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Assessment of Flood Inundation Using Hydrologic-Hydraulic Modelling: A Case Study for Hebbal Valley, Bengaluru Urban

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***Abstract*—Urban flooding has emerged as a major concern in rapidly growing cities due to increasing impervious surfaces, altered drainage patterns, and intense rainfall events. Accurate estimation of runoff and flood extent in an ungauged urban valleys are essential for effective flood management and infrastructure planning. The present study focuses on Hebbal valley located in the northern and northeastern regions of Bengaluru urban, Karnataka which is geographically lies between 12º 58' and 13º 12'N latitude and 77º 31' and 77º 47'E longitude and covering an area of 312.29 km². An integrated hydrologic and hydraulic modelling approach is adopted using HEC-HMS and HEC-RAS 2D to simulate flood scenarios under various return periods. The HEC-HMS model is used to simulate rainfall-runoff process using the SCS-CN method, incorporating rainfall depth from IDF curves, land use from Sentinel-2, soil data for infiltration, and SRTM DEM for topography. The output hydrographs are then input into HEC-RAS 2D to simulate spatial flood extents. Results reveal that the inundation areas expand significantly from 18.74 km² to 30.93 km² for the 2 year and 100 year respectively. The built-up zones being the most vulnerable to flooding, accounting about 43 % for 2 year event to increasing upto 57 % for 100 year event. This shift underscores the risk faced by urbanized regions during extreme hydrological events. The study demonstrates the integration of physically based models with geospatial datasets offers a reliable and scalable solution for flood risk assessment in urban ungauged valleys, supporting evidence-based urban flood mitigation strategies.**

***Index Terms*—Urban flooding, HECHMS, HECRAS, SCS CN, IDF**

I. INTRODUCTION

Floods are the most devasting and recurring disaster often leading to significant loss of life, infrastructure damage and socio-economic disruptions especially in urban areas. In recent years, the urban areas across the globe have been witnessing a surge in flood related challenges. Bengaluru urban, being located on a natural ridge, forms three valleys which drains precipitation as runoff in three directions along the valleys namely, Hebbal, Koramangala–Challaghatta (KC) and Vrishabhavathi, This is attributed to increase in impervious surfaces, reduced infiltration, rapid urbanisation and change in LU/LC pattern over the years. This transformation disrupt the natural drainage mechanisms, leading to higher surface runoff and increasing urban flood risks. With rapid urbanization and climate variability, the frequency and intensity of urban flooding events have increased globally, making flood risk assessment a critical component of urban planning and disaster mitigation (IPCC, 2021). In this scenarios, ungauged catchments pose an even greater challenge due to the absence of hydrological data. In such contexts, physically based hydrological models are essential to simulate runoff processes using available spatial and climatic data (Teng et al., 2017). Hence, hydrological models namely HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) become an essential tools for estimating runoff and peak flood discharge in these catchments, utilizing rainfall data, catchment characteristics, and land use parameters (Feldman, 2000). Ali et al., 2011 demonstrate the applicability of HEC-HMS in estimating discharge for urban ungauged basins with satisfactory accuracy when integrated with remote sensing and GIS datasets. The HEC-RAS (Hydrologic Engineering Center – River Analysis System) model is employed for hydraulic modelling to determine flood extent, depth, and velocity across the catchment. To address the urban flood risks, coupling hydrological and hydraulic models for accurate flood prediction and risk assessment are necessary particularly in complex and ungauged urban valleys. In the present study, an attempt has been made to assess the flood inundation across the Hebbal valley using an integrated modelling approach by coupling physically based hydrological models such as HEC-HMS with 2D hydraulic models like HEC-RAS which provides a reliable framework to assess runoff generation and flood inundation under varying rainfall scenarios. By using geospatial data such as LU/LC alongside long term rainfall records, this study aims to produce spatially explicit flood estimates that support urban flood risk assessment and planning. The outcomes are intended to inform sustainable drainage design and enhance resilience against future urban flooding events.

II. STUDY AREA

Hebbal valley is one of the three major valleys contributing to the natural drainage systems of Bengaluru urban which is situated in the northern and north eastern parts of the Bengaluru. It is located between 12º 58' N and 13º 12'N latitude and 77º 31'E and 77º 47'E longitudes covering an area of 312.29 km^2. The valley flows eastwards and confluence with Dakshina Pinakini at Kadugodi plantation, Bengaluru. The area is characterised by gently undulated to steep terrain with elevation ranging from 955 m to 854 m. The region experiences summer temperatures rising upto 34°C and winters upto 13–15°C. The drainage system is characterised by dendritic pattern and the valley is interconnected with several prominent lakes such as Hebbal, Yelahanka, Jakkur, Kalkere, Horamavu Agara, Doddabommasandra and Yelemalappashetti, which collectively supports flood moderation and groundwater recharge. Rainfall in the valley is primarily influenced by southwest monsoon, average rainfall of 479.22 mm to 783.23 mm (Amrutha Rani and Ravikumar, 2024). In general, the valley is characterised by red soil derived from gneiss as its rock source. Plate 1 shows the location map of the study area.

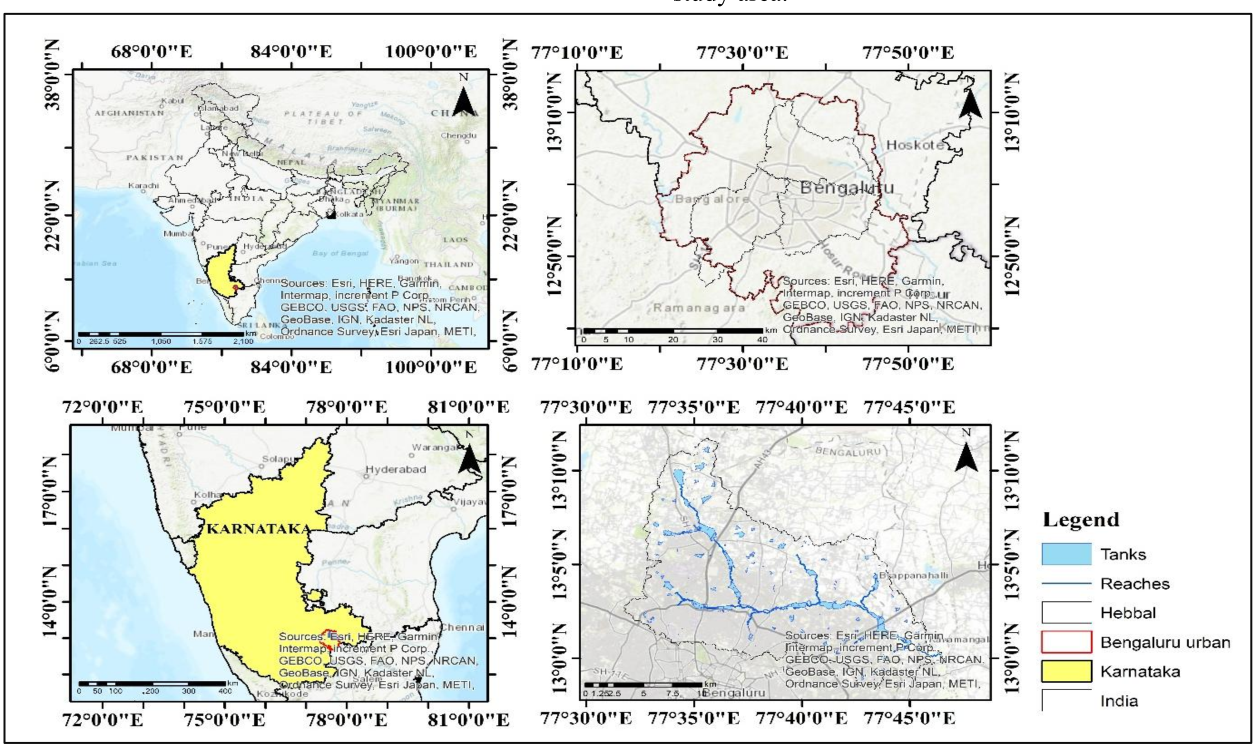

Plate 1 Location map of the study area

III. DATA PRODUCTS

In the present study, an attempt has been made to prepare the flood inundation map using coupling hydrological and hydraulic modelling. The following data products are used in the present study. Table 1 shows the details of the data used in the present study.

Table 1 Data used in the study

Sl No	Data	Source	Purpose
1	Daily Rainfall data (1980-2022)	Water Resources Development Organization (WRDO), Bengaluru	IDF (Rainfall depth)
2	Sentinel 2 (10 m resolution)	ESRI	Land use / Land cover
3	SRTM DEM (30 m resolution)	USGS Earth Explorer	Topography
4	Soil	Digital Soil Map of World	Infiltration layer

IV. METHODOLOGY

The study integrates the hydrological and hydraulic modelling (HEC-HMS and HEC-RAS) along with GIS and RS data to evaluate flood inundation of Hebbal valley. The methodology describes the steps involved in flood modelling using 2D unsteady flow simulation through HEC-RAS.

HECHMS

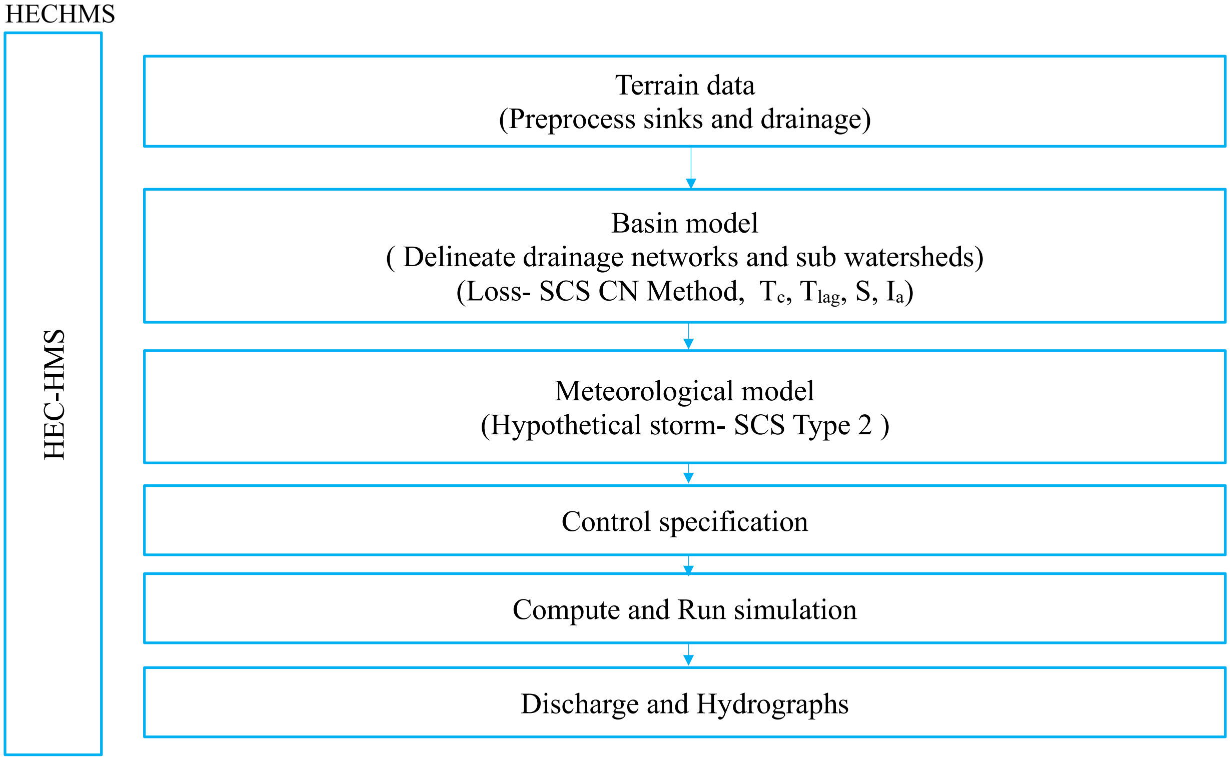

Fig. 1 Methodology of work (HEC-HMS)

HEC-HMS is employed to simulate the rainfall-runoff response of the Hebbal valley. The following are the steps followed to obtain the peak discharges (Fig. 1).

i. the hydrologic model setup begins with preprocessing of DEM using GIS tools to extract flow direction, flow accumulation, and delineate sub-valley boundaries.

ii. each sub-valley is treated as an independent hydrologic unit and the SCS Curve Number (CN) method is adopted to estimate rainfall losses, with

CN values derived from LU/LC and hydrologic soil groups from the standard reference table (Chow et al., 1988), which provides CN ranges for various combinations of land use and soil types (Table 2).

iii. the meteorological model incorporates a hypothetical storm using SCS Type II temporal distribution, suitable for high-intensity short-duration rainfall scenarios. Rainfall depths for various return periods (2, 5, 10, 25, 50, 100 years) are obtained using IDF curves (Table 3).

iv. the SCS Unit Hydrograph method is applied to transform excess rainfall into direct runoff, with the time of concentration (t_c) estimated using the equation (Kirpich's, 1940) and lag time (t_{lag}) being 60 % of time of concentration. Table 4 and 5 represents the calculated t_c and t_{lag} for sub valleys and reaches of Hebbal valley respectively.

$$t_c = 0.0195 \times L^{0.770} \times S^{-0.385} \quad (1)$$

where, t_c= time of concentration (min), L= channel flow length (m) and S = main channel slope (m/m).

$$t_{lag} = 0.6 \times t_c \quad (2)$$

v. baseflow is estimated using the constant monthly method due to the lack of detailed groundwater data. As per the recommendations of the Central Water Commission (CWC), a baseflow rate of 0.05 cumecs/km² is adopted for estimating baseflow in sub valleys (CWC 1986). This guideline has been followed in the present study, and the estimated baseflow values are assigned accordingly. The simulation results include hydrographs and peak discharges at outlets and junctions, which are subsequently used as inputs for hydraulic simulation in HEC-RAS.

Table 2 Curve numbers (AMC II) for hydrological soil cover complex

Sl No	Land use/land cover classifications	Hydrological Soil Group			
		A	B	C	D
1	Agricultural land without conservation (Kharif)	72	81	88	91
2	Double crop	62	71	88	91
3	Agriculture Plantation	45	53	67	72
4	Land with scrub	36	60	73	79
5	Land without scrub (Stone waste/rock outcrop)	45	66	77	83
6	Forest (degraded)	45	66	77	83
7	Forest Plantation	25	55	70	77
8	Grass land/ pasture	39	61	74	80
9	Settlement	57	72	81	86
10	Road/railway line	98	98	98	8
11	River/Stream	97	97	97	97
12	Tanks without water	96	96	96	96
13	Tank with water	100	100	100	100

(Source: Ven Te Chow, 1988)

Table 3 Rainfall depths for sub valley of Hebbal valley on different return periods

Sub valley	Return period (years)					
	2	5	10	25	50	100
	Rainfall(mm)					
S1	71.2	127.4	164.6	211.7	246.5	281.2
S2	70.3	100	119.7	144.6	163	181.3
S3	66.5	115.4	147.7	188.6	219	249.1
S4	37.7	55.1	66.7	81.2	92.1	102.8
S5	34.4	53.2	65.6	81.4	93	104.6

S6	35.8	54.2	66.5	81.9	93.4	104.7
S7	49.6	75	91.8	113.1	128.8	144.5
S8	34.4	53.2	65.6	81.4	93	104.6
S9	34.7	53.4	65.7	81.3	92.9	104.3
S10	53.3	71.8	84	99.5	111	122.4

Table 4 t_c and t_{lag} for Sub valleys of Hebbal valley

Sub valley	Area (km^2)	t_c (min)	t_{lag} (min)	Baseflow (m^3/s)
S1	48.51	88.4	53.1	2.43
S2	28.42	62.5	37.5	1.42
S3	46.81	90.5	54.3	2.34
S4	15.39	62.8	37.7	0.77
S5	16.13	53.1	31.9	0.81
S6	33.69	80.7	48.4	1.68
S7	28.49	81.8	49.1	1.42
S8	32.69	82.8	49.7	1.63
S9	28.04	67.9	40.7	1.40
S10	25.77	82.6	49.6	1.29

Table 5 t_c and t_{lag} for different reaches of Hebbal valley

Reaches	t_c (min)	t_{lag} (min)
R1	307.7	184.6
R2	68.8	41.3
R3	291.8	175.1
R4	167.1	100.3
R5	170.6	102.4
R6	217.5	130.5
T1	161.1	96.7

HECRAS

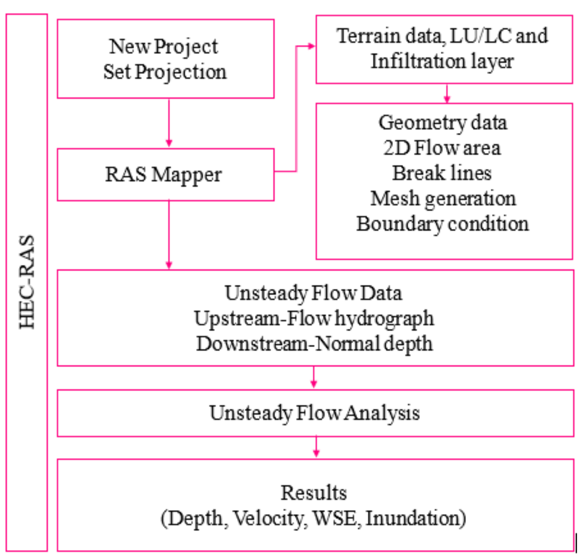

Fig. 2 Methodology of work (HEC-RAS)

HEC-RAS is utilized for 2D hydraulic modelling to assess the flood inundation based on discharges derived from HEC-HMS (Fig. 2). The model begins with setting up a project in HEC-RAS with the appropriate coordinate system to ensure GIS compatibility. Terrain data (DEM) is imported into RAS Mapper to define the topography of each valley. LU/LC maps are used to assign Manning's roughness coefficients for surface resistance based on land type (Table 6). An infiltration layer based on hydrologic soil group information is also included to estimate spatial variability in rainfall absorption.

A 2D flow area is defined by using a computational mesh. Break lines are then drawn along the main channels to align mesh elements with natural flow paths. Upstream boundary conditions are defined by flow hydrographs from HEC-HMS, while downstream boundaries are set using normal depth based on terrain slope. The unsteady flow analysis is executed with a 1-minute computation time step and 15-minute output interval. Model outputs includes flood depth, velocity, and water surface elevation. These are visualized as spatial inundation maps allowing planners to assess urban flood susceptibility under various rainfall scenarios.

Table 6 Manning's n value for different LU/LC categories

LU/LC	Manning's n value
Trees	0.126
Builtup area	0.092
Rangeland	0.038
Waterbodies	0.038
Crops	0.035
Bare ground	0.027
Flooded vegetation	0.061

V. RESULTS AND DISCUSSION

The present study evaluates the hydrologic and hydraulic response of the Hebbal valley for extreme rainfall events using HEC-HMS and HEC-RAS models. The hydrologic simulations in HEC-HMS generate peak discharge values and hydrographs for various return periods, while the hydraulic simulations in HEC-RAS assess the spatial extent of flooding, water depths, and flow velocities. Together, these models provide an integrated understanding of flood behaviour across the urban valley under multiple extreme event scenarios.

HECHMS Model simulation

The HEC-HMS model is applied to simulate rainfall-runoff processes across Hebbal valley for various return periods. Table 7 summarizes the peak discharge values generated at various hydraulic elements for different return period. The model outputs include time-varying hydrographs and maximum discharge values, offering critical insight into the hydrologic behaviour of the valley under different storm intensities.

As expected, peak discharge values increase progressively with higher return periods, indicating intensified rainfall and corresponding runoff generation. The outlet point, Sink-1, records the highest discharges, ranging from 293.1 m^3/s to 1504.3 m^3/s for the 2 year and 100 year return period respectively. These estimates are vital for assessing downstream flood hazards and guiding the planning and design of flood mitigation infrastructure during extreme rainfall events.

Table 7 Peak discharges for different return periods

Hydraulic elements	Return period (years)					
	2	5	10	25	50	100
	Peak Flood (m^3/s)					
R1	234.6	523.2	716.3	959.8	1138.7	1316.3
R2	293.7	623.4	843.6	1121.1	1325.1	1527.4
R3	296.9	628.7	850.4	1129.7	1335.1	1538.8
R4	309	647.6	873.8	1158.7	1368.2	1575.9
R5	312.4	652.9	880.5	1167.3	1378.1	1587.3
R6	288.2	594.3	809.4	1084.7	1289.7	1492.5
S1	234.6	523.8	717.5	961.6	1141	1319
S2	172.2	285.1	361.1	457.5	528.6	599.2
S3	200.9	437.1	596.6	798.3	947.6	1094.8
S4	31.4	63	85.7	115	137.5	159.7
S5	30.4	69.7	98	135.3	163.2	191.3
S6	52.2	112.7	156.6	213.8	257.4	300.7
S7	81.2	157.5	210.2	278.5	329.2	379.9
S8	45.7	104.2	146.3	202	243.7	285.7
S9	45.8	103.3	144.7	198.9	240	280.7
T1	171.2	283.8	359.7	455.9	526.8	597.3
S10	82.5	132.7	166.9	211	244	276.9
Sink-1	293.1	601.2	817.6	1094.4	1300.4	1504.3

HECRAS Model simulation

The HEC-RAS 2D hydraulic simulations utilize the hydrographs generated by HEC-HMS as upstream boundary conditions to estimate flood propagation across the Hebbal valley. The model simulates flood depths, velocities, and inundation extents for each return period, providing spatial visualization of flood-prone areas within the urban watershed. Flood inundation results indicate a progressive increase in the total affected area with increasing return period. The flood extent expands from 18.74 km² to 30.93 km² for the 2 year and 100 year scenario (Table 8). Plate 2 represents the water surface elevation of Hebbal valley for different return periods and Plate 3 shows the flood inundation extents of Hebbal valley for different return periods

Table 8 Inundated area for different return periods

Hebbal valley	Return period (years)					
	2	5	10	25	50	100
	Area (km^2)					
Total Inundation	18.74	22.51	25.03	27.76	29.29	30.93

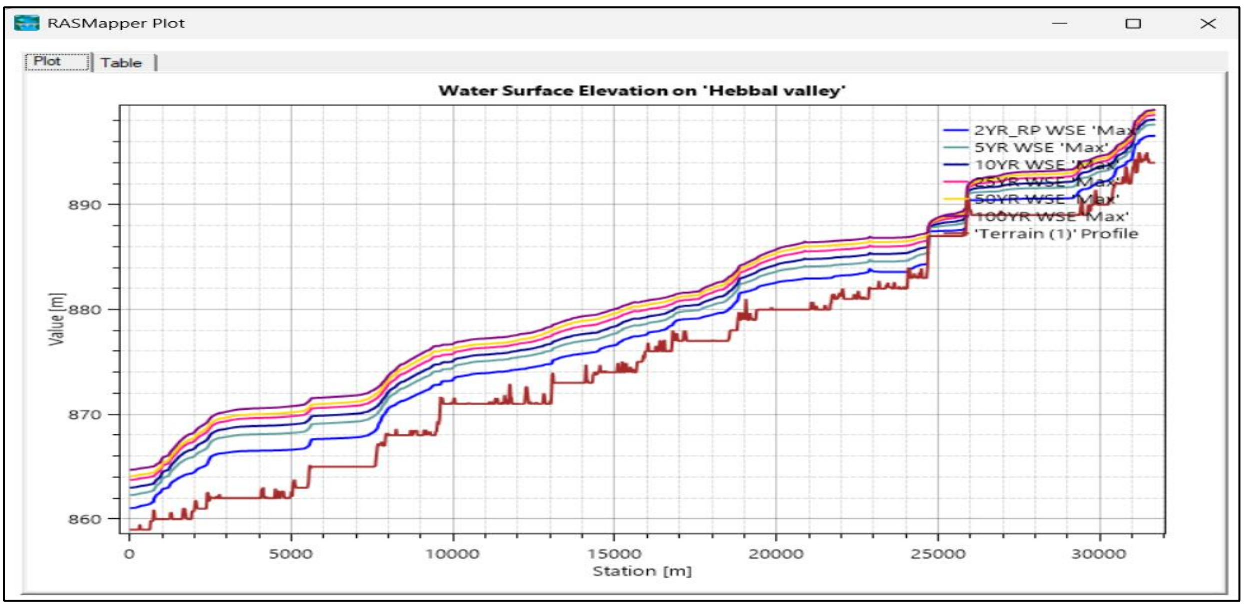

Plate 2 Water surface elevation profile for different return periods

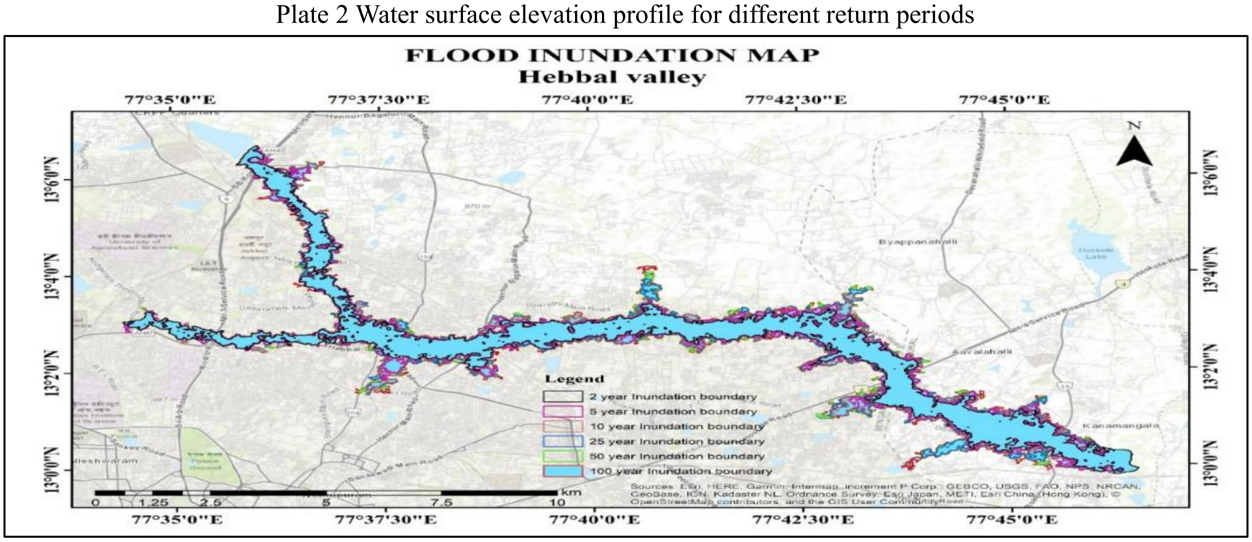

Plate 3 Flood inundation map for different return periods

HECRAS-LU/LC analysis

An overlay analysis of flood inundation extents with the LU/LC map for various return periods reveals built-up areas dominate the inundated zones, with their share increasing from 43 % to 57 %, underscoring the heightened flood vulnerability of urbanized regions. Agricultural land, which contributes approximately 19 % of the inundation area in low return periods, sees a gradual decline to 14 % for more extreme events. Similarly, forest areas show a slight reduction from 24 % to 19 %, indicating marginal loss of flood spread in less impervious zones. The inundation contribution from waterbodies remains relatively stable, varying between 10 % and 14% These spatial variations in flood exposure across land use classes are tabulated in Table 9.

Table 9 Percentage of inundated area for different return period under different land use / land cover (Hebbal valley)

LU/LC	Return period (years)					
	2	5	10	25	50	100
	% of area					
Bare ground	-	-	-	-	-	-
Builtup land	43	48	52	54	55	57
Agricultural land	19	17	16	16	15	14
Forest land	24	23	21	20	20	19
Waterbodies	14	12	11	10	10	10

VI. CONCLUSIONS

The study effectively demonstrates the applicability of integrated hydrologic and hydraulic modelling for flood assessment in the Hebbal valley, an ungauged urban valley in Bengaluru urban. Using HEC-HMS, the rainfall-runoff response for various return periods is simulated, resulting in accurate estimates of peak discharge across multiple sub-valleys and hydraulic elements. These discharge values, when incorporated into HEC-RAS 2D simulations, provide a detailed spatial representation of flood inundation extents. The flood extent progressively increases with higher return periods, highlighting the vulnerability of low-lying and highly urbanized zones.

The overlay of inundation results with land use data reveals that built-up areas are consistently the most affected, accounting up to 57 % of the inundated region under extreme events. The methodology adopted in this study proves to be robust, especially in data-scarce environments, and offers a reliable framework for urban flood risk assessment and mitigation planning. The integration of remote sensing, GIS, and open-source modelling tools ensures replicability and scalability for other rapidly urbanizing watersheds facing similar flood hazards.

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