Impact of Development Density on Flood Response: Two Watersheds in Bengaluru, India.

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Abstract

Urban areas are subjected to various anthropogenic interferences, thus disturbing the ecology, environment, and livability. These changes in the urban environment can have long and short-term impacts like increased precipitation, flooding, loss of biodiversity, and many more. Research suggests considerable changes in LULC in urban areas and its impact on various urban issues, including urban floods. However, many of these studies have concentrated on the overall growth and extent of cities. With varying development patterns and densities, it is essential to understand the impact of density on flood response. A watershed-based approach can also lead to a better understanding of the urbanization impact on the flood response of a geographical region.

In this paper, temporal changes of LULC for three watersheds within the Koramangala Challaghatta Valley of Bengaluru are evaluated using Landsat 7 and Landsat 8 images. Hydrology responses in subbasins of the three study watersheds—peak discharge, volume, and peak time—are calculated for the study area between 2003 and 2021 using HEC HMS. Changes in different LULC classes, namely built-up area, vegetation, and open land, between 2003 and 2021 are then correlated with the hydrology metrics changes.

Results indicate that Geographic unit-level analysis of LULC changes and their impact on urban floods can lead to new dimensions and methods in land use mapping and urban design guidelines to manage urban floods better, thus improving the urban landscapes and ecology.

Keywords: LULC changes, watershed approach, urban floods, urban density

Introduction

Floods and waterlogging have become significant causes of concern in most urban areas globally (Locatelli, 2016; Nasrin, 2018; Griffiths & Singh, 2019; Lin et al., 2022). Expanding urban areas impact the urban ecology resulting in various ecological issues like urban heat islands (UHI), increased frequency and intensity of precipitation, flooding and waterlogging, and resource pollution (Sjöman and Gill, 2014; Zimmermann et al., 2016; Sanzana et al., 2017). While urbanization is a continuous process, maintaining urban ecology to create ambient living conditions and safeguarding lives and wealth during floods and waterlogging is challenging for the urban local bodies (ULB).

Urban floods and waterlogging can be considered both a hydrologic as well as hydraulic responses. They are caused largely due to increases in impervious cover, thus generating excess surface runoff, loss of vegetation, and conversion of land cover for various socio-economic and political requirements. Further, there is often insufficient storm water infrastructure to receive and dispose of the floodwaters and garbage, thus overloading infrastructure (Miller et al., 2014; Dai, Wu and Du, 2018; Zhao et al., 2019). Interestingly, much research has gone into understanding and simulating methods, and models for stormwater management (SWM) (Kayembe and Mitchell, 2018; Bruwier *et al.*, 2020). Among them, Spatio-temporal changes in LULC, increase in impervious cover and its location, green infrastructure (G.I.), and sustainable urban drainage systems (SUDS) have been vividly explored (Sharma et al., 2019; Zimmermann et al., 2016;; Zope et al,. 2016). Future urban sprawl and flood simulations have also emphasized the changes in impervious cover at the urban level (Nithila Devi, Sridharan and Kuiry, 2019; Lin et al., 2022). Research shows that LULC changes at the urban (macro) level confirm the increase in impervious cover and loss of green cover (Zope, Eldho and Jothiprakash, 2016).

Unfortunately, at meso-level, understanding of LULC changes and the composition of urban landscapes is least explored (Miller, 2018). Hence, assessing the LULC changes at the watershed level, which are an integral part of different political boundaries, needs to be assessed for a clear understanding of the hydrologic processes.

This study aims to assess the impact of LULC changes at the watershed (meso) level on flood metrics. To achieve this, we have four objectives as follows.

(a) To identify different watersheds in an urban area,
(b) To explore the LULC changes in the watershed over a period,
(c) To simulate the flood metrics and compare the LULC changes with the difference in flood metrics, and
(d) To assess the relation between LULC changes in the different watersheds on the flood metrics.

Literature Review

Urban hydrology is altered with extensive changes to the existing landscape (Alberti, 2006). According to Nazari, Seo and Muttiah (2016), in a natural condition, precipitated water intercepts the vegetation before reaching the ground, undergoes evapo-transpiration, infiltrates into the ground and the excess water reaches the nearby streams or other water bodies. Traditional vernacular buildings considered water an integral element of building (Verma, Kamal and Brar, 2022). However, due to increased impervious cover (IC) in urban areas, there is an excess surface runoff generated from the built-up areas overwhelming the capacity of the Storm Water Drainage (SWD) systems (Du et al., 2015). This can lead to accumulation before reaching the SWD systems and further spreading into the surrounding areas leading to inundation. This, combined with increased urban land temperature can result in unprecedented precipitation in urban areas (Naidu, Chundeli and Rao, 2022).

Miller et al. (2014) has pointed out that an increase in IC in the urban centers can have many effects including increased flood events. The change in IC in urban areas has not just resulted in increased flood inundation and depth but more areas subjected to flooding (Redfern et al., 2016; Zope, Eldho and Jothiprakash, 2016). Many flood modeling techniques, simulation methods and tools have been used to assess urban flooding. Extensive literature is available on a list of tools like TUFLOW (Huxley & Syme, 2016), EIM (Zhao et al., 2019), SWMM (Jang et al., 2007), Infoworks ICM (Sidek et al., 2021), LISFLOOD-FP (O'Loughlin et al., 2020), MIKE URBAN (Bisht et al., 2016) illustrating the physical flooding process in urban areas. However, most of these tools are either computationally expensive or restricted commercially as not being open access. Future simulations using Artificial Neural Networks (ANN), machine learning, Entropy, and FLUS models are applied to assess the urban flood models (Li & Bortolot, 2022; Lin et al., 2022; Nithila Devi et al., 2019). These models suffer from data availability undermining the changing urban conditions.

In addition to increasing the IC, urbanization has also interfered with and has modified the natural terrain (Kayembe and Mitchell, 2018). Yet, the impact of the natural terrain cannot be undermined. In this context, Suriya and Mudgal (2012) have suggested employing a watershed-based approach to developing flood-sensitive measures in urban areas. Kadhim, Mourshed and Bray, (2016) point out that the advent of Remote Sensing (RS) and Geographic Information Systems (GIS) have played a prominent role in understanding and the analysis of changing urban conditions.

As discussed above, extensive research is done pertaining to mapping the extent and depth of flood inundation in urban areas located on river fronts and coastal cities and limited studies on inland cities. However, these simulations highlight the changes in the urban patterns and their impacts at the macro-level (City-level). While macro-level changes indicate the comprehensive understanding, a built- environment level study suggests the impact of ground coverage of a plot on urban floods (Bruwier *et al.*, 2020). However, a meso-level assessment of LULC changes based on different development density patterns in inland cities is less considered and needs to be addressed.

Case Study Area

Bengaluru (Fig. 1), known as the "Silicon City of India," is the capital of the Indian state of Karnataka. The city spread across 741 Sq. Kms had registered the highest population growth (Ramachandra, Shivamurthy and Aithal, 2017). Located at an elevation ranging between 740M and 960M above the MSL, Bengaluru has a pleasant climate throughout the year.

Summer temperatures range between 21^{0}C- 34^{0}C, and winter temperatures are 15^{0}C-25^{0}C. Bengaluru receives an average annual precipitation of 800mm. The city has an undulating topography and an interconnected lake system falling into three valleys—known as the K.C. Valley (Koramangala Challaghatta Valley) which extends East and South, Hebbal Valley to the North, and Vrishabahavathi Valley to the West and South (Ramachandra, Aithal and Kumar, 2019).

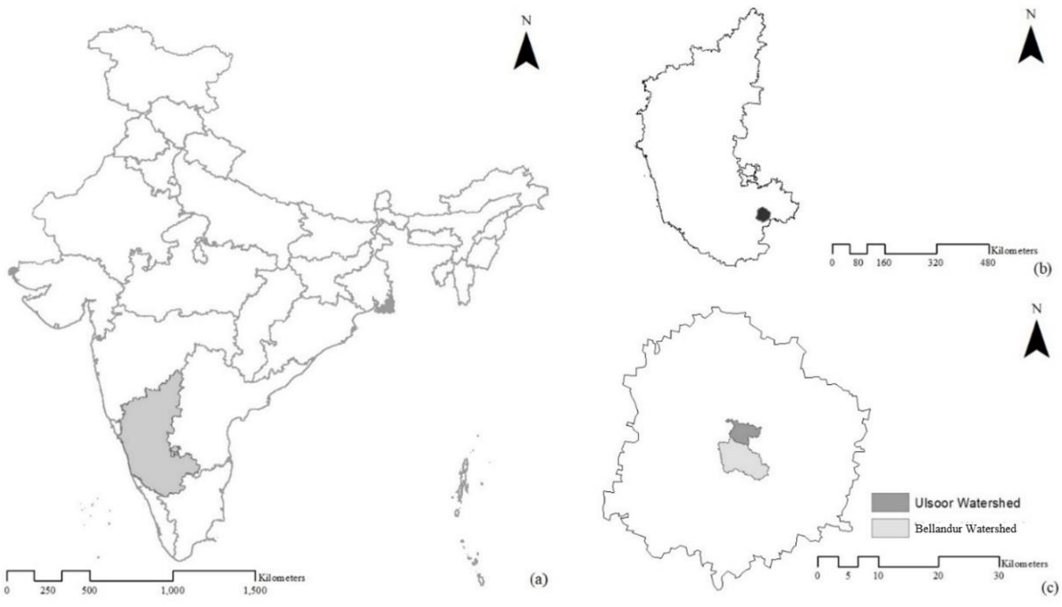

Fig. 1: Location map of the Study area (Bengaluru) and Ulsoor and Bellandur watersheds,
(a) India map with state boundaries; (b) Karnataka state map with Bengaluru boundary, (c) Bengaluru city boundary with two watersheds (study area)
(b) Source: Author

Varthur Lake series from the K.C. Valley is the largest of all the existing lake series within the city and has two giant lakes-Bellandur and Varthur. Ulsoor Lake has a catchment area of 11.13 sq. km, and the catchment of Bellandur Lake extends over 28.81 Sq. Km.

Research Methods

Subbasin Delineation

Advanced Space Borne Thermal and Reflection Radiometer Digital Elevation Model (ASTER DEM) provides accurate data and is used to determine the K.C. valley watershed of Bengaluru, as is given in the Fig. 2 (Khasanov, 2020). Hydrology tools from the Spatial Analyst toolbar of ArcGIS are used to delineate the watersheds. Lake boundaries of Ulsoor and Bellandur are vectorized using the Google Earth Raster Image and are used for further delineation of sub-basins of the watershed. HEC HMS 4.9 could perform the GIS processing and further identify the streams and sub-basins within the watershed (U.S. Army Corps of Engineers, 2017).

LULC Mapping of Macro and Meso levels

Using Landsat satellite data, temporal changes in LULC were mapped for 2003 and 2021. Study area data was downloaded from Landsat 8 Operational land Imager (OLI) for 2021 and Landsat 7 Enhanced Thematic Mapper (ETM) of United States Geological Survey (USGS) Earth Explorer archives. Data was collected for March and April to minimize the cloud presence and other seasonal influences. Much popular Maximum Likelihood Image classification tool from ArcGIS 10.8 is used to identify the four different LULC classes: Built-up areas, Vegetation, Open land/Agriculture, and Water (Ramachandra, Shivamurthy & Aithal, 2017). Training samples for the different LULC types were randomly selected across the image. The confusion matrix and Kappa coefficients were calculated to assess the accuracy of the classified images (Maps & GIS Library, 2017).

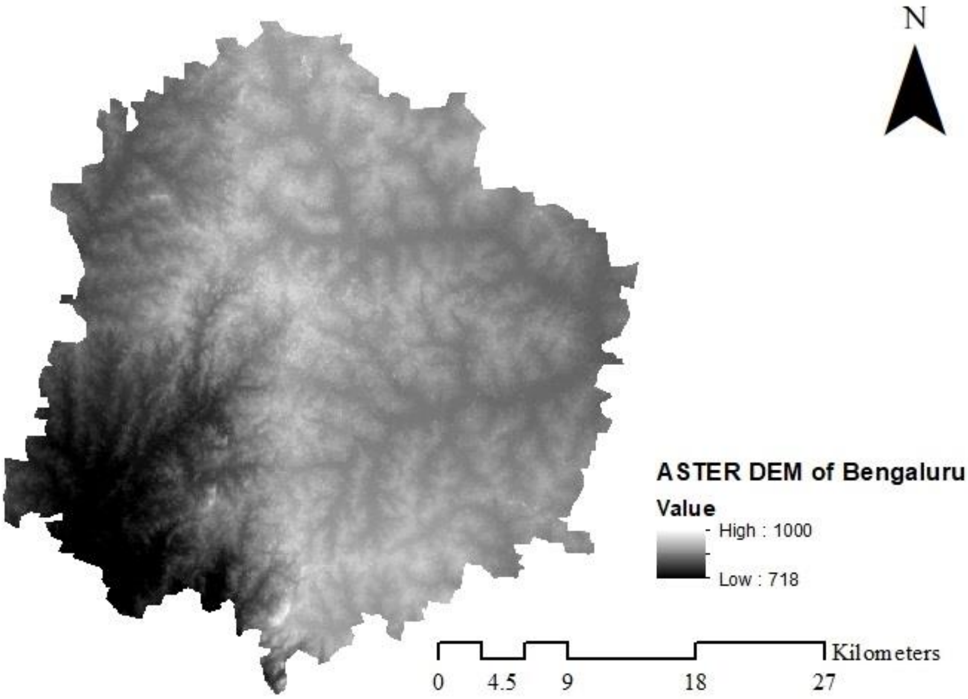

Fig 2: ASTER DEM Model of Bengaluru
Source: USGS Earth explorer archives, Author

Curve Number Generation

A 250-M resolution soil map from the Global Hydrologic Soil Group (GHSG) data is used for the Curve number generation (Ross et al., 2018). This data is retrieved from the Distributed Active Archive Centre (ORNL DAAC) repository. Curve numbers for different soil groups are considered in the HEC HMS manual (U.S. Army Corps of Engineers, 2017) as shown in the Table 3. Curve numbers are generated with QGIS using a semi-automatic plugin that uses LULC map and soil group-specific curve numbers as inputs. Curve numbers are generated for the years 2003 and 2021.

Hydrologic Modelling

HEC HMS essentially requires a basin model that uses the terrain data as input, a meteorologic model, and a control specifications manager to simulate the hydrologic event. The watershed of the study lakes: Ulsoor and Bellandur are delineated using Hydrology tools in ArcGIS and exported to HEC HMS for hydrologic modeling, as shown in Fig. 5. SCS curve number calculated using the GHSG data was used as input to the loss method, and the SCS unit hydrograph was adapted for the Transformation. Lag time was calculated and used to input the Muskingum routing method. A 48-hour storm rainfall data with an interval of one hour is given as input to the precipitation data. A frequency storm of 1-hour duration is calculated for two days. Flood metrics- Peak Discharge (m3/s), Peak volume (m3), and time of peak are collected for the study watersheds between 2003 and 2021 (P.E. Zope, 2016).

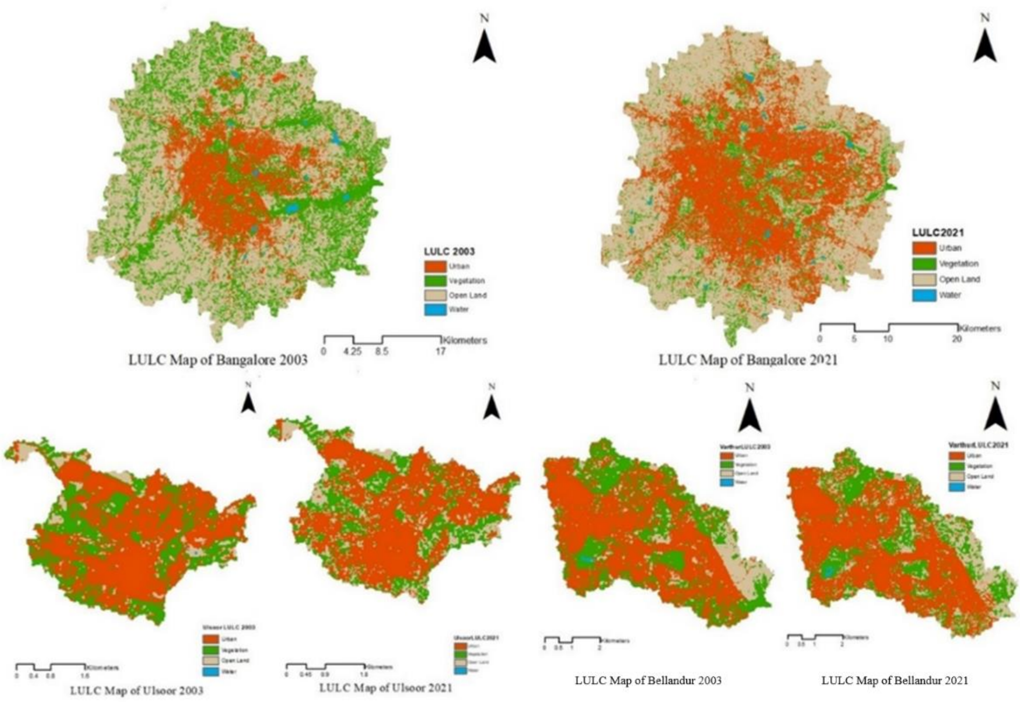

Fig 3: Land use map of macro (Bengaluru) and meso (Ulsoor and Bellandur) between 2003 and 2021
Source: Author

Findings

LULC Changes

The temporal changes in LULC between 2003 and 2021 in Bengaluru, Ulsoor watershed, and Bellandur watershed are given in Table 1 and Fig. 4. LULC maps generated using ArcGIS are shown in Fig. 3.

The built-up area of Bengaluru had nearly doubled between 2003 and 2021, with an increase of 98.1% from 244.17 sq. Km to 485.20 sq. Km. However, the built-up area in the Ulsoor watershed recorded a small 0.02% increase. Bellandur watershed experienced a slight increase in the built-up area from 18.94 sq. km in 2003 to 19.31 sq. Km in 2021, with a 1.92% increase. As given in Table 1, a decrease in vegetation is observed at macro and meso levels, explaining the loss of vegetation. Bengaluru lost over half of its greenery, 59.20%, from 389.17 sq. km to 158.77 sq. km. A similar decline is observed in Ulsoor and Bellandur, with a decrease of 16.76% and 18.66%, respectively. Open land/ agriculture land depicted positive and negative changes at macro and meso levels. While open areas had slightly reduced in Bengaluru (macro-level) by 1.94% with a fall of 11.0 sq. km, there is an increase of open land in Ulsoor and Bellandur with 87.02%, and 33.94%, respectively. With doubled built-up area and losing half of the greenery, Bengaluru has experienced significant LULC changes due to extensive urbanization.

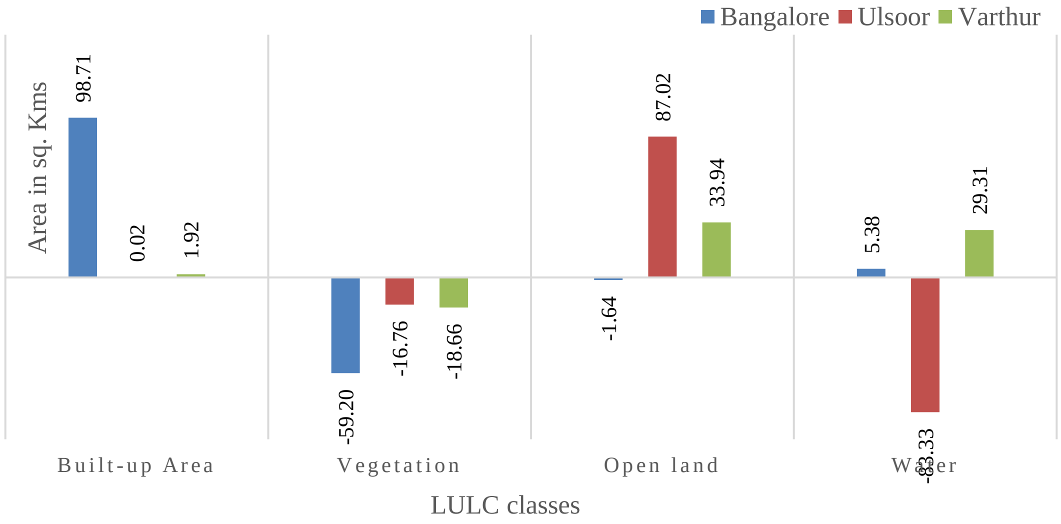

Fig 4: Percentage change of the four LULC classes at Macro (Bengaluru) and Meso Levels (Ulsoor and Bellandur) between 2003 and 2021
Source: Author

Accuracy Assessment of LULC

A total of 160 ground truth points each were selected for 2003 and 2021 from the Landsat images to assess the accuracy of the classified image. Producer's accuracy (P.A.) and User's accuracy (U.A.) are calculated for each year along with overall accuracy and Kappa Coefficient to indicate the dependability of the LULC classification (Table 2). The Kappa coefficient was higher than 90% for each year. With average PA of 96.87% and 93.75% in 2003 and 2021, the LULC classification can be relied upon for the study. Kappa values are higher than the acceptable values of 0.75; hence, the LULC classification is reliable for the study.

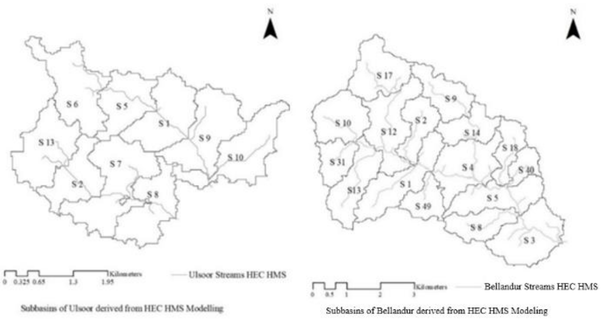

Fig. 5: Subbasins of Ulsoor and Bellandur watersheds
Source: Author

Table 1: LULC changes in Bengaluru, Ulsoor, and Bellandur areas between 2003 and 2021
Source- Author

		Built-up	Vegetation	Open land	Water
Bengaluru	**2003 (Area in Sq. Km)**	244.17	389.17	673.40	7.41
	2021 (Area in Sq. Km)	485.20	158.77	662.38	7.80
	Change (Area in Sq. Km)	241.03	-230.40	-11.03	0.40
	% Change	98.71	-59.20	-1.64	5.38
Ulsoor	**2003 (Area in Sq. Km)**	7.88	3.84	1.24	0.01
	2021 (Area in Sq. Km)	7.90	3.20	1.86	0.00
	Change (Area in Sq. Km)	0.02	-0.64	0.62	0.00
	% Change	0.25	-16.76	49.96	-83.33
Bellandur	**2003 (Area in Sq. Km)**	18.9441	9.8451	4.293	0.0522
	2021 (Area in Sq. Km)	19.3086	8.0082	5.7501	0.0675
	Change (Area in Sq. Km)	0.36	-1.84	1.46	0.02
	% Change	1.92	-18.66	33.94	29.31

Table 2: Accuracy assessment of the LULC classification
Source: Author

	Year	Built-up area	Vegetation	Open land	Water
Producer's Accuracy	2003	100	100	90	97.5
	2021	100	100	97.5	77.5
User's Accuracy	2003	88.89	100	100	100
	2021	97.6	81.6	100	100
Overall Accuracy	2003		0.968		
	2021		0.937		
Kappa Coefficient	2003		0.958		
	2021		0.917		

LULC changes of the subbasins

Meso-level growth directions of different LULC classes are compared with the flood metrics calculated for the study period and are shown in Table 4. Ulsoor also experienced a decline in built-up and green areas in most subbasins and a rise in the open lands. However, the reason for the exact needs to be explored. The change in the areas can be relied upon based on the accuracy assessment and kappa coefficient. However, the built-up area in the subbasin of the Bellandur watershed demonstrated both positive and negative growth. Most subbasins in Bellandur experienced a decline in the vegetated areas and increased open lands.

Flood Metrics

It is noted from Table 4 that in Ulsoor, Peak discharge had reduced while the peak volume from the subbasins had increased. Though the changes in time taken to achieve Peak are not significant, it highlights the early occurrences of flood events at the outlets. Peak volumes, however, had increased considerably. Similarly, the Bellandur watershed has also experienced little to no change in peak discharge while the peak volumes have increased and range between 0.6m^3 to 16.4 m^3. Two subbasins within the Bellandur watershed had experienced a fall in the peak volume. Noticeable changes are the decreases in time of Peak with as low as 9 minutes to 58 minutes. Though the change trends in LULC are similar in both watersheds, the changes in flood metrics are not similar.

Table 3: Runoff curve numbers of the study area
Source: HEC HMS Manual

Land-use Type	Runoff Curve Numbers (C.N.) for various soil groups					
	A	B	C	D	C/D	D/D
Built-up area	57	72	81	86	83.5	86
Vegetation	30	59	71	78	74.5	78
Open Land	67	77	83	87	85	87
Water	100	100	100	100	100	100

Analysis of changes in LULC and Flood Metrics

The difference in the LULC areas of the subbasins and flood metrics for the study between 2003 and 2021 are compared. Normality tests are performed for the data to assess the normality distribution. Normality test results suggested the data as a non-normal distribution with high skewness and kurtosis values. Spearman's correlation coefficient is calculated for the non-normally distributed data. Data is correlated to know the change in LULC class that have impacted the change in flood metrics, as given in the Table 5. As different growth directions are observed in LULC and flood metrics, correlation can help better understand the composition of the watershed and the impact of changing conditions on flood scenarios. Factors with correlation >0.75 and 2-tailed significance values less than 0.05 are highlighted.

The built-up area has a positive correlation with Peak discharge (0.822) and volume (0.952) of the watershed, whereas the time of the peak is strongly correlated with the change in open land (0.848) of the watershed. However, built-up area shift in a much larger Bellandur basin has not been associated with the flood metrics with a much higher *p-value*. Change in vegetation negatively correlates with the volume (-0.978) and positively relates to peak time (0.956). Similarly, Open land exhibited a positive correlation (0.863) and is negatively correlated with the Time of Peak (-0.875).

An increase in the built-up area of Ulsoor has resulted in higher Peak discharge and volume, whereas no significant relation is found in the built-up areas in Bellandur. Similarly, an increase in vegetation has resulted in the decline of the volume, extended the peak time in Bellandur, and has no considerable significance in the Ulsoor watershed. A positive shift in the open land in Bellandur has resulted in an increase in the volume in Bellandur. With the increased available land in Ulsoor, the peak time has been extended, whereas the peak time has been pushed earlier in Bellandur.

Table 4: Change in the Land use and hydrology metrics of the Ulsoor and Bellandur Subbasins between 2003 and 2021.
Source: Author

Watershed/Sub-basin	Change in the area (in KM2)			Changes observed in Hydrologic Modelling			
				Peak Discharge		Volume	Time of peak
	Built-Up area	Vegetation	Open Land	m3/s	m3/h	m3	Minutes
Ulsoor Subbasin 1	-0.045	-0.035	0.080	0.6	2160	21	2
Ulsoor Subbasin 2	-0.023	-0.150	0.174	0.4	1440	18.1	3
Ulsoor Subbasin 5	-0.063	-0.073	0.136	0.6	2160	15.5	2
Ulsoor Subbasin 6	0.375	-0.293	-0.082	0.8	2880	25.3	3
Ulsoor Subbasin 7	-0.023	-0.068	0.090	0.9	3240	31.7	2
Ulsoor Subbasin 8	0.046	-0.119	0.073	0.6	2160	18	2
Ulsoor Subbasin 9	-0.077	-0.008	0.085	0.7	2520	22.8	0
Ulsoor Subbasin 13	-0.049	-0.021	0.072	0.8	2880	27.3	3
Bellandur Subbasin 1	0.054	-0.1521	0.0981	0.1	360	8.2	-22
Bellandur Subbasin 10	0.0117	-0.0144	0.0027	0	0	0.7	-2
Bellandur Subbasin 12	-0.0081	-0.0459	0.054	0	0	2.6	-9
Bellandur Subbasin 13	-0.0189	-0.0846	0.0873	0.1	360	6.5	-20
Bellandur Subbasin 14	-0.1179	-0.1269	0.2448	0	0	8.2	-34
Bellandur Subbasin 17	0.0747	-0.2574	0.1827	0	0	14.6	-37
Bellandur Subbasin 18	-0.0675	-0.1827	0.2502	0	0	10.9	-59
Bellandur Subbasin 2	-0.0011	-0.0882	0.0909	0	0	4.9	-23
Bellandur Subbasin 3	0.2538	-0.3978	0.144	0.1	360	19.7	-49
Bellandur Subbasin 31	0.0279	-0.0522	0.0243	0.1	360	2.6	-9
Bellandur Subbasin 4	-0.0477	-0.0585	0.1062	0	0	3.9	-10
Bellandur Subbasin 40	-0.0072	0.0378	-0.0297	0	0	-1.7	-3
Bellandur Subbasin 49	0.126	-0.0999	-0.0261	0	0	4.4	-14
Bellandur Subbasin 5	0.0234	0.1818	-0.2598	0	0	-9.8	33
Bellandur Subbasin 8	0.0491	-0.112	0.0639	0.1	360	5.9	-25
Bellandur Subbasin 9	-0.0423	-0.1593	0.2016	0.1	360	9.8	-37

Conclusions

Urbanization has caused extensive damage to the ecological resources, hampering the livability of cities, and resulting in man-made disasters like UHI, urban floods, and waterlogging. This study considered the hydrologic response (flood metrics) caused by meso-level LULC changes between 2003 and 2021 for Bengaluru. While macro-level changes of LULC present a general condition of the overall situation, each geographical region exhibits an apparent response to the conditions prevailing. Analysis done using various tools and methods in ArcGIS, QGIS, and HEC HMS present a strong picture of LULC changes in the two study watersheds-Ulsoor and Bellandur of K.C. Valley of Bengaluru.

The results are not uniform in the two study areas and suggest that a specific LULC class from each watershed significantly impacts the hydrologic response. The built-up area in the Ulsoor watershed has a considerable impact on the peak discharge and peak volume, whereas vegetation noticeably affects the Bellandur watershed. Open land exhibited different results in Ulsoor and Bellandur watersheds. While the increase in open land has resulted in a reduction in the peak time in Bellandur, Ulsoor has experienced an increase in the peak time. This study offers new insights into planning and managing the flood responses in the different areas. The findings can present ideas for meso and micro level regulations for better flood responses and ecological conditions. Future research can focus on the composition of urban landscapes, topography, and urban morphology at meso and micro levels for essential zoning regulations and the maintenance of ecology.

Table 5: Spearman's Correlation between the Land use changes and resultant flood metrics for Ulsoor and Bellandur watersheds.

Source: Author

	Peak Discharge		**Volume**		**Time of peak**	
	Spearman's Correlation Coefficient	*p-value*	Spearman's Correlation Coefficient	*p-value*	Spearman's Correlation Coefficient	*p-value*
Ulsoor Subbasin						
Built-up area	**0.822**	0.012	**0.952**	0	0.261	0.533
Vegetation	-0.209	0.62	-0.143	0.736	-0.391	0.338
Open Land	0	1	0.286	0.493	**0.848**	0.008
Bellandur Subbasin						
Built-up area	0.28	0.293	0.069	0.799	0.034	0.901
Vegetation	-0.336	0.203	**-0.978**	0	**0.956**	0
Open Land	0.14	0.605	**0.863**	0	**-0.875**	0

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