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Flood-susceptibility-based building risk under climate change, Hyderabad, India

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ABSTRACT

Urban floods have been highly prominent natural disasters occurring in catchments across the globe, causing financial loss and damage to buildings. This necessitates effective and sustainable mitigation mechanisms. In this context, flood-susceptibility-based building risk (FSBR), a combined index for evaluating flood susceptibility and building risk simultaneously to understand the impact of the flood, is proposed by fusing XGBoost (facilitates flood susceptibility) and Hydrologic Engineering Center River Analysis System 2D (enables building risk) in climate change situations. The methodology is applied to Greater Hyderabad Municipal Corporation, India. Six combinations of FSBR, namely, high building risk and high flood susceptibility (HH), high and medium (HM), medium and medium (MM), medium and high (MH), low and medium (LM), and low and high (LH) are employed to study the urban floods. The total affected areas for HH, HM, MH, MM, LH, and LM are 63.40 km^2 (52.627%), 28.92 km^2 (24%), 9.52 km^2 (7.9%), 4.81 km^2 (3.99%), 9.26 km^2 (7.686%), and 4.56 km^2 (3.79%) (totalling 120.47 km^2). The number of corresponding buildings is 182,178, 84,136, 46,238, 22,691, 48,092, and 23,781. Waterproofing as a mitigation measure is considered. The total cost of waterproofing is Rs 4,964.60 cr.

Key words: climate change, flood susceptibility-based building risk, HEC-RAS 2D, urban floods, waterproofing, XGBoost

HIGHLIGHTS

- Machine learning and hydraulic modelling are complemented to derive an indicator, flood-susceptibility-based building risk (FSBR), for the urban catchment.
- Six combinations of FSBR are employed to study urban floods.
- Waterproofing as a mitigation measure is studied.

ABBREVIATIONS

AUROC	area under the receiver operating characteristic
BRT	boosted regression tree
CART	classification and regression tree
Cr	crores
DB	deep boost
DLNN	deep learning neural network
EAC	equivalent annual cost
FSBR	flood-susceptibility-based building risk
FSM	flood susceptibility modelling
GCMs	general circulation models
GEE	Google Earth Engine
GHMC	Greater Hyderabad Municipal Corporation
HEC-RAS 2D	Hydrologic Engineering Center River Analysis System 2D
HH	high building risk and high flood susceptibility
HM	high building risk and medium flood susceptibility
HRB	high-risk buildings
LH	low building risk and high flood susceptibility
LM	low building risk and medium flood susceptibility
LRB	low-risk buildings

MH	medium building risk and high flood susceptibility
ML	machine learning
MM	medium building risk and medium flood susceptibility
MODIS	MODerate Resolution Imaging Spectroradiometer
MRB	medium-risk buildings
NN	neural networks
NRSC	National Remote Sensing Centre
RCPs	representative concentration pathways
RF	Random Forest
SVM	support vector machine
TGPHMED	Telangana Public Health & Municipal Engineering Department
TSDPS	Telangana State Development Planning Society
XGBoost	eXtreme Gradient Boosting

INTRODUCTION

Urban floods have been highly prominent natural disasters occurring in catchments across the globe. Some related factors are low-lying areas, clogged drains, settlements in flood-plain areas, and impervious surfaces. In addition, the widening gap between the increase in urbanization and available infrastructure is a major challenge. This inadequacy, in turn, will not be able to mitigate the impact of urban floods effectively. Another dimension is climate change, evidenced by high-intensity, short-duration, high-frequency rainfall affecting cities significantly (Nkwunonwo *et al.* 2020). This increases the quantity of water during most of the mentioned situations, which impacts the flooding area and escalates the flood susceptibility (Hammond *et al.* 2015).

Many floods have occurred in Hyderabad, Mumbai, Chennai, Bengaluru, and Vadodara. These cities have faced substantial financial losses and property damage (Flood Report 2021). In Hyderabad, severe floods occurred in 2000, 2006, 2016, 2018, and 2021. The flood depth range is 1–4 m in many locations (Rangari *et al.* 2021). Mumbai is another major city affected by urban floods due to climate change, as evidenced by the extreme rainfall of 944 mm for 24 h in 2005 (Sahany *et al.* 2010; Mumbai floods 2021). The case is similar with cities like Chennai, Bengaluru, and Vadodara, which are highly affected by urban floods (Vadodara floods 2019; Bengaluru floods 2021; Chennai floods 2021).

Literature review

Numerous modelling approaches are employed to compute flood susceptibility. Machine learning (ML) is gaining momentum in classifying flood-susceptible regions due to its flexibility and adaptability (Baghbani *et al.* 2022; Saha *et al.* 2022). Shahabi *et al.* (2021) employed a deep belief–back propagation–genetic algorithm for Iran's Haraz watershed to generate flood susceptibility modelling (FSM). It was compared with other benchmarking ML techniques and found to be superior. Abedi *et al.* (2022) implemented the classification and regression tree (CART), XGBoost, random forest (RF), and boosted regression trees (BRT) to create an FSM of the Bâsca Chiojdului river basin. RF was found to be the best. Antzoulatos *et al.* (2022) employed RF, support vector machine (SVM), naive-based RF, and neural networks (NNs) to assess flood susceptibility in the Trieste, Monfalcone, and Muggia municipalities, northeast Italy. The RF model was highly rated with an F1 score of 0.99, followed by SVM, naive-based RF, and NN. Taromideh *et al.* (2022) reviewed ML applications to flood aspects at length. CART, RF, BRT, and several other models were employed to create an urban flood risk map for a case study in Iran. CART performed better than other ML algorithms.

General circulation models (GCMs) and associated representative concentration pathways (RCPs) are utilized for climate-based study. They help reproduce the historic observed climatic changes. Zennaro *et al.* (2021) studied the role of ML algorithms in climate change risk assessment and provided future directions. Chakrabortty *et al.* (2021) assessed flood susceptibility based on artificial neural networks (ANNs), deep boost (DB), and deep learning neural network in a climate change perspective for a case study in West Bengal, India. DB is the most preferred when compared with the others. They also studied flood susceptibility in detail in climate change scenarios. In summary, ML algorithms predict flood susceptibility but not flood depth (or building risk), which only hydraulic models can handle.

A few researchers have considered building risk an essential objective in vulnerability assessment for urban cities (Hossain & Meng 2020). It could be computed with inundation areas and flood depth information at the location. Park *et al.* (2021) studied flood risk assessment in Ulsan City, South Korea, using Hydrologic Engineering Center River Analysis System 2D (HEC-RAS 2D) for 2016. The inundated area was found to be 0.01–11.71 km^2, and the average flood depth for each administrative district was 0.47–1.20 m. A total of 20.6% of buildings were exposed to flood, resulting in high flood damage. Chen *et al.* (2022) assessed the flood risk map of Taiwan under RCP 8.5. It was concluded that approximately 14% of townships had high-risk buildings (HRBs). Ventimiglia *et al.* (2020) suggested waterproofing measures for the Mela River in northeastern Sicily, and Alabbad *et al.* (2022) for Iowa Middle Cedar Watershed to reduce property vulnerability and losses that would minimize building risk.

It is understood from the mentioned literature that both flood susceptibility and building risk are considered individually to judge the effect of flood. In this context, it is felt that by a combined index that considers flood susceptibility and building risk simultaneously, the impact of flood and possible mitigation measures can be understood holistically, which is the primary focus of this article. The authors propose flood-susceptibility-based building risk (FSBR) that addresses the mentioned challenge. Accordingly, the following objectives are formulated in the RCP 2.6 scenario:

(i) Computation of FSBR
(ii) Computation of cost of waterproofing that mitigates FSBR

The framework is applied to Greater Hyderabad Municipal Corporation (GHMC), India, due to its high population density and proneness to urban floods. The city has suffered major floods, and related details are presented in Table 1 (Rangari *et al.* 2021). Details of the case study are presented in the next section.

Study area and data collection

The GHMC area is 625 km^2 and is divided into various zones and circles (Greater Hyderabad Municipal Corporation 2023). The annual average rainfall is 840 mm and is at the maximum from June to September, leading to heavy flash floods. Average temperatures during winter and summer are 22 and 30 °C. The mean hottest and coldest months are May and December, respectively. The average annual rainy days and dry days are 56 and 265. The average maximum and minimum relative humidities in winter are 79% and 31%, whereas those in summer are 67% and 26%, respectively (TSDPS 2021).

GHMC falls in the Musi River catchment (Figure 1(a)). The altitude ranges from 456 to 637 m, as shown in Figure 1(b). Slope ranges from 0.3 to 19.82°. The slope falls gradually from west to east, leading to the valley near the Musi River. The water bodies in the catchment act as storage reservoirs for drinking water and groundwater recharge. GHMC has three major storage reservoirs: Osman Sagar, Himayat Sagar, and Hussain Sagar, besides a minor one, Mir Alam Tank, as shown in Figure 1(a). These add flora and fauna to the catchment, increasing the catchment's ecology. There was a rapid increase in the impervious percentage from 2006 to 2016. The present research considered climate change aspects based on GCM, GFDL-CM3, and RCP 2.6. Extreme rainfall of 1,740.62 mm, likely to occur in 2040 for RCP 2.6 (three-day event, July 23–25), is considered a high-intensity, short-duration rainfall for this purpose. The following data are used for the modelling (Table 2).

Table 1 | Details of year and rainfall, flood water depth, and damage to the city of Hyderabad

Year and date	Details of rainfall (mm)	Flood water depth (m)	Representative impacts	References
26 August 2000	241.5	2–4	Damage to houses/ livelihood/number of people affected/ financial loss	Hyderabad floods 2000
8 August 2006	220.7	0–1		Hyderabad floods 2006
9–10 August 2008	137	2–3		Rangari *et al.* (2021)
23 September 2016	165	1–3		Hyderabad floods 2016
25 September 2019	133	1–2		Hyderabad floods 2019
14 October 2020	300	1–4		Hyderabad floods 2020
8 October 2021	150	1–4		Hyderabad floods 2021

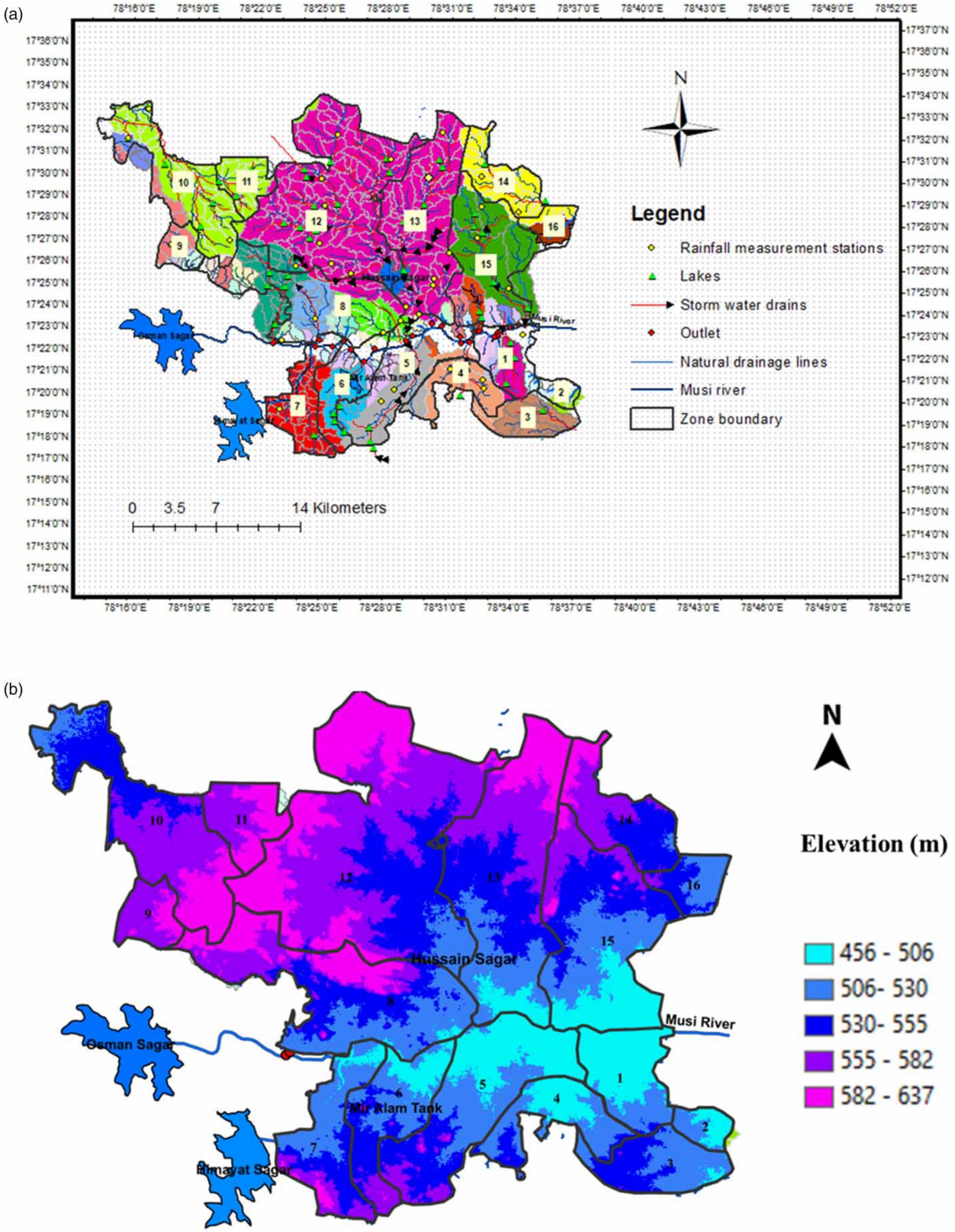

Figure 1 | (a) Watershed area of GHMC (modified and adapted from GHMC; numbers indicating storm water zones) and (b) elevation map of GHMC.

Table 2 | Data and its sources

Data	Sources
GCM and pathway	GFDL-CM3 and RCP 2.6
The future extreme rainfall event	1,740.62 mm (likely to occur over three days in 2040)
Rainfall data	India Meteorological Department and GHMC
Soil data	Directorate of Agricultural Commissionerate, Telangana
Digital elevation	The United States Geological Survey
Curve number	land use data, GHMC, and Open Street maps
Evapotranspiration, land surface temperature, normalized density vegetative index	MODerate Resolution Imaging Spectroradiometer (MODIS) of Google Earth Engine (GEE)
Flood locations	GHMC Disaster Management Cell and National Remote Sensing Centre (NRSC)
Cost of waterproofing	Telangana Public Health and Municipal Engineering Department (TGPHMED 2021)

Description of methods employed and modelling ahead

The present article is a logical extension of the previous works of the authors (Madhuri *et al.* 2021a, 2021b), where information about modelling was discussed in detail for GHMC. Five ML algorithms, SVM, logistic regression (LR), *K*-nearest neighbour (KNN), AdaBoost, and XGBoost, are applied to understand the flood susceptibility of GHMC for historical data. Eight flood-influencing factors were used for this purpose. The area under the receiver operating characteristic (AUROC) is one of the standard methods for validating the model's performance (Tehrany *et al.* 2015). It is a graphical approach that describes the change in the algorithm's classification ability, as the probability threshold is altered (Shahabi *et al.* 2021). It compares and validates ML algorithms.

XGBoost is found to be the best, with a mean AUROC score of 0.83 and a standard deviation of 0.04. It is closely followed by AdaBoost, which has a mean AUROC score of 0.82 with a standard deviation of 0.04. Both algorithms significantly outperformed LR, SVM, and KNN with respective AUROC scores of 0.71, 0.74, and 0.77. Corresponding standard deviations are 0.07, 0.06, and 0.06.

Later, the study was analysed in climate change situations, as mentioned in the study area section. The flood susceptibilities generated from XGBoost for RCP 2.6 are classified into two different ranges, i.e., 30%–70% as moderate (M) and 70%–100% as high susceptibility (H), respectively. The 30% flood susceptibility value indicates a 30% chance of flooding in that location/pixel.

Furthermore, HEC-RAS 2D was employed to compute the submergence area and flood-depth-based building risk. Three levels, namely, low-risk buildings (LRBs), medium-risk buildings (MRBs), and HRBs were categorized. Corresponding flood depths are <0.5 m, ≥ 0.5 m and <1 m, ≥ 1 m (Abdulrazzak *et al.* 2019; Rangari *et al.* 2019; Rangari *et al.* 2021). Figure 2 presents the workflow for generating FSBR (Madhuri 2022).

If building risk due to flood depth obtained by HEC-RAS 2D is high (H) and flood susceptibility obtained by ML algorithm is high (H), it is termed HH in the context of FSBR. It is high-priority combination that needs immediate action for mitigation measures by policy-makers. Suppose two buildings with high risk are situated in medium- and low-susceptibility areas; in that case, the priority is a medium-susceptible area. Six combinations of FSBR, namely, high building risk and high flood susceptibility (HH), high and medium (HM), medium and medium (MM), medium and high (MH), low and medium (LM), and low and high (LH) are employed to study the urban floods. Results related to flood susceptibility, building risk, and FSBR are discussed in the next section.

RESULTS AND DISCUSSION

Flood susceptibility using XGBoost

Table 3 presents zone-wise flood areas of buildings and roads under high, moderate, and low flood susceptibilities. Zones 12, 8, and 15 are highly susceptible, with exposed building areas of 14.61, 7.75, and 7.27 km^2, respectively. In the case of roads,

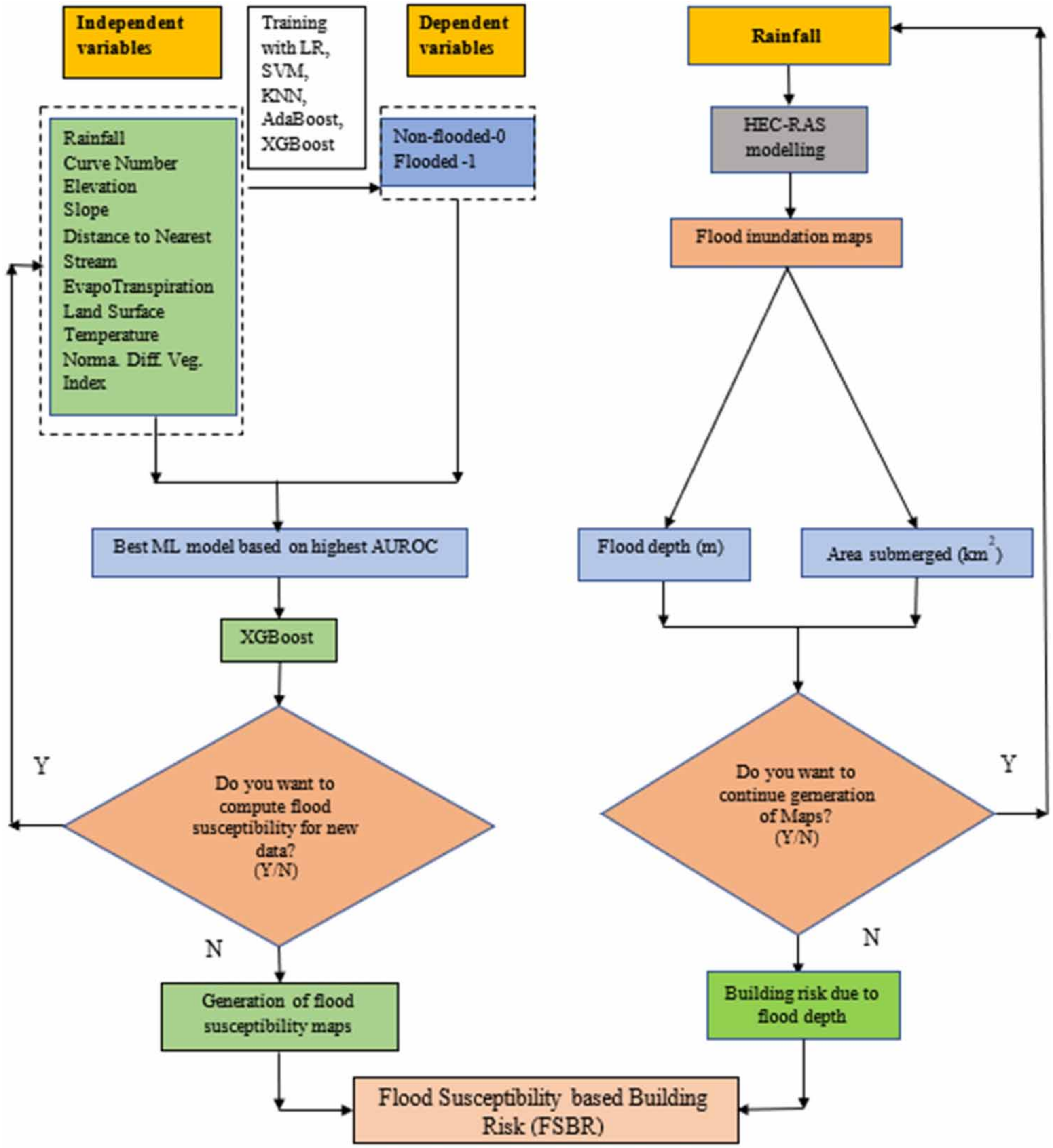

Figure 2 | Workflow for generating FSBR.

zones 12, 5, and 13 are highly susceptible, with areas of 3.52, 3.11, and 2.65 km^2, respectively. In moderate susceptibility, buildings in zones 13, 15, and 12 are exposed in areas of 5.97, 4.74, and 4.29 km^2, respectively. In the case of roads, exposed zones are 12, 13, and 8, with areas of 6.41, 4.48, and 3.29 km^2, respectively. None of the zones have low flood susceptibility. Buildings and roads are highly susceptible in GHMC, with areas of 57.59 and 22.76 km^2.

Table 3 | Flood-susceptible areas (in km^2) for RCP 2.6 (Madhuri *et al.* 2021a)

	Buildings		**Roads**	
Zone number (1)	**High (2)**	**Medium (3)**	**High (4)**	**Medium (5)**
1	1.9	1.49	1.52	0.44
2	0.21	0	0.49	0
3	1.88	0.41	1.34	0.58
4	1.65	2.94	1.23	1.2
5	6.29	1.25	3.11	2.38
6	0.74	0.4	0.79	1.11
7	1.31	0.32	0.55	0.91
8	7.75	2.24	2.35	3.29
9	0.12	0.09	0.08	0.21
10	3.54	1.65	1.23	1.84
11	1.12	0.75	0.43	0.92
12	14.61	4.29	3.52	6.41
13	6.84	5.97	2.65	4.48
14	1.91	0.64	0.79	1.19
15	7.27	4.74	2.32	2.71
16	0.45	0.15	0.36	0.21
Total (GHMC)	57.59	27.33	22.76	27.88

Note: No buildings and roads are in the low-susceptibility category.

Table 4 | Percentage of flooded and non-flooded zones and zone-wise flood depth ranges and percentage of HRB, MRB, and LRB for RCP 2.6 (Madhuri *et al.* 2021b)

Zone number (1)	**% Flooding (2)**	**% Non-flooding (3)**	**Flood depth range (m) (4)**	**% HRB (5)**	**%MRB (6)**	**%LRB (7)**
1	81	19	0.3–5.7	69	8	23
2	71	29	0.1–2.0	42	16	42
3	64	36	0.1–1.9	38	18	44
4	70	30	0.1–2.1	50	15	35
5	75	25	0.2–5.8	70	9	21
6	69	31	0.1–4.6	65	9	26
7	68	32	0.1–4.1	64	8	28
8	61	39	0.1–4.3	49	12	39
9	62	38	0.1–2.3	39	12	49
10	69	31	0.1–2.1	40	15	45
11	61	39	0.1–1.9	40	16	44
12	62	38	0.3–8.0	41	15	44
13	65	35	0.2–6.8	51	14	35
14	62	38	0.1–1.6	38	17	45
15	69	31	0.2–5.1	55	12	33
16	70	30	0.1–1.9	64	10	26
GHMC	67	33	0.1–8.0	51	13	36

Building risk based on HEC-RAS 2D

Information about flood inundation mapping, flood depth, and building risk are presented in Table 4. The most vulnerable locations to flooding are situated near the Hussain Sagar and Musi River.

Zones 1 and 5 have high percentage inundation areas of 81% and 75% as they are near the Musi River and exist in low-lying areas. Zone 11 has the least percentage of inundation area of 61% due to its high elevation level. Zones 12 and 13 have flood depths of 0.3–8 and 0.2–6.8 m. This is due to rapid urbanization in these zones. Zones 1, 5, 8, and 15 are equally vulnerable, with flood depth ranges of 0.3–5.7, 0.2–5.8, 0.1–4.3, and 0.2–5.1 m. This may be due to their proximity to the Musi River and its low elevation of 466–525 m. The ranges of zone-wise percentages of HRB, MRB, and LRB are 38%–70%, 8%–18%, and 21%–49%, respectively. The highest number of HRBs was found in Zone 5, followed by Zone 1. It can be found that there is a greater number of LRB in zones 9, 3, and 14, as these are at relatively higher elevations. Inundated area, flood depth, and percentage of HRB, MRB, and LRB, respectively, GHMC-wise, are 442.53 km^2, 0.1–8 m, 51%, 13%, and 36%, respectively. The inundation area is 67%, more than half of the catchment area. This may be due to high-intensity, short-duration rainfall in the catchment.

The vulnerability of buildings due to flooding is assessed using a footprint map (Figure 3). It is the primary information needed to analyse the situation spatially during and after a flood. It is prepared using the images from Open Street maps and case-study-related data (Open Street Maps 2016). The raster images are geo-referenced and are then digitized into a vector format in the form of polygons. Each building has a unique identifier and is represented by a polygon. Identification helps divide the buildings by area, perimeter, location, or zone. The high, medium, and low flood depth data from HEC-RAS 2D are merged with the obtained vectorized building data. This overlaying of the building features provides the exact number of HRB, MRB, and LRB, as shown in Figure 3. It can be observed from Figure 3 that 51% of the buildings which are in red are HRB.

Flood-susceptibility-based building risk

Efforts were made to study the FSBR regarding the total affected area (summation of rooftop area and surface area) and the number of affected buildings (Figures 4 and 5). It is to be noted that the higher the flood depth, the greater the total affected

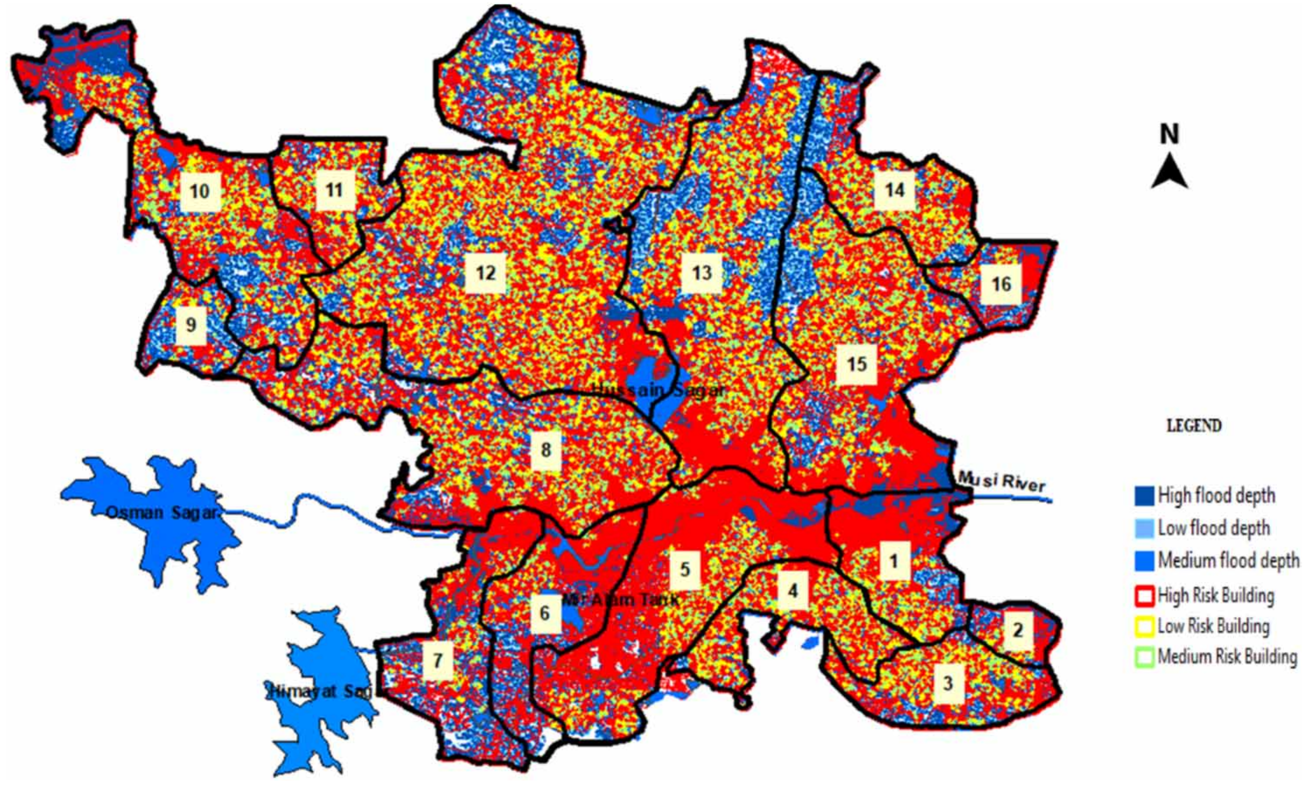

Figure 3 | Building footprint map showing LRB–MRB–HRB as inundated with low, medium, and high flood depths.

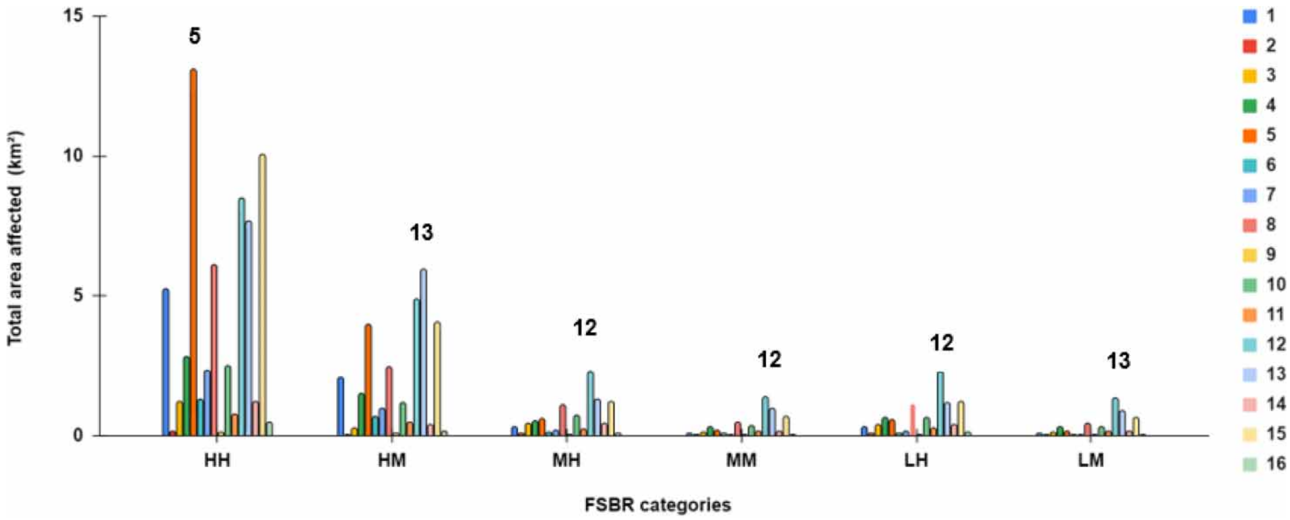

Figure 4 | FSBR for total area affected for RCP 2.6 (numbers on top of bars are zone numbers, where the maximum affected area is observed).

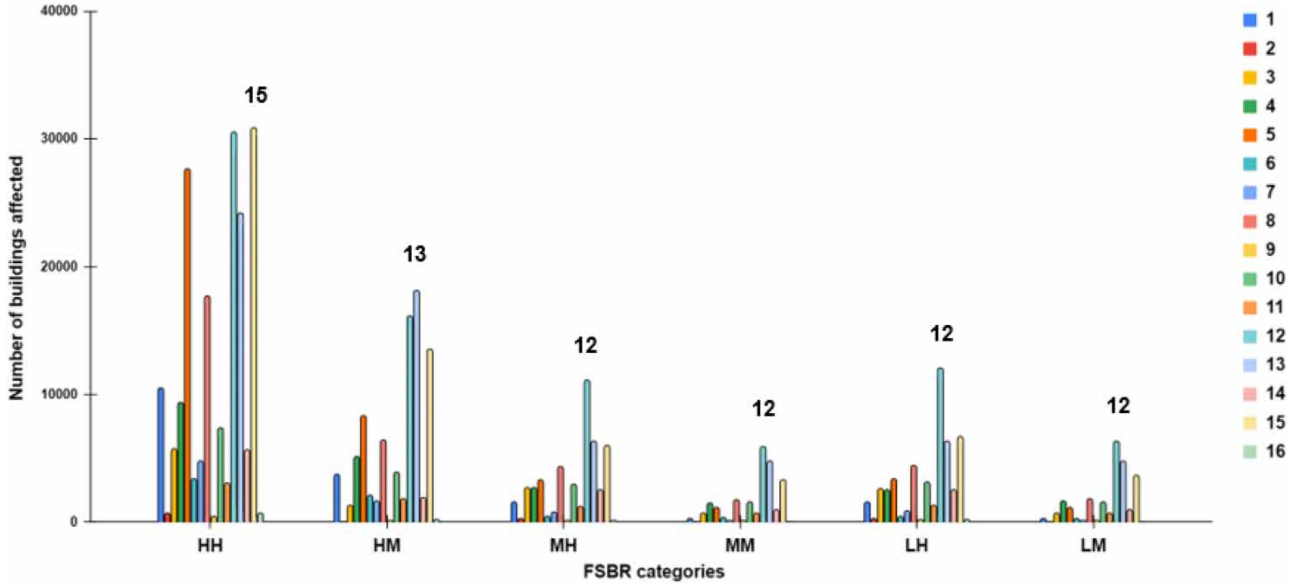

Figure 5 | FSBR for number of buildings affected for RCP 2.6 (numbers on top of bars are zone numbers, where maximum number of affected buildings are observed).

area and vice versa. Among the 16 zones, only 5, 8, 12, 13, and 15 are found to have high total affected areas as examined here. Other zones have less FSBR/less affected areas than the mentioned zones. The ML algorithm does not identify low flood susceptibility (Table 3). Hence HL, ML, and LL categories are not applicable here.

In the HH category, zones 5, 15, 12, and 3 have affected areas of 13.07, 10.04, 8.50, and 7.64 km^2 with the corresponding number of buildings, 27,622, 30,850, 30,462, and 24,159, respectively. In contrast, the number of buildings in zone 9 is significantly less. This may be because of high elevation levels between 561 and 602 m. Zones 5 and 15 together occupied 36% of the total affected area. This may be due to their vicinity to the Musi River. In the HM category, zones 13, 12, 15, and 5 have 18,112, 16,148, 13,476, and 8,313 buildings with affected areas of 5.92, 4.85, 4.05, and 3.94 km^2, respectively. Zones 2, 7, 9, and 14 are the least affected.

In the case of MH, zones 12, 13, 15, and 8 have 11,102, 6,353, 5,996, and 6,411 buildings with affected areas of 2.25, 1.28, 1.22, and 1.09 km^2, respectively. Zones 12 and 13 have the highest curve number values, leading to high FSBR to flooding. In the MM category, zones 12, 13, 15, and 8 have 5,886, 4,732, 3,257, and 1,714 buildings with total affected areas of 1.36, 0.95, 0.66, and 0.46 km^2, respectively. Zones 2, 6, 9, and 16 have fewer buildings affected by floods as they are very far from the Musi River or at high elevation levels. Also, they have fewer pervious areas than zones 12, 13, 15, and 8.

In the LH category, zones 12, 15, 13, and 8 have 12,075, 6,652, 6,288, and 4,445 buildings with total affected areas of 2.28, 1.20, 1.18, and 1.11 km^2. Zones 12 and 15 occupy 25.1% and 13.83%, respectively, of the total affected buildings in this category.

Both these zones are more prone to flooding. In the LM category, zones 12, 13, 15, and 8 have total affected areas of 1.34, 0.88, 0.64, and 0.42 km^2 with 6,338, 4,794, 3,624, and 1,825 buildings. Almost 26.6% and 20.16% of the total affected buildings are in zones 12 and 13, respectively. In the HH, HM, MH, and MM categories, the maximum total affected areas in zones 15, 13, 12, and 12 are 10.04, 5.92, 2.25, and 1.36 km^2. The high slope of 19.13° for zone 15, areas near the Musi River, and the imperviousness of zone 12 are causes of urban flooding.

GHMC: In the case of the HH, HM, MH, MM, LH, and LM categories, the total affected areas are 63.40, 28.92, 9.52, 4.81, 9.26, and 4.56 km^2 (totalling 120.47 km^2) with 182,178, 84,136, 46,238, 22,691, 48,092, and 23,781 buildings (totalling 407,116). The least number of buildings and flood-affected areas are in the LM category.

Waterproofing for reducing FSBR

Waterproofing is the mechanism to restrain the entry of water into the walls and rooftops of a building (Kubal 2008). In addition, it will increase the life cycle of buildings considerably. It is employed to reduce the FSBR in terms of the total affected area and the number of exposed buildings (TGPHMED 2021). This demands the investment to reduce the affected areas/number of buildings to a minimum (equivalent annual cost (EAC) is computed (refer to Equation (1)):

$$\mathrm{EAC} = \frac{C \times i}{1 - (1 + i)^{-n}} \tag{1}$$

where $C =$ capital investment, $i =$ discount rate, and $n =$ life of waterproofing. This provides comprehensive information about the required yearly investment. Here, the capital investment was established on the rooftop waterproofing and surface waterproofing, as presented in Equations (2)–(4):

$$\text{RWP cost} = \text{rooftop area} \times \text{cost/m}^2 \tag{2}$$

$$\text{SWP cost} = \text{building perimeter} \times \text{waterproofing depth} \times \text{cost/m}^2 \tag{3}$$

$$\text{total capital cost } C = \text{RWP cost} + \text{SWP cost} \tag{4}$$

Only salient points are described here to understand the impact of waterproofing measures on the affected area and exposed buildings.

Zone-wise analysis

Waterproofing costs for zones 5, 15, and 12 for the HH category are Rs 538.71 cr, 413.91 cr, and 350.38 cr; and costs for the corresponding EAC/building are Rs 27,800, 19,100, and 16,400 (refer to column 14, Table 5). Zones 2, 3, and 14 require less EAC/building of Rs 13,900, 12,500, and 12,800 (refer to column 14). EAC/building for zones 13, 15, and 12 in the HM category are Rs 19,200, 17,700, and 17,600 (refer to column 15). These values in the MH category are Rs 11,900, 12,000, and 11,900 (refer to column 16); those in MM are Rs 11,900, 11,900, and 13,600 (refer to column 17); those in LH are Rs 11,000, 10,700, and 11,100 (refer to column 18); and those in LM are Rs 10,800, 10,500, and 12,400 (refer to column 19). A decrease in EAC/building is observed in MH compared with HM due to there being less affected area.

EAC/building for the HM category for zones 3 and 14 are Rs 12,000 and 12,400. These buildings have larger surface areas than those in the MH, MM, LH, and LM categories. Due to this, EAC/building is higher than in the mentioned categories (refer to column 15). Waterproofing costs (summation of all categories) of zones 5, 12, 13, and 15 are Rs 761.88 cr, 849.26 cr, 736.40 cr, and 735.57 cr. The cost of the corresponding EAC/building is Rs 24,200, 14,700, 16,300, and 16,400 (refer to columns 20–21).

Table 5 | Number of buildings, waterproofing cost, and EAC/building for RCP 2.6

	No. of buildings						**Cost (cr) Rs**						**EAC/building Rs**						**Total cost (Rs) (cr) (20)**	**EAC/ building/ (Rs) (21)**
Zone no. (1)	**HH (2)**	**HM (3)**	**MH (4)**	**MM (5)**	**LH (6)**	**LM (7)**	**HH (8)**	**HM (9)**	**MH (10)**	**MM (11)**	**LH (12)**	**LM (13)**	**HH (14)**	**HM (15)**	**MH (16)**	**MM (17)**	**LH (18)**	**LM (19)**		
1	10,468	3,743	1,517	207	1,506	224	215.22	84.61	13.21	2.05	12.38	1.82	29,300	32,200	12,400	14,100	11,700	11,600	329.28	26,500
2	644	0	254	0	278	0	6.30	0.00	1.93	0.00	1.74	0.00	13,900	0	10,800	0	8,900	0	9.97	12,100
3	5,718	1,304	2,659	654	2,595	645	50.00	10.98	18.45	3.91	15.23	3.41	12,500	12,000	9,900	8,500	8,400	7,500	101.98	10,700
4	9,353	5,125	2,687	1,490	2,477	1,645	115.30	62.32	21.83	11.95	26.36	12.95	17,600	17,300	11,600	11,400	15,200	11,200	250.71	15,700
5	27,622	8,313	3,282	1,147	3,354	1,129	538.71	162.51	24.61	7.57	22.04	6.43	27,800	27,800	10,700	9,400	9,400	8,100	761.88	24,200
6	3,394	2,091	418	320	421	229	52.59	28.42	3.51	2.13	3.11	1.42	22,100	19,300	12,000	9,500	10,500	8,800	91.18	18,900
7	4,741	1,627	792	73	811	78	95.57	39.20	6.61	0.61	5.79	0.37	28,700	34,300	11,900	11,800	10,200	6,800	148.15	26,000
8	17,691	6,411	4,294	1,714	4,445	1,825	252.22	99.89	45.24	18.98	45.74	17.45	20,300	22,200	15,000	15,800	14,700	13,600	479.52	18,800
9	381	84	96	43	175	54	3.74	2.36	0.77	0.51	1.24	0.84	14,000	40,000	11,400	17,000	10,100	22,100	9.46	16,200
10	7,349	3,880	2,951	1,566	3,074	1,538	102.63	48.16	29.96	14.02	25.75	12.29	19,900	17,700	14,500	12,800	11,900	11,400	232.82	16,300
11	2,985	1,782	1,215	683	1,323	689	31.17	20.14	9.31	6.57	10.01	6.04	14,900	16,100	10,900	13,700	10,800	12,500	83.25	13,700
12	30,462	16,148	11,102	5,886	12,075	6,338	350.38	199.96	93.07	56.31	94.13	55.41	16,400	17,600	11,900	13,600	11,100	12,400	849.26	14,700
13	24,159	18,112	6,353	4,732	6,288	4,794	314.96	243.95	53.00	39.40	48.66	36.43	18,600	19,200	11,900	11,900	11,000	10,800	736.40	16,300
14	5,639	1,900	2,514	900	2,491	944	50.63	16.48	17.46	5.92	16.49	5.36	12,800	12,400	9,900	9,400	9,400	8,100	112.34	11,100
15	30,850	13,476	5,996	3,257	6,652	3,624	413.91	167.26	50.65	27.31	49.77	26.66	19,100	17,700	12,000	11,900	10,700	10,500	735.57	16,400
16	722	140	108	19	127	25	18.97	5.37	2.79	1.00	3.34	1.35	37,400	54,600	36,800	75,000	37,500	77,100	32.83	41,000
Total	182,178	84,136	46,238	22,691	48,092	23,781	2,612.31	1,191.60	392.40	198.24	381.80	188.25							4,964.6	

GHMC: HH, HM, MH, MM, LH, and LM category buildings require an investment of Rs 2,612.31 cr, 1,191.60 cr, 392.40 cr, 198.24 cr, 381.80 cr, and 188.25 cr (refer to column 8–13) and the total cost of waterproofing is Rs 4,964.6 cr. On average, Rs 17,400 as EAC/ building can be invested in preparedness for urban floods. As a note, HEC-RAS 2D provides limited information on high, medium, and low building risks. On the other hand, the FSBR has three options related to high risk (HH, HM, HL), medium risk (MH, MM, ML), and low risk (LH, LM, LL). This flexibility in decision-making makes FSBR preferable over individual usage of XGBoost and HEC-RAS 2D. A brief discussion to prove the potentiality of FSBR is as follows: HH covers 35% of the submergible building area and requires Rs 2,612.31 cr for waterproofing. These values for HM are 16% and Rs 1,191.60 cr, whereas HRB covers 51% and Rs 3,808.91 cr. This gives an edge to policy-makers even in demarcating HRB into two categories and provides leverage while prioritizing the critical buildings for mitigation measures when the budget is limited. Similar inferences can be drawn for other categories.

There can be different ways for possible funding and its operations to encourage citizens to explore waterproofing measures, which are as follows:

- The tax benefits for implementing waterproofing measures can be provided to the house owner. This can be 1%–2% of the construction cost. This will encourage an individual to invest in waterproofing measures.
- Flood insurance/waterproofing bonds can be a better option for encouraging house owners to invest in waterproofing measures. This will enable people to safeguard their houses and families from a catastrophe.
- Use corporate social responsibility funds to safeguard public buildings against flood risk.

SUMMARY AND CONCLUSIONS

Urban floods have been highly prominent natural disasters occurring in catchments across the globe. This requires effective and sustainable mitigation mechanisms to minimize damage. In this context, a holistic approach, FSBR, is proposed by fusing XGBoost and HEC-RAS 2D (that provides building risk) in climate change situations and is applied to GHMC, India. The following conclusions are drawn:

- Buildings and roads have high susceptible areas of 57.59 and 22.76 km^2.
- The inundated area is 442.53 km^2, with ranges of flood depth being 0.1–8 m.
- Percentages of HRB, MRB, and LRB, respectively, are 38%–70%, 8%–18%, and 21%–49%.
- Total affected areas for HH, HM, MH, MM, LH, and LM are 63.40, 28.92, 9.52, 4.81, 9.26, and 4.56 km^2 totalling 120.47 km^2. Corresponding buildings are 182,178, 84,136, 46,238, 22,691, 48,092, and 23,781, totalling 407,116. The total cost of waterproofing is Rs 4,964.60 cr.

This is the first-time application where ML and hydraulic modelling are complemented to derive an indicator, FSBR, for the urban catchment. The aim of this study is not to replicate the previous research works, but to give a new framework to researchers interested in this research area.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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