC, Hyderabad office. The complete detailed methodology of the present study is shown in figure (2).

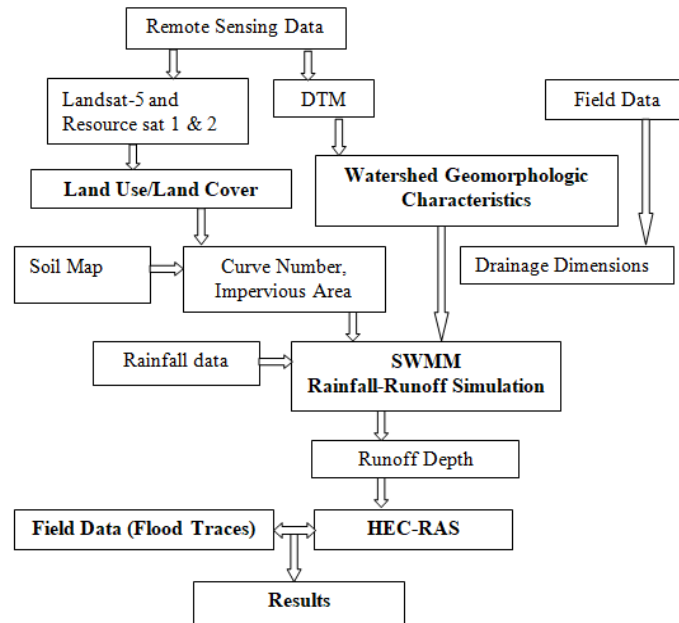


Figure 2: Flow chart representing Methodology Followed

3.2. Land Use/Land Cover (LULC) classification

Zone-IV was divided into sub-watersheds in GIS tool using 50 cm DTM data on the basis of natural drainage network. Soil type map was plotted from FAO (Food and Agriculture Organization) world soil map. Thematic maps were prepared processing the DTM using hydrology tool. Land use and land cover (LULC) plots was generated for each sub-catchment using SOI 1973 top sheet, Landsat-5 30 m resolution for the year 1990 and 2000, and 5m resolution of Resource sat 1&2 for 2005, 2010, 2015 and 2020 images. Using maximum likelihood classification, the area was classified into six classes namely; water body, plantation, vegetation, barren land, roads and built-up area to observe the variability in study area. These LULC maps were used to estimate the percentage pervious and impervious area in the basin for corresponding years. Accuracy assessment (and Kappa Coefficient) was carried out to ensure precise change detection using training areas and test data. LULC plots and soil maps were used to calculate the curve number for each sub-catchment.

3.3. Hydraulic Modeling using SWMM and HEC-RAS

The flood modeling for the study area is carried out using EPA's SWMM (Storm Water Management Model) and HEC-RAS (Hydrologic Engineering Centre's River Analysis System) numerical model. The SWMM model is set up for different year from 1973-2020 to simulate the urban runoff in Zone-IV of GHMC for single rainfall event occurred on 13th October 2020.

As there is no proper drainage network at present in the upstream portion of the watershed, therefore various sub-watersheds are merged and weighted average parameters was calculated for each year. The sub-watershed characteristics such as area, width, percentage mean slope, percentage imperiousness, curve number, details of storage reservoir and rainfall intensity as time series were given as input parameters for each year. In addition various LULC details for the year 1973, 1990, 2000, 2005, 2010, and 2015 were incorporated in the model to estimate the runoff coefficients, runoff depth and flood peaks accordingly. The complete model was set up in EPA's SWMM consisting of 31 sub-catchments, 5 storage nodes, 7 junctions, 12 conduits, 1 rain gauge and 1 outfall. The runoff depths for year 2020 were further used for numerical simulation of inundation in the study area. Both SWMM and HEC-RAS include a Dynamic wave routing combined solving the continuity and momentum equations known as Saint Venant equation. The SCS-CN method is used in runoff calculation to study the behavior of drainage system. The model was run at 5 min time steps and the results were analyzed.

Runoff simulated depth from SWMM models is used as input boundary condition to 2D-hydrodynamic model HEC-RAS 5.0 and 2D flood map have been prepared for the event on 13th October 2020. The water surface profile can be computed using an external GIS application interface known as RAS mapper. The simulated inundation depths were compared with the flood traces at the field at different location to determine the feasibility of the analysis.

4. RESULT AND DISCUSSIONS

4.1. Thematic mapping

The soil map analysis indicated that about 83% of soil comes under moderately deep, well-drained clayey soil, followed by rocks and hilly region of about 12% rest other are well-drained and gravelly clay soil. In this study, soil group C is considered for estimation of curve numbers because the majority of the portion covered by well-drained clayey soil cover. Hence, most of the barren land has moderately high potential to generate runoff. Land use/land cover change classification from 1990-2020 is shown in figure (3). For year 1973, 1990 and 2000, the LULC plots were classified into four classes namely water body, vegetation, built-up area and vegetation. Since the better resolution images were found for 2005-2020, the LULC plots were classified into six classes sub classifying vegetation into forest and agricultural land while built-up area sub classified as roads.

The land use/land cover analysis shows 32.17% of pervious area was lost in between 1973-2020. With just 12% of vegetation area, 21% barren land and 2 % water body in year 2020 shows encroachment of agricultural land, stress on developed area and shrinkage of water body from 24%, 50% and 4% area in 1973 respectively. The gradual increase in built-up area and roads from 2005 to 2020 indicates the extent of urbanization within a short span of just 15 years. The continuous increase of 25.7% in impervious layer was observed except from 1973 to 1990 (figure 4), which was because of manual plotting of LULC classes on toposheet or due to increased vegetation the infiltration capacity improved as the built-up area for both year is observed to be almost same . However, the maximum change of about 12% is noticed between years 2015-2020. The accuracy assessment was performed on GIS platform. The random points was selected for six classes and with the help of Google Earth Pro Platform, the ground truth points for each period from 2005-2020 was finalized. The overall classification efficiency was assessed as 89, 91, 88 and 86 percent and Kappa coefficient as 0.86, 0.88, 0.85 and 0.84 for the years 2005, 2010, 2015 and 2020 respectively. For the kappa coefficient, values above 0.8 are considered as perfect. Therefore, from the observed results, it can be concluded that the classified images found was to be fit for further research studies.

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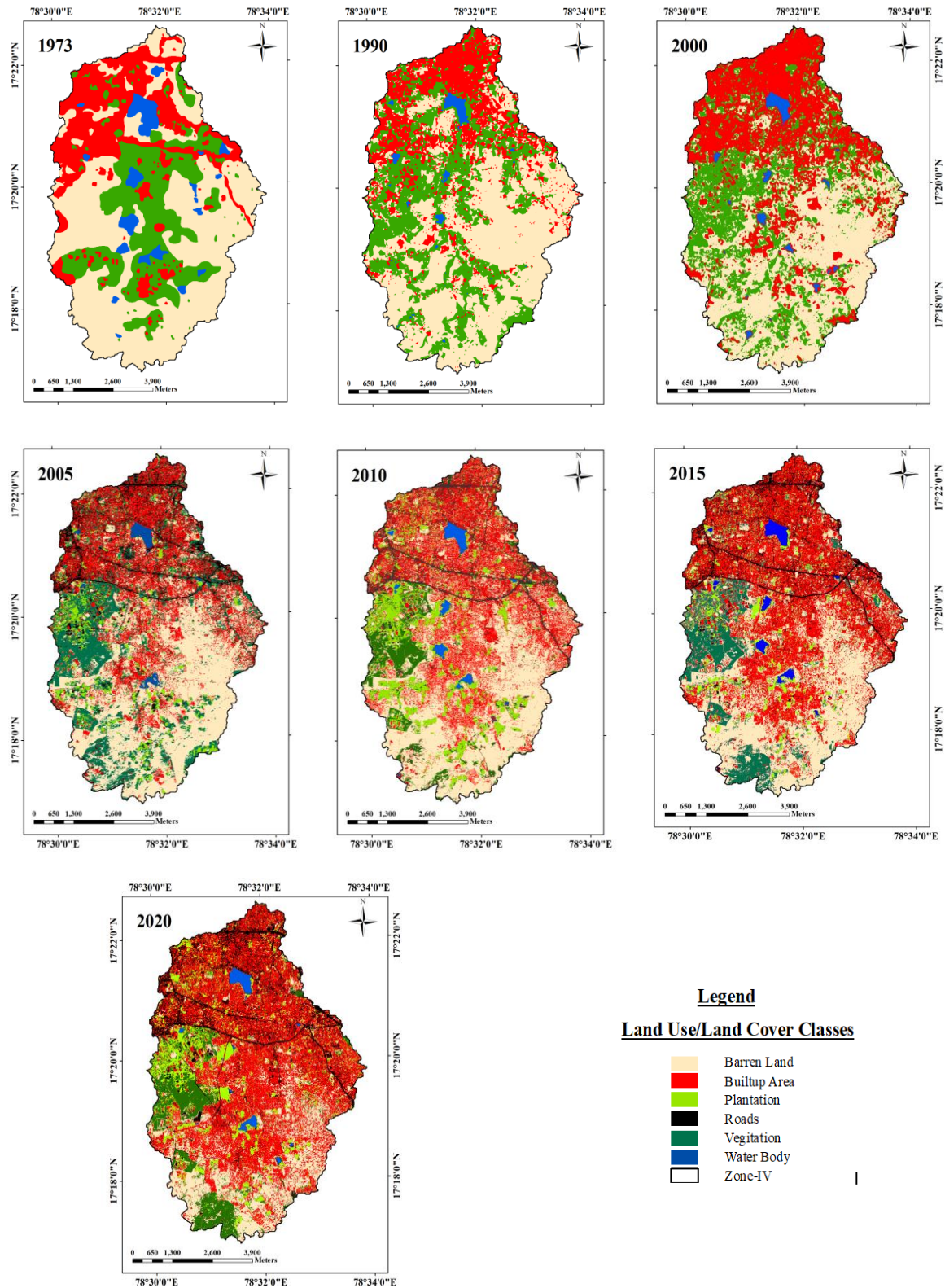


Figure 3: Land Use/Land Cover mapping throughout the period of study (1973-2020) chronologically.

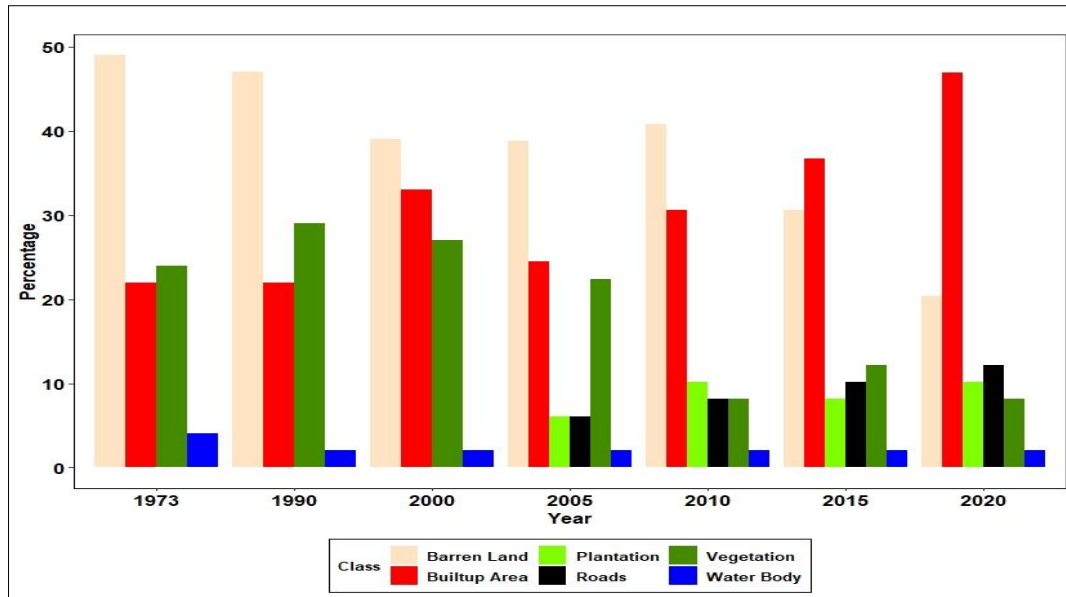


Figure 4: Percentage pervious and impervious area under different classes in corresponding years.

4.2. Rainfall-runoff simulation: SWMM

After the model was set-up individually for year 1973, 1990, 2000, 2005, 2010, 2015 and 2020 and runoff results were simulated for same rainfall event of 13th October 2020, with cumulative rainfall of 346 mm (table 1). The corresponding percentage impervious area, runoff coefficient, peak discharge and runoff depth throughout the years are compared and a positive correlation was observed between them. With percentage increase in impervious area due to urbanization, with subsequent period time, resulted in simultaneous increase in runoff coefficient, runoff depth and peak discharge. This can be attributed with increasing imperviousness which limits the infiltration process by increasing the total runoff from the urbanized watershed (Sen and Atunkaynak, 2006). An exception was also observed for year 1990 with sudden drop in slope. The decrease in impervious area (18.7%) from year 1973 to 1990 can be attributed due to higher vegetative cover in 1990 improving infiltration capacity of the soil simultaneously decreasing the runoff, runoff coefficient and peak discharge (figure 5a).

Table 1: Model output for different year for same rainfall event.

Year	Runoff Coefficient	Runoff (mm)	Peak Discharge (Qmax)	Percentage of Impervious Surface
1973	0.869	301.11	1208	27.19
1990	0.851	294.98	1186	22.10
2000	0.894	309.794	1209	34.09
2005	0.903	312.89	1223	33.66
2010	0.910	315.42	1269	39.07
2015	0.925	320.57	1294	47.68
2020	0.956	331.4	1330	59.36

From the simulation results, a substantial increase of 12.14% in peak runoff was observed from 1990 to 2020. Similar increasing trends were observed for runoff coefficient (10.9%) and total runoff (27.6%) as well. The runoff coefficient indicates the amount of water flowing from particular precipitation and reflects the impact of natural geomorphologic elements on the flow.

With an impervious area of 59.36%, year 2020 witnessed the peak discharge of about 1330 m³/s and runoff coefficient of 0.956 severely damaging the life and property simultaneously drawing attention to the inadequacy of the existing drainage system. The output flow hydrograph for year 2020 was used to calculate the elevation of flood water marks in the study area. The results from the storm simulation are presented in figure (5a and 5b) for different year and same single rainfall event.

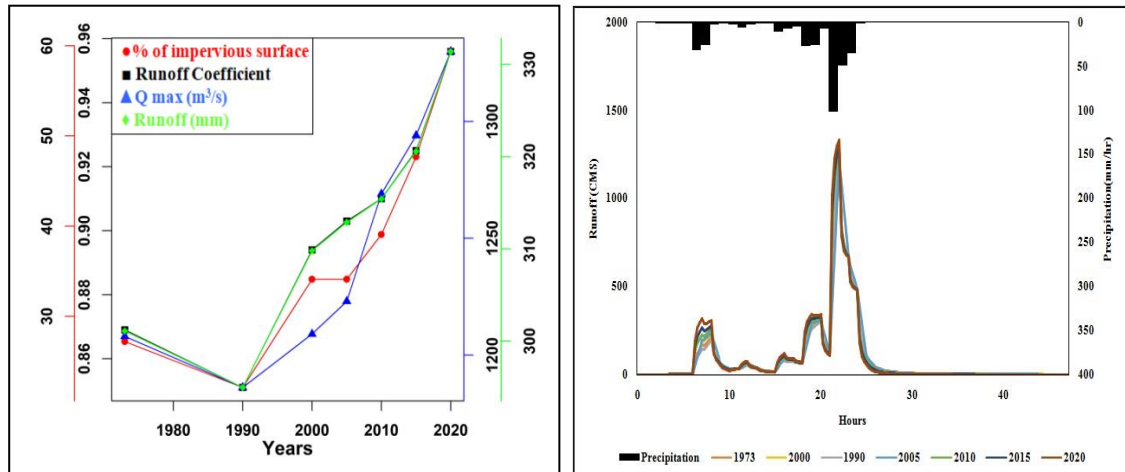


Figure 5: (a) Comparative change in runoff coefficient and peak discharge for same rainfall event throughout the period from 1973 to 2020 and (b) Runoff simulation results for different year for the precipitation on 13th October 2020

4.3.2D Hydrodynamic Numerical Modeling: HEC-RAS

The output flow hydrograph obtained from simulation results in SWMM model (figure 5b) are then used as the input boundary condition for runoff flow simulation in the 2D HEC-RAS model. After running simulation, the results indicated rise in water level throughout the banks of drainage network, water storage tanks and outlet. The computed water depth ranges from 0 to 23 m, at upstream area with higher elevation to outlet with lowest elevation respectively. The model was used to categorize the inundation into 5 categories on the basis of water depth such as 0-1m, 1-3m, 3-6m, 6-9m and 9-23m.

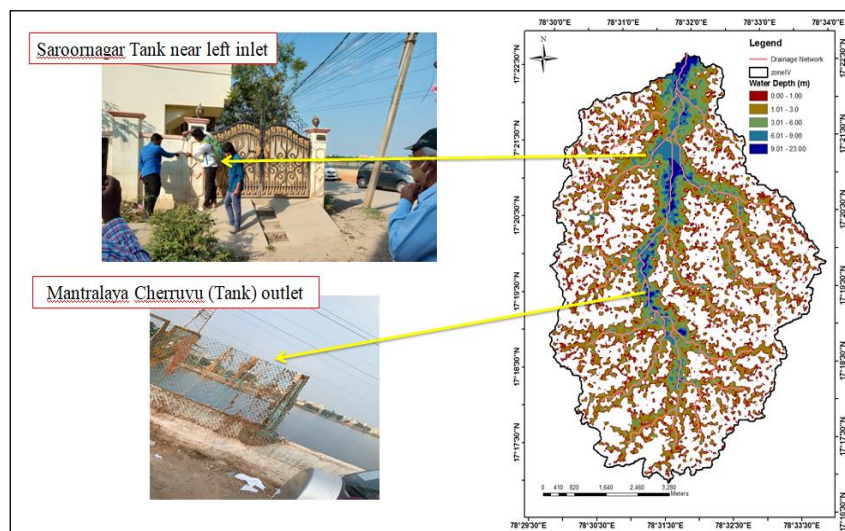


Figure 6: Measuring water depth during 13th and 14th October 2020 at field location.

The maximum water depth of 23 m was found at the outlet and majorly at the areas adjoining the main drainage channel, connecting the water tanks to the outlet of the study area. In addition, the areas adjacent to the natural drainage system were severely affected with the flood depth ranging from 3m to 9m. Reliability of the simulated results was tested by measuring the inundation marks and traces in the study area at multiple locations such as former flood marks on the walls of the resident's houses. The results indicated that the model computed values are in good agreement with the field data. The flood marks measured near inlet of Saroornagar tank and at the outlet of the Mantralaya Cherruvu (tank) are depicted pictorially in figure (6). Therefore, the HEC-RAS modeling results are considered to be feasible and could be further referred for future studies on urban flooding extent, planning and mitigation measures for the study area.

5. SUMMARY AND CONCLUSIONS

Urban flooding is a serious problem observed in urban watersheds due to uncertain climatic changes, increasing flood frequency and growing urban sprawl. The prerequisite for watershed sustainability and flood mitigation requires urgent attention towards the spatial flood patterns and zoning flood risk assessment. This study aims to simulate the catastrophic flood event occurred on 13th October 2020 Hyderabad (zone-IV, GHMC) and extent of flood risk zones. The assessment was carried out using SWMM and HEC-RAS hydraulic model in integration with the application of ARC-GIS. The land use/land cover analysis shows 32.17% of pervious area was lost in between 1973-2020. On runoff simulation of rainfall event using SWMM, the positive correlation was observed between percentage impervious areas, runoff coefficient, runoff depth and peak discharge throughout the period of study (1973-2020). The flow hydrograph for year 2020 was used as input boundary condition for hydraulic analysis of the rainfall. The HEC-RAS model was used to categorize the inundation into 5 categories on the basis of water depth such as 0-1m, 1-3m, 3-6m, 6-9m and 9-23m. The simulated depths were compared with flood marks and found that the simulated results are in good agreement with field data indicating successful application of tool. This study is useful to determine the potential flood risk zones in the study area for the local authority and plan the mitigation method accordingly.

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