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ORIGINAL ARTICLE

Quantification of flood mitigation services by urban green spaces using InVEST model: a case study of Hyderabad city, India

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Abstract
Urban floods have become more frequent across the globe. The transformation of the urban landscape with increased concretization and dwindling green cover has resulted in excess run-off generation thereby causing the flash floods. The protective role and ecosystem benefits of urban green spaces needs to be quantified so that it will unlock the possibilities of integrating natural capital thinking into policymaking. Hence in this study, we quantified the flood mitigation service of green spaces and estimated the tangible economic damage to the built infrastructure in the Hyderabad metropolitan city, India using the Integrated Valuation of Ecosystem Services and Trade-offs model. The analysis was carried out for 2-years and 5-years design precipitation of 1 h duration. Results show that 44–50% of the precipitation is retained by the urban green and open spaces. With an increase of 13% in the rainfall intensity (from 2-years to 5-years), the run-off volume has increased by 21%, while the run-off retained has increased only by 5%, which indicates that even slight increase in rainfall intensity results in huge run-off generation that causes commensurate economic damages. The economic damage due to flood inundation of the built infrastructure is estimated to be 1.39 million USD using the unit cost method. Overall, the indicator of run-off retention service is quantified as $4.25E+13$ and $4.46E+13$ for the 2-years and 5-years return period precipitation, respectively. The structural and non-structural flood mitigation measures are also enumerated along with the limitations of the model.

Keyword Economic assessment · Urban green spaces · Hyderabad city · InVEST model · Mitigation measures · Flash floods

Abbreviations

AMC	Antecedent moisture condition
DEM	Digital elevation model
GEE	Google earth engine
HSG	Hydrologic soil group
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
LULC	Land use land cover
NbS	Nature-based solutions
QGIS	Quantum geographic information system
RS-GIS	Remote sensing and geographic information system
SCS-CN	Soil conservation service-curve number
SDG	Sustainable development goals
UGS	Urban green spaces
UHI	Urban heat island

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Introduction

Urban floods have become more frequent across the globe. The vulnerability due to urban flooding is increasing due to rapid urbanization and climate change. It is estimated that nearly 68% of global population lives in urban agglomerates by 2050 (O'Donnell and Thorne 2020), which further induces stress on urban centers in coping with extreme weather events. In the last two decades (2000–2018) there were 3798 flash flood events worldwide, which have caused ~592 billion USD loss and killed around 0.1 million (NatCatSERVICE 2020). India is one of the most disaster-prone countries in the world (Bhatt 2018), and it ranks

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second only to Bangladesh in flooding event. In India, nearly 80% of the precipitation occurs in short duration between June and September months in the monsoon season (NDMA 2010; Singh and Kumar 2017). It is estimated that 14.6% of Indian Territory is flood-prone (Bisht et al. 2016). There were 2443 flooding events in India during 1978–2006 which have caused 16 billion USD damage to the nation (Singh and Kumar 2013). Especially in urban areas, the flooding occurs frequently, even due to short-duration precipitation (of high intensity) and is creating widespread damage to life and property. A total of 5161 urban local bodies out of 7935 in India are prone to floods (NDMA 2010).

Several studies accentuate that, urban morphology redefines the local precipitation pattern, mainly because of urban heat island (UHI) effect, aerosol loading and modifications in the urban canopy structure (surface friction due to high rise buildings) (Richards and Edwards 2017). City size and high-intensity precipitation are positively correlated over 75% of tropical cities (Pathirana et al. 2014). It is observed that urban centers in India receive 30–40% more rainfall than neighboring rural regions (Kishtawal et al. 2010). The aggravated rainfall patterns over the urban centers in combination with insufficient stormwater management infrastructure have multiplied the economic losses (Gupta 2020). The losses are further aggravated by the urban sprawl.

The land use dominated by built-up area inhibits the infiltration of rainwater and causes excessive run-off (Shanableh et al. 2018). The urban catchments have high proportions of built-up area, and hence lead to increased flood peaks by 1.8–8 times and the flood volume is increased by six times (NDMA 2010). Further, the design storm estimated using the intensity density frequency (IDF) curves based on stationary extreme value theory (EVT) has become obsolete in the light of changing climate scenarios. A difference of nearly 10 mmh^{-1} rainfall intensity is observed between traditionally used stationarity IDF and non-stationarity IDF curves of 2-years return period rainfall of 1 h duration in Hyderabad city (Agilan and Umamahesh 2017). The majority of urban sewerage and hydrological control units were designed based on the obsolete design storm values, which needs to be reassessed and are to be upgraded to cope with the changing urban rainfall profile and urban characteristics.

The load on stormwater drainage can be substantially reduced by encouraging urban green and blue infrastructure comprising of vegetation patches and water bodies (lakes, drains) which act as sponges in the event of flash floods. Moreover, the co-benefits associated with the urban green spaces (UGS) in moderating the urban meteorological conditions are evident in reducing the intense precipitation. The protective role of green and blue spaces is widely acknowledged in various international reports [for example UFCOP (2016) and WHO (2017)] and is also mentioned as one of the nature-based solutions (NbS) towards achieving sustainable development goals (SDG) through flood mitigation. The green infrastructural measures not only control the urban flooding but also add to aesthetic values of cities and improve the microclimatic conditions (Bardhan et al. 2016; Kadaverugu et al. 2011, 2019; Quan et al. 2020). The bio-retention mechanism through green infrastructure soaks the excess run-off and allows infiltrating into sub-strata and thereby fosters the groundwater recharge (Gurunadha Rao and Surinaidu 2012). Encouraging permeable pavements and rooftop green cover will reduce the peak flow time during the urban flooding events (Richards and Edwards 2017).

The quantification of flood retention and economic damage avoided by the urban green spaces is necessary to develop the economically viable flood mitigation strategies. Considering the co-benefits of green infrastructure, apart from the direct benefits, aids in assessing the trade-offs in flood mitigation budgeting (Alves et al. 2019). The economic damage estimation due to the urban floods includes two aspects viz. flood inundation/hazard mapping and vulnerability mapping. The overlap between the flood hazard and built-up area/agricultural area is typically used as a measure to estimate the direct and tangible economic losses. The damage to the built-up area is generally assessed through insurance data, unit cost method and stage-depth damage curves. The damage curves are used in several studies (for example Huizinga et al. 2017; Martínez-Gomariz et al. 2019; Kim et al. 2020) and social survey-based monetary damage estimation is also a prevalent method adopted in Indian cities (Suriya et al. 2012; Thakur et al. 2012). But these methods are highly technical in nature and the damage curves obtained using a few samples may lead to high uncertainty (Albano et al. 2015).

Flood inundation over a region is mapped using the hydrological modeling tools such as HEC-RAS (Rangari et al. 2019), MIKE Urban (Bisht et al. 2016), ANUGA (Issermann and Chang 2020), Tuflow and SWMM (Quan et al. 2020). These deterministic approaches are computationally expensive and require accurate input datasets, which becomes challenging to achieve, especially for the policymakers. For high-resolution urban flood inundation modeling, the coupling with sewer network is imperative, along with refined topographic data, buildings, and narrow watercourses (Bulti and Abebe 2020). In addition, the benefit of complex flood modeling is not fulfilled when there is a lack of proper validation data (Afifi et al. 2019). Moreover, the scalability of flood inundation depths over a large urban area is questionable owing to the interplay of multiple local factors, which poses challenges with the applicability of complex hydrodynamic models. In contrast, simple empirical models based on statistical correlations or machine learning algorithms (Darabi et al. 2019), remote sensing and GIS (geographical information system) applications (Rong et al. 2020), and hybrid approaches (Nkwunonwo et al. 2019) serve as a handy tool in the event of limited availability of hydrological data and also prove significant over large study areas. Nevertheless, the successful conversion of modeling results from high to low spatial resolution is important for wider applicability of the models without losing the hydrological essence (Hou et al. 2019). These simple models are well agreed with the unit cost method of damage estimation over large study areas (Olesen et al. 2017).

Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) is an open-source modeling platform developed by Natural Capital Foundation (Sharp et al. 2020) with an objective to promote the valuation of natural capital in policy planning. The InVEST model has a variety of modules to assess the economic benefits offered by the natural resources such as water bodies, green spaces, rivers and habitats. The quantification of ecosystem benefits will unlock the possibilities of integration of natural capital thinking into policy making for achieving human wellbeing. The InVEST model is applied as a policy tool for ecologically balanced urban planning (Liu et al. 2017; Xu et al. 2019) and to quantify the ecosystem services due to carbon storage (Lyu et al. 2019; Zhao et al. 2019), water yield (Yang et al. 2019), habitat quality (Terrado et al. 2016) and soil conservation (Zhou et al. 2010). However, very few studies have reported on applications of the InVEST model for urban flood mitigation. Urban flood mitigation module of InVEST framework is designed to accommodate the hydrological aspects for easy implementation in policy research. The model utilizes the US soil conservation service-curve number (SCS-CN) method for estimation of run-off, which is based on the water balance equation of the rainfall. The SCS-CN method is a widely accepted empirical method with limited data requirements. The SCS-CN-based hydrological modeling was applied for several Indian cities (Satheeshkumar et al. 2017; Wakode et al. 2018; Natarajan and Radhakrishnan 2019; Nageswara Rao 2020) and other global cities and catchments (Shanableh et al. 2018; Meresa 2019), but very few have dealt with the damage assessment aspect.

The historic city of Hyderabad has once faced cataclysmic river flood in 1908, which served as an eye-opener, and after the event several upstream reservoirs were constructed on the *Musi* river. However, in recent years due to unprecedented economic growth, the city is now facing a huge challenge in mitigating the localized urban floods. The floods during 2000 and 2016 in the Hyderabad city have caused havoc and chaos (Gupta 2020). Hence, we have oriented the present study on Hyderabad city to understand the protective role of urban green spaces in flood mitigation. The run-off retention and the potential economic damage to the built infrastructure have been quantified based on a design precipitation using the InVEST model. We have utilized the layers of built-up area, soil characteristics and land use categories for the analysis. The analysis helps in assessing the trade-offs between the cost of flood mitigation measures and damage caused by the flooding events, which becomes a vital component in devising flood management policies.

Study area

The heritage city of Hyderabad (also known as the Pearl City) is the capital of Telangana State situated in Deccan plateau of southern India. As the metropolitan region of the city is 7257 km^2 encompassing Sangareddy, Medak, Siddipet, Yadadri Bhuvanagiri and Rangareddy administrative districts of Telangana, it is challenging to quantify the flood damage. Hence we concentrated our study on the highly-dense central region of the city enveloped by the outer ring road, which occupies 1444 km^2 of area (hereafter referred as a study area). The length of the outer ring road is around 158 km. The study area (Fig. 1) extends between 17.20–17.59° N and 78.24–78.69° E at an average altitude of + 506.0 above MSL (mean sea level). Hyderabad is located in the hot semi-arid climate (BSh, Koppen-Geiger classification). The temperature ranges from 14.8 to 39.8 °C, and May month is the hottest, while December is the coolest. Rainfall is predominant in southwest monsoon during the period from July to October with an average annual precipitation of 766 mm.

The population in the city was 7.7 million as per 2011 Census, which ranks it as the sixth-largest metropolitan (Das 2015), fourth-most populous city in India, and it is growing at a rate of 2.7%. The population density was 8480 persons per km^2 of area (Census 2011). The 400 years old city region is first located along the *Musi* river banks, which is then gradually expanded towards the north and later started expanding towards north-west until recently to become a world-renowned Information and Technology hub. The melange of cultural and historic flavor is reflected in the building morphology of the city, with high dense building footprint in the old city areas, while high rise buildings in central commercial areas, and lavish villas in the outskirts. Majority of the commercial utility buildings are situated along the arterial roads, following the ribbon development. The hitherto commercial and industrial hubs are now interwoven into the residential zones as the city has been expanding at the fringes.

There is no separate network for stormwater disposal in the entire city. The run-off gets freely mixed with the sewer channels and ends up in the sewage treatment plants. Choking up of the sewer channels due to the solid waste (especially plastics) is also one of the main causes for waterlogging conditions during the flooding in Hyderabad city (DTE 2016).

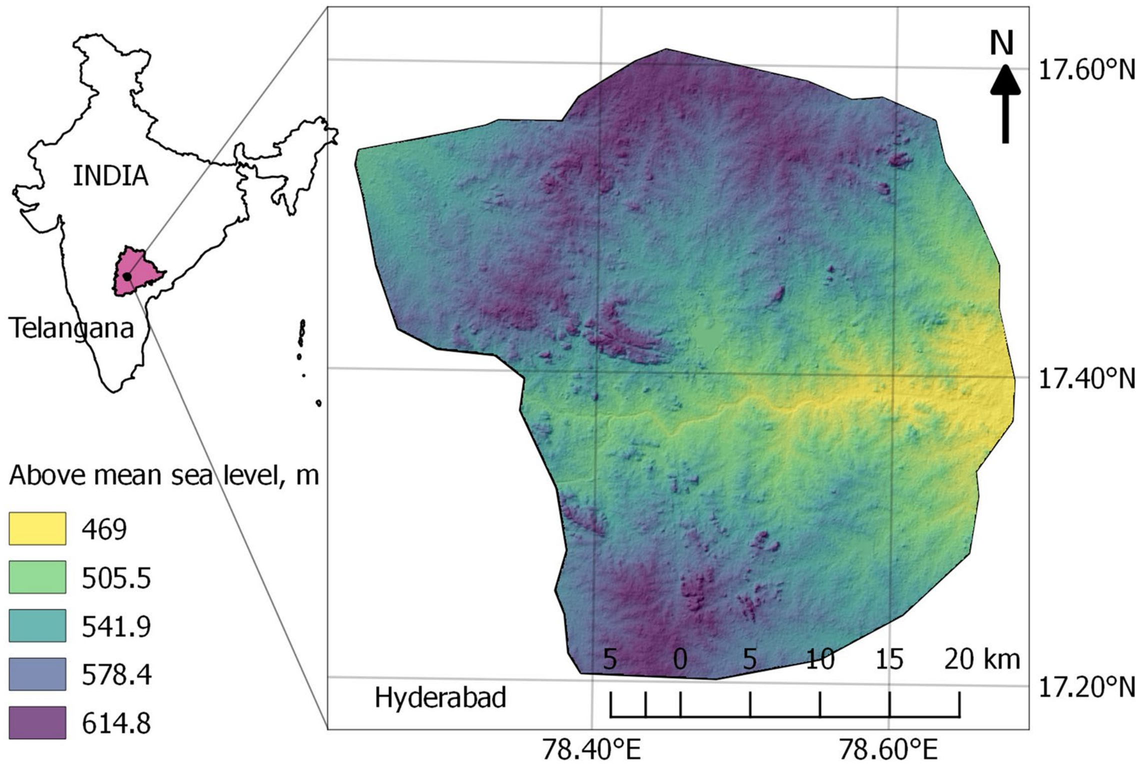

Fig. 1 Location of Hyderabad city in Telangana state of India and the study area is overlaid with a digital elevation model

Materials and methods

We have carried two separate exercises in the study. First one is to assess the historic land-use changes in the study area using the *Trends.Earth* plug-in of QGIS software "Land use land cover trends using *Trends.Earth*". And the second one is to quantify the run-off retention and economic damage assessment using the InVEST model. The input data requirements for the InVEST model is provided in "Input data for the InVEST model" (summarized in Table 1) and the description of the InVEST model is provided in "InVEST model description". The methodology followed for the run-off quantification and damage assessment is shown as flow chart in Fig. 2.

Land use land cover trends using *Trends.Earth*

Historical trends in land use land cover in the study area were analyzed as a separate exercise to verify the urbanization and land degradation. *Trends.Earth-v0.66* module (Trends.Earth 2018) of Quantum-Geographic Information System (QGIS-v2.18) platform was utilized for quantifying the historical changes that occurred in the built-up area in the study area. The module is a front end of Google earth engine (GEE) platform for data crunching of the satellite imageries (European Space Agency CCI-LC, https://www.esa-landcover-cci.org/, from years 2005 to 2015 at 250 m spatial resolution). The vector map covering the study area was prepared for obtaining the statistics of land-use change and land degradation. A

Table 1 Data sources used in the modeling

Data	Sources
Design storm of 1 h duration for 2 and 5 years retention period	Agilan and Umamahesh (2017)
Hydrologic soil group (HSG) layer	Global hydrologic soil groups having 250 m spatial resolution (Ross et al. 2018)
Digital elevation model (DEM)	Shuttle radar topography mission (SRTM) data of 30 m spatial resolution
Land use land cover for the year 2019	Processed using Sentinel-2 satellite data (https://scihub.copernicus.eu/apihub)
Curve number (CN) layer	Chow et al. (1988)
Urban building footprint layer	OpenStreetMaps (https://www.openstreetmap.org)

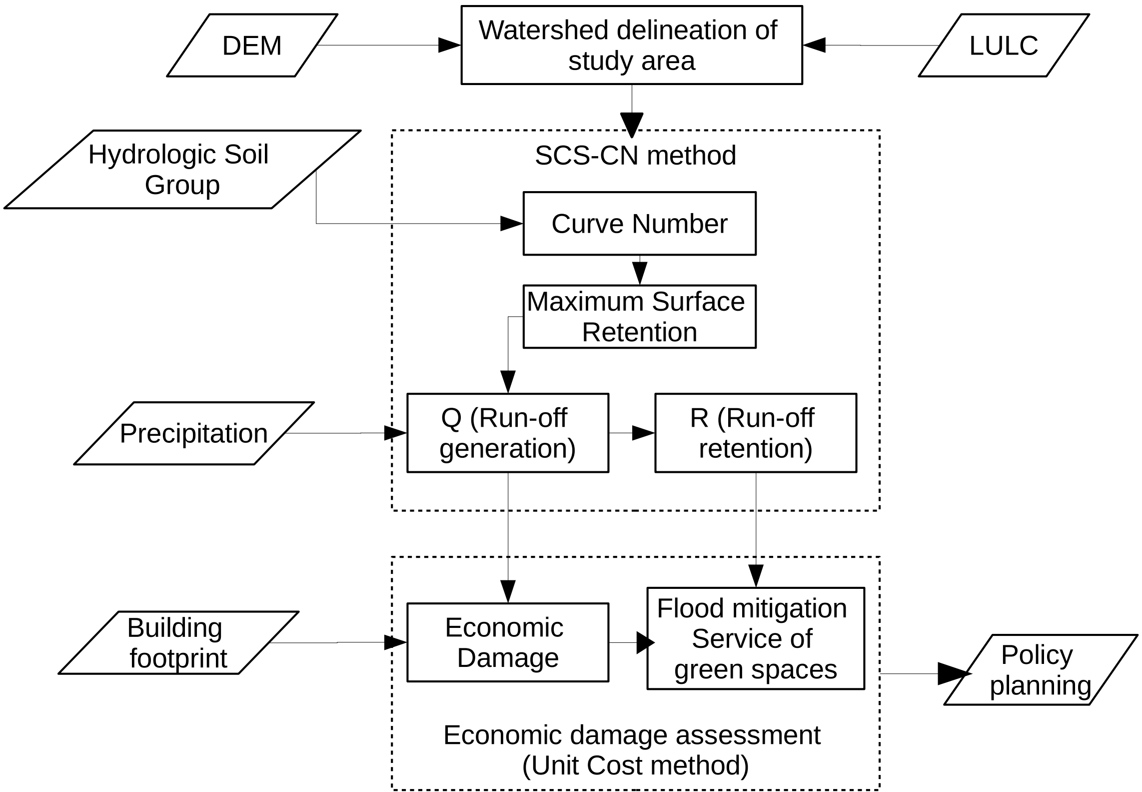

Fig. 2 Flow diagram of the methodology

buffer of 2 km distance around the study area was considered in the *Trends.Earth* analysis to capture the changes at the fringes. The land degradation index was calculated by analyzing the land-use conversion (loss in tree cover and wetlands, conversion of croplands and grasslands into built-up or barren lands) over multiple time periods (2005–2015). All the parameters for running the *Trends.Earth* were kept at their default values (see Trends.Earth 2018).

Input data for the InVEST model

The InVEST flood mitigation model calculates the flood retention due to the green spaces and also estimates the economic damage avoided due to the flood inundation (or economic benefits due to the flood retention) according to the building footprint. The model requires the raster layer of hydrologic soil group, land use land cover, and curve number (CN) over the study area. In addition, vector layers of delineated watersheds and building polygons are required from the study area. The following subsections describe the methodology followed, for the input data generation.

Hydrologic soil group layer

The hydrologic soil group (HSG) layer covering the study area was prepared using the soil classification data obtained from global hydrologic soil groups [HYSOGs, Ross et al. (2018)] having a spatial resolution of 250 m. Each soil group is represented by A, B, C or D category with varying degrees of responsiveness towards the generation of run-off.

Channel network and watershed delineation

The hydrological terrain analysis of the study area was carried out using the digital elevation model (DEM) Shuttle Radar Topography Mission (SRTM) data of 30 m spatial resolution. The DEM data was pre-processed to fill the voids prior to further hydrological analysis. Flow tracing algorithm *rho8* was implemented on the processed DEM layer for the generation of flow accumulation information using SAGA-GIS library in QGISv-2.18. Based on the flow accumulation data (catchment area), the channel network was estimated with the parameters values of—initiation threshold $> 1E+7$, maximum divergence $= 10$ and minimum segment length $= 10$ units.

Land use land cover data

The land use land cover classification of the study area for the year 2019 was carried out using the least cloud cover (0.75%) Sentinel-2 satellite data (https://scihub.copernicus.eu/apihub) of resolution 10 m, acquired on 9th May of 2019. After applying DOS1 (dark object subtraction) atmospheric correction algorithm, the surface reflectance values of the bands 2 (blue), 3 (green), 4 (red), 5 (vegetation red edge), 6 (vegetation red edge), 7 (vegetation red edge), 8 (near infra-red), 8A (vegetation red edge), 11 (short-wave infra-red) and 12 (short-wave infra-red) were used for the supervised pixel classification. Signature classes were prepared for each land use category in the study area and were used to train the maximum likelihood model. Maximum Likelihood algorithm, implemented using the Semi-Automatic Classification plug-in of QGIS-v2.18.15 was used for the land use classification. Land use classification validation metric Kappa coefficient was computed from the confusion matrix generated from 200 random locations in the study area. Ground truthing of the randomly selected spatial locations were verified using the Google Earth Pro imageries. Each pixel in the study area was classified into the following land use categories viz. built-up, vegetation cover, open spaces and water body. The land use category – vegetation cover includes the urban green spaces (institutions/universities forest land), avenue plantations, parks and residential gardens. Open spaces include the playgrounds and grass patches in the city. Built-up area accounts for residential, industrial and commercial buildings and roads. Water bodies include lakes and drains.

Curve number values

The run-off curve numbers (CN) are dimensionless values which are empirical estimations for quantification of run-off depth from the rainfall events. The CN values are dependent on the Hydrologic soil group (HSG-A, B, C and D), land use land cover and antecedent moisture condition (AMC) of soil, on a particular geographical location. Typically the CN values vary between 0 and 100 representing the extreme values of low and high run-off generation. The CN values developed for urban environments by Chow et al. (1988) were adapted in the present study. Out of several land-use classes defined in Chow et al. (1988) we have considered the built-up category with < 1/8 acre layout, vegetation with forest and shrub structure, and open spaces with grass cover < 50% classes in the present study (Table 2). The water bodies including lakes and drains are considered to absorb the run-off instead of overflowing, hence the CN values for the water bodies were assigned as zero. The CN values representative for AMC-II (medium soil moisture) condition was considered in the study. However, based on simple empirical relations the CN values for AMC-I (dry) and AMC-III (highly moist) pixels can be derived to represent the dry and wet soil moisture levels.

Table 2 Curve numbers (CN) for a combination of land use categories and Hydrological soil groups (HSG) used in InVEST urban flood mitigation model. The CN values are suffixed with soil hydrological groups A, B, C and D (sourced from Chow et al. (1988))

Land use	CN_A	CN_B	CN_C	CN_D
Water body	0	0	0	0
Vegetation	33	47	64	67
Built up	77	85	90	92
Open space	68	79	86	89

Urban building footprint

The building footprint vector layer of the study area was obtained from the OpenStreetMaps (OSM) database (https://www.openstreetmap.org) available as on April 30, 2020. The polygons representing the residential buildings (individual houses and apartments), commercial buildings (shopping complexes, colleges, schools, universities, hospitals and under-construction buildings), industrial complexes, and public spaces were clipped with the vector layer of the study area for the analysis. The glimpses of the two-dimensional building footprint vector are shown in Fig. 2c.

InVEST model description

The InVEST-v3.8.0 urban flood risk mitigation model solves the empirical representation of the hydrological processes for estimation of the run-off production and retention over the study area. The run-off quantification is mainly based on the precipitation (P in mm) received over the study area and the land use characteristics. The run-off production ($Q_{p,i}$) due to precipitation (P) is estimated by SCS-CN method using the potential maximum retention ($S_{\max,i}$) and CN$_i$ values on each pixel (I) (Eq. 1). The empirical relation between $S_{\max,i}$ and CN$_i$ is provided in Eq. 2. Initial abstraction (λ) factor as 0.2 times of $S_{\max,i}$ was considered for the study area. The hydrological behavior of the study area at the pixel level is reflected in terms of the CN values, which itself is based on the HSG, land use land cover and AMC. The model also calculates the run-off retention index (R_i), which is a ratio between the quantity of precipitation retained (P–Q) and the total precipitation (Eq. 3) over a pixel. The volume of run-off retained ($R_{\mathrm{vol},i}$ m^3) is calculated by multiplying the run-off retention index per pixel (mm) with the area of each pixel (m^2), as shown in Eq. 4. Similarly, the run-off generated ($Q_{\mathrm{vol},i}$ m^3) is calculated using Eq. 5. The run-off retention index, R_i value is directly proportional to the direct economic damage avoided due to the floods. As the green spaces contribute to the retention of run-off, the run-off retention index is also directly proportional to the mitigation services provided by the urban green spaces in the study area.

The InVEST model calculates the potential economic damage to the built infrastructure per watershed by overlaying the flood extent potential information with buildings' polygon layer (Sharp et al. 2020). The monetary value of the damage per unit area (m^2) of the building type (residential, commercial, industrial or public utility) was assigned, and the cumulative economic damage of the entire study area is calculated by summing up the individual damage caused to each building. The model also calculates an indicator of the run-off retention service for the watershed, which is a product of run-off volume retained and affected built infrastructure (Eq. 6).

$$Q_{\mathrm{p,i}} = \frac{\left(P - \lambda S_{\mathrm{max,i}}\right)^2}{\left(P + (1-\lambda) S_{\mathrm{max,i}}\right)} \quad \textit{if } P > \lambda S_{\mathrm{max,i}} \text{ otherwise } Q_{\mathrm{p,i}} = 0, \tag{1}$$

$$S_{\mathrm{max,i}} = \frac{25400}{CN_i} - 254, \tag{2}$$

$$R_i = 1 - \frac{Q_{\mathrm{p,i}}}{P}, \tag{3}$$

$$R_{\mathrm{vol},i} = R_i \times P \times \mathrm{PixelArea}, \tag{4}$$

$$Q_{\mathrm{vol},i} = Q_{\mathrm{p,i}} \times \mathrm{PixelArea}, \tag{5}$$

$$\mathrm{Service} = \mathrm{AffectedBuild} \sum\nolimits_{\mathrm{watershed}} \left(P - Q_{p,i}\right) \times \mathrm{PixelArea}, \tag{6}$$

The design storm of 1 h duration rainfall with intensity 53.86 mm h^{-1} for a 2-years return period and 60.85 mm h^{-1} intensity for a 5-years return period were considered in the study. These design precipitation values were calculated based on the non-stationarity IDF curves representing the Hyderabad city (Agilan and Umamahesh 2017).

Results and discussion

Historic and present land use land cover analysis

Historical land use analysis carried out using *Trends.Earth* tool indicates that the built-up area in the study area has tremendously increased during the time period from 2000 to 2015. Significant expansion occurred in the fringes, mainly in the last decade (Fig. 3a). The conversion of vegetation, forest land, water bodies or wetlands into built-up is measured as land degradation, which is reflected at the periphery surrounding the core area of the city (Fig. 3b). It is evident from the analysis that the city is expanding radially outwards, especially in the north-west direction.

The present land use classification carried out using the Sentinel-2 satellite observations of May 2019 indicate a high level of accuracy with a Kappa coefficient of 0.85. The results show that 62% of the study area is occupied with open spaces, mainly at the peripheries, 31.2% is occupied with the built-up area, followed by vegetation 5.6% and water bodies 0.8% (Fig. 3c). These land-use percentages are calculated for the entire study area of 1444 km^2 and are not to be related to that of the core area of Hyderabad city.

As the city expands, the rural areas with meager stormwater infrastructure at the fringes are now engulfed into the urban conglomerations. The newly urbanized areas are unable to cope up with the increased urban flood situations (Gupta 2020). In addition, there has been a significant rural migration to Hyderabad city during the last five decades (Das 2015). The migration has induced enormous stress on urban infrastructure, leading to the forced growth of the city without much planning for disaster resilience. The migrant habitats are established in slums or makeshift homes; often in low lying river banks and lakes, hitherto unoccupied. In addition, the urban wetlands, riverbanks, and dried up lakes are prone to illegal occupation by the real-estate developers, which is often unchecked by the urban authorities. The dwindling blue/green spaces thereby increase the flood vulnerability during the rainy season in general, and in specific during the flash floods. Instead of expanding the urban blue spaces (water bodies), they have been exploited in the veil of urbanization and have become one of the reasons for urban flooding (NDMA 2010).

Characteristics of the study area

The HSG layer for the study area contains only two soil groups C and D, that have moderately high to highest run-off potential (Fig. 4a). The HSG A soils have low run-off potential and have high infiltration rates (> 7.6 mm h^{-1}), B soils have moderately low infiltration rates (3.8–7.6 mm h^{-1}), while C soils have moderately high run-off potential due to low infiltration rates (1.8–3.8 mm h^{-1}) and D soils have the highest run-off potential due to the lowest infiltration rate (< 1.8 mm h^{-1}). These HSG C and D category soils contain 20–40% and > 40% clay, respectively and < 50% of sand. The soils have high swelling potential, low infiltration rates when thoroughly wetted, and impedes downward movement of water, which causes run-off.

The study area was delineated into two broad watersheds namely 1 and 2 having an area of 1259 and 185 km^2, respectively (Fig. 4b), based on the channel network and watershed delineation analysis. The flood mitigation and economic

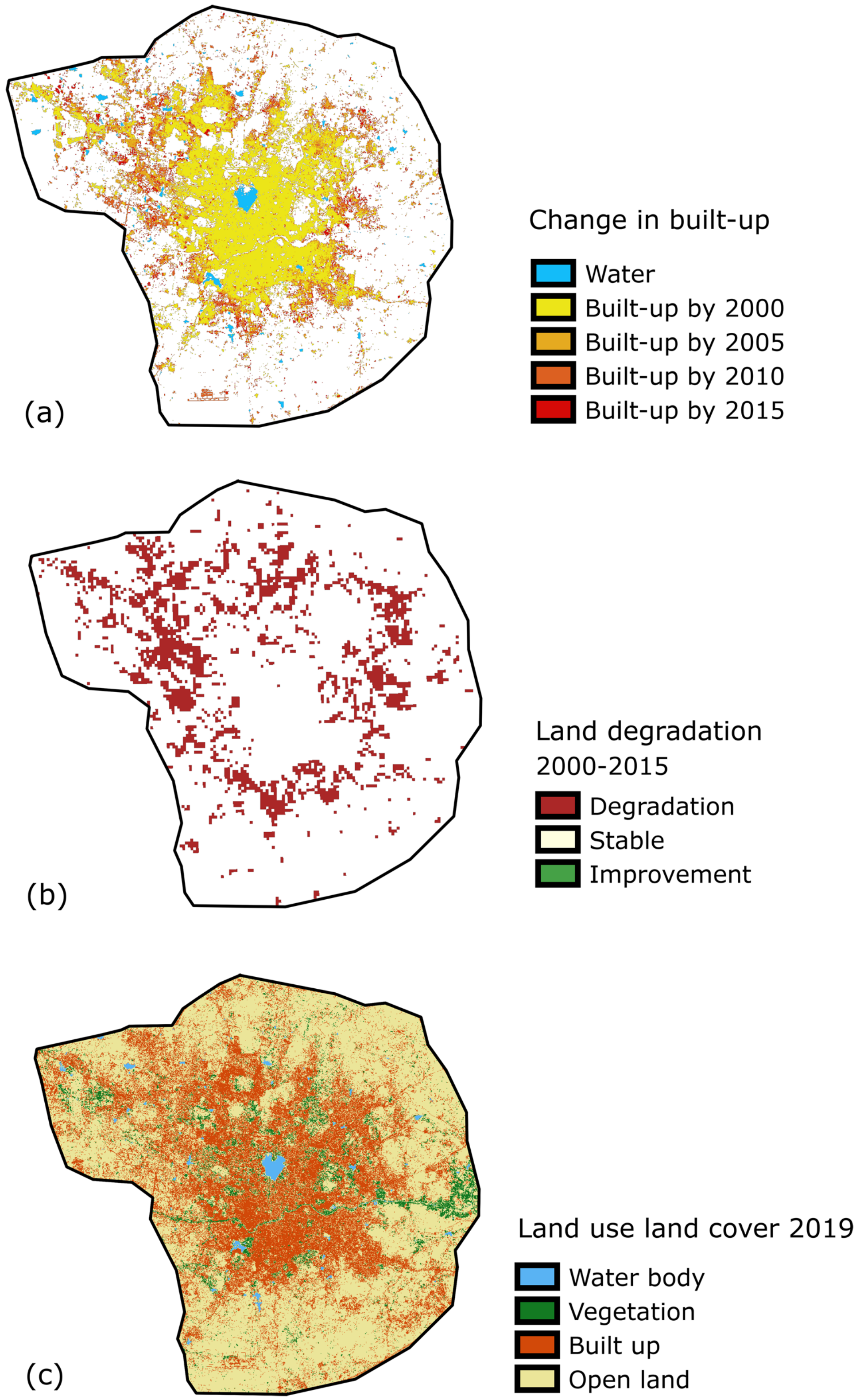

Fig. 3 **a** Changes in the built-up area of Hyderabad city in the study area during 2000–2015, **b** the land degradation and **c** land use land cover classification for the year 2019

assessment of urban green spaces are summarized according to the delineated watersheds.

The building footprint vector layer used in the flood damage assessment consists of 0.66 million polygons, representing the residential, commercial, industrial and public buildings (Fig. 4c). As the multi-stories information about the buildings is not available, we have considered the floor area of each building in the present study. The

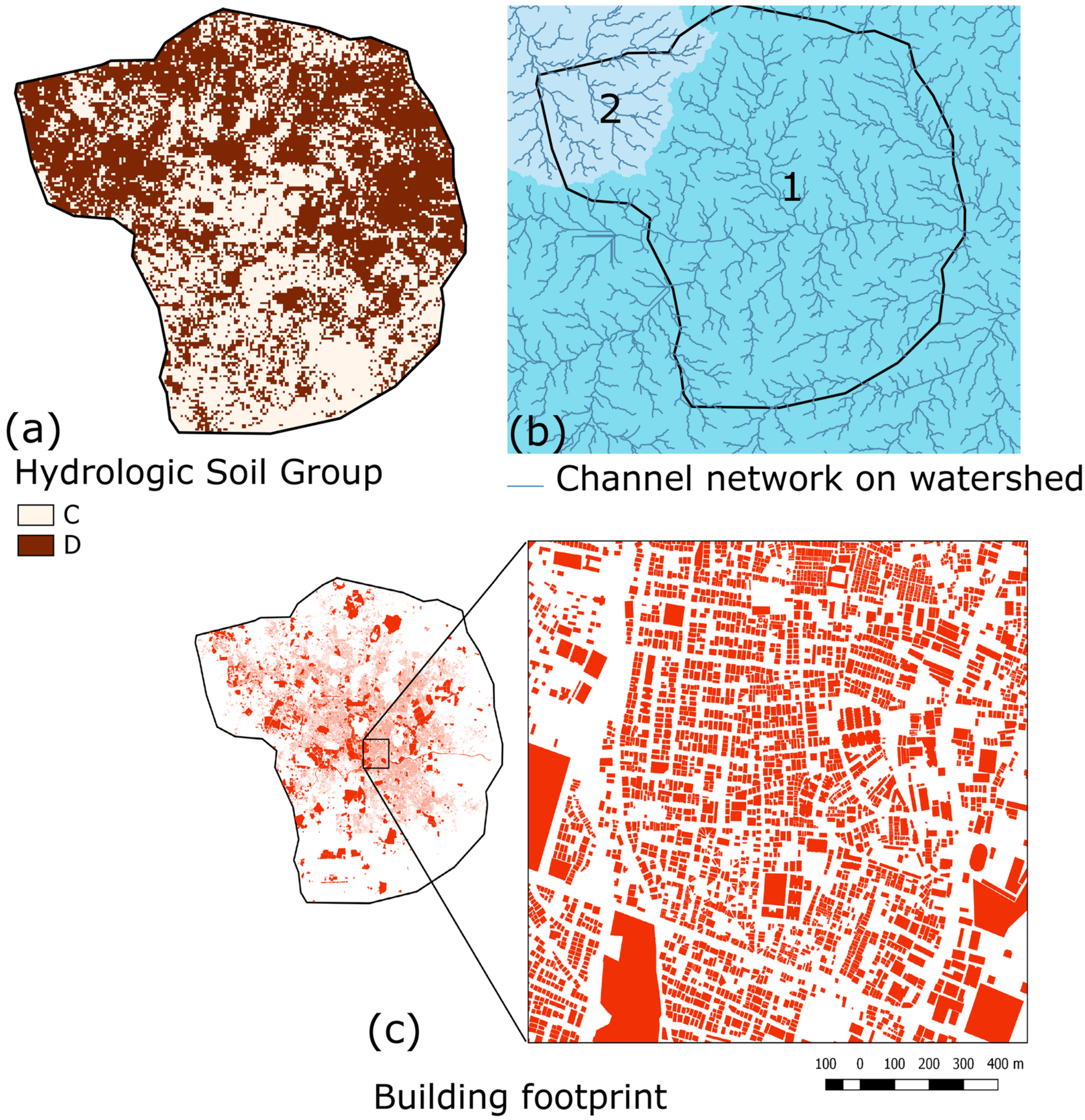

Fig. 4 **a** Hydrologic soil groups layer with values 3 and 4 indicative of Group C and D, **b** channel network overlaid on watersheds delineated as 1 and 2, and **c** building footprint layer of the study area

cumulative building footprint in the study area is 106.5 km^2. The area of the building polygons spread within three quartiles: 73.5, 113.0 and 168.2 m^2, respectively in ascending order. The average area of the building polygons in the study area is 160.3 m^2. This indicates that around three quarters of the buildings have an area that is less than the average building area of the study area, which reflects the uneven urban structure of the city, with highly dense households.

The CN values varied between 64 and 92 for various pixels (excluding water bodies) in the study area and the average values for each watershed 1 and 2 is calculated to be 61.3 and 67.0, respectively, which represents a moderate degree of run-off generation from the catchment (Fig. 5a). Pandey et al. (2009) has reported an average CN value of 76.99 for the core area of Hyderabad, which mainly consists of built-up area. High CN values indicate a high potential for the run-off generation and vice-versa. The maximum potential retention (S_{max}) for the study area varied between 22 and 143 (excluding the water bodies) (Fig. 5b). As the urban landscape becomes increasingly concretized with impervious structures, the generation in run-off also increases and it is reflected through higher CN values.

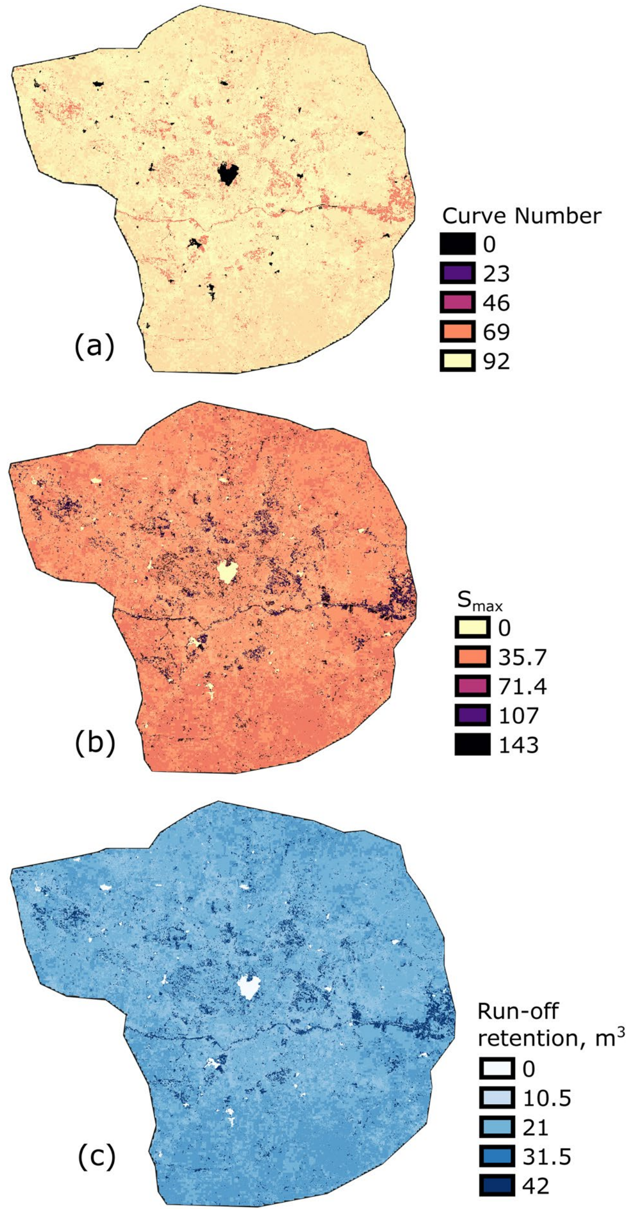

Fig. 5 **a** Curve number (CN) raster, **b** maximum potential retention S_{max} raster and **c** run-off retention (m^3) calculated by InVEST model for 2-years return period design storm

Quantification of flood mitigation by urban green spaces

The total run-off (Q_{vol}) calculated by the InVEST model in the study area for 2-years return period design storm of 1 h duration having 53.86 mm h^{-1} intensity is 39.39 million m^3. While for a 5-years return period design storm of 1 h duration having 60.85 mm h^{-1} intensity, the run-off generated is 47.67 million m^3. With an increase of 13% in the rainfall intensity, the run-off volume has increased by 21%, while the run-off retained has increased only by 5%, which indicates that even slight increase in rainfall intensity results in huge run-off generation that causes commensurate economic damages. Flood mitigation by the urban green spaces and open land is quantified in terms of run-off retention, and the volume of run-off retained at each pixel during the 2-years design precipitation is shown in Fig. 5c (not shown for 5-years). The higher retention values are observed over the areas with a high green cover and followed by open spaces. The total run-off retained inclusive of both the watersheds for 2 and 5-years return periods are 38.44 million m^3 and 40.25 million m^3, respectively (Table 3). The run-off retention index (R_i), which is a relative measure of run-off volume retained with respect to the precipitation volume, varied between 0 and 0.93 for 2-years return period precipitation, and varied between 0 and 0.90 for 5-years return period precipitation. The high values of R_i are observed over the pixels of vegetation land use followed by the open spaces. The average R_i values on two watersheds for 2-years and 5-years return period precipitation varied between 0.440 and 0.496, indicating that 44–50% of the precipitation is retained in the study area, as 62% of the land use is open space and 5.6% of land use is covered with vegetation having lower CN values (measure of run-off production capacity) in comparison with the built-up area. For instance, a model rain garden implemented in an institutional area is shown to delay the peak flow by 4–6 min for a rainfall of 6 mmh^{-1} intensity over a watershed of 3 ha (Gurunadha Rao and Surinaidu 2012).

Table 3 Summary of hydrological and economic damage assessment for 2-years and 5-years return period design storm of 1 h duration over the two watersheds in the study area

Variable	Unit	2-years return period rainfall of 53.86 mm h^{-1}		5-years return period rainfall of 60.85 mm h^{-1}	
		Watershed 1	Watershed 2	Watershed 1	Watershed 2
Precipitation (P)	m^3	67,809,740	9,964,100	76,610,150	11,257,250
Cumulative run-off generated (Q_{vol})	m^3	34,176,108	5,211,224	41,369,481	6,304,060
Cumulative run-off retention (R_{vol})	m^3	33,676,850	4,758,798	35,275,612	4,973,392
Average run-off retention index (R_i)		0.496	0.477	0.460	0.440
Economic damage due to run-off	$	1,243,876	143,946	1,243,876	143,946
Run-off retention indicator	$m^3	4.17E+13	6.85E+11	4.39E+13	7.16E+11

Damage estimation

The total building area affected due to the run-off generated during the extreme precipitation of 2-years and 5-years return period are 95.7 km^2 and 11.1 km^2, respectively for the watersheds 1 and 2. By considering the damage at the rate of an unit amount in Indian Rupee (INR) 1 per every square meter of the affected building area, the cumulative potential damage to the built infrastructure is estimated to be 1.39 million USD (1 USD = 76.92 INR) inclusive of both the watersheds (Table 3). However, the realistic damage to the property could be quantified by multiplying the government estimated damage rates for different building utilities. The indicator of the run-off retention service for the present study is calculated to be $4.25E+13$ and $4.46E+13$, respectively, for the 2-years and 5-years design storms, inclusive of both the watersheds (Table 3). There is only a marginal increment by 5% in the indicator values among the two precipitation scenarios, this is due to the same amount of increase in the run-off retention volume, by keeping a fixed value of affected buildings.

The indicator for run-off retention comes handy in assessing the flood retention services of watersheds when multiple scenarios including the combination of land use land cover and precipitation patterns are assessed in decision making. For instance, studies in Hanoi city by Kefi et al. (2018) accentuated that the increase in green infrastructure has substantially reduced the flood damage. Also stated that the damage could be reduced by 8–29% in scenarios in which the restoring urban lakes and flood mitigation activities are implemented.

Limitations and future challenges

The analysis of the study can be further improved by overcoming the limitations as listed below:

1. Spatial variability and duration of the precipitation can be integrated into the modeling.
2. CN values as per the variable antecedent soil moisture conditions can be integrated.
3. The indirect economic disruptions due to the flooding as outlined by the O'Donnell and Thorne (2020) are not considered in this study, which might be challenging to collate the relevant information through socio-economic surveys.
4. The Unit Cost Method with unit damage amount is considered in the present study, which can be multiplied with the actual surveyed damage values according to different building utilities. Further studies on comprehensive economic damage can be integrated with the questionnaire-based survey on socio-psychological aspects.
5. The spatial resolution of the DEM layers, play a pivotal role in accuracy of the flood inundation model or in generation of run-off volume. The economic losses are halved by reducing the spatial resolution of DEM from 1 to 10 m (Kim et al. 2020).

Depending upon the scale of the study area, the complexity of the hydrological model and method of damage estimation vary, and great care should be exercised in economic damage assessment. Nevertheless, the present study provides a working methodology for potential damage estimation and run-off retention service quantification due to the flooding events, using a natural capital model InVEST with minimal data.

Mitigation measures

Flood mitigation measures in urban agglomerations require a multi-pronged approach involving (1) precipitation regulation, (2) run-off reduction and (3) run-off retention measures. In addition, as a policy intervention, the building by-laws should promote rain-water harvesting and home gardens, apart from the overall development of urban green infrastructure in the city landscape. Some measures are suggested as following:

Precipitation regulation measures

1. Efforts have to be made in reducing the UHI effect and air pollution in the cities, which are however co-benefits of promotion of urban green spaces.
2. Effects of building morphology and geometry (high rise buildings/skyscrapers) on urban local microclimate and precipitation are to be understood for effective flood mitigation measures.

Run-off reduction and retention measures

1. Sufficient cross-drainage works shall be constructed to ensure the free flow of the run-off and to avoid stagnation and overflow on the roads during the flash floods.
2. Promotion of urban green infrastructure and urban social forestry.
3. Public participation in decentralized rainwater harvesting with proper designing of rain-gardens according to the topographic information. Urban forestry in private lands should be encouraged through incentives.
4. Revival and preservation of water bodies in the urban areas such as check dams, retention ponds, percolation wells and their interconnectivity through streams or canals is to be ensured.

5. Casing of open drainage channels or protection of natural streams in the city is imperative to avoid dumping of municipal solid waste, which eventually leads to the choking.

Miscellaneous measures

1. Creation of an integrated flood management system for each and every urban area should be prepared and implemented based on Nature-based Solutions, which also provides local employment opportunities.
2. Encroachment of urban wetlands, lakes and river banks should be checked.
3. Increasing the setbacks (compulsory open space surrounding a building) for new construction projects should be made mandatory, so that these spaces will act as a buffer in reducing the run-off if utilized for home gardens and infiltration pits.
4. The overhead tanks on the penultimate floors are suggested, so that the roof topwater can be channelized to fill these tanks (can be used for household utilities), which reduces bulk of the run-off especially during non seasonal high-intensity rains. This measure will increase the initial abstraction of precipitation, reduces the peak run-off volume and delays the peak flow time.

Kadaverugu et al. (2016) may be referred for detailed review on impacts and mitigation measures of urban flash floods. The flood run-off retention due to some of the above-enumerated mitigation measures can be quantified using the InVEST model, by appropriately varying the corresponding CN values, initial abstraction factor, built infrastructure geometry and land use. Multiple scenarios with the mitigation strategies can be tested using the models for enhanced policymaking.

Conclusion

Increased concretization has resulted in the reduction of urban green spaces and blue spaces, which made the cities vulnerable to urban floods. Flood resilience planning of a city should be encouraged on nature-based solutions such as the promotion of urban green and blue spaces for their multitude of ecosystem benefits. The quantification of flood mitigation (run-off retention) and economic benefits from the urban green spaces is essential to better appreciate their protective role. We utilized InVEST model for studying the Hyderabad city. The model quantifies the run-off retention using SCS-CN method and also estimates the direct economic damage to the built infrastructure using the unit cost method.

The historic city of Hyderabad is ever expanding radially outwards and consuming the peri-urban areas into the newly formed urban agglomerations. Due to haphazard growth, the city is facing a challenge in managing the stormwater during the events of frequent and high-intensity precipitation. The run-off generated, retained and economic damage for the study area are calculated based on the 2-years and 5-years return period design storm of 1 h duration. Results indicate that the study area produces 39.39 and 47.67 million m^3 of run-off due to 53.86 and 60.85 mm h^{-1} design precipitation respectively. About 44–50% of precipitation is retained by the green and open spaces. Due to an increase of 13% in the rainfall intensity, the run-off volume has increased by 21% and the run-off retained has increased only by 5%, which infers that even a slight increase in rainfall intensity results in huge run-off generation. This study iterates the significance of the flood mitigation measures that the cities should be equipped for coping with extreme weather events and climate variability. The flood due to the design precipitation has caused a potential economic damage of 1.39 million USD the built infrastructure. Further, the flood retention service indicator is quantified as $4.25E+13$ and $4.46E+13$ during the 2 and 5-years return period precipitation, respectively. The steep increase in run-off generation can be halted by increasing the green cover in the city and by converting the open spaces into rain gardens.

The potential economic damage assessment due to the floods provide vital inputs for benchmarking the flood insurance instruments. Further, the flood mitigation service offered by the green spaces is considered as one of the supporting services of urban ecosystems, whose valuation also provides key inputs in the evaluation of Environmental Performance Index of a state or a country. Various structural and non-structural flood mitigation measures, and suitability of the InVEST model in quantification of the trade-offs are discussed in the study. Limitation of the study and future areas of research are also presented for advancing the similar kind of assessments across the globe. Integration of multi-disciplinary fields such as hydrology, remote sensing and geographic information system, economic valuation models, natural capital assessment tools, and building by-laws and regulations. is imperative for achieving the flood resilience and sustainability goals of the urban systems for human wellbeing.

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