



Flood vulnerability assessment of urban micro-watersheds using multi-criteria decision making and InVEST model: a case of Hyderabad City, India

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Abstract

Urban areas are increasingly getting vulnerable to floods due to high-intensity precipitation and increasing concretization. To identify the flood vulnerability status of urban micro-watersheds for an improved mitigation strategy, we propose a Flood Vulnerability Index (FVI) with readily available urban infrastructure and hydrological data. The criteria variables for FVI calculation include urban infrastructure data (building and road density), run-off retention capacity, the fraction of vegetation cover, and open spaces. The Soil Conservation Service Curve Number (SCS-CN) method has been applied to estimate run-off retention using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model. The weighted linear combination of the criteria variables was used to derive the FVI of each micro-watershed. The Analytical Hierarchical Process (AHP) has been utilized for the weight assignment. This method is applied to the Hyderabad City area, India. The city is densely populated and often devastated by urban floods. Results indicate that out of 85 micro-watersheds classified in the region, 24 are highly vulnerable with FVI > 3, requiring immediate flood mitigation action. A near-future flood mitigation strategy is required for 36 micro-watersheds with FVI in the range of 2–3. The remaining 25 micro-watersheds are relatively less vulnerable with FVI < 2. The proposed FVI accounts for the watershed's hydrological behavior, which is highly relevant in flood vulnerability estimation. The developed method is extremely simple to adapt to any city for flood vulnerability estimation and policy planning based on easily available open data.

Keywords Flood vulnerability index · Analytical hierarchical process · Flood mitigation · Green infrastructure · Urban policy · InVEST model

Abbreviations

AHP Analytical hierarchical process
DEM Digital elevation model
FVI Flood Vulnerability Index
HSG Hydrologic Soil Group

InVEST Integrated valuation of ecosystem services and trade-offs
IPCC Intergovernmental panel on climate change
LULC Land use land cover
MCDM Multi-criteria decision making
QGIS Quantum Geographic Information System
RS-GIS Remote Sensing and Geographic Information System
SCS-CN Soil conservation service-curve number
UGS Urban green spaces
WLC Weighted linear combination

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Introduction

Anthropogenic actions such as deforestation, rapid industrialization, and urbanization have been disturbing the hydrological cycle over the last few decades. High-intensity rainfalls and associated flooding have become a frequent

phenomenon in urban centers. Evidence shows a positive feedback between urbanization and the erratic rainfall pattern in the cities, which is alarming (Paul et al. 2018). Anthropogenic heat, building morphology, aerosol loading, and urban heat island intensity modify the urban rainfall pattern (Richards and Edwards 2017). For instance, urban centers in India receive 30–40% higher rainfall than the surrounding areas (Kishtawal et al. 2010).

Rainfall in urban centers is quickly converted into run-off because of increased concretization, dwindling green spaces, and insufficient stormwater infrastructure (Kadaverugu et al. 2021b), which leads to rapid inundation (Borga et al. 2011; Albuquerque et al. 2019). Further, due to climate change and anthropogenic drivers, the intensity and frequency of extreme weather events, including flooding events, are increasing alarmingly (Nilsen et al. 2011; Zhou et al. 2019), which are inflicting heavy damages to lives and property (Majra and Gur 2009; Hossain et al. 2011; Dhara et al. 2013). There has been a rise of ~79% in flood events from 2010 (149 events) to 2018 (267 events) across the world (NatCatSERVICE 2020).

Effects of urban floods can be (a) immediate and direct, and (b) post-flood and indirect. Immediate tangible effects of urban floods include fatalities, inconvenience to transportation, traffic congestion, evacuation of people, interruption to electricity and telecommunications, damage to property, and other discomforts (Suriya et al. 2012; Leal et al. 2018). Post-flood effects include water contamination, deposition of solid waste in the waterlogged areas, and spread of water-related, water-borne, and vector-borne diseases (Phalkey et al. 2012). Besides, the inundation of houses induces enormous psychological distress among the affected residents (Wind et al. 2013). Thus, directly or indirectly, the floods in urban areas account for substantial economic loss to the government and individuals in restoring normalcy.

Hence, it is necessary to understand the hydrological responses of urban watersheds for an effective flood mitigation action. More accurate prediction of the spatial extent and inundation depth due to urban floods, especially in high-resolution, is quite challenging. Several studies have attempted to simulate the urban floods in 2D and 3D domains (for example, Almeida et al. 2018; Wang et al. 2019; Xing et al. 2019), but with varying degrees of success. These models demand high-resolution data on surface topography, building geometry, open drains, sewerage/stormwater network, land use, lakes, soil properties (Kadaverugu et al. 2021a). Further, the hydrodynamic coupling of the stormwater pipe network with the urban area inundation, wetting, and drying of the land surface is quite challenging to capture with the model boundary conditions. Despite these challenges, the 2D and 3D flood models provide a near-real approximation of flood inundation in a city, but at the cost of heavy computational burden, intensive data

requirements, and uncertainties. The model uncertainties might arise from rainfall data (Zhou et al. 2021), soil hydrological parameters (Baroni et al. 2010), and structural aspects. For instance, Almeida et al. (2018) argue that even with slight changes in the height of the surface features, the model predictions deviate significantly.

The trade-offs between intensive (2D or 3D modeling within a limited area) and extensive modeling (2D empirical or remote sensing analysis on a vast area) of urban floods are to be understood for using numerical modeling as a policy tool. Availability of data sets is challenging, especially in developing countries at the local administration. Efforts to harmonize the data on urban features are still in infancy in India and most developing countries. Further, high-resolution 2D or 3D urban flood modeling will not necessarily paint a broader picture of the hydrological behavior of urban watersheds. The effect of surface topography, stream networks, run-off retention by vegetation, and open spaces in flood mitigation can be aptly captured by regional-scale models with tested empirical hydrological relationships (for example, soil conservation service curve number (SCS-CN) method). For instance, Bera et al. (2021) applied the SCS-CN method to understand urbanization's influence on run-off. Natarajan and Radhakrishnan (2019) used the SCS-CN model due to its simplicity for studying the run-off pattern in an urban catchment.

Highly vulnerable urban micro-watersheds prone to flood damages are to be identified to prioritize the flood mitigation strategy. The number of studies on flood mitigation and adaptation is increasing compared to the studies on flood risk estimation (Lima and Bonetti 2020). The prioritization is better accomplished with the classification of urban micro-watersheds according to a Flood Vulnerability Index (FVI). The traditional meaning of the vulnerability mentioned by Turner et al. (2003) “is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor.” In addition to that, the IPCC Fourth Assessment Report on climate change has redefined the vulnerability with the dimensions representative of *exposure*, *sensitivity*, and *adaptive capacity* towards any hazard (IPCC 2007). For instance, the *exposure* dimension may consist—exposure of people to urban floods or other extreme weather events; *sensitivity* dimension may include—population or property susceptible to damage; and *adaptive capacity* dimension may consist—the vegetation cover, socio-economic profile, infrastructural capacity that will enable to overcome the damages, etc. There is no consensus in selecting these criteria variables for calculating a FVI (Bonetti and Woodroffe 2016). However, most studies have considered certain standard variables representing hydrological structural, socio-cultural, infrastructural, and demographical aspects at pixel level or averaged over a watershed. The weighted average

of these criteria variables is used in the calculation of the vulnerability index.

Although previous studies considered the hydrological structural aspects of a watershed like digital elevation model (DEM) (Prasad and Pani 2017), slope, and soil characteristics along with the demographic (Ali et al. 2019), and infrastructural aspects, very few have accommodated the hydrological behavior in calculating a FVI. For instance, considering the run-off generation layer would have more impact than merely considering the elevation layer in calculating a FVI. Hydrological behavior is an aggregate of several structural interactions that influence a watershed's run-off generation by accounting for the non-linear relationships (Kadaverugu et al. 2021b). The run-off generation and retention capacity can be estimated using the SCS-CN method.

Generally, FVI is calculated with multi-criteria decision making (MCDM) tools like Analytical Hierarchical Process (AHP), fuzzy-AHP, entropy-based algorithms, and choosing by disadvantage method. The AHP method is widely applied in socio-environmental systems as a powerful tool for simplifying complex decision-making problems, especially when multiple objectives are involved with a certain degree of mutual correlations. The AHP has been extensively used in MCDM studies in flood vulnerability, risk, and mitigation (Stefanidis and Stathis 2013; Du et al. 2020). For instance, Souissi et al. (2019) mapped the flood susceptibility areas in an arid region of Tunisia, Radwan et al. (2019) assessed the flood risk in an arid and semi-arid regions, Ghosh and Kar (2018) identified the flood risk zones in West Bengal district, India, and Ghaffari Gilandeh et al. (2020) mapped flooding potential in an Iranian city. The relative ranking and significance weight assignment of the criteria variables (objective variables) are performed using Saaty's pair-wise comparison matrix method (Saaty 2012) as a part of AHP. The Weighted Linear Combination (WLC) method is applied to criteria variables to derive the FVI for decision-making. For instance, Saha and Bhattacharya (2021) developed a river avulsion index based on criteria variables using the AHP method and WLC.

In this context, we propose a simple methodology for identifying the flood vulnerability and developed the FVI with the criteria variables—building density, road density, run-off retention capacity, vegetation cover, and open spaces in the urban micro-watersheds. The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) Urban Flood Risk Mitigation model has been utilised in this study, which depends on the SCS-CN method for estimating run-off retention capacity (Kadaverugu et al. 2021b). The micro-watersheds having high infrastructural density and high run-off generation potential (without significant green cover and

open spaces) are flagged according to the FVI ranking. The micro-watersheds with high FVI ranking require immediate attention from urban policymakers in flood mitigation and accordingly prioritized.

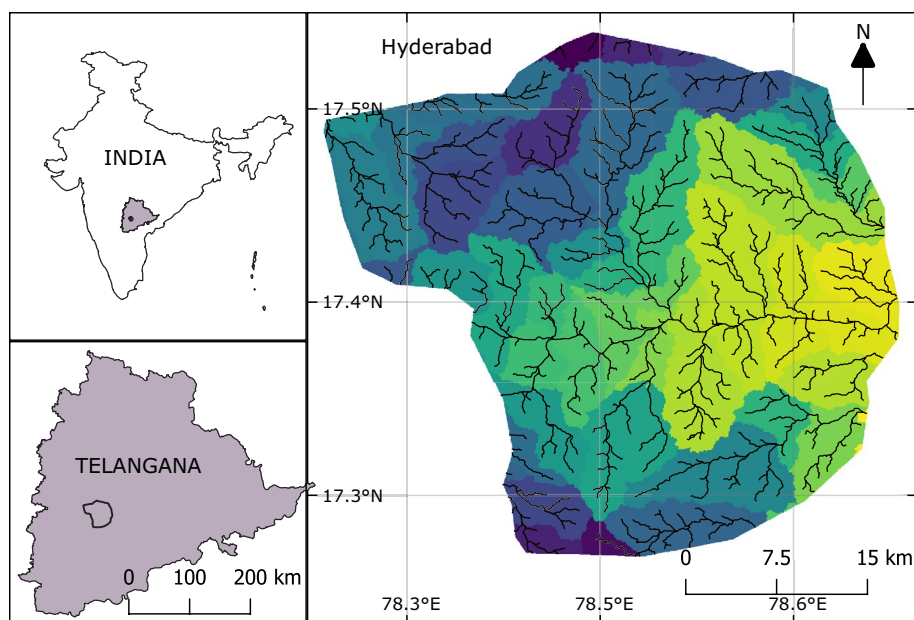
The proposed method is applied over Hyderabad City, India, which is densely populated and often devastated by flash floods. Earlier studies on the city have studied the flood risk (for example, Vemula et al. 2019), but very few have demarcated the flood vulnerable zones. The details of Hyderabad City, the methodology followed in the spatial data generation for the InVEST model, and the prioritization of micro-watersheds according to the proposed FVI using the AHP are provided in “[Materials and methods](#)”. The prioritization ranking and the implications of the results are provided in “[Results and discussion](#)”. The discussion on nature-based mitigation measures and limitations of the study are provided in “[Mitigation measures](#)” and “[Limitations and future scope](#)”, respectively.

Materials and methods

Study area

The historic city of Hyderabad (aka the *City of Pearls*) is situated in the Deccan plateau of southern India in Telangana state. The study area consists of the Hyderabad metropolitan region enveloped within the outer ring-road covering 1444 km² (Fig. 1). The area extends between the latitude 17.20°–17.59° N and the longitude 78.24°–78.69° E with an average altitude of +506.0 m above mean sea level (MSL). The city is located in a hot semi-arid climate zone with temperatures ranging from 14.8 to 39.8 °C. May is the hottest month, while December is the coolest. Annual average rainfall of 766 mm is received during the southwest monsoon from July to October. The city's population was 7.7 million and growing at a rate of 2.7% (Das 2015). The city has been expanding following the ribbon development and gradually engulfing the peri-urban fringe areas into commercial centers (Kadaverugu et al. 2021b). In the process of continuous expansion of the city, the existing green spaces are converted into built-up land use. The decline in vegetation over the last two decades and increased built-up has resulted in a high volume of run-off and shortened the peak flow time, causing urban flash floods. Even a low-intensity rainfall could paralyze the city by flooding the built-up areas, streets, and roads. Studies show that the rainfall intensity over Hyderabad City has increased by 20–25% due to urbanization in the last two decades (Boyaj et al. 2020).

Fig. 1 Study area delineated with micro-watersheds and stream network



Micro-watersheds delineation

Digital elevation model (DEM) data obtained from the Shuttle Radar Topography Mission (SRTM) having 30 m spatial resolution were analyzed to delineate the micro-watersheds of the study area. The hydrological terrain analysis was performed on the void-filled DEM layer to generate information on catchment area, stream network, and watershed delineation. The methodology presented in Kadaverugu et al. (2021b) was adopted for the analysis. Flow tracing algorithm *rho8* of SAGA-GIS library in QGISv-2.18 was used to generate flow accumulation (catchment area) at each pixel in the study area, based on which the stream network was mapped. We then utilized the stream network layer for the delineation of the micro-watersheds with a minimum pixel size of 1000. The delineated micro-watersheds are shown in Fig. 1.

Land use classification

Sentinel 2A satellite data of May 2019 having 10 m resolution were used for the land use and land cover classification. The maximum likelihood supervised classification algorithm of the Semi-Automatic Classification plug-in of QGIS-v2.18 was used to classify the pixels into—built-up, water bodies, vegetation, and open spaces in the study area. The accuracy of the analysis was quantified by the Kappa coefficient by comparing the true positive and false negative instances. The ground verification of the classified land use was compared with the Google Earth pro images. Refer to our earlier study, Kadaverugu et al.

(2021b), for further details on the land use classification for the analysis. The percentage of vegetation and open spaces in each micro-watershed was calculated by dividing the area occupied by these land-use classes with the area of the micro-watershed in consideration.

InVEST model

The InVEST-v3.8.0 urban flood risk mitigation model (Sharp et al. 2020) was used in the present study to estimate the run-off generated and retained in each micro-watershed. The InVEST flood risk mitigation model employs the SCS-CN method, a widely applied empirical relation for flood estimation over the spatial scales ranging from regional to sub-regional scales. The InVEST flood risk mitigation model requires input raster layers of hydrologic soil group (HSG), land use land cover (LULC), and curve number (CN) values. These input layers were prepared using the QGIS-v3.16 software. The rainfall data required by the InVEST model to generate the run-off was considered to be a 2-year return period design storm of 1-h duration having the precipitation of 53.86 mm h⁻¹ intensity (P), as derived by Agilan and Umamahesh (2017). Since the city has been experiencing floods more frequently, even due to the short rainfalls, the study considered more realistic precipitation of 1-h duration. Further details on input data layers preparation for the InVEST model are explained in the following sections.

Typically the soil is classified into four hydrological groups—A, B, C, and D according to its infiltration rate in the descending order, which is a useful parameterization required to estimate surface run-off by the InVEST model. The HSG layer for the study area was prepared from the

Global Hydrologic Soil Groups layer (HYSOGs, Ross et al. 2018) of 250 m spatial resolution. Details on land use layer preparation are mentioned in “Land use classification”. Further, the raster layer of CN was prepared by assigning the CN values at a pixel based on the underlying land-use class and HSG. The CN is an empirical parameter applied in hydrological modeling to estimate surface run-off due to rainfall. The CN values range between 0 and 100, representing the extremes of low run-off and high run-off generation potential. In the present study, a moderate antecedent soil moisture condition was considered, based on which the CN values were assigned after Chow et al. (1988).

Based on the design precipitation, the InVEST model calculates the run-off generated (Q_p) in each micro-watershed by accounting for the potential maximum retention (S_{max}) and initial abstraction factor ($\lambda = 0.2$) as mentioned in Eqs. (1) and (2). The run-off retention capacity (R) is the ratio of run-off retained ($P - Q_p$) to the precipitation (Eq. 3). The InVEST model calculates the R values at each pixel in the study area, but they were averaged over a micro-watershed for further calculating the FVI. The run-off retention capacity of a micro-watershed characterizes its hydrological behavior by accounting for the land use, HSG, and CN values.

$$Q_p = \frac{(P - \lambda S_{max})^2}{(P + (1 - \lambda)S_{max})} \quad \text{if } P > \lambda S_{max} \quad \text{Otherwise } Q_p = 0 \tag{1}$$

$$S_{max} = \frac{25400}{CN} - 254 \tag{2}$$

$$R = 1 - \frac{Q_p}{P} \tag{3}$$

Urban infrastructure density

The building footprint and road network vector layers were obtained from the OpenStreetMap (OSM) database (<https://www.openstreetmap.org>). The raw data were cleaned to remove the overlapping building polygons. The building infrastructure density (m^2/m^2) over each micro-watershed region was calculated by dividing the total built-up area in the micro-watershed by the area of that micro-watershed. Similarly, the road density (m/m^2) was calculated by dividing the total road length in a micro-watershed by the area of that micro-watershed.

Flood Vulnerability Index

The Flood Vulnerability Index (FVI) was developed by considering *flood sensitivity* and *adaptive capacity*. Flood

sensitivity comprises urban morphological aspects and demographic information, which are vulnerable to floods representing the building and road density. While, the adaptive capacity is expressed through sub-components: hydrological responses in terms of run-off retention capacity, existing green cover (vegetation percentage), and available open spaces (open spaces percentage). It is needless to iterate that in developing countries like India, road connectivity is one of the indicators of economic development. Buildings are essential components of economic activity (Marvi 2020). Hence, if the road and building densities are higher in a micro-watershed, the damage inflicted through urban floods will be increased. Similarly, the micro-watersheds with high run-off retention capacity, green cover, and open spaces have increased adaptive capabilities in overcoming the flood damages (or highly resilient). The opposing effects of flood sensitivity and adaptive capacity are weighted with significance values for calculating the FVI.

The criteria variables viz. building density (v1) and road density (v2) representing the flood sensitivity, and vegetation cover (v3), open space (v4), and run-off retention capacity (v5) representing the flood adaptive capacity, respectively, were used in the calculation of the FVI. The criteria variables were centered with respective minimum values and scaled with the range (max–min) to harmonize the data to make it independent of the units (Eq. 4). Further, the scaled variables (S) were ranked on a scale of 1–4 for inter-variable comparability. The ranks were assigned based on the quartile ranges. Building and road density were rated from 1 to 4 (from first to third quartiles) as they positively contribute to the proposed FVI. In contrast, run-off retention, percentage of vegetation, and open spaces were assigned from 4 to 1 (from first to third quartiles), as they negatively contribute to the FVI.

These variables were compared pair-wise, following Saaty's method (Saaty 2012) to derive the significance weights. As the first step in multi-criteria decision making through AHP, the relative importance of the criteria variables was derived according to the domain knowledge, expert judgment, thorough literature analysis, and screening of policy documents. The relative importance of each criteria variable in terms of weights (W) was determined using the pair-wise comparison matrix following the Saaty's comparative scale method. According to this method, integers from 1 to 9 are assigned to a factor when compared against another, where 1 is assigned when the two factors are equally important, while 9 is assigned when one factor is extremely more important than another. The inverse of these factors is assigned when the compared variables are reversed in the comparison matrix. The factor assignment, although not an objective method of evaluation, it accommodates the system's responses at a higher level, especially when multiple variables are contributing to the output. The Consistency Ratio (CR) was calculated to check

the consistency of the factor assignment, which is a measure of deviation from the standard (Reference Index (RI) shown in Eq. 5). Here, RI is derived from a set of randomized statistical experiments run by choosing several criteria variables by Saaty (2012). The Consistency Index (CI) is calculated using the maximum Eigenvalue (E_{max}) of the rank matrix according to Eq. (6), where n is the number of criteria variables. Once the factor assignment exercise is consistent according to the CR (should be <0.1, according to Saaty (2012)), the FVI for each micro-watershed was calculated by taking the weighted linear combination (WLC) of the scaled criteria variables and its weights (estimated by the factor assignment) according to Eq. (7). The methodology adopted for ranking the delineated micro-watersheds in the order of priority of flood mitigation is depicted through a flow diagram show in Fig. 2.

$$V_{scaled} = \frac{(V_i - V_{min})}{(V_{max} - V_{min})} \tag{4}$$

$$CR = \frac{CI}{RI} \tag{5}$$

$$CI = \frac{(E_{max} - n)}{(n - 1)} \tag{6}$$

$$FVI = S \times W \tag{7}$$

Results and discussion

The study area is delineated into 85 micro-watersheds based on the catchment and stream network analysis. The area of these micro-watersheds ranges from 0.73 to 80 km², with an average of 16.9 km². The Kappa coefficient of LULC analysis carried out in the study was 0.85 (as shown in our previous study, Kadaverugu et al. 2021b), which indicates an accurate classification. The percentage of vegetation cover and open spaces of the micro-watersheds ranges from 0 to 29.7% and 12.7–100.0%, respectively. The micro-watersheds that are in the heart of the city with negligible greenery have almost 0% vegetation cover, while a few micro-watersheds at the fringes away from the city center (that have very little built-up area) have vegetation cover reaching up to 29.7% and open spaces reaching up to almost 100%. Regarding the

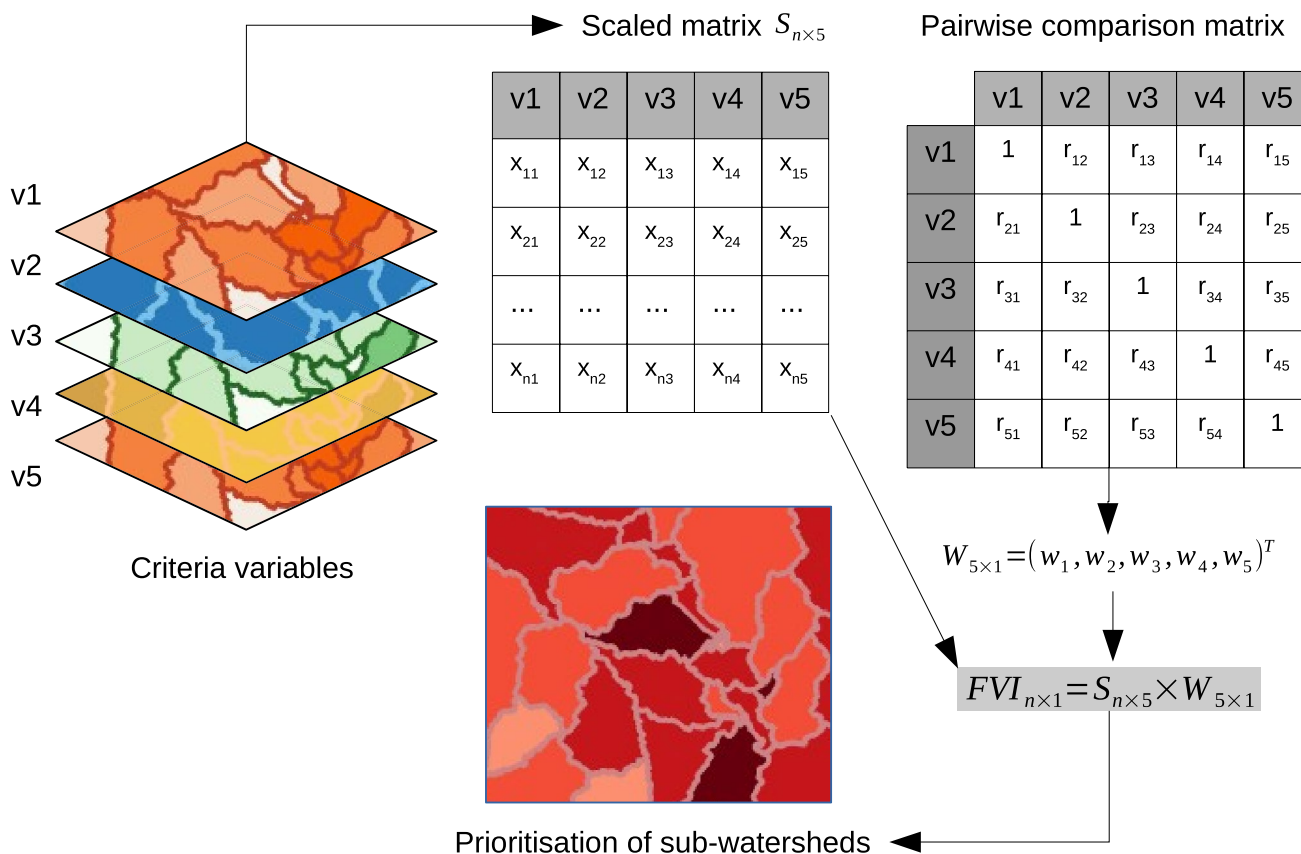


Fig. 2 Figurative depiction of the methodology

soil type, all micro-watersheds in the study area fall into either HSG category C or D soils. These soil types have moderately high run-off potential with low infiltration rates ($< 3.8 \text{ mm h}^{-1}$).

The run-off generated and retained in the study area has been estimated using the InVEST model according to the precipitation intensity of 53.86 mm h^{-1} . The model estimated 39.38 million m^3 as run-off (Q_{vol}) volume in the entire study area. The run-off retained was estimated to be 38.43 million m^3 ($P-Q$) on study area as the whole. The average run-off retention capacity of the study area is 0.49 (R), which is a ratio between run-off retained and total precipitation (Eq. 3). Whereas, the run-off retention capacity of 85 micro-watersheds ranges from 0.28 to 0.60. The micro-watersheds with low run-off retention capacity have high flooding potential, while with high values have low flooding potential. The extent of green cover, concretization, and soil infiltration capacity have been accounted for implicitly in the run-off retention value of a micro-watershed through the CN value assignment (which is one of the inputs to the SCS-CN method utilized in the InVEST model).

The cumulative area of buildings in these micro-watersheds range from 176 m^2 to 8 km^2 , and the cumulative road

length ranges from 0 to 1330 km. Whereas, the building density and road density vary from 0 to $0.32 \text{ m}^2/\text{m}^2$ and $0-0.03 \text{ m}/\text{m}^2$, respectively. The minimum values of building and road densities are from the watersheds situated in the study area's fringes. The descriptive statistical summary of the criteria variables used in the calculation of FVI is provided in Table 1. The choropleth of the scaled variables is presented in Fig. 3. From the figure, it appears that the micro-watersheds with high run-off retention capacity are spread across the fringes of the study area (Fig. 3a), which is in agreement with patterns observed in vegetation and open spaces (Fig. 3b, c). On the contrary, the choropleth of building and road density (Fig. 3d, e) are high in the central parts of the study area with high urbanization. These scaled variables are classified into four classes, ranked from 1 to 4 according to the quartiles, which are useful in the calculation of FVI are presented in Table 2.

The pair-wise importance assignment of the criteria variables is presented in Table 3. The values reflect that the building density and road density were assigned with equal importance. Building density is treated as weakly more important than vegetation cover, strongly more important than open space, and equally important with

Table 1 Descriptive statistics of the criteria variables

Variables	Building density (m^2/m^2)	Road density (m/m^2)	Vegetation cover (%)	Open land cover (%)	Run-off retention capacity (mm/mm)
Minimum	0	0	0	12.71	0.28
Maximum	0.32	0.03	29.71	100.00	0.60
Mean	0.08	0.01	6.19	59.48	0.49
Standard deviation	0.08	0.01	5.83	23.03	0.04
Kurtosis	2.69	2.49	7.29	1.97	10.93
Skewness	0.92	0.43	1.82	-0.31	-1.81
Median	0.04	0.01	3.99	65.54	0.49

Fig. 3 Sub-watershed layers representing scaled criteria variables **a** run-off retention capacity, **b** green cover, **c** open spaces, **d** building density and **e** road density. All the variables are unit less

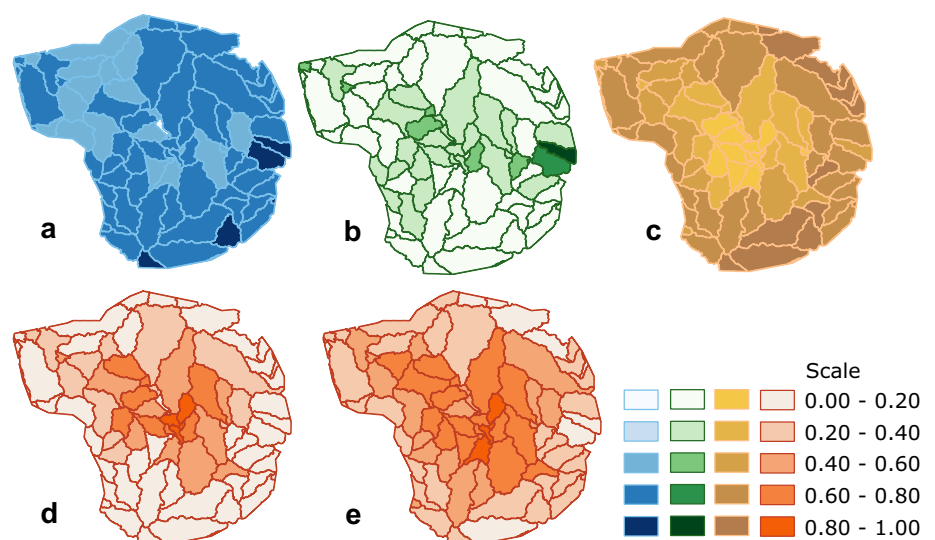


Table 2 Classification of the scaled variables according to quartiles

Variables	Quartile range	Rating
Building density	0.00–0.03	1
	0.03–0.13	2
	0.13–0.49	3
	0.49–1.00	4
Road density	0.00–0.23	1
	0.23–0.38	2
	0.38–0.59	3
	0.59–1.00	4
Vegetation cover	0.00–0.07	4
	0.07–0.13	3
	0.13–0.33	2
	0.33–1.00	1
Open land cover	0.00–0.29	4
	0.29–0.60	3
	0.60–0.72	2
	0.72–1.00	1
Run-off retention capacity	0.00–0.59	4
	0.59–0.65	3
	0.65–0.75	2
	0.75–1.00	1

run-off retention capacity. Vegetation cover is treated weakly as more important than open space in terms of flood mitigation. The run-off retention capacity is given more importance than the green cover and open spaces. The weights assignments in this study were attempted to be as rational as possible with respect to the study area, but the aspect of uncertainty in weight assignment has not been studied here. The normalization of weights derived from the pair-wise importance matrix indicates that the

building density and run-off retention capacity have equal importance of 28%, followed by the road density and others (Table 4 and Fig. 4). The Consistency Ratio (CR) was calculated (according to Eq. 5) to be 0.098, which is less than the limit 0.1, hence the assignment of weights was consistent according to Saaty’s method, and the values are summarized in Table 5.

The FVI values vary from 1 to 4 (1 = low to 4 = high), which depicts the flood vulnerability in the ascending order (Fig. 5). Results indicate that the FVI values of 85 micro-watersheds ranged from 1.04 to 3.84. The inverse relation between FVI and the run-off retention is reflected in Fig. 6. A similar inverse trend is observed between the FVI and vegetation and open spaces fraction. On the contrary, the FVI is directly influenced by building density (Fig. 6) and road density. The observed relationship between the FVI and criteria variables is in agreement with the rank and weight assignment.

Based on the FVI values, the micro-watersheds were categorized in the order of flood vulnerability. In turn, the vulnerability determines the need for the mitigation with respect to time, such as immediate action is required for the micro-watersheds with $FVI > 3$; micro-watersheds with $3 > FVI > 2$ can have an action plan distributed over 3–5 years, finally the micro-watersheds with $FVI < 2$ can be targeted for long-term action of around ten years. The categorization of these micro-watersheds is presented in Table 6. Results indicate that about 24 micro-watersheds with $FVI > 3$ require immediate flood mitigation due to high building and road density and less run-off retention capacity (0.28–0.49). These watersheds are situated in the center of the study area, in the core of Hyderabad City, while some are spread in the northwest and southeast of the study area.

Table 3 Pairwise comparison matrix of the criteria variables following the Saaty’s methodology

Variables		<i>v1</i>	<i>v2</i>	<i>v3</i>	<i>v4</i>	<i>v5</i>
Sensitivity	Building density (<i>v1</i>)	1	1	2	5	1
	Road density (<i>v2</i>)	1	1	1	1	1
Adaptive capacity	Vegetation cover (<i>v3</i>)	1/2	1	1	3	1/3
	Open land cover (<i>v4</i>)	1/5	1	1/3	1	1/3
	Run-off retention capacity (<i>v5</i>)	1	1	3	3	1
	Column total	3.70	5.00	7.33	13.03	3.66

Table 4 Normalized matrix and significance weights of each variable

Variables	<i>v1</i>	<i>v2</i>	<i>v3</i>	<i>v4</i>	<i>v5</i>	Sum of weights	% of weights
Building density (<i>v1</i>)	0.27	0.20	0.27	0.38	0.27	1.40	28
Road density (<i>v2</i>)	0.27	0.20	0.14	0.08	0.27	0.96	19
Vegetation cover (<i>v3</i>)	0.14	0.20	0.14	0.23	0.09	0.79	16
Open space (<i>v4</i>)	0.05	0.20	0.05	0.08	0.09	0.47	9
Run-off retention capacity (<i>v5</i>)	0.27	0.20	0.41	0.23	0.27	1.38	28

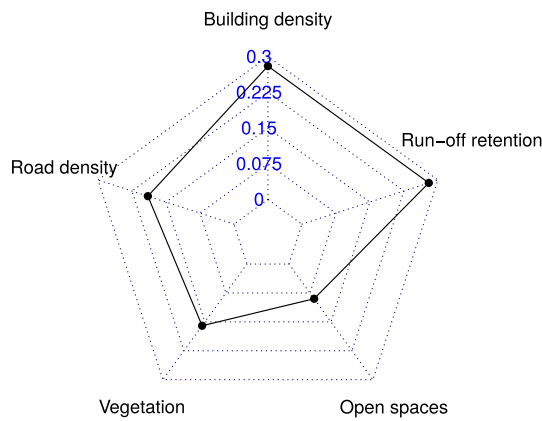


Fig. 4 Radar plot of the weights assigned to the criteria variables based on Saaty’s comparison matrix

Table 5 Rank matrix parameters for calculating consistency of weights

Variable	Value
Maximum of Eigen values (E_{max})	5.44
Consistency Index (CI)	0.11
Reference Index (RI) for five variables (Saaty 2012)	1.12
Consistency ratio (CR)	0.09

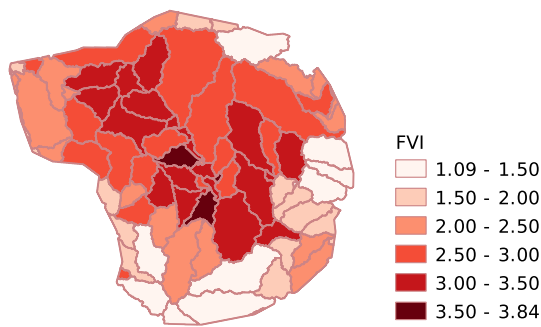


Fig. 5 Choropleth of the micro-watersheds according to the Flood Vulnerability Index (FVI)

Around 36 micro-watersheds having FVI in the range of 2–3 require planned mitigation in the near future. These micro-watersheds spread in the north and north-west of the study area and having the run-off retention capacity in the range of 0.41–0.60. The rest 25 micro-watersheds are categorized as less-vulnerable that require near to long-term mitigation action, and the development should be planned so that it least affects their current

less-vulnerability status. These micro-watersheds have low built infrastructure but with high green and open space fractions. They are located at the periphery of the city, with semi-urban landscapes having vast expanses of open land. The micro-watersheds under a particular slab of FVI classification can be further sub-ranked according to the availability of open spaces or existing green cover or built infrastructure density for further micro-planning.

Mitigation measures

Flood mitigation measures in urban centers can be structural and non-structural measures. Structural measures include constructing stormwater retention ponds, rainwater harvesting structures, adequate stormwater networks, and developing green infrastructure, etc. (Albuquerque et al. 2019; Rahman and Islam 2019). Non-structural measures include flood forecasting, early warning systems, implementing stringent building bylaws, spreading community awareness, and implementing regulations that mainly deal with the best practices to avoid or minimize flood damages. The nature-based structural approaches involve increasing urban forestry and rain gardens, which act like sponges in floods and retain the run-off significantly. Burden (2006) reported that trees would slow down stormwater by obstructing 30% of the precipitation through foliage and another 30% through their root system. Trees also filter out the pollutants carried along with the run-off.

In the light of increasing urbanization and climate variability, especially these nature-based flood mitigation practices have been reiterated as a win-win alternative, which not only combat the floods but also regulate the urban micro-climate and offers a multitude of other urban ecosystem services (Chan et al. 2019; Charoenkit and Piyathamrongchai 2019; Kadaverugu et al. 2019, 2021b, c; Singh et al. 2020). Also, bio-retention of excess run-off through the urban green spaces helps in groundwater recharge. However, increasing the urban green infrastructure is a long-term strategy, which involves strategic planning. As the results indicate, the proposed FVI aids the policymakers in the prioritization of the urban micro-watersheds for optimized results.

Some of the immediate mitigation actions or policy measures are converting the open spaces into green cover and rain gardens, implementing large-scale groundwater recharge pits, household rainwater harvesting pits, or rooftop harvesting structures. These measures will increase the run-off retention capacity and hence lowers the flood vulnerability. The existing policies of the Telangana State government include the plantation drive across the state (Telanganaku Harita Haram) and the development of

Fig. 6 Flood Vulnerability Index (1–4) of micro-watersheds arranged in the descending order which is overlaid with scaled (unit less) building density (0–1) and runoff retention capacity (0–1)

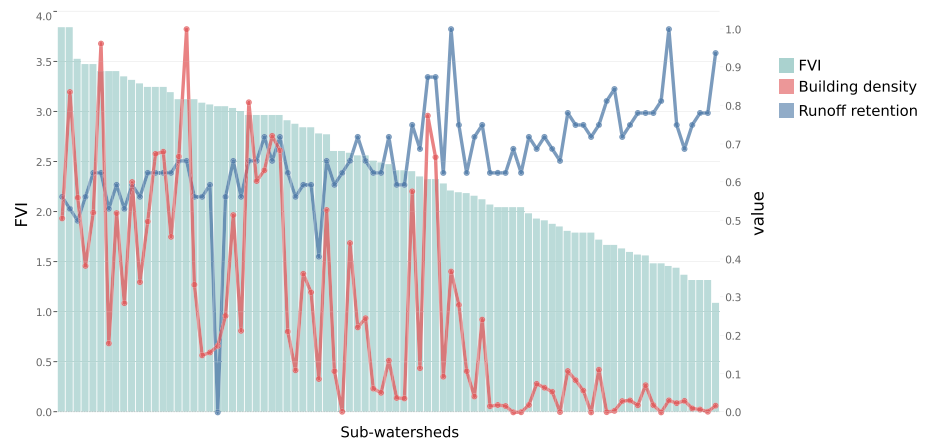


Table 6 Prioritization of sub-watersheds in the order of flood mitigation action

Priority	Flood Mitigation Index	Number of sub-watersheds	Building density (m ² /m ²)	Road density (m/m ²)	Run-off retention capacity (mm/mm)	Vegetation cover (%)	Open spaces (%)
Urgent action	> 3.0	24	0.05–0.31	0.01–0.04	0.28–0.49	1.21–12.51	12.71–67.64
Near future action	2.0–3.0	36	0.00–0.25	0.00–0.03	0.41–0.60	0.00–29.71	22.50–100.00
Near to long term action	< 2.0	25	0.00–0.03	0.00–0.01	0.49–0.60	0.11–28.79	56.75–91.49

oxygen parks (Urban Forest Park scheme), which should be oriented more towards the highly vulnerable urban micro-watersheds (FVI > 3).

In micro-watersheds with almost negligible vegetation cover or open spaces, the structural flood retention measures can be adopted, like promoting green roofs and walls, rainwater harvesting pits or underground stormwater network or collection pool, infiltration trenches or wells, micro-reservoirs or cisterns, and porous pavements, to mention a few. Run-off overflow on urban roads can be avoided by providing adequate cross-drainage works, which will also prevent stagnation during flash floods. Choking the stormwater drains with municipal solid waste can be avoided by ensuring proper casing and frequent cleaning. Providing steel or plastic meshes at the cross drainage structures prevents them from clogging during floods. Some of the non-structural measures to minimize the urban floods include but not limited to—implementation of hydrological property tax (proportional to the non-permeability in the premises), strategic planning of urban land use based on the flood vulnerability status, incentivizing the promotion of greenery in private lands and social forestry, increasing the environmental awareness and public participation, and ensuring a sense of ownership and belongingness. Revival and preservation of water bodies in the urban areas such as check dams, retention ponds, lakes, percolation wells, and their inter-connectivity through

streams or canals are some of the flood retention measures (Kadaverugu et al. 2021b).

Quantification of the ecosystem services of natural capital in cities helps to appreciate nature's benefit and aids in more resilient policy planning (Bedi and Mahavir 2020; Li et al. 2020). Further, emerging concepts in urban landscape planning such as Water Sensitive Urban Design (WSUD, Myers and Pezzaniti 2019) and Sponge Cities (Jiang et al. 2018) have to be adopted by the city planners.

Nevertheless, despite implementing several structural and non-structural measures, evidence suggests that the socio-demographic and capital (for example, health infrastructure, flood relief centers) or infrastructural adaptive capacity also plays a vital role in the post-flood mitigation measures (Braun and Aßheuer 2011). The social connections, helping attitude, financial instruments, sense of inter-connectedness among the neighborhood, self-help groups and non-governmental charity groups, etc., are also contributing to the preparedness to the vulnerability towards natural hazards. It is essential to understand the direct or indirect drives pushing the complex urban systems to the verge of collapse (for example, rural–urban migration, climate change-driven changes, etc.). Successful climate change adaptation strategies should be planned with the implementation of transformative adaption outlined in IPCC'S Fifth Assessment (Revi et al. 2014).

Limitations and future scope

The run-off retention was calculated by considering the 2-year return period rainfall of 1-h duration by assuming a uniform spatial distribution across the study area. Future studies can integrate the ensemble of multiple precipitation scenarios to capture the sensitivity and uncertainty in the calculation of the FVI. Further, increasing the land use categories might refine the flood retention calculations of the watersheds. Moderate soil moisture conditions were considered in the study, which could vary over prolonged rainfall events that can affect the run-off estimation in the micro-watersheds. The MCDM using AHP ranking could be more generalized by considering the higher number of opinion matrices.

The scope of the study can be expanded by considering other socio-demographic factors such as—average family income, age, and literacy rate while calculating the flood sensitivity and adaptive capacity. The flood preparedness and perception of the citizens can be measured by several survey instruments. Validation of the proposed FVI with the post-flood effects based on the inter-disciplinary survey could help to understand the devastating effects of the floods (Borga et al. 2019), including casualties, property loss, injuries, among others. Nevertheless, the present study incorporates quite a number of significant variables that affect the flood vulnerability of urban areas and uses a more simplistic approach for prioritizing flood mitigation as a policy tool.

Conclusion

In the light of climate variability-driven extreme weather events, urban floods have become more frequent and are inflicting significant damages to lives and property. Flood mitigation measures through nature-based solutions such as increasing green cover, blue spaces, and other non-structural run-off reduction practices are proven solutions, but they require long-term planning in a phased manner. The present study has applied a multi-criteria decision making analysis to prioritize the urban micro-watersheds for planning a flood mitigation roadmap. A case of Hyderabad City, India, has been considered for demonstrating the proposed methodology. The micro-watersheds of the city have been ranked as per their vulnerability towards urban floods using the Flood Vulnerability Index (FVI) developed in the study. The FVI proposed is based on using minimal data available with the municipal authorities. The criteria variables that reflect the *sensitivity* and *adaptive capacity* of the urban micro-watersheds due to the floods are used for the FVI calculation. The sensitivity criteria variables include building density and

road density in the micro-watersheds. The damages to these variables are directly correlated with the extent of floods. In contrast, the adaptive capacity criteria variables include the fraction of green cover, open spaces, and the run-off retention capacity of the micro-watersheds. These variables are negatively correlated with the extent of flood damages. Unlike several other studies, we have utilized the run-off retention capacity as a surrogate to the hydrological behavior of the watersheds for calculating the FVI.

The relative weights to these variables have been assigned using the Analytical Hierarchical Process (AHP) based on expert judgment, domain knowledge, and screening of policy documents. The hydrological terrain analysis of the city has delineated the city into 85 micro-watersheds, and the respective values of the criteria variables for each micro-watershed were obtained from GIS analysis and InVEST model. The FVI of each micro-watershed has been calculated by the weighted linear combination of the weights and the scaled criteria variables. The FVI ranges between 1 (less vulnerable) and 4 (highly vulnerable).

Results indicate that 24 micro-watersheds have been classified as highly vulnerable to floods with $FVI > 3$. While, 36 micro-watersheds have the FVI in the range of 2–3, which are classified as medium vulnerable. And the remaining 25 micro-watersheds have $FVI < 2$, which are classified as less vulnerable to floods. We strongly advocate that the urban policies on flood mitigation should primarily target highly vulnerable micro-watersheds to achieve a tangible reduction in the losses due to floods. In the circumstances of rapid urbanization and drastic changes in land use and land cover, the proposed methodology can be run with the updated data sets for re-classifying the vulnerability status of an urban micro-watershed. The study can help the urban policymakers to prioritize the flood mitigation strategy of several micro-watersheds into immediate, near-future, and long-term actions and aids in the smart allocation of budget and workforce deployment.

The proposed FVI can be applied to several other cities across the globe and can aid in climate-smart policy-making for achieving resilience in the cities to improve human well-being. The findings of the paper also resonate with the global action on climate-smart cities. The Cities Alliance Movement emerged in the Climate Adaption Summit 2021, and the global alliance of 40 cities (C40), among others, endorsed the resilience planning of several cities across the world to the climate impacts. United Nations program on Cities and Climate change also reiterate the need to transform cities across the globe into more climate-resilient. These global level policies have been percolating into national ambitions in revamping the cities across the world, but the local action necessary

for the translation of the policy is needed to be improved with the commitment from all stakeholders. The fragility of the urban systems to the shocks of extreme weather events, including that resulting from the urban floods, is to be minimized with the applications of nature-based solutions and green infrastructure aided by proper prioritization planning.

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Availability of data and material The data could be made available if requested.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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