Performance evaluation of potential inland flood management options through a three-way linked hydrodynamic modelling framework for a coastal urban watershed

Mousumi Ghosh, Mohit Prakash Mohanty, Pushpendra Kishore and Subhankar Karmakar

ABSTRACT

This study proposes a novel comprehensive hydrodynamic flood modelling framework over Mithi river watershed in Mumbai, India, a coastal urban area, to reduce the inundation extent by incorporation of different inland hydraulic scenarios. First, the study addresses the issue of data scarcity by adapting alternate robust techniques to estimate design rainfall, tidal elevation and discharge, the key inputs for a flood model. Following that, a three-way linked flood model has been developed in the MIKE FLOOD platform, considering river, stormwater, overland flow and tidal influence to generate flood inundation and subsequently hazard maps for various inland hydraulic scenarios, by incorporating different feasible cross-sections and lining materials. The flood inundation and hazard maps have been derived for 10-, 50- and 200-year return periods of design rainfall, discharge and tide to identify the best possible flood-reducing hydraulic scenario. It is observed that a 'trapezoidal river cross-section lined with concrete' relatively maximizes the reduction in flooding extent. The proposed framework can be implemented as an effective flood mitigation strategy in data-scarce, densely populated and space-constrained areas.

Key words | flood inundation, hazard maps, hydraulic scenarios, MIKE FLOOD, Mithi watershed

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HIGHLIGHTS

- This study proposes a novel comprehensive hydrodynamic flood modelling framework to reduce the inundation extent by incorporation of different inland hydraulic scenarios considering various combinations of cross-sections and lining material options.

- The maps are derived for 10, 50, and 200 year return periods of design rainfall, discharge and tide to identify the best possible flood-reducing hydraulic scenario.

- This easy-to-implement, user-friendly framework has the potential based on modifications along the river channel of being an effective flood mitigation strategy, especially in data-scarce areas, socially-relevant set-ups, and densely populated and space-constrained areas where implementing structural measures like construction of dams, reservoirs etc., are no simple panacea.

- The area considered in this study comprises the Mithi river catchment – a highly flood-prone region in Mumbai, the commercial capital of India.
- This framework would prove beneficial particularly for densely populated urban catchments wherein space constraints render the adaptation of structural measures for flood management difficult.

INTRODUCTION

The cataclysmic impacts due to the frequent advent of flooding events have increased drastically across the globe. The United Nations (UN) 'The Human Cost of Weather-Related Disasters' reports 157,000 flood-caused deaths in the last 20 years (UNDRR & CRED 2015). Floods pose a greater risk to urban areas owing to higher population density and concentrated economic resources such as infrastructure, commercial centres and so on. Lack of proper drainage systems coupled with low permeable catchments causes excessive runoff during heavy rainfall, thus leading to floods (Shahapure *et al.* 2010) and inundation of cities from a few hours to several days. It results in an extensive adverse impact, such as hindrance of traffic, disruption of communication links, relocation of people, deterioration of water quality, etc. Climate change (Loukas & Quick 1999) and human-induced land cover changes (Yang *et al.* 2016) have only worsened the situation. This rising trend of urban floods has posed a greater challenge for urban planners necessitating immediate and efficacious flood management strategies to minimize the potential harmful impacts as much as possible. The conventional implementation of structural measures such as the development of flood storage structures, reservoirs, etc. often becomes difficult in urban areas owing to space constraints and rapidly thriving populations. Therefore, it has become desirable to solve these flood damage-related problems through optimal planning and integration of non-structural measures along with the structural ones.

Flood hazard assessment and mapping is a very significant non-structural measure which is being increasingly implemented by governing authorities to quantify characteristics of flood such as flood depth, flood duration, and velocity in the spatial domain. Flood depth, the commonly used hazard indicator, generally forms the basis for all construction activities in flooding zones (Chowdhury & Karim 1997; Islam & Sado 2000), whereas flood wave height, debris flow, sediment load, etc., are a few other parameters affecting flood hazard (Merz *et al.* 2010). The product of depth and flow velocity ($d \times v$), signifying the momentum, has been used in previous studies in combination with flood depth (d) (Tingsanchali & Karim 2005; Mohanty *et al.* 2020b). Of the numerous options available for flood hazard assessment, flood modelling through hydrological and hydrodynamic flood models has been widely put into practice (Kalyanapu *et al.* 2012). The hydrological models do not simulate the hydraulic behaviour of flood propagation but rather are used as input for hydrodynamic models (Hénonin *et al.* 2010). Hydrodynamic models are mathematical tools which are governed by laws of physics to describe or replicate the motion of the fluid (Teng *et al.* 2017). HEC-RAS, ISIS, LISFLOOD-FP, TELEMAC-2D, TUFLOW, and MIKE FLOOD are some of the widely used hydrodynamic models. The data-intensive requirements of these models, such as meteorological data, topographical data, hydraulic data, etc., enables detailed and accurate assessment of flood characteristics. Urban flood modelling is more complicated since natural drainage lines get affected through modification of landscapes, stormwater networks, buildings and other constructions.

The flow through river channels is highly sensitive to parameters such as slope, elevation, the direction of slope orientation, topography, vegetation, soil type, patterns of the drainage network, land use and land cover across the region. Hence, slight changes in these parameters can result in considerable changes in the flood inundation pattern over an area. This results in inherent uncertainties associated with flood modelling due to uncertain variables such as topography, hydro-meteorological inputs like

precipitation, streamflow, modelling techniques and parameters (Merwade *et al.* 2008). Various studies have been performed in the past decades to study the impact of these parameters over the streamflow for urban regions (Krapesch *et al.* 2011; Berggren *et al.* 2012; Grimaldi *et al.* 2013; Hardesty *et al.* 2018). The literature suggests that adopting natural or artificial river channels to alter their carrying capacity (conveyance) modifies their natural state. Other ways to change a river's natural form include increasing the cross-sectional area of the channels, lining the channel with suitable materials or stabilizing the slope by proper excavation and earthwork; however, things may 'go south' and cause an adverse effect (Jha *et al.* 2011).

Very few studies have adapted a linked approach considering one-dimensional river flow with a two-dimensional overland flow in the past that highlight the impact of changes in hydraulic parameters of river channel on the flooding pattern and extent over an area. Moreover, lack of availability of reliable long-term data forms a major barrier for modelling flood events, especially for underdeveloped and developing countries. Under such circumstances, making valid assumptions to model the flooding parameters like flood depth, flood velocity, discharge, etc., is a necessity. For instance, in the case of lack of availability of observed rainfall data, a regionalization technique has been adapted, and, in various studies (Lin *et al.* 2010; Sarkar *et al.* 2010), satellite-based products are being increasingly implemented in data-scarce regions to study various characteristics of flood (Yan *et al.* 2015). Similarly, hydrological models are employed to simulate water level and discharge, which are essential inputs for flood modelling, in the case of unavailability of observed data. Given this context, a novel approach has been designed for comprehensive flood management in the form of a three-way hydrodynamic flood modelling framework. This framework would prove beneficial particularly for densely populated urban watersheds where space constrains the adaptation of structural measures for flood management. We have attempted to evaluate the impact of hydraulic changes channelled along the river network on the flooding pattern. Various possible hydraulic scenarios after multiple discussions with civic governing authorities are considered based on different combinations of lining material and river cross-sections, which are compared with respect to the spatial domain of

flood inundation and hazard for 10-, 50- and 200-year return periods.

DESCRIPTION OF STUDY AREA

Mumbai city, the business capital of India, lies along the south-west monsoon belt and is subjected to flood disasters almost annually. The area considered in this study comprises the Mithi river watershed, a river playing a crucial part in the drainage network of Mumbai and influencing the flooding in the city to a great extent. Therefore, the Mithi watershed is affected the most during high flooding events. This makes the slum dwellers residing along the river banks more vulnerable to flooding. Located between 19°1′36″ N and 19°10′9″ N and 72°49′59″ E and 72°56′33″ E, the river originates at a height of 246.5 m above sea level, in the hills located in the east of the Sanjay Gandhi National Park. The river gathers water from surface runoff of the entire watershed and Tulsi, Vihar, Powai lakes and travels 18.4 km to the Mahim bay (Figure 1). The watershed area of Mithi River is 73 km². The width of the river varies from 5 m in the upper reaches to 70 m in the lower reaches. The average depth of the Mithi River is 5.5 m.

Mithi River has four distinct reaches (Zope *et al.* 2015):

I–II Origin to Jogeshwari Vikhroli Link Road (JVLR): bed gradient is 1:200 (very steep gradient).

II–III JVLR to MV Road: bed gradient is 1:450 (steep gradient).

III–IV MV Road to CST Bridge: bed gradient is 1:850 (moderate gradient).

IV–V CST Bridge to Mahim causeway in BKC area: bed gradient is 1:4,000 (flat gradient).

The sudden and drastic changes in the gradient of the watershed and the high density of population pose a major challenge for urban planners for efficient flood management. In the case of heavy precipitation events, the inadequate drainage capacity of the stormwater networks throughout the city further contributes to high flooding events almost every year. Mumbai witnessed 'very heavy' rainfall on 26th July 2005 when the historic highest
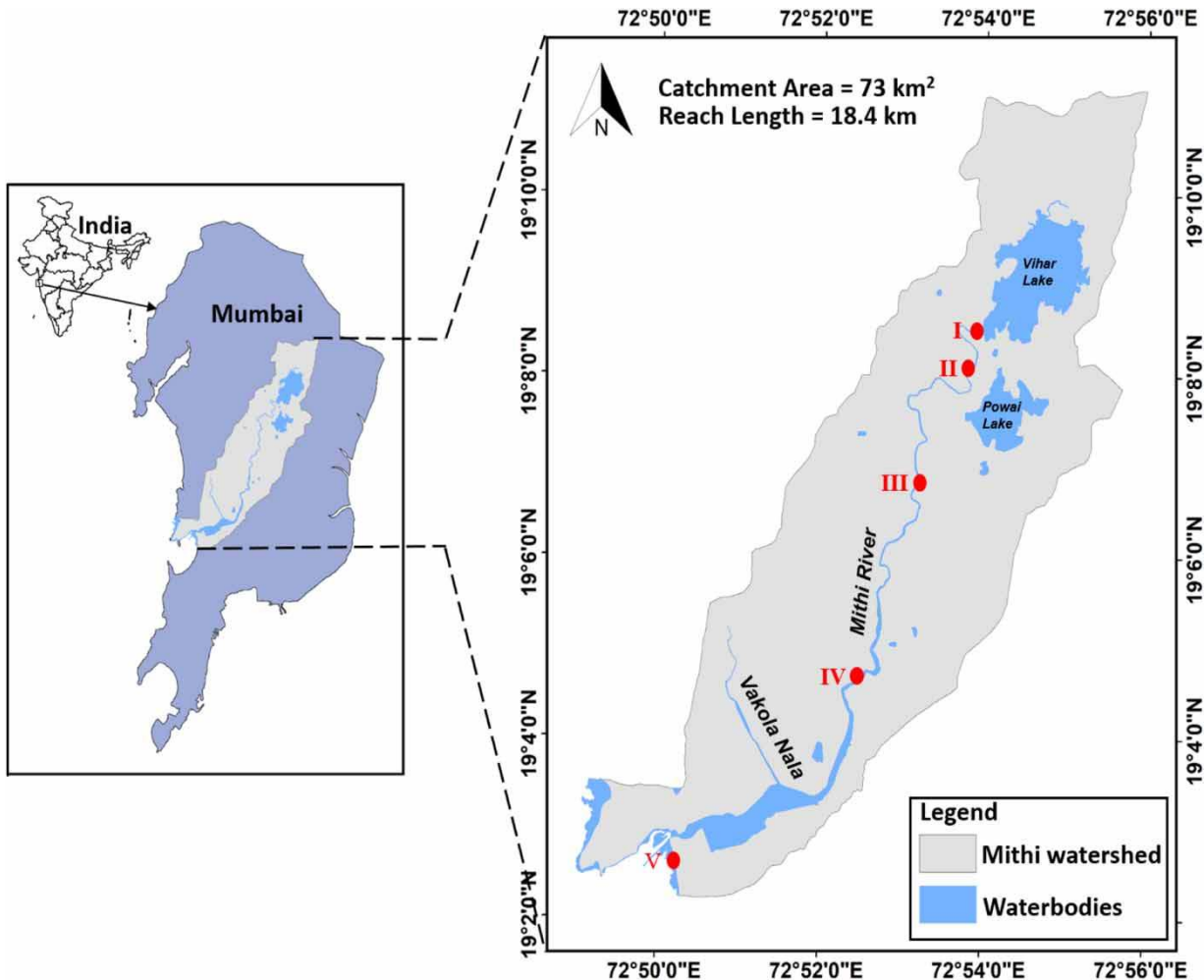
Figure 1 │ Location of Mithi watershed. I–V mark the change in gradients along the watershed.

precipitation of 944 mm was recorded in 24 hours, concurrently with a high tide of 4.48 m in the city. The inadequate drainage system further aggravated the situation leading to high inundation in a major portion of the city, claiming around 500 human lives and economic damage of US$ 2 billion (Government of Maharashtra 2006). Consequently, the administration took several measures for better preparedness and adaptation towards managing future flooding events, such as setting up dense automatic weather station networks over the entire city, desilting, deepening, rock removal, construction of retaining walls and gabion walls along river and nallahs. Even though the situation has improved due to the stringent steps adopted to curb the harmful impact of floods, there exists a major knowledge gap which needs to be explored for proper management of the flooding scenarios.

After the catastrophic floods of 2005, a few studies have been conducted to analyse the flooding scenario over Mumbai and the reasons responsible for it. Ramesh *et al.* (2008) performed an extreme value analysis to estimate the flood levels for maximum precipitation conditions. Shahapure *et al.* (2011) used the FEM model and remote sensing and GIS techniques to simulate flood during flooding and non-flooding events. A rapid inundation mapping was conducted in GIS environment using geospatial techniques by Gupta & Nikam (2013). Zope *et al.* (2012) used geospatial techniques to study the temporal variability of land use land cover changes over flood hazard maps. However,

very few studies have been conducted to perform comprehensive flood modelling over the region and take steps to minimize the impact of flooding. The lack of availability of high quality, rigorous and reliable data makes the study area even more complex. Long-term rainfall data for the watershed are available only for Santacruz and Colaba areas. Similarly, details of stormwater drainage networks, which are important inputs for any flood model, are not available for Mumbai. The current study attempts to overcome these limitations and perform an exhaustive hydrodynamic flood modelling in MIKE FLOOD framework for the flood-prone Mithi watershed by making valid assumptions after discussions with Municipal Corporation of Greater Mumbai (MCGM), the civic governing authority of Mumbai, which has been described in great detail in the following sections. These methodologies can be implemented to perform flood modelling in other data-scant regions as well. The various data and their sources utilized in the flood modelling framework are enumerated in the Supplementary material (Text S1 and Table S1).

METHODOLOGY

The present study focuses on the development of a unified framework for inland flood management, for a densely populated urban watershed where adaptation of structural measures is difficult. It has been graphically represented in Figure 2 with a detailed elucidation in the following subsections.

It should be noted that coastal flooding is influenced by multifaceted interactions between inland coastal drivers such as rainfall, streamflow and tidal impact, often termed as compound or coincident flooding. Despite not being individual extremes, their combination may render an event exceptional resulting in extreme flooding scenarios (Zscheischler *et al.* 2018; Bermúdez *et al.* 2019). Studying the amalgamation of these drivers, and addressing their complex interactions in hydrodynamic modelling frameworks to determine the extreme flood frequencies, is itself a pertinent topic with mammoth potential. Several significant studies have been taken up by researchers in recent times to explore this area and develop frameworks and algorithms to characterize compound hazards (Hawkes

2008; Leonard *et al.* 2014; Moftakhari *et al.* 2017; Bermúdez *et al.* 2019). However, the combined forcing using joint probability approach has not been investigated in this study due to the unavailability of long-term observed storm tide data and river discharge data. The observed rainfall data are available between the period of 1969–2012 for two stations while the observed storm tide data are available from 2010 to 2015. The combined interaction between these three drivers may be taken up as relevant research in future when substantial high-quality data sets of these parameters are acquired. Therefore, in the current study, the same return period for rainfall, discharge and tide has been considered since the primary focus is to explore the potential inland hydraulic options to reduce the flood inundation over an urban watershed. However, the graphical illustration of the proposed framework (Figure 2) represents both marginal and combined events scenarios.

Design rainfall

Design rainfall forms an integral part of flood modelling for estimation of flood for a different return period of rainfall. For the rainfall analysis, the historic rainfall records from multiple rain gauge stations are obtained and data conditioning is performed. A reliable historical sub-daily meteorological data repository is available with India Meteorological Department (IMD), the apex meteorological agency of India. For Mumbai city, long-term data are available for Santacruz and Colaba rain gauge stations (Figure 3(a)). Since the Santacruz IMD station lies within our study area, the long-term rainfall data recorded at this station have been utilized in this study. However, before using this data as representative of the entire watershed for further analysis, it is desirable to analyse the rainfall pattern in the Mithi watershed, which necessitates a dense rain gauge network within the study area.

After the infamous heavy precipitation event of 26th July 2005, the Municipal Corporation of Greater Mumbai (MCGM), the governing civic body of Mumbai, took the initiative to set up a dense automatic weather station (AWS) network across the city in 2006 to capture the spatio-temporal pattern of rainfall in Mumbai. Nevertheless, based on data consistency, continuity and reliability of the rainfall data, the present analysis has utilized the daily
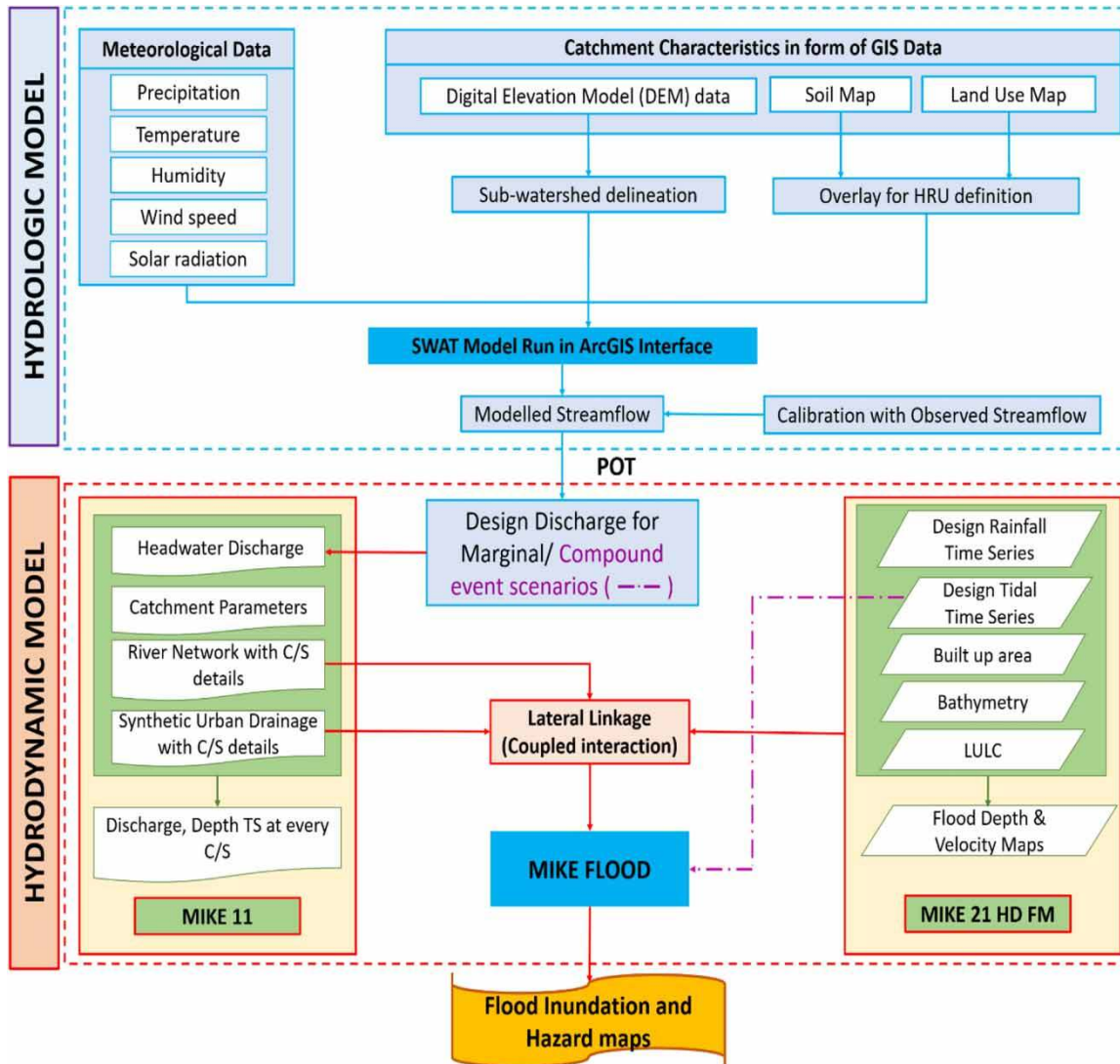
Figure 2 │ Framework adapted for the development of three-way linked MIKE FLOOD model.

JJAS data of seven AWS set up by the MCGM from 2015 to 2019 present within the watershed represented in Figure 3(a) to calculate the Pearson's correlation coefficient (Text S2) between all the seven stations. Figure 3(b) represents the correlation matrix of the rainfall observed at the AWS. As observed, all the stations show a high correlation of greater than 0.6, thus reflecting a strong association between rainfall throughout the area, thereby validating our assumption to utilize a single station rainfall data, i.e., Santacruz IMD station data between JJAS for the years 1969–2012 for the entire area. In the present case, the methodology mentioned in Sherly *et al.* (2015a) (Figure S1) is adapted for estimation

of 10, 50 and 200 years of the return period of rainfall. The rainfall events are delineated from that hourly historical record. An optimum threshold is chosen for rainfall depth for peak-over-threshold (PoT) analysis (or extreme value analysis) based on selection criteria of thresholds in generalized Pareto distribution (GPD).

Design discharge

Design discharge at the mouth of the river, used as an upstream flow boundary condition, is a key input for running the 1-D model. In the absence of observed discharge
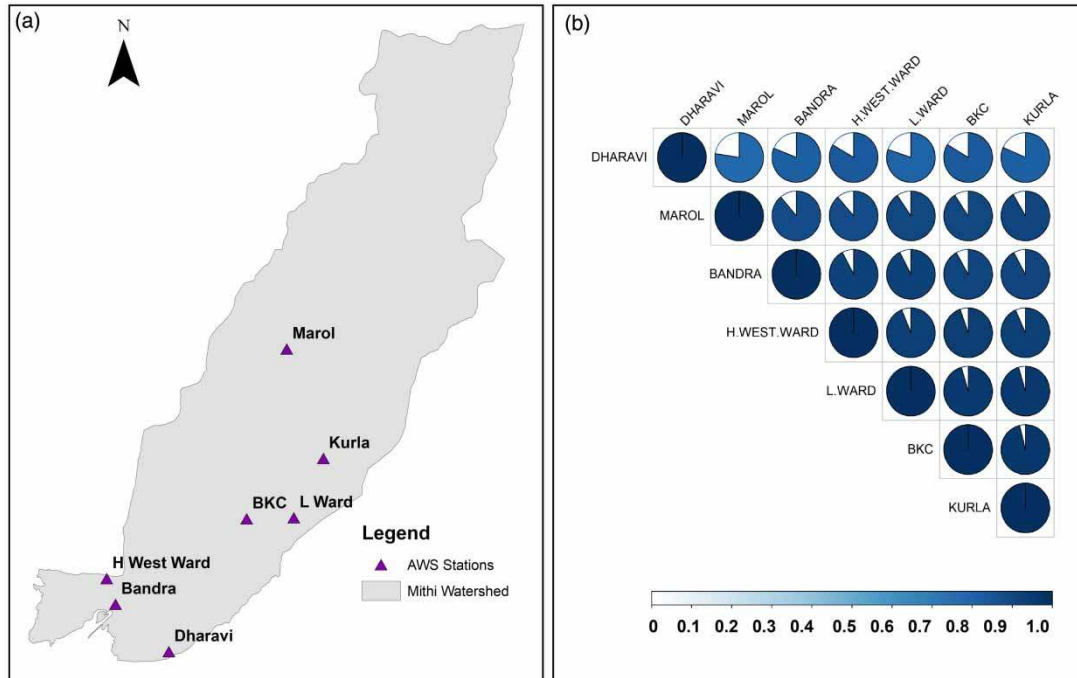
Figure 3 │ (a) Location of MCGM AWS and IMD stations in Mithi watershed and Mumbai city, respectively. (b) Correlation matrix for rainfall at different MCGM AWS.

data at the mouth of the river near *BMC office, NITIE Campus*, the hydrological model SWAT (Arnold *et al.* 1998) was used to generate the discharge for the hydrodynamic flood modelling framework (discussed later). The setup consisted of preparation of the input data, delineation of the watershed using the digital elevation model (DEM) data, HRU definition using soil, slope, land use and agricultural practice data, weather data definition, and followed by the model run to estimate the streamflow which is graphically illustrated in Figure 2.

In the present case, the 43 years' (1969–2012) rainfall corresponding to June, July, August, September (JJAS) along with the other parameters are used to get a daily discharge for the whole period, and finally, POT analysis is performed to obtain the design discharge corresponding to different return periods. The discharge is simulated for three significant locations of the watershed, i.e., near *BMC office, NITIE campus* (Site A), near *The Qube Hotel* (Site B) and near *Sion-Bandra Link Road* (Site C) where the observed discharge data are obtained by extensive manual monitoring conducted for the years 2016 and 2017 during the monsoon represented in Figure S2. However, among

the three monitoring points, the regression analysis is performed at Site B due to the presence of uniform cross section for validation, which makes the discharge measured here comparatively more reliable. The design discharge at Site A (upstream boundary condition for MIKE 11 model) for 10-, 50- and 200-year return period of rainfall is found to be 52 m³/s, 70 m³/s and 84 m³/s, respectively.

Design tide

Mumbai, being a coastal city, is regularly affected by semi-diurnal tides. High tide makes water enter the low-lying areas, leading to damage to life and property and toppling coastal defences in the process. The tide height at any instant depends upon factors such as ocean currents, changing water density, meteorological factors, hydrological effects from the nearby water bodies like rivers, estuaries, etc. (Marfai & King 2008). The tide height at any instant time, t, is given by Equation (1) as:

$$Z(t) = Z_0(t) + Z_s(t) + Z_{so}(t) \tag{1}$$

where $Z(t)$ represents the observed water level or tide height at time t, $Z_0(t)$ represents the mean water level measured from the tide datum at time t, $Z_s(t)$ represents the height of astronomic tide at time t, and $Z_{so}(t)$ represents the height of surge at time t. The astronomic tide $Z_s(t)$ is computed from multiple factors, like the Earth's rotation, the Moon's altitude (elevation) above the Earth's equator, the position of the Moon and Sun relative to the Earth and bathymetry which impact tidal changes over certain periods. The tidal constituents mentioned in Equation (2) define the nature of its distribution (Fang *et al.* 1999):

$$
\begin{aligned}
Z_a(t) = Z_0 &+ A_1 \cos\ (at + E - k)_1 \\
&+ A_2 \cos\ (at + E - k)_2 + A_n \cos\ (at + E - k)_n \\
&+ \dots A_n \cos\ (at + E - \kappa)_n
\end{aligned}
\tag{2}
$$

where $Z_a(t)$ represents the height at any time t, a is the frequency (speed), Z_0 represents the height of mean water level above a selected datum, A_i represents the amplitude of the ith constituent, E represents the equilibrium argument of a constituent at $t = 0$ (from the astronomic event to $t = 0$), k stands for the lag or Epoch (from the astronomic event to the maximum amplitude of the constituent), and n represents the number of constituents. The tidal constituents are determined with the help of a tide fitting toolbox using the astronomical tide observations available from 1900 to 2100 (Pawlowicz *et al.* 2002). Subsequently, a synthetic tide series for the observed duration of 2001–2011 is created using these constituents. The surge component of the tide is determined from the difference between the observed and synthetic tide for the observed duration (Mohanty *et al.* 2020a). The astronomical tide height for various return periods and durations are estimated by fitting into a generalized extreme value (GEV) model, while the surge component is obtained by fitting into a GPD fit. The design tidal time series (24 hours) calculated using this methodology is applied as a boundary condition in the MIKE 21 model.

Hydrodynamic flood model setup

The Mithi watershed is a complex study area in terms of modelling since there is an abrupt change in slope across the watershed, the presence of unplanned settlements along banks of the river and high tidal impact. Therefore, MIKE FLOOD, a versatile hydrodynamic flood model, with steep slope module and provision for inclusion of tidal impact, is used for flood modelling in the present case study (DHI 2017). It integrates both MIKE11 (1-D) model (considering river streamflow) with stormwater drainage network and MIKE 21 (2-D) model (considering overland flow) in MIKE FLOOD framework (Figure 2). MIKE 11 simulates fully dynamic 1-D flows in water bodies like rivers, estuaries, irrigation systems, channels, etc. (Ngo *et al.* 2005). MIKE 21 is a widely implemented tool to simulate physical, biological and chemical processes in coastal and marine regions (Kadam & Sen 2012). The interaction between 1-D river network, stormwater drains and 2-D flood plain established through lateral linkage in the comprehensive hydrodynamic flood modelling framework gives a clearer and more accurate picture of the proliferation of flood during an extreme event. The river shapefile obtained from MCGM and the urban drainage system are used to create the Mithi river network shapefile. On account of unavailability of stormwater drainage network data, after having multiple rounds of discussions with MCGM, it was unanimously agreed that the major stormwater drains of the watershed lie along the major roads. Hence, open drains with square cross sections and widths of $2\,\text{m} \times 2\,\text{m}$ are created in MIKE HYDRO with the help of DEM and major road networks located in the watershed. The governing equations, particularly the continuity and the momentum equations, are solved for all drainage networks and the river using suitable boundary conditions. The MIKE 21 flexible mesh platform was utilized for the 2-D model setup. The land boundary, lake boundary and open boundary for the study area along with the building layers and DEM data were utilized to create a flexible mesh. The land use land cover (LULC) data procured from National Remote Sensing Centre (NRSC) were fed into the model in the form of Manning's n values for different land use classes (Mohanty *et al.* 2018).

It is essential to quantify the uncertainties associated with flood inundation modelling rather than following a single deterministic approach. Some relevant studies have been taken up in the past to quantify uncertainties in flood modelling due to parameters like DEM, Manning's n,

channel geometry, etc. (Jung & Merwade 2012; Alvarez *et al.* 2017). In the current work, we have utilized a high-resolution DEM of 2 m resolution derived from ground surveyed data. Hence, two other important parameters in hydrodynamic modelling, the mesh size and Courant number, were inspected to analyse the uncertainty associated with this modelling framework described in detail in Text S5 and Figure S3. Finally, a flexible mesh of 2,500 m^2 grid size and Courant number of 0.7 was considered optimal for carrying out further simulations. A flooding and drying depth of 0.2 and 0.1 m, respectively, was fixed for the model setup. The design rainfall and tidal data were utilized for MIKE 21 model run. After the 1-D and 2-D models were formulated and stabilized, they were linked in MIKE FLOOD framework and the model was run for 10-, 50- and 200-year return periods of rainfall, discharge and tidal elevation data for the different hydraulic scenarios considered for river network as described in the following section. Coupling of atmospheric, hydrologic and hydraulic models has been carried out in the past, in which, generally, a cascading approach is followed where one model is driven by input from another (Biancamaria *et al.* 2009; Paiva *et al.* 2013; Sampson *et al.* 2015). Bermudez *et al.* (2017) developed a nested regional local-scale framework to incorporate the local rainfall dynamics and uncertainties of boundary conditions for hydraulic simulations. Zischg *et al.* (2018) coupled a surrogate model with a hydrologic–hydraulic model to compute the high number of flood scenarios at river-basin scale. With these noteworthy studies having explored the interactions between the various processes and drivers responsible for extreme events, few studies have been carried out in the Indian context to evaluate the performance of 1-D 2-D flood models for imitating the flooding scenarios. In the current study, the river network (1-D), the flood plain (2-D) and stormwater drainage network have been linked in MIKE FLOOD modelling framework. A lateral link was utilized to simulate the overflow from a river channel onto a flood plain through a structure equation. A string of MIKE 21 cells which constitute the flood plains were laterally linked with the available reach of MIKE 11 river channel and stormwater drainage network in this approach. The design discharge (simulated by the SWAT hydrological model), water levels and design tides were provided as boundary conditions in the MIKE

FLOOD model where the hydrologic–hydraulic interactions were established.

Ideally, to verify the credibility of the flood modelling framework, the observed flood inundation maps should be compared with the simulated maps. The spatial extent of the flood may be derived from remote sensing over large watersheds. However, the geospatial approach may not appear efficient over urban areas due to the presence of heterogeneous urban canopy. Therefore, to overcome this data-scarce situation, the model was run for two recent very heavy rainfall events, i.e., 18th–19th June 2015 and 28th–29th August 2017, which resulted in huge losses. Trustworthy news articles were considered to identify the areas reported to be flooded during these events and were tallied with the flooded areas simulated by the model. Finally, the model was run for 10-, 50- and 200-year return periods of rainfall, discharge and tidal elevation data for the different hydraulic scenarios considered. The flood inundation and hazard maps are developed for all the considered scenarios for the return periods of rainfall. The flood inundation is represented in terms of flood depth and the hazard is quantified by taking into consideration both inundation and velocity as per Australian Flood Hazard Classification (AIDR 2017). In the current study, inundation is categorized into *less severe* (I, II), *moderately severe* (III, IV) and *very severe* (V, VI, VII) classes based on depth only; and hazard is categorized into *less severe* (I, II), *moderately severe* (III, IV) and *very severe* (V, VI) classes in terms of both depth and velocity considering the impact over human and economic livelihood.

Proposed hydraulic scenarios for the river channel

Considering the work done for flood mitigation and rehabilitation in the Mithi River and discussions with MCGM, the governing civic authority of Mumbai, it was concluded that cross-sectional change along with river-lining forms the main basis for mitigating flood in the area. Therefore, two sets of cross-sections, trapezoidal and rectangular, are given in Table 1 and Figure S4. All these simulations performed under the considered scenarios were individually compared with those performed with the surveyed cross-sectional data.

The monitoring point, the road bridge at Site B (chainage ≈ 10,395 m), was chosen because it was continuously

Table 1 │ Different hydraulic scenarios considered for the lining of the river channel

Sl. No.	Cross section	Description
I	Original C/S (surveyed data)	
II	Trapezoidal C/S	
II (A)	Trapezoidal C/S	Fully lined with concrete ($n = 0.012$)
II (B)		Fully lined with gravel ($n = 0.02$)
II (C)		Lined with concrete ($n = 0.012$). Only after *The Qube Hotel*
II (D)		Lined with gravel ($n = 0.02$). Only after *The Qube Hotel*
II (E)		Original C/S with default Mannings $n = 0.04$ until *The Qube Hotel*, but practically feasible C/S lined with concrete ($n = 0.012$) after *The Qube Hotel*
II (F)		Original C/S with default Mannings $n = 0.04$ until *The Qube Hotel*, but practically feasible C/S lined with gravel ($n = 0.02$) after *The Qube Hotel*
III	Rectangular C/S	
III (A)	Rectangular C/S	Fully lined with concrete ($n = 0.012$)
III (B)		Fully lined with gravel ($n = 0.02$)
III (C)		Lined with concrete ($n = 0.012$). Only after *The Qube Hotel* (chainage $\approx 10{,}395$ m)
III (D)		Lined with gravel ($n = 0.02$). Only after *The Qube Hotel*
III (E)		Original C/S with default Mannings $n = 0.04$ until *The Qube Hotel*, but rectangular C/S lined with concrete ($n = 0.012$) after *The Qube Hotel*
III (F)		Original C/S with default Mannings $n = 0.04$ until *The Qube Hotel*, but rectangular C/S lined with gravel ($n = 0.02$) after *The Qube Hotel*

monitored during times of high flood flows, and also since the inundation noted downstream of this area is very high as compared to the upstream. As a part of the theoretical study, the last few scenarios for each cross-section were considered to avoid the cost of excavation and lining the channel to the proposed sections. Therefore, all feasible 45 (15×3) scenarios were simulated in the developed flood modelling framework where 15 stands for hydraulic options and 3 stands for 10-, 50- and 200-year return periods. Finally, the best scenario is identified based on the ability of the model to reduce flood inundation and hazard.

RESULTS AND DISCUSSION

The hydrodynamic flood modelling framework developed is utilized to derive flood inundation maps for two observed very heavy rainfall events (as per IMD classification), i.e., 18th–19th June 2015 and 28th–29th August 2017. Due to the absence of spatial extent of the inundated areas and satellite images for validation of the model developed, the areas

reported to be severely flooded within our study area during these events from with the information collected from leading newspaper articles are highlighted in black circles in Figure 4 (TNN 2015; Times of India 2017). It is observed that the model shows *moderately severe* to *very severe* inundation in those areas, which indicates satisfactory modelling performance.

Following this, the model was run for 10-, 50- and 200-year return periods. Figure S5 representing the MIKE 11 streamflow values indicates that the outflow exceeds the inflow, which can be attributed to the contributions from the 22 different stormwater drain discharges joining the river at various locations. The design discharge values increase with an increase in the return period, which shows that the models perform well and can simulate well.

Figure 5 shows the flood inundation and hazard maps obtained from MIKE FLOOD modelling framework for different return periods for the original cross-section. The moderately severe and very severe areas in terms of inundation and hazard are introspected in particular since they are unsafe and expected to cause more inconvenience.
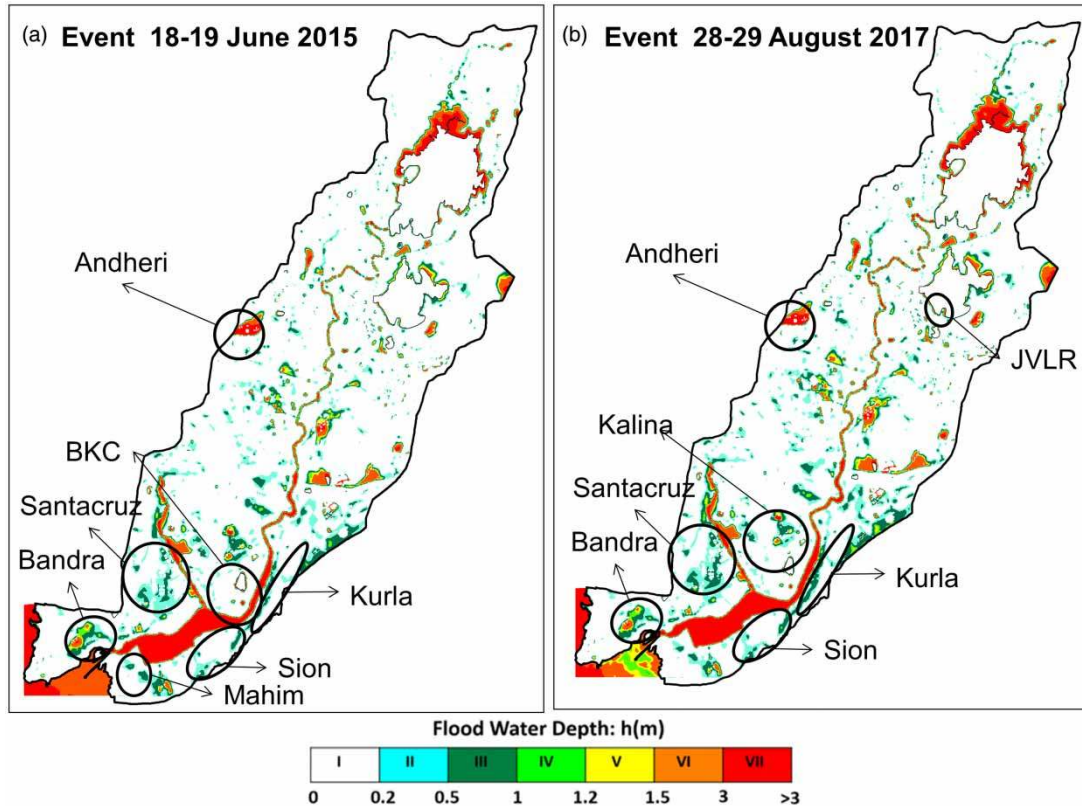
Figure 4 | Inundation maps for observed flood events. Black circles indicate the areas reported to be flooded from newspaper articles.

The cells under classes III to VII and III to VI are assessed in this regard for inundation and hazard, respectively. The rise in the percentage of high flood inundation areas is reflected in the flood maps, as a higher rainfall depth, discharge and tide with a higher return period contributes to more flooded areas. The same trend is reflected in flood hazard as well, as high intensity of rainfall leads to more inundation as well as increased flow velocities. The flood inundation and hazard maps for all sets of scenarios were generated for the three return periods in MIKE 21 as well as MIKE FLOOD. However, the maps derived from MIKE FLOOD for 50- and 200-year return periods are considered for further evaluation because they provide a better picture of the interaction between the river, stormwater drainage and overland flow. Moreover, it is obvious that the higher return periods are of particular interest to policymakers and stakeholders.

The best scenarios for the return periods of 50 years and 200 years are represented in Figures 6 and 7, respectively. A noticeable difference between the inundation extent does not exist among the proposed scenarios which can be attributed to the fact that the area considered is small in this study. However, when compared to the original one there is a significant reduction in the percentage of *very severe* flooded areas. A better declining trend in the flooding pattern may be observed with larger areas, as any changes in the channel cross-sections will have a substantial influence on the channel and overland flooding. Among the 45 maps derived for all the scenarios, the two scenarios with the least flooded areas (in terms of inundation and hazard) for trapezoidal and rectangular cross-section are each selected.

The number of cells under *very severe* condition reduces for flood inundation and hazard maps under these scenarios. Further, it may be noted that the trapezoidal cross-section is found to perform better than the rectangular cross-section as it displays a greater reduction in flooded areas. The trapezoidal cross-section is characterized by the highest carrying capacity of the channel than other sections, which ultimately leads to an increased storage volume and minimal overtopping of floodwater over the river channel
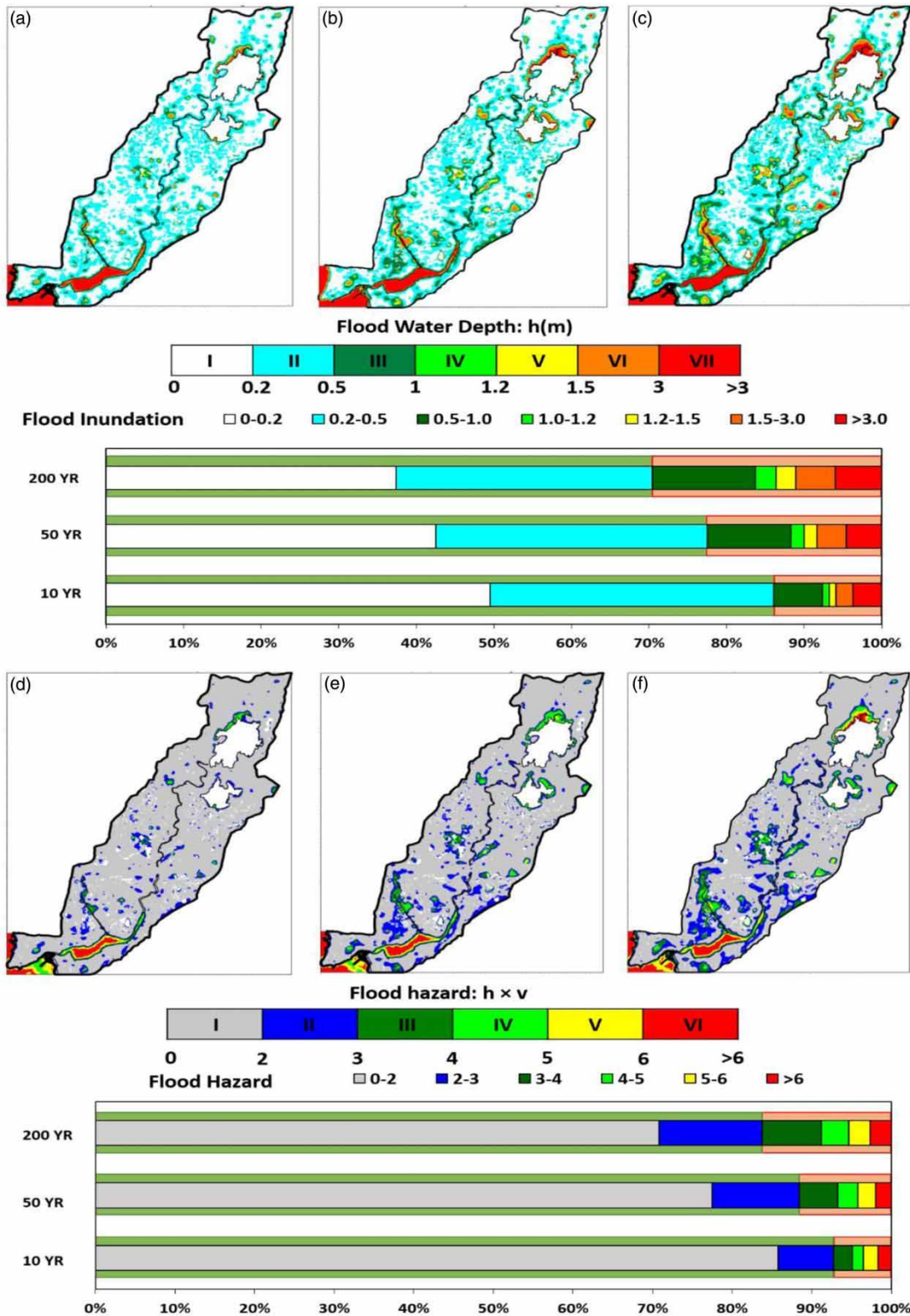
Figure 5 | Flood inundation maps for (a) 10-year, (b) 50-year and (c) 200-year and hazard maps for (d) 10-year, (e) 50-year and (f) 200-year return periods for original C/S.
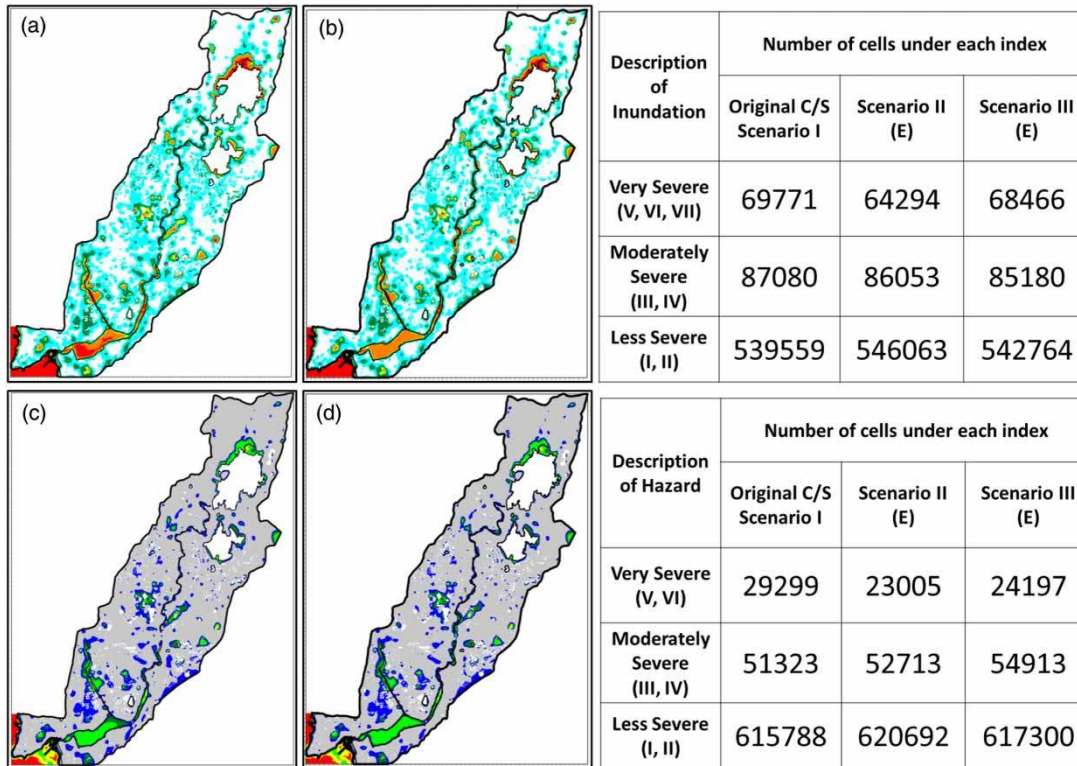
Description of Inundation	Number of cells under each index		
	Original C/S Scenario I	Scenario II (E)	Scenario III (E)
Very Severe (V, VI, VII)	69771	64294	68466
Moderately Severe (III, IV)	87080	86053	85180
Less Severe (I, II)	539559	546063	542764

Description of Hazard	Number of cells under each index		
	Original C/S Scenario I	Scenario II (E)	Scenario III (E)
Very Severe (V, VI)	29299	23005	24197
Moderately Severe (III, IV)	51323	52713	54913
Less Severe (I, II)	615788	620692	617300

Figure 6 | Flood inundation maps for (a) Scenario II (E) and (b) Scenario III (E) and hazard maps for (c) Scenario II (E) and (d) Scenario III (E) for best trapezoidal C/S for 50-year return period.

banks. From all the above analyses, Scenario II (E), i.e., the scenario in which the original C/S with default Manning's n is maintained until The Qube Hotel while the trapezoidal C/S is adapted for the section beyond it and is lined with concrete is considered the best one as it shows the least percentage of high inundated areas and is more economical than other scenarios as well. The section before Site B consists of steep river channel slope and hence imparting channel modifications is not an easy task. However, after Site B, significant changes can be brought about in the channel cross-sections as the river channel slope is gentle and would not pose significant structural failures and would save significant lining and excavation costs as well. This implies that the trapezoidal cross-section is a better option to reduce flood inundation, but the effect diminishes as the intensity of flooding increases, as we can see in the 200-year return period.

Moreover, with changes in the cross-section to trapezoidal, the impact of overtopping of river water beyond the banks can be reduced drastically, as this section can hold a larger floodwater volume than the original cross-section could have. The social vulnerability map of the study area derived by Sherly *et al.* (2015b) towards heavy flooding events (Figure S6) indicates that most of the very severe inundated areas fall within the medium to very high vulnerable zones. Although there is a slight increase in moderately severe zones, there is a considerable reduction in very severe inundation zones (Figure S7). Hence, the reduction in very severe inundation zones in the highly vulnerable area will provide tangible benefits in terms of reduced economic and human losses, especially to the densely populated slum population in the reaches beyond Site B. In support of the proposed scenarios, we observed a substantial reduction in highly inundated areas and associated flood hazard after modifying the C/S. The proposed alterations in the river channel cross-section may serve as a suitable measure to mitigate floods, especially in the D/S locations of densely populated BKC and Dharavi areas.
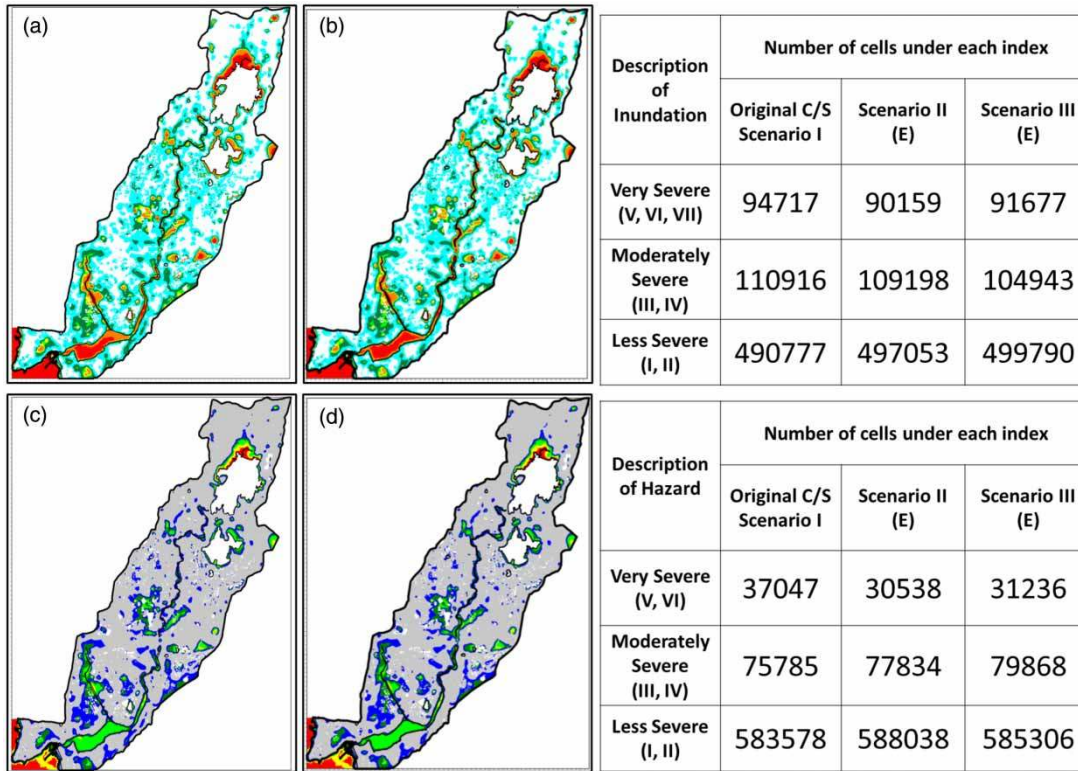
Description of Inundation	Number of cells under each index		
	Original C/S Scenario I	Scenario II (E)	Scenario III (E)
Very Severe (V, VI, VII)	94717	90159	91677
Moderately Severe (III, IV)	110916	109198	104943
Less Severe (I, II)	490777	497053	499790

Description of Hazard	Number of cells under each index		
	Original C/S Scenario I	Scenario II (E)	Scenario III (E)
Very Severe (V, VI)	37047	30538	31236
Moderately Severe (III, IV)	75785	77834	79868
Less Severe (I, II)	583578	588038	585306

Figure 7 | Flood Inundation maps for (a) Scenario II (E) and (b) Scenario III (E) and hazard maps for (c) Scenario II (E) and (d) Scenario III (E) for best rectangular C/S for 200-year return period.

CONCLUSION

For the current study, a three-way linked approach has been adapted to develop a comprehensive flood modelling framework for a densely populated urban area under data-scarce situations. Particularly, unavailability of fine resolution rainfall data and stormwater drainage network were the major obstacles. First, rainfall, streamflow and tidal data – the three major inputs required for hydrodynamic flood modelling – are obtained for 10-, 50- and 200-year return periods. Due to the absence of dense rain gauge networks over the study area, the regionalization approach from Sherly *et al.* (2015a) is adapted for one long-term observed time series of rainfall to estimate various return periods of rainfall. Prior to this, the rainfall pattern of the area is analysed with recently available dense AWS rainfall data which shows high correlation. Hence, the return period estimated through the regionalization framework is assumed to be representative of the entire area and utilized in the flood model. Due to the absence of long-term observed streamflow data, the hydrological model SWAT is set up to simulate streamflow which is provided as input to the flood model. Similarly, a synthetic time series for tidal elevation is utilized to determine the astronomical tide height for various return periods by fitting into a GEV model. Second, the MIKE 11 model which considers streamflow with the drainage network is linked with the MIKE 21 model that accounts for overland flow in MIKE FLOOD environment to develop a standalone hydrodynamic flood modelling framework. The framework is demonstrated over Mithi river watershed of Mumbai city, an extremely flood-prone, densely populated urban area. Due to the absence of a surveyed stormwater drainage network, a synthetic drainage network has been utilized in the study by assuming that the major stormwater drains lie along major roads, which was verified by the governing authorities. Third, the influence of the various considered hydraulic scenarios (for rectangular and trapezoidal cross-sections and different lining materials) over flood inundation and hazard maps for 10-, 50- and 200-year return periods of rainfall, discharge and tidal elevation

are analysed. These inundation maps, also referred to as design flood maps, for the watershed will assist in identifying the high hazard areas and thus accordingly prioritize mitigation and response efforts. From the considered hydraulic scenarios, the 'trapezoidal C/S lined with concrete' was found to be the best possible scenario for flood control adaptation strategy. However, flood control options that depend upon flood modelling capability and watershed characteristics also need to be taken into account. High urbanization and the density of population of Mumbai city pose restrictions in planning other flood control measures such as flood control reservoirs, water diversions, holding ponds, etc. A detailed cost–benefit analysis for these structural measures may also be performed to help stakeholders and civic authorities make informed decisions.

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DATA AVAILABILITY STATEMENT

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

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