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Modelling impact of future climate and land use land cover on flood vulnerability for policy support – Hyderabad, India

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Abstract

The study analyses the impact of climate change and land use land cover (LULC) on runoff of Hyderabad city, India for the years 1995, 2005, 2016 and 2031. Flood vulnerability was evaluated for extreme historic and future rainfall events. Maximum daily rainfalls of 132, 181 and 165 mm that occurred in the decades of 1990–2000, 2001–2010 and 2011–2016 were considered for historic rainfall–runoff modelling. Complementarily in climate change, maximum daily rainfall of 266 mm predicted during 2020–2040 by Geophysical Fluid Dynamics Laboratory-Coupled Model 3 (GFDL-CM3) Representative Concentration Pathway (RCP) 2.6, was analysed for rainfall-runoff scenario in 2031. LULC was assessed from historic maps and the master plan of the city. Peak runoff was modelled in Storm Water Management Model (SWMM) for corresponding daily rainfall and LULC. The floodplain of the river Musi was modelled in Hydrological Engineering Center-River Analysis System (HEC-RAS). Results showed that changing rainfall and LULC increased peak runoff by three times, and flood depth in the river increased by 22% from 1995 to 2031. In 2016 and 2031, 48 and 51% of the city was highly vulnerable. Five detention basins were proposed to combat increasing runoff, due to which highly vulnerable areas reduced by 8% in 2016 and 9% in 2031.

Keywords: Climate change; Flood zoning; HEC-RAS; Land use land cover; Rainfall; SWMM

Highlights

- Flood vulnerability mapping using thematic layers.
- Mitigation measures for climate change.
- Combined impact of land use and rainfall on runoff.
- Detention basins in combating runoff.
- Analysis of flood extent of River Musi.

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Introduction

The increasing rainfall magnitudes and rapid urbanisation impact the hydrologic regime of an area (Alaghmand *et al.*, 2010). During the 21st century, most parts of the world have experienced changing climate with warm temperatures and changes in rainfall (Groisman *et al.*, 2005; Solomon *et al.*, 2007; Douglas & Fairbank, 2010). The climate modelling studies suggest that these trends may accelerate, although they could vary regionally (Solomon *et al.*, 2007). Additionally, increasing impervious areas are one of the major contributors to runoff, and can increase runoff by two to six times that of conventional runoff (Sowmya *et al.*, 2015), necessitating best management practices for runoff reduction.

Many researchers have studied the impacts of land use land cover (LULC) as well as climate change on runoff. Amini *et al.* (2011) assessed the impact of LULC on the floods of Damansara watershed, Malaysia with Hydrological Engineering Center-Hydrological Modeling System (HEC-HMS). The results indicated that peak runoff increased with increase in urbanisation. Kalantari *et al.* (2014) quantified overland runoff for a catchment in Norway under four extreme rainfalls and LULCs using MIKE SHE. Decreasing pervious areas by 30% resulted in increasing peak discharge by 60% and total runoff by 10% for a 50-year rainfall. Zope *et al.* (2017) analysed the impacts of LULC on hydrology for the years between 1966 and 2009 for Poisar river basin, India for rainfall of various return periods using the Storm Water Management Model (SWMM), and found that peak discharge increased by 20% from 1966 to 2009. The impact of LULC was found to be prominent on discharge of low return period rainfalls. Astuti *et al.* (2019) examined shifts in surface runoff due to changes in LULC between 1995 and 2015 for a catchment in East Java, Indonesia. Runoff was modelled using the Soil and Water Assessment Tool (SWAT) model. Increase in urbanisation of 20% resulted in increased runoff depth by 8% from 1995 to 2015. Desta *et al.* (2019) investigated runoff response in Tigray catchment, northern Ethiopia for changes in LULC from 1995 to 2015. Increase in urban area was observed from 1.39 to 7.50%. Runoff was modelled using the Water and Energy Transfer between Soil, Plants, and Atmosphere (WetSpa) model. Results showed that annual runoff increased by 44.6% from 1995 to 2015. A few studies, i.e., Cochin (Sowmya *et al.*, 2015) and Mumbai (Zope *et al.*, 2017) have reported on the aspects of flood zoning on Indian cities without considering the impacts of climate change.

Mishra *et al.* (2018) studied the impact of climate change on flood inundation of a river basin in Greater Jakarta using rainfall from three global climate models (GCMs) for the period 2020–2039. Rainfall–runoff modelling showed that the flood inundation area increased by 31%. Zhou *et al.* (2019) studied the effect of urbanisation and climate change on a catchment in China, using SWMM. They found that urbanisation was the main reason for increased annual surface runoff rather than the effects induced by climate change. Resende *et al.* (2019) predicted future rainfall during 2046–2070 using CanESM2 for Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 for a catchment in Parana, Brazil. Runoff was modelled using Hydrus model. Maximum increase in rainfall was 9.5 and 10.2% for RCP 4.5 and RCP 8.5 in comparison with 1982–2005. Correspondingly, runoff increased by 16.9%. Li *et al.* (2020) simulated future rainfall during 2021–2050 and 2051–2080 using three GCMs, under RCP 4.5 for Heihe river basin, China. GCM results showed that average rainfall increased by 10% during 2021–2050 and 12% during 2051–2080. Changes in runoff were modelled using Budyko and Zhang's model. They found that for 2021–2050, a 36% increase in rainfall increased runoff by 20.5%. Increase in rainfall by 47% increased runoff by 26% during 2051–2080.

Encountering the uncertainty of future rainfall, LULC and available infrastructure, it is necessary to develop flood adaptation strategies to cope with a wide range of plausible scenarios. A few researchers, Jayasooriya *et al.* (2018), Yang *et al.* (2018) and Mani *et al.* (2019), emphasised the importance of mitigation measures. Low impact development (LID) is one of the accomplished mitigation strategies that increases infiltration, retains storm water and reduces surface runoff (Ahiablame *et al.*, 2012). Denault *et al.* (2006), Zahmatkesh *et al.* (2014), Kalantari *et al.* (2014), Zope *et al.* (2017) and Zhu *et al.* (2019) studied the performance of LIDs in reducing runoff.

It is evident from the literature that urban flooding could increase with changes in LULC and high intensity rainfalls. From the literature presented here and elsewhere it was found that:

- The study by Sowmya *et al.* (2015) used various thematic flood layers in developing vulnerability maps. However, no study looked into determining weightages of these layers and their influence on flood vulnerability maps.
- No studies reported the effect of LID/mitigation measures on anticipated floods of a city from a climate change perspective.
- No study reported the combined impact of future LULC and future rainfall on runoff and vulnerability.

Specifically, no such analysis/study has been reported on Hyderabad city to date. Hence, keeping the limitations in view, and necessity, the present analysis was undertaken with the following objectives:

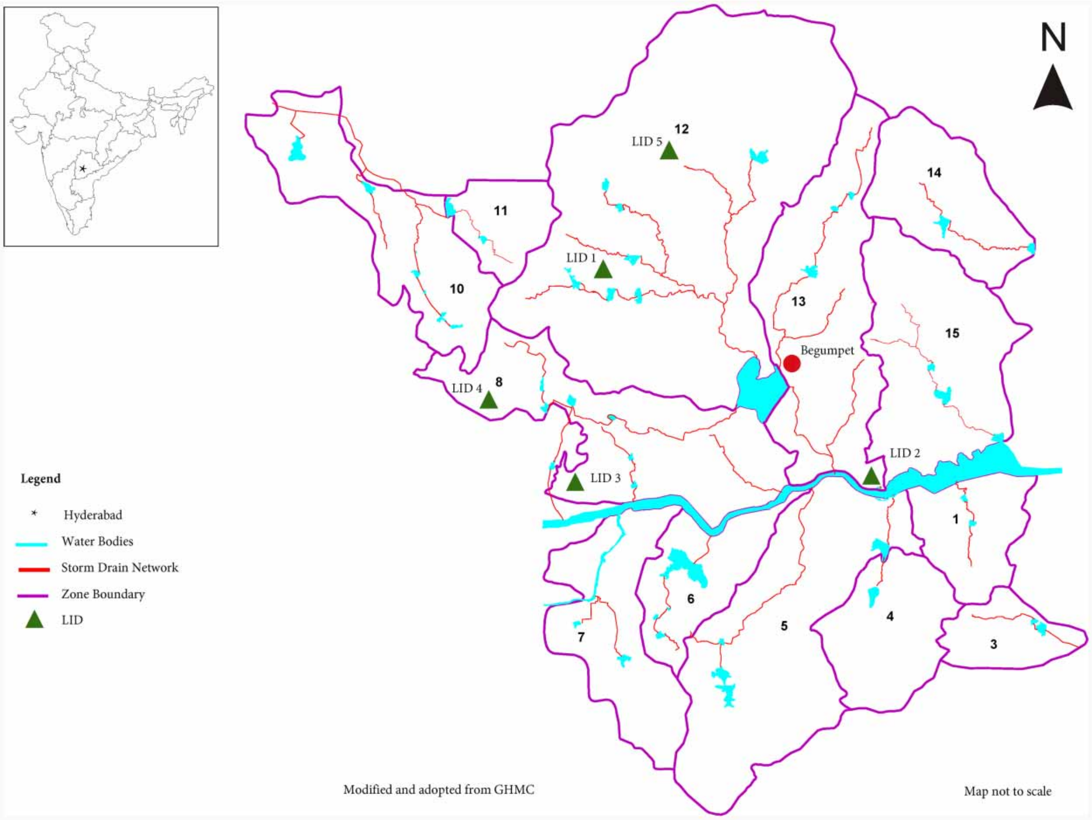
1. Application of SWMM to model runoff for LULC and rainfall for the years 1995, 2005, 2016 and 2031.
2. Modelling detention basins and evaluating their efficiency in combating storm water runoff for the years 2016 and 2031 with SWMM.
3. Employing Hydrological Engineering Center-River Analysis System (HEC-RAS) to analyse flood extent and depth of river Musi for the years 1995, 2005, 2016 and 2031.

As LULC would not change significantly within a period of three to four years, the scenario of 2016 was assumed to be applicable even to 2020. The description and the reason to choose the study area are discussed in the next section. The paper is organised in six sections, Introduction to the study, Study area, Data collection, Methodology, Results and discussion, and Conclusions.

Study area

Hyderabad is the capital of Telangana state. Greater Hyderabad Municipal Corporation (GHMC) is the coordinating agency for the infrastructure of the city. GHMC covers an area of 625 km^2, and land use of the city comprises residential, industrial and commercial areas besides a few village settlements. The city storm water network has 16 storm water zones (Figure 1). Zones 2, 9 and 16 are not included in the study area (Figure 1), as the storm water network is under construction. The total length of the storm water network is 390 km, mostly with open rectangular drains (GHMC, 2007). All the zones (except zones 3, 10 and 14) flow into the Musi river. The river originates from the Anantagiri hills in Vikarabad, which is 60 km upstream from Hyderabad. The river has a gradient of 2 m per km and flows eastwards. Musi experienced flooding in 1908 due to a rainfall of magnitude 430 mm, which occurred over the duration of 2 days (Ahmed *et al.*, 2013) and they studied the impact of flood in Hyderabad. After the devastating flood, two reservoirs, Osmansagar and Himayatsagar, were built upstream of the city to protect it from flooding (Ramachandraiah & Prasad, 2004). Riverine flooding has not occurred in the city since 1908.

The city has witnessed incidences of high intensity rainfalls in the past; a few of them occurred in 2000, 2008 and 2016. Although urban flooding is a recurring event during monsoon, damage and loss of life are very rare as the rainfall is for a short duration (Sarala & Sreelakshmi, 2014). The flooding caused inundation of low-lying areas, blockage of storm drains, interruptions to traffic, water logging



Modified and adopted from GHMC

Map not to scale

Fig. 1. Map showing storm water zones of Hyderabad.

and back-water flooding. Major causes of flooding are (a) decrease in the hydraulic capacity of storm drains by silting, (b) solid waste disposal and (c) shrinkage of pond areas in the city (Ramachandraiah & Prasad, 2004; Deccan Chronicle, 2017; Vemula *et al.*, 2019; Swathi, 2020).

Data collection

Infrastructure details including storm water network were collected from GHMC. A 30 m spatial resolution digital elevation model (DEM) was obtained from National Remote Sensing Centre (NRSC) Bhuvan (NRSC, 2017). Hourly rainfall data (1990–2016) were provided by India Meteorological Department (IMD) and GHMC.

The maximum daily rainfalls that occurred in the decades of 1990–2000, 2001–2010 and 2011–2016 constituted the aim of this study with a view to analysing flood vulnerability under extreme rainfall events. The daily rainfall during 2020–2040 was predicted by Geophysical Fluid Dynamics Laboratory-Coupled Model 3 (GFDL-CM3) under RCPs 2.6, 4.5, 6.0, 8.5 using the non-linear regression-based statistical downscaling method (Vemula *et al.*, 2019; Swathi, 2020). For the present analysis, the maximum daily rainfall (highest among all four RCPs) of 266 mm predicted during 2020–2040 was considered to analyse the rainfall–runoff scenario in 2031. Here, the entire rainfall events considered are decadal maximum daily rainfall values. The extreme rainfall events' occurrence was assessed to understand the broader and potential impacts on flood vulnerability.

To get an appreciable change in land use, we considered a decadal period for LULC for the years 1995, 2005 and 2016. The Landsat 7 open source images with a spatial resolution of 60 m and scale of 1:250,000 were obtained from Earth-explorer website (USGS Earth-Explorer, 2019) for 1995, 2005 and 2016. The Hyderabad Metropolitan Development Authority (HMDA) proposed the master plan of the city for 2031 with a scale of 1:100,000 (HMDA, 2019). From the master plan, it is envisaged that imperviousness is likely to increase with the construction of new flyovers, bridges and expansion of the metro rail network. According to the master plan, the increase in impervious areas is concentrated in the north-east and north-west directions (HMDA, 2019).

Methodology

Flood vulnerability is an integrated approach consisting of catchment modelling and policy requirements (Smajgl *et al*., 2009). Policy requirements of a region include environmental, social and economic aspects. Information on 'what can happen' and 'where it can happen in future' is necessary to find the optimal path or mitigation strategy for a plausible scenario/trajectory. Modelling can explore these plausible scenarios in the present and the future (Smajgl *et al*., 2009). In the present paper, we are using SWMM and HEC-RAS models. SWMM is a hydrological model by the United States Environmental Protection Agency. This model has various computational blocks to model the rainfall–runoff process (Rossman, 2010). The non-linear reservoir method was used to compute runoff and dynamic routing was used to route flows in storm drains. The HEC-RAS 2D model was used for routing flows in the Musi river. The model routes flows in natural channels using Saint Venant equations with four-point implicit box finite difference scheme (Burner, 2002). The flows were routed as unsteady flows. The runoff hydrographs generated from SWMM were input to HEC-RAS to compute water levels of the river. Based on SWMM inputs, floodplain maps were generated for LULC, rainfall scenarios, with and without detention basins. The floodplain maps were further used for developing flood zoning maps. The methodology proposed is presented in Figure 2 which is self-explanatory.

Results and discussion

In this section, we discuss results related to (a) SWMM calibration, (b) effect of rainfall and LULC on runoff, (c) impact of mitigation strategies on runoff, (d) impact of LULC, rainfall and detention basins on floodplain of river Musi and (e) flood zoning maps in detail.

SWMM calibration

The catchment area was modelled in SWMM and consists of a total of 494 sub-catchments, 1,012 storm drains and the river Musi as outfall. Hence, the model needs to be effectively calibrated so that the user can use it with more confidence.

Non-dominated Sorting Genetic Algorithm-III (NSGA-III) was used for automatic calibration of SWMM (Deb & Jain, 2014). Three daily rainfall events, i.e., R1, R2, R3, respectively, of 165 mm, 130 mm, and 70 mm magnitude were used to calibrate the model and one rainfall event R4 with

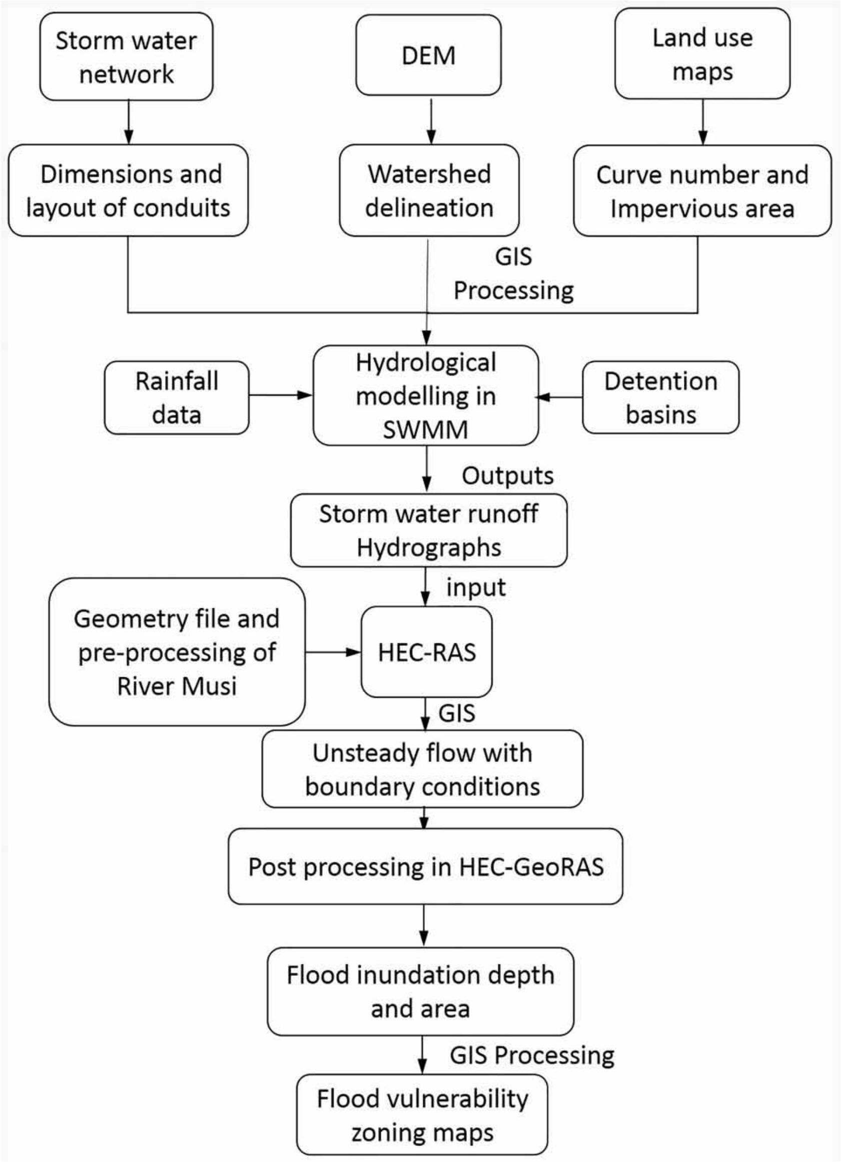


Fig. 2. Methodology of the study.

120 mm magnitude was used for validation. Here, zones 12 and 13 were used only for calibration as these zones discharge runoff to Hussain Sagar lake and parameters established after calibration are applied to the remaining zones of Hyderabad.

Initially, an iterative approach (IA) was done for a daily rainfall R1, i.e., 165 mm, to identify model parameters which are sensitive among six (Table 1). These were varied, one at a time, and the anomaly between SWMM output and observed data was evaluated using the criteria, Nash–Sutcliffe (NSE), linear correlation coefficient (CC) and percentage error in peak flow (PEP) (Krebs *et al.*, 2013).

Table 1. List of parameters for calibration.

Parameters		Range of values	After calibration R1	R2	R3
Manning's roughness	Impervious area (M_i)	0.011–0.017	0.012	0.016	0.014
	Pervious area (M_p)	0.15–0.8	0.4	0.8	0.2
	Conduits (M_c)	0.011–0.04	0.02	0.035	0.02
Depression storage (mm)	Impervious area (D_i)	1.5–3	2	3	1.8
	Pervious area (D_p)	2.5–5.5	3	5	3
	Sub-catchment width (SW) (m)	100–1,500	1,400	900	1,000

NSE, PEP and CC were assessed for each iteration. IA was performed throughout the specified range of model parameter values as presented in Table 1. The model output was highly sensitive to Manning's roughness coefficient of conduits (M_c) and sub-catchment width (SW), and moderately sensitive to other parameters. Hence, all parameters were studied for the purpose of calibration.

Prior to calibration, factor-tuning of NSGA-III (Basu, 2011) was performed for population (50–400), crossover (0.2–0.9), mutation (0.2–0.9) and generation (50–350) in various combinations and optimal factor values obtained after several trials are 280, 0.9, 0.6 and 150, respectively. NSE, PEP and CC corresponding to optimal factor values are 0.5, 3 and 0.7.

These optimal factor values were chosen for calibrating the two remaining rainfall events R2 and R3. SWMM parameter values obtained during calibration of three rainfall events are shown in Table 1 (Swathi *et al.*, 2019). Interested readers may contact the corresponding author for more details. The three calibrated sets from rainfall R1, R2 and R3 were used to validate rainfall R4. The calibrated set of R1 simulated peak flow and runoff volume with a deviation of 3 and 10%. R2 had peak flow and runoff volume with a deviation of 10 and 20%, whereas R3 had 4% deviation in peak flow and 24% in runoff volume. In this regard, the calibrated set of R1 performed better compared to R2 and R3. Hence, the calibrated set R1 was selected to model rainfall–runoff for LULCs and RCP 2.6 rainfall scenario.

Effect of rainfall and LULC on runoff

LULC maps were classified into three land use classes, i.e., urban areas, vegetation and barren land, and water bodies using the 'supervised classification' process in Arc GIS. Variation in land use classes from 1995 to 2031 are shown in Figure 3. Urbanisation increased from 345 km^2 in 1995 to 500 km^2 in 2031. During 1995 to 2016, vegetation decreased from 232 km^2 to 117 km^2 (i.e., 50%) and the area of major water bodies decreased from 16 km^2 to 7 km^2. Similar findings were reported by Ramachandraiah & Prasad (2004). Rainfall–runoff was modelled in SWMM individually for each rainfall and LULC. Table 2 presents SWMM results.

It is observed from Table 2 that peak runoff from 1995 to 2031 increased by more than 150%, showing that changes in LULC and rainfall have significant impact on runoff. For the scenarios of 2016 and 2031, the overflown drains constitute 27 and 32% of the existing storm water drain network. The highest runoff was generated in 2031 which was due to the high percentage of impervious areas. The rainfall magnitude varied relatively less in all four scenarios (i.e., 132 to 266 mm). However, there was high

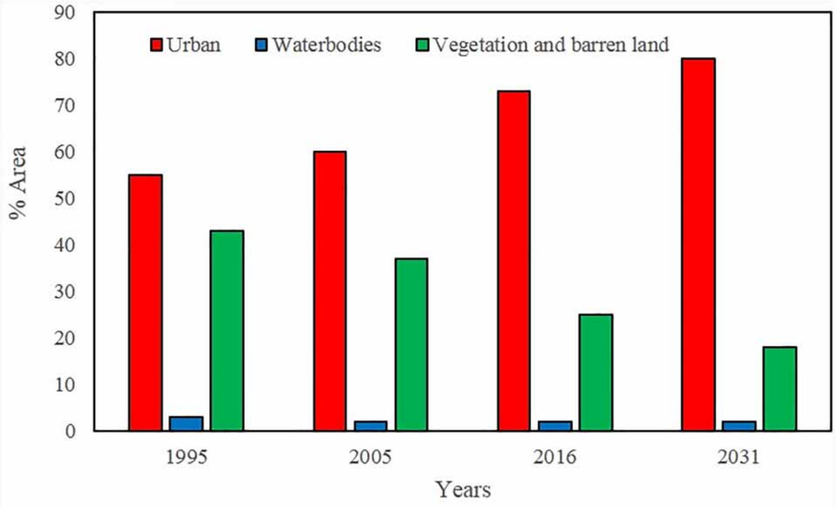


Fig. 3. LULC changes in years 1995–2031.

Table 2. Rainfall–runoff modelling results for 1995, 2005, 2016 and 2031 without detention basins.

Scenario	Impervious area (%)	Decadal maximum daily rainfall (mm)	Peak runoff (m^3/s)	Overflowed drains
1995	55	132	0.94	43
2005	60	181	1.82	238
2016	73	165	2.11	276
2031	80	266	2.6	312

variation in impervious areas (55–80%). It can be inferred that impervious areas are one of the major causes affecting runoff rather than rainfall.

Impact of mitigation strategies on runoff

Mitigation measures are planned to prevent urban floods and to reduce flood vulnerability. A policy-maker needs to analyse various mitigation strategies to know their effectiveness in runoff reduction. Mitigation strategies and corresponding runoff reduction were modelled in SWMM for a daily rainfall R1 of 165 mm in 2016. Explored mitigation strategies in this paper are (a) detention ponds, (b) desilting of major storm water drains, i.e., 0% silting of drains, and (c) capacity enhancement of storm drains by 15%.

A hypothetical scenario with five detention basins was proposed (Figure 1) and the resultant decline in peak runoff was assessed for 2016 and 2031. Detention basins were designed for a rainfall return period of two years with an average intensity of 40 mm/hour and duration of 160 minutes (PUB, 2014). The average intensity of rainfall was acquired from intensity-duration-frequency (IDF) curves for the period 1990–2016. Volume and size of detention basins were calculated using rational method and guidelines from PUB (2014). The runoff coefficient of 0.68 was considered (Van Rooijen *et al*., 2005). These are based on the impervious areas in the existing catchment, assuming that there are no runoff controls. However, the runoff coefficient post-implementation of detention ponds was considered as 0.5 (PUB, 2014). The difference in runoff volume between pre- and post-implementations of detention basins was the required storage volume and, accordingly, the detention basin was sized (PUB, 2013). Only five detention basins were proposed based on the catchment area and space availability. Total storage volume was divided among five equally sized detention basins each having a volume of 2 million m^3. Detention basins were placed in the barren land available (Figure 1), and their location was determined from open street maps (Google Earth, 2018).

The SWMM results showed that with a provision of five detention basins, the peak runoff reduced by 30% (i.e., from 2.11 m^3/sec to 1.48 m^3/sec) compared to existing catchment and overflowed drains that were reduced from 276 to 210. Desilting drains and storm drain capacity enhancement obtained a peak runoff of 1.63 m^3/sec and 1.79 m^3/sec. Peak runoff reduced by 23 and 15% by desilting drains and enhancing storm drain capacity. Among all mitigation strategies, provision of detention basins reduced the runoff significantly.

Hence, only detention basins were modelled for the future scenario of 2031. In 2031, detention basins reduced peak runoff by 26% and overflowed drains reduced from 324 to 230. The flood hydrographs obtained from SWMM were input to HEC-RAS to analyse floodplains of the river Musi.

Impact of LULC, rainfall and detention basins on the floodplain of river Musi

In HEC-RAS, the SWMM-generated runoff hydrographs for 1995, 2005, 2016 and 2031 were provided as upstream boundary condition and the normal depth as downstream boundary condition. The HEC-RAS model was run to attain water levels of the river Musi for unsteady flow. The floodplain results are in Table 3.

It is seen from Table 3 that from 1995 to 2031, the flood depth in the river Musi increased from 0.5 m to 3.5 m. Provision of detention basins in 2016 and 2031 decreased the flood depth by 16 and 22% compared to the existing catchment without detention basins. The results derived from storm water network modelling and floodplain modelling of the river Musi were further used in developing flood zoning maps.

Flood zoning maps

In order to prepare flood zoning maps, initially, various thematic layers were developed based on the characteristics/requirements of the study area (Sowmya *et al*., 2015). The thematic map layers

Table 3. Flood depth for scenarios with and without detention basins.

S. no.	Years	Without detention basins Flood depth (m)	With detention basins Flood depth (m)
1	1995	0.5–1.2	–
2	2005	1–1.5	–
3	2016	1–3.0	1–2.5
4	2031	1–3.5	1–2.7

considered were: (1) elevation (EL), (2) population density (PD), (3) distance from drainage block/overflow sites (DDB) (m), (4) distance from water bodies (DWB) (m) and (5) distance from floodplain of the river Musi (DFPM) (m). The innovativeness of the present study lies in considering various thematic layers from different factors. The spatial distribution of these factors was considered in identifying vulnerable areas. Higher weightage was assigned to thematic layers which would have higher influence on flood vulnerability. The descriptions of thematic map layers are as follows:

- EL – DEM was processed and classified into various elevation classes.
- PD – Population data were available for all the years (1995, 2005 and 2016) from GHMC, and projected population data for 2031 were available from Swerts *et al*. (2014). Population data were converted to a 'feature class point' in Arc-Geographic Information System (GIS). Population density was generated using the 'density' tool in ArcGIS.
- DDB – Overflowed storm drains were identified from SWMM results and their locations were mapped using ArcGIS. Distance from drainage overflow sites was calculated using the 'distance tool' in ArcGIS.
- DWB – Major water bodies were digitised and converted to shape files from Google maps for the years 1995, 2005 and 2016. These maps show variations in the size of water bodies in the city. The size of water bodies was assumed to remain the same from 2016 to 2031.
- DFPM – The floodplain of the river Musi was obtained from HEC-RAS modelling. The distance from the floodplain map was calculated using the 'distance tool' in ArcGIS.

To develop flood zoning maps, thematic layers EL, PD, DDB, DWB and DFPM were created in GIS. Three experts were identified – one with field experience (E1), the second with academic experience on hydrology (E2) and the third (E3) is the first author of this study who has done extensive modelling in the study area. They have given weightages to thematic layers, based on the layers' influence on urban flooding on a scale of 0–100%. The weightages provided by experts are shown in Figure 4. Higher weight of thematic layer indicates higher influence on urban flooding. Each thematic layer was further reclassified into sub-classes using the 'reclass' tool in GIS. Each sub-class was given a score from 0 to 10, according to its vulnerability to urban flooding.

Figure 4 shows the relative weights of thematic layers and vulnerable scores of sub-classes based on expert judgement. The weights given by each expert varied based on their perception and knowledge of how important the thematic layer was in influencing urban flood. For example, E1 and E2 agreed upon the importance of elevation and floodplain in urban flooding by giving equal weightage. E2 and E3 agreed upon the importance of distance from water bodies. However, experts' judgements differed on the importance of population density in urban flooding.

Variations in relative weights of thematic layers could influence the extent of vulnerable areas. Weightages given by all the three experts were used to create individual flood zoning maps, and the vulnerable area was estimated. However, the flood zoning maps of only E1 are presented (Figure 5) to minimise repetition.

After fixing weights of the thematic layers, the layers were added to the same sequence of their ability to influence urban flooding. These layers were integrated to a single map using the 'raster calculator' option in GIS, which sums weights of all layers. The weighted layers help in identifying the most vulnerable zones. Based on vulnerability score, the vulnerability was categorised into low, medium, high and very high (Figures 5 and 6).

From the flood zoning maps in Figures 5 and 6, it is seen that in the 36 years (1995–2031), city areas vulnerable to high floods expanded by 150 km^2. The moderate vulnerable area decreased from 430 km^2 to 300 km^2 and the low vulnerable area decreased from 125 km^2 to 44 km^2. With the provision of detention

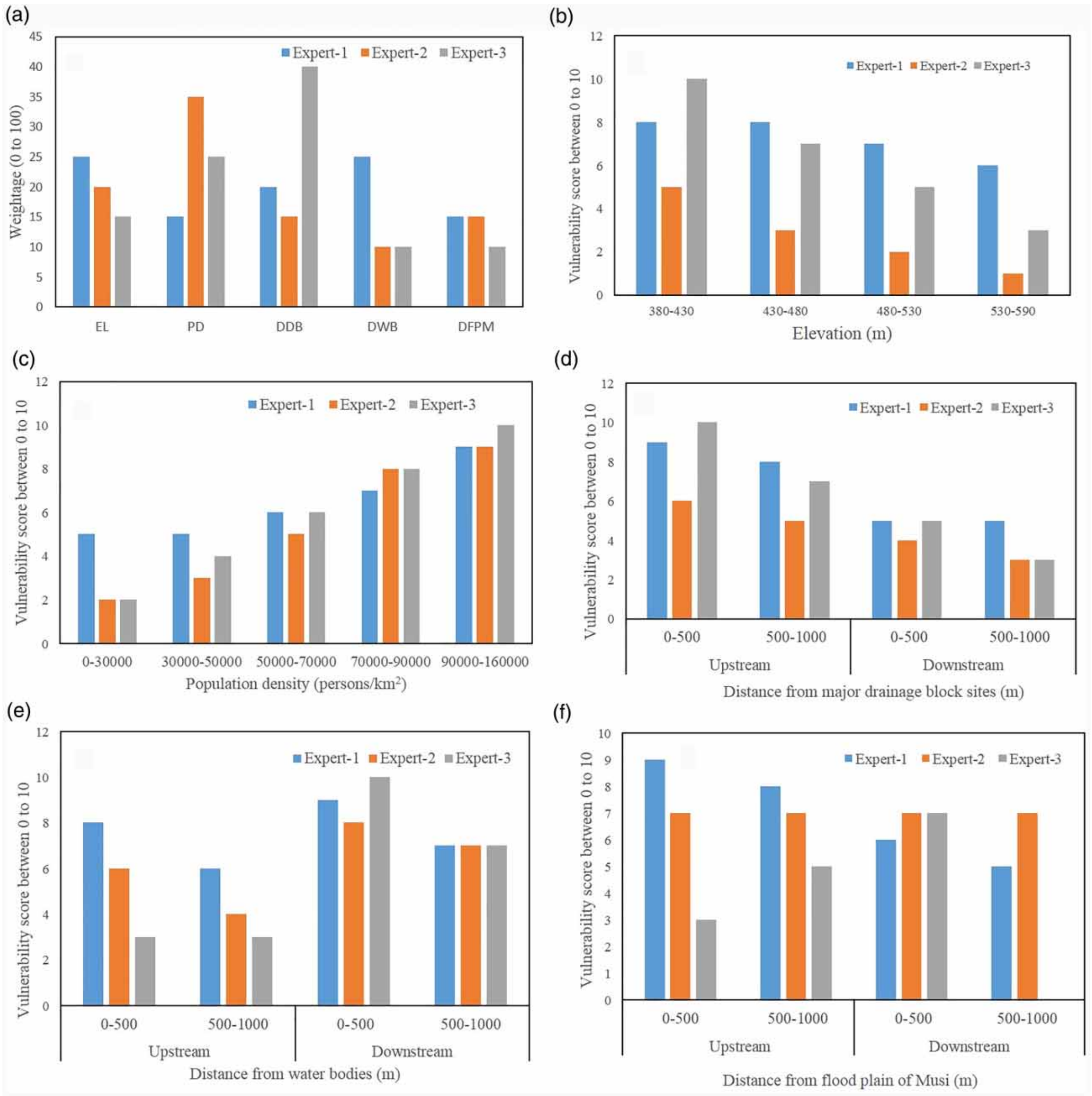


Fig. 4. Relative weights of thematic layers and vulnerable scores of sub-classes based on expert opinion: (a) weights of thematic layers, (b) EL, (c) PD, (d) DDB, (e) DWB and (f) DFPM.

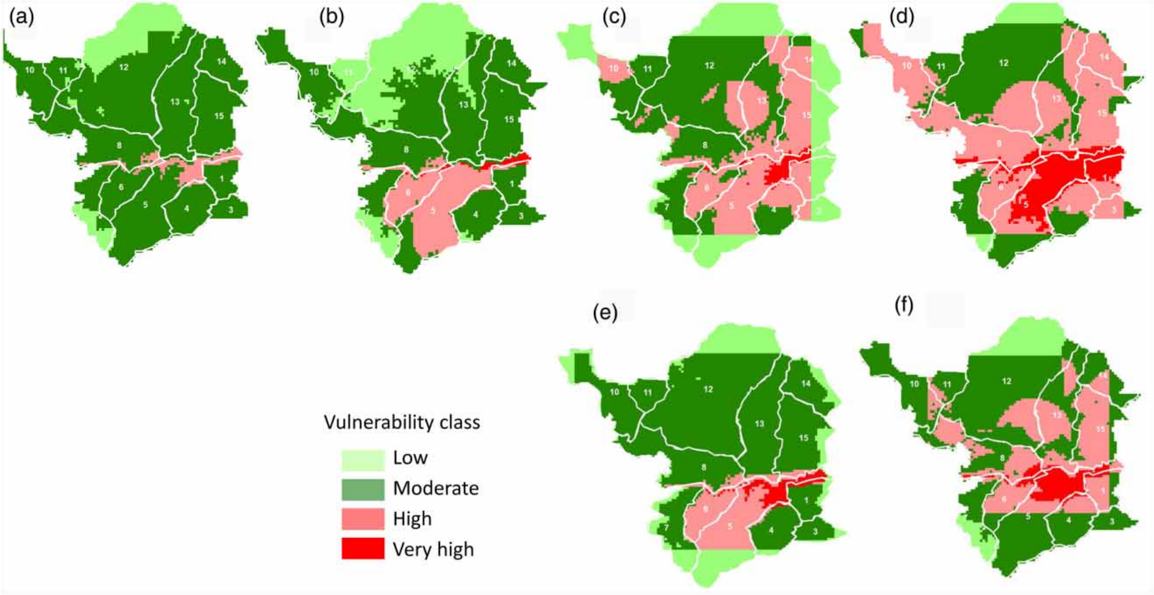


Fig. 5. Flood zoning maps of Hyderabad for (a) 1995 without detention basins, (b) 2005 without detention basins, (c) 2016 without detention basins, (d) 2031 without detention basins, (e) 2016 with detention basins and (f) 2031 with detention basins.

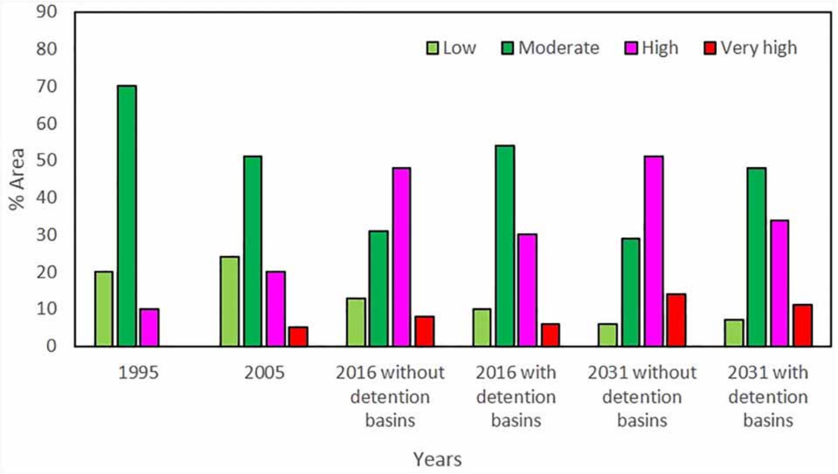


Fig. 6. City's flood vulnerability for various scenarios (1995 and 2005 were not considered for implementing detention basins).

basins in 2016 and 2031, the high flood vulnerable area of the city reduced by 37 and 44%, respectively, compared to the existing catchment. Flood zoning maps show that for 2016, areas of zone 5 are very highly vulnerable and areas of zones 1, 4, 10, 12, 13, 14 and 15 are highly vulnerable. In 2031, the zones 1, 5 and 6 are very highly vulnerable and areas in zones 1, 3, 4, 5, 6, 8, 10, 13, 14 and 15 are highly vulnerable.

Conclusions

The study analyses the impact of LULC and rainfall on runoff using SWMM. Due to rapid urbanisation, impervious areas of the city increased from 55% in 1995 to 80% in 2031 and pervious areas decreased from 43 to 18% in the same period. Due to increase in impervious areas in these 36 years (1995–2031), the peak runoff increased three times and the flood depth in the river Musi increased by 22%. The scenario considering five detention basins was explored and the reduction in runoff was analysed. It was evident from the modelling results that catchment with detention basins substantially reduced peak runoff by 23% compared to existing catchment.

Flood zoning maps were developed for Hyderabad city for vulnerability analysis. In 2016 and 2031, 48 and 51% of the city was identified as highly vulnerable. Zones 1, 5 and 6 are very highly vulnerable until 2031. Provision of detention basins reduced the highly vulnerable area of the city by 8 and 9% in 2016 and 2031.

Developing such flood zoning maps can improve the understanding of policymakers and stakeholders. These maps could be developed for various scenarios to assess policy mechanisms and mitigation strategies. As flood zoning maps are spatially distributed, the areas for flood mitigation measures can be prioritised. Hence, flood vulnerability should be considered holistically for better physical significance.

This study can be considered a flood vulnerability baseline for the entire city, and further detailed study can be performed on specific areas. Due to insufficient data, the study is done on the assumption that the storm water network remained unchanged over the period of time. In addition, different types, sizes and number of LIDs/mitigation strategies and cost–benefit ratio can be explored. Methodology and outcomes of this study were based on the available data, data quality and perceptions of experts.

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Data availability statement

All relevant data are included in the paper or its Supplementary Information.

References

Ahiablame, L. M., Engel, B. A. & Chaubey, I. (2012). Effectiveness of low impact development practices: literature review and suggestions for future research. *Water, Air, & Soil Pollution 223*, 4253–4273.

Ahmed, Z., Rao, D. R. M., Reddy, K. R. M. & Raj, Y. E. (2013). Urban flooding–case study of Hyderabad. *Global Journal of Engineering, Design and Technology 2*, 63–66.

Alaghmand, S., Bin Abdullah, R., Abustan, I. & Vosoogh, B. (2010). GIS-based river flood hazard mapping in urban area (A case study in Kayu Ara river basin, Malaysia). *International Journal of Engineering and Technology 2*, 488–500.

Amini, A., Ali, T. M., Ghazali, A. H. B., Aziz, A. A. & Akib, S. M. (2011). Impacts of land-use change on streamflows in the Damansara watershed, Malaysia. *Arabian Journal for Science and Engineering 36*, 713.

Astuti, I. S., Sahoo, K., Milewski, A. & Mishra, D. R. (2019). Impact of land use land cover (LULC) change on surface runoff in an increasingly urbanized tropical watershed. *Water Resources Management 33*(12), 4087–4103.

Basu, M. (2011). Economic environmental dispatch using multi-objective differential evolution. *Applied Soft Computing 11*, 2845–2853.

Burner, G. (2002). *HEC-RAS Hydraulic Reference Manual*. USACE, California, USA.

Deb, K. & Jain, H. (2014). An evolutionary many-objective optimization algorithm using reference-point-based nondominated sorting approach, part I: solving problems with box constraints. *IEEE Transactions of Evolutionary Computation 18*, 577–601.

Deccan Chronicle (2017). *Drainage Shortage Cripples Hyderabad*. Available at: https ://www.deccanchro nicle.com/nation/current-affairs/070917/drainage-shortage-cripples-hyderabad.html (accessed January 2018).

Denault, C., Millar, R. G. & Lence, B. J. (2006). Assessment of possible impacts of climate change in an urban catchment. *JAWRA Journal of American Water Resources Association 42*, 685–697.

Desta, Y., Goitom, H. & Aregay, G. (2019). Investigation of runoff response to land use/land cover change on the case of Aynalem catchment, North of Ethiopia. *Journal of African Earth Sciences 153*, 130–143.

Douglas, E. M. & Fairbank, C. A. (2010). Is precipitation in northern new England becoming more extreme? Statistical analysis of extreme rainfall in Massachusetts, New Hampshire, and Maine and updated estimates of the 100-year storm. *Journal of Hydrologic Engineering 16*, 203–217.

GHMC (2007). *General Information on Drains*. Greater Hyderabad Municipal Corporation, Hyderabad, India.

Google Earth v 6 (2018). Hyderabad, Telangana, India, 17.45 lat, 78.44 long at eye alt 35.16 miles. (accessed May 2016).

Groisman, P. Y., Knight, R. W., Easterling, D. R., Karl, T. R., Hegerl, G. C. & Razuvaev, V. N. (2005). Trends in intense precipitation in the climate record. *Journal of Climate 18*, 1326–1350.

HMDA (2019). *Master Plan of the City*. Available at: hmdaprojects.hmda.gov.in/masterplan. (accessed January 2019).

Jayasooriya, V., Muthukumaran, S., Ng, A. & Perera, B. (2018). Multi criteria decision making in selecting stormwater management green infrastructure for industrial areas part 2: a case study with TOPSIS. *Water Resources Management 32*(13), 4297–4312.

Kalantari, Z., Lyon, S. W., Folkeson, L., French, H. K., Stolte, J., Jansson, P. E. & Sassner, M. (2014). Quantifying the hydrological impact of simulated changes in land use on peak discharge in a small catchment. *Science of the Total Environment 466*, 741–754.

Krebs, G., Kokkonen, T., Valtanen, M., Koivusalo, H. & Setälä, H. (2013). A high resolution application of a Stormwater Management Model (SWMM) using genetic parameter optimization. *Urban Water Journal 10*, 394–410.

Li, Z., Li, Q., Wang, J., Feng, Y. & Shao, Q. (2020). Impacts of projected climate change on runoff in upper reach of Heihe River basin using climate elasticity method and GCMs. *Science of the Total Environment 716*, 137072.

Mani, M., Bozorg-Haddad, O. & Loáiciga, H. A. (2019). A new framework for the optimal management of urban runoff with low-impact development stormwater control measures considering service-performance reduction. *Journal of Hydroinformatics 21*(5), 727–744.

Mishra, B. K., Rafiei Emam, A., Masago, Y., Kumar, P., Regmi, R. K. & Fukushi, K. (2018). Assessment of future flood inundations under climate and land use change scenarios in the Ciliwung River Basin, Jakarta. *Journal of Flood Risk Management 11*, 1105–1115.

NRSC (2017). *Digital Elevation Model*. Available at: http://bhuva n.nrsc.gov.in/bhuvan_links .php (accessed May 2018).

Public Utilities Board (PUB) (2013). *Managing Urban Runoff – Drainage Handbook*. PUB, Singapore.

Public Utilities Board (PUB) (2014). *Technical Guide for On-Site Stormwater Detention Tank Systems*. PUB, Singapore.

Ramachandraiah, C. & Prasad, S. (2004). *Impact of Urban Growth on Water Bodies: The Case of Hyderabad*. Centre for Economic and Social Studies, Hyderabad, India.

Resende, N. C., Miranda, J. H., Cooke, R., Chu, M. L. & Chou, S. C. (2019). Impacts of regional climate change on the runoff and root water uptake in corn crops in Parana, Brazil. *Agricultural Water Management 221*, 556–565.

Rossman, L. A. (2010). *Storm Water Management Model User's Manual, Version 5.0*. National Risk Management Research Laboratory, Office Of Research and Development, US Environmental Protection Agency, Cincinnati, OH, USA.

Sarala, C. & Sreelakshmi, G. (2014). Improvement of storm water drainage system in Greater Hyderabad Municipal Corporation. *International Journal of Advances in Engineering & Technology 7*, 605.

Smajgl, A., Morris, S. & Heckbert, S. (2009). Water policy impact assessment–combining modelling techniques in the Great Barrier Reef region. *Water Policy 11*, 191–202.

Solomon, S., Qin, D., Manning, M., Averyt, K. & Marquis, M. (2007). *Climate Change 2007 – the Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the IPCC*. Cambridge University Press.

Sowmya, K., John, C. & Shrivasthava, N. (2015). Urban flood vulnerability zoning of Cochin City, southwest coast of India, using remote sensing and GIS. *Natural Hazards 75*, 1271–1286.

Swathi, V. (2020). *Analysing the Linkages Between Urban Floods, Climate Change and Land Use*. *PhD Thesis*, BITS Pilani Hyderabad campus.

Swathi, V., Srinivasa Raju, K., Varma, M. R. & Sai Veena, S. (2019). Automatic calibration of SWMM using NSGA-III and the effects of delineation scale on an urban catchment. *Journal of Hydroinformatics 21*(5), 781–797.

Swerts, E., Pumain, D. & Denis, E. (2014). The future of India's urbanization. *Futures 56*, 43–52.

USGS Earth-Explorer (2019). *Earth-explorer Data Portal*. Available at: http://earthexplorer.usgs.gov/ (accessed January 2019).

Van Rooijen, D. J., Turral, H. & Wade Biggs, T. (2005). Sponge city: water balance of mega-city water use and wastewater use in Hyderabad, India. *Journal of the International Commission on Irrigation and Drainage 54*, S81–S91.

Vemula, S., Raju, K. S., Veena, S. S. & Kumar, A. S. (2019). Urban floods in Hyderabad, India, under present and future rainfall scenarios: a case study. *Natural Hazards 95*, 1–19.

Yang, W., Pang, Y., Shi, J. & Wang, C. (2018). Linguistic hesitant intuitionistic fuzzy decision-making method based on VIKOR. *Neural Computing and Applications 29*(7), 613–626.

Zahmatkesh, Z., Burian, S. J., Karamouz, M., Tavakol-Davani, H. & Goharian, E. (2014). Low-impact development practices to mitigate climate change effects on urban stormwater runoff: case study of New York City. *Journal of Irrigation and Drainage Engineering 141*, 401–404.

Zhou, J., Liu, J., Yan, D., Wang, H., Wang, Z., Shao, W. & Luan, Y. (2019). Dissipation of water in urban area, mechanism and modelling with the consideration of anthropogenic impacts: a case study in Xiamen. *Journal of Hydrology 570*, 356–365.

Zhu, Z., Chen, Z., Chen, X. & Yu, G. (2019). An assessment of the hydrologic effectiveness of low impact development (LID) practices for managing runoff with different objectives. *Journal of Environmental Management 231*, 504–514.

Zope, P., Eldho, T. & Jothiprakash, V. (2017). Hydrological impacts of land use–land cover change and detention basins on urban flood hazard: a case study of Poisar river basin, Mumbai, India. *Natural Hazards 87*, 1267–1283.

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