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Thane City Action Plan for Flood Risk Management 2024

Thane Municipal Corporation, Thane

Prepared by: Council on Energy, Environment and Water

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Thane City Action Plan for Flood Risk Management 2024

June 2024

ठाणे महानगरपालिका, ठाणे
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FOREWORD

Growing urbanisation along with climate change-induced extreme events such as floods are posing serious development-related challenges for planners, city administration, and policymakers. As cities grow, land use changes towards the higher built-up areas that increase the extent of impervious surfaces and generate greater runoff, especially during storm events. Consequently, this leads to a problem of urban flooding that happens quickly and fast, leading to the loss of lives and property.

Thane district is the second largest contributor to Maharashtra's economy and Thane city is emerging as a destination hub for the IT/ ITES sector and associated residential and retail developments in the state. Therefore, it is important to make Thane city resilient to extreme vents like floods for the welfare of its people and economy.

The ***'Thane City Action Plan for Flood Risk Management 2024'*** offers a framework for the city administration to prepare for and respond to urban floods and reduce the long-term risk by providing actionable and holistic recommendations for strengthening the adaptive capacity of the city, which would transform Thane into a flood resilient smart city.

I am pleased to declare that ***'Thane City Action Plan for Flood Risk Management 2024'*** has been put in place before the onset of monsoon season, which will help the city administration to undertake the priority measures as suggested in the plan and develop a robust response and relief mechanism for effective management of urban floods and water logging events, especially in areas where there is a high risk of such occurrences.

This action plan integrates scientific assessments of past and current rainfall trends, and peak flood flow generation with the analysis of the existing responsibilities for the stakeholders that will serve as guiding principles for various departments to mitigate flood risk in Thane.

Thane Municipal Corporation remains committed to addressing developmental challenges and reducing climatic risks for its people, infrastructure, and economy. I am confident that effective monitoring, robust implementation, and periodic revision of the ***'Thane City Action Plan for Flood Risk Management 2024'*** will contribute significantly to disaster risk reduction and contribute to building a climate-resilient and prosperous Thane city. The plan will serve as a model for other cities in Maharashtra and elsewhere in the country to develop or revise their urban flood action plans.

I extend my heartfelt gratitude to the leadership of the Guardian Secretary of Thane, Ms Sujata Saunik (IAS), Additional Chief Secretary (Home), Government of Maharashtra for her vision for the city. Also, I would like to congratulate the officers of various departments of Thane Municipal Corporation who supported the development of the plan. I sincerely acknowledge the technical support of the Council on Energy, Environment and Water (CEEW), New Delhi who led the development of this plan.

(Saurabh Rao)
Commissioner
Thane Municipal Corporation

About the Thane City Action Plan for Flood Risk Management

The Thane City Action Plan for Flood Risk Management (APFRM) has been formulated using daily rainfall data from the Indian Monsoon Data Assimilation and Analysis (IMDAA) for the period 1970–2021. It combines climatic datasets with on-ground socioeconomic and satellite-derived data to map Thane City's urban flood risk and provides recommendations on making the city resilient to floods.

This city action plan has been prepared as per the *National Disaster Management Plan 2019*, the National Disaster Management Authority *Guidelines on the Management of Urban Flooding, 2010*, and the standard operating procedures on urban flooding notified by the Ministry of Urban Development (now Ministry of Housing and Urban Affairs), 2020.

We sincerely acknowledge the substantial contributions of the expert team from the Council on Energy, Environment, and Water (CEEW). The plan was formulated under the supervision of Mr Nitin Bassi, Dr Vishwas Chitale, and Ms Saiba Gupta. The plan was drafted with the equal contribution of Mr Kartikey Chaturvedi, Mr Aditya Vikram Jain, and Ms Ayushi Kashyap with the support of Mr Kushal Pratap Mall. We also acknowledge the contributions and support of Ms Shreya Wadhawan, Mr Shravan Prabhu, Ms Sneha Maria Ignatious, and Dr Mohammad Rafiuddin.

We thank Dr Thiruppugazh Venkatachalam for his constant guidance throughout the development of this plan and for providing valuable insights through his review. Our heartfelt gratitude goes to the Maharashtra state and Thane district administration. We would like to make special mention of Ms Sujata Saunik, IAS (Additional Chief Secretary GAD-AR&OM and Home, Government of Maharashtra), Mr Saurabh Rao, IAS (Commissioner, Thane Municipal Corporation), Mr Prashant Rode (Additional Commissioner, Thane Municipal Corporation), Mr Sandip Malvi (Additional Commissioner, Thane Municipal Corporation), Ms Manisha Pradhan (Senior Environment Officer, Thane Municipal Corporation), Mr Yasin Tadvi (Regional Disaster Management Cell, Thane Municipal Corporation), and Mr Ramdas Shinde (Deputy City Engineer, Stormwater Department, Thane Municipal Corporation) for their valuable feedback and review to enhance the robustness of the plan.

We also thank Mr Abhijit Bangar, IAS (former commissioner of Thane Municipal Corporation), for providing seamless support during his tenure when the plan was in the preparatory stage.

Further, we are thankful to all the officers at Thane Municipal Corporation, including those from the Stormwater Department, Regional Disaster Management Cell, Environment Department, and other relevant departments, for their support in collating data and providing granular information to develop this plan. We also thank the National Disaster Management Authority and the Central Public Health and Environmental Engineering Organisation for providing guidelines and frameworks used to develop this plan.

Lastly, we express gratitude to the Premji Invest and the India Climate Collaborative for providing funding support to CEEW for undertaking the research associated with this plan.

Contents


F.E.W.S.

Executive summary

Urban centres worldwide are experiencing a common trend of increasing concentration of population and economic activities but are inadequately prepared in terms of planning. It is expected that 70 per cent of the global population will live in urban areas by 2050 (Ferguson et al. 2023, IPCC n.d). Further, unplanned development in urban centres increase the risk of climate change-induced disasters such as storms and floods. These will increase the exposure and vulnerability of the urban population and infrastructure. Approximately 1.54 billion people, or 20 per cent of the world's population, are directly exposed to substantial flood risk (Rentschler, Salhab, and Jafino 2022).

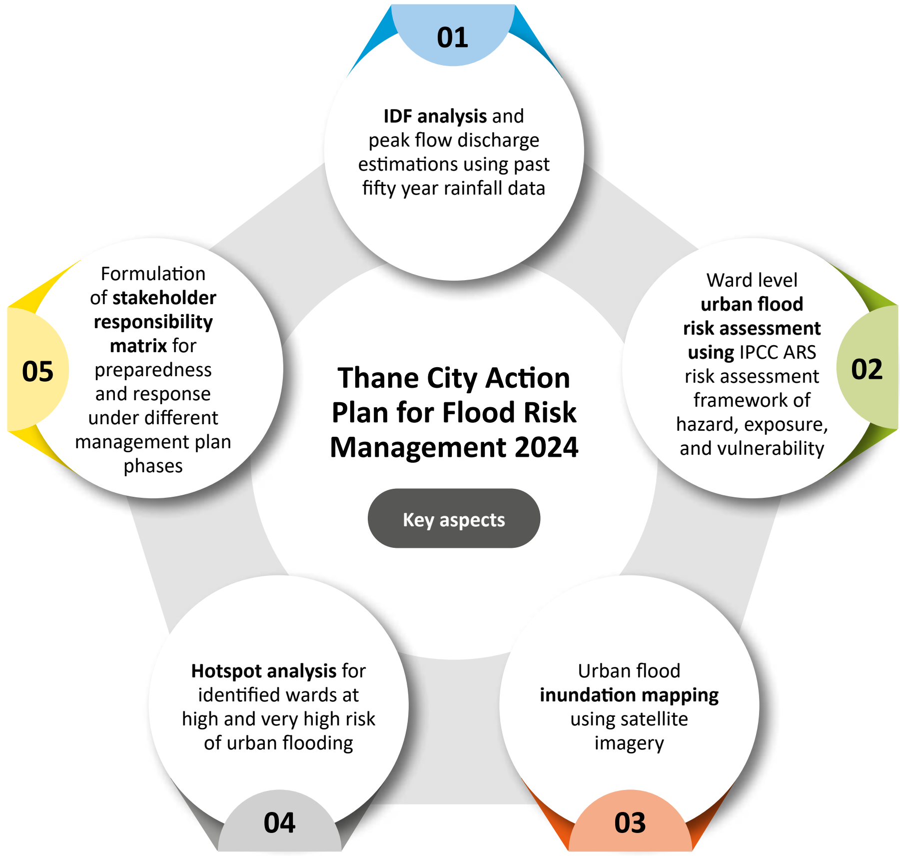
India has 5,052 urban local bodies (ULBs) (MoHUA 2015), which represent more than 31 per cent of the country's total population. As is the case with cities and metropolitan areas worldwide, urban areas in India face multifaceted challenges that are becoming complex due to climate-driven changes. One such challenge is the increasing frequency of high-intensity rainfall events. These extreme climate events that occur over a very short time significantly impact the existing adaptive capacity of governments and communities. Vulnerable population, especially senior citizens, children, and persons with disabilities, are impacted the most. Such social repercussions escalate the risks associated with urban flooding.

With the number and intensity of instances of urban flooding increasing due to climate change, cities must take action to protect vulnerable communities by mitigating floods and maintaining and restoring existing ageing urban flood control infrastructure. To adopt a proactive and holistic approach to urban flooding, cities must first conduct a flood risk assessment as recommended by the *National Disaster Management Plan (NDMP), 2019*. This assessment should focus on hazard, exposure, and vulnerability, followed by the development of effective mitigation, preparedness, and response mechanisms as outlined in the NDMP (NDMA 2019) and the World Bank's *Urban Flood Risk Handbook* (Ferguson et al. 2023).

Coastal cities are most impacted by sudden and extreme storms and floods. For instance, Thane, in Maharashtra, witnesses floods on a recurrent basis. Thane City is situated between east longitude 72.50° and north latitude 19.10°, covers an area of approximately 128 sq km, and is subdivided into 9 *Prabhag Samitees* (PS) (administrative wards) and 33 electoral wards.

CEEW and the administration of Thane City collaborated to address the challenges posed by urban floods by developing a city-level flood action plan. This report presents an analysis of historical rainfall data that was used to prepare the intensity-duration-frequency (IDF) curve and estimate the peak flow discharge. It further identifies the hydrological, governance, social, and economic factors at the ward committee/*Prabhag Samitee* level that can influence the risks posed by urban floods; maps urban flood hotspots; and suggests recommendations to prepare and respond to flood events (Figure ES1).

Figure ES1: Key aspects of urban flood risk action plan for Thane Municipal Corporation



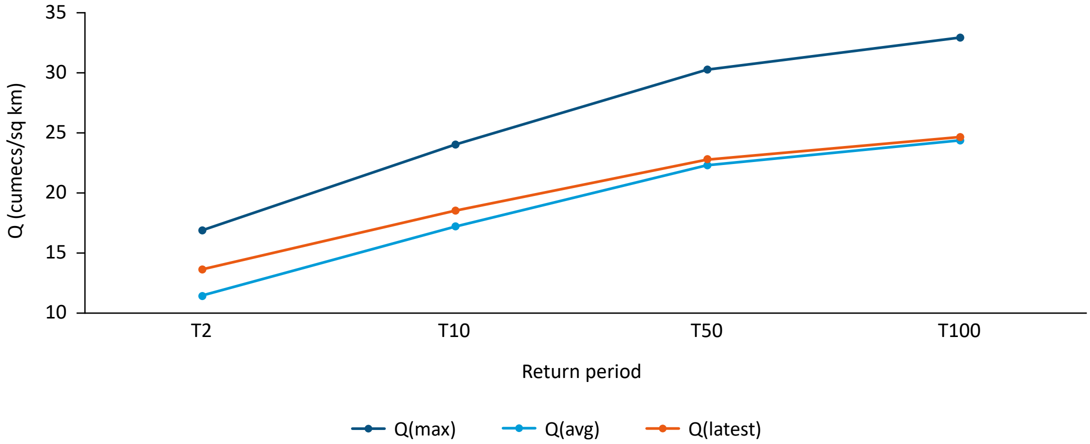
Source: Authors' compilation

Thane City's Action Plan for Flood Risk Management (APFRM) comprises three specific components: why take action, where to prioritise, and who will take action.

Why take action: This section involves tracing rainfall trends using historical rainfall data (1970–2021) and preparing the IDF curve. The 24-hour maximum precipitation over the last 52 years ranged from 72 mm to 267 mm, representing a high temporal variability; the coefficient of variation was 32 per cent. Such a high variation in precipitation presents a challenge to the city administration, especially during years with high rainfall that can potentially cause urban flooding. In the last 52 years (1970–2021), the peak flow discharge for a return period of two years was 16.77 cubic metres per second (cumecs) per sq km, and for a ten-year return period, it was 17.13 cumecs per sq km (Figure ES2). However, the current carrying capacity of the drainage system in Thane is just 16.73 cumecs per square km, indicating that the city is not equipped to manage a rainfall event with a return period of ten years. Hence, there is a need to upgrade the existing stormwater drainage network both in terms of constructing a new network and maintaining existing infrastructure. The Thane Municipal Corporation (TMC) already has plans to upgrade its stormwater network by adding 131 km as part of a new drainage network under its *Integrated Nullah Development Programme* (INDP); the city needs to ensure that its capacity is sufficient to handle the rainfall event that happens every ten years.

Over the past 52 years, Thane has received a daily maximum rainfall ranging from 72 mm to 267 mm

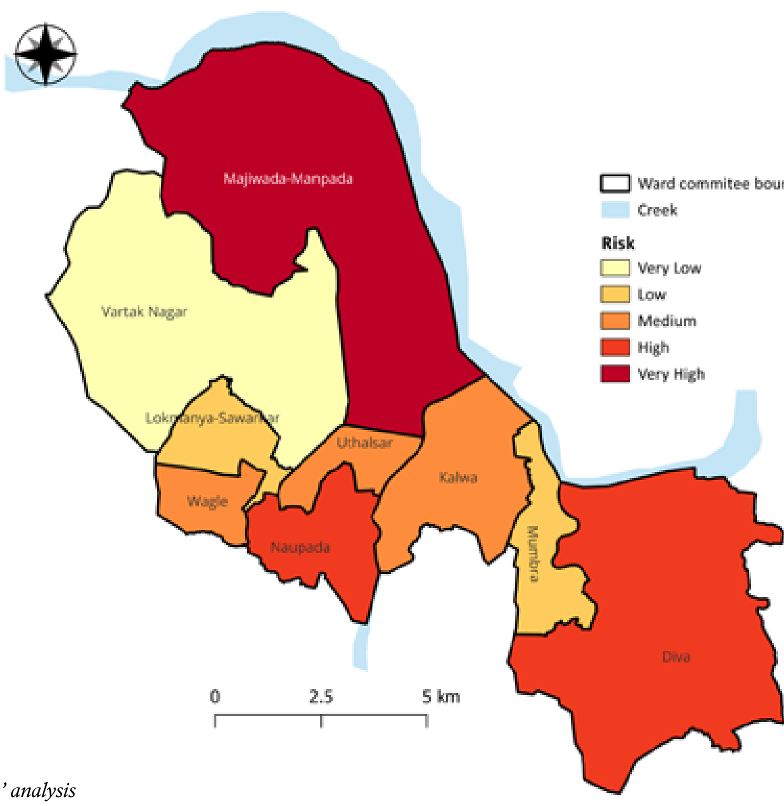
Figure ES2: Peak flow discharge estimation for areas under Thane Municipal Corporation for different scenarios



Source: Authors' analysis using IMD rainfall data; Q (max) refers to the period of 2002–2006, when the maximum discharge was observed, and Q (latest) peak discharge refers to the period of 2017–2021

Where to prioritise action: According to Thane City's urban flood risk index (Figure ES3), the Majiwada-Manpada administrative block is at very high risk, followed by the Diva and Naupada blocks, which fall in the high-risk category. They are followed by Kalwa, Wagle, and Uthalsar blocks, which show moderate risk. The Lokmanya-Sawarkar Nagar and Mumbra blocks fall in the low-risk category, followed by the Vartak Nagar block, which has a very low risk. The risk analysis will help decision-makers prioritise interventions and identify relevant stakeholders and the type of interventions needed in each administrative block.

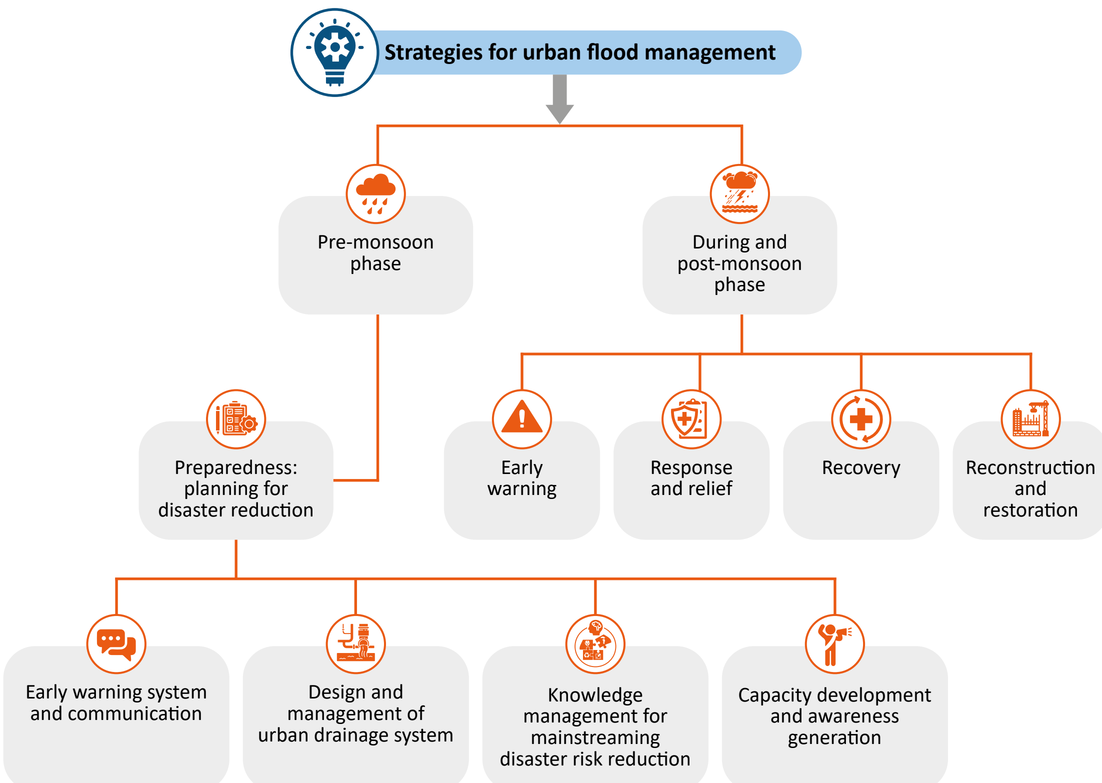
Figure ES3: Urban flood risk index for Thane City across different Prabhag Samitees



Source: Authors' analysis

Who will (and how to) take action: Stakeholders' engagement is central to validating the urban flood risk assessment findings and ensuring uptake and efficient coordination and implementation of the plan. The APFRM provides a set of actionable recommendations for the TMC, which, once implemented, would play a pivotal role in strategising urban flood risk management and adaptation at the administrative level. The plan has adopted a phased approach consisting of the pre-monsoon (December-May), monsoon (June-September), and post-monsoon (October-November) phases (see Figure ES4). The pre-monsoon phase is considered the preparedness period, for which short-, medium-, and long-term recommendations have been provided. The hub-spoke model is followed for the recommendations for the monsoon and post-monsoon phases. As per this approach, an Emergency operation centre (EOC) will coordinate the activities of each relevant department of the TMC. The responsibility of each department during this phase is divided into four major heads: early warning, response and relief, recovery, and reconstruction and restoration.

Figure ES4: An effective urban flood management underlines the importance of phase-wise strategies



Source: Authors' compilation

1. Introduction

Before 2005, flood disaster management mainly focussed on riverine floods that largely affected rural areas. However, many Indian cities have also experienced flooding in recent times. In the case of some cities, flood peaks have increased by 1.8 to 8 times, and due to higher built-up areas, flood volumes by up to 6 times (NDMA 2019). As a result, flooding occurs very quickly. Though the nature of urban flooding is significantly different from that of rural areas, in the absence of any dedicated strategy for flood management in cities, they are dealt with the same yardstick as those of riverine floods.

However, the 2005 Mumbai floods turned out to be a watershed moment. In 24 hours, the city received 944 mm of rainfall, a 100-year high, which brought the city to a complete halt. The floods resulted in nearly 500 casualties and led to an economic loss of approximately INR 28 billion (INR 2800 crore) (Singh 2019). The magnitude of the distraction resulting from these urban floods made the authorities realise that the causes of urban flooding are quite different, requiring appropriate strategies for dealing with such events. This realisation led India's National Disaster Management Authority (NDMA) to formulate the *National Guidelines for the Management of Urban Flooding* to boost urban flood disaster management efforts and strengthen the national vision of moving towards a more proactive pre-disaster preparedness and mitigation-centric approach.

In recent years, Indian cities have witnessed rising trends of urban flooding. Some of the most notable among them were the floods in Hyderabad in 2020 and 2021, Chennai in November 2021, Bengaluru and Ahmedabad in 2022, parts of Delhi in July 2023, and Nagpur in September 2023 (Singh 2022). The major reasons behind this rising urban flood risk are the combination of changing precipitation patterns due to climate change and rapid and unplanned urbanisation. Due to unplanned urbanisation, there has been a massive rise in the built-up areas in cities, leading to the creation of concrete jungles with sprawling networks of impervious surfaces. Such developments lead to increased surface run-off, resulting in frequent floods in a very short period. The encroachment of natural drains, flood plains, lakes, and other water bodies in urban areas is also a major challenge that has substantially decreased the water-retaining capacity of the natural water systems, thus exacerbating the risks of flooding. For instance, in Bengaluru, the built-up area has increased from 8 per cent in 1973 to 93.3 per cent in 2020 (Ramachandra et al. 2016). Due to this concretisation, 98 per cent of lakes in the city have been encroached upon, and 90 per cent of them are fed with untreated sewage. Moreover, drainage infrastructure bottlenecks combined with the issues of operation and maintenance are further making cities vulnerable to flooding. Therefore, an optimum mix of adaptation strategies is urgently needed, including water-sensitive urban planning along with localised forecasting, monitoring, and early warning systems. Developing institutional capacity and an effective awareness strategy is necessary to effectively deal with urban floods in the long run.

In collaboration with the Thane Municipal Corporation, CEEW has developed this Thane City Action Plan for Flood Risk Management (APFRM). After analysing 52 years of rainfall data, we developed IDF curves to aid in creating flood-resilient drainage infrastructure. Further, the administrative ward committee–wise urban flood risk index was calculated to assess the extent of relative flood risk at each ward committee. This plan has been developed based on the flood risk index to provide a set of actionable recommendations for different monsoon phases. The aim is to assist TMC in preparing a comprehensive urban flood risk reduction strategy.

2. Profile of Thane district and municipal corporation

The Thane district, located in the north Konkan division, was split into the Palghar and Thane districts in 2014. Covering 4,214 sq km, Thane district is 1.37 per cent of Maharashtra's area and is the third-most populous in the state, as per the 2011 Census. Bound by Nashik, Pune, Ahmednagar, and Palghar districts, Thane is divided into the seven talukas of Thane, Kalyan, Ulhasnagar, Ambernath, Bhiwandi, Shahpur, and Murbad. Thane district is drained by two main rivers, Varanasi and Ulhas. Further, the district is bordered by the Sahyadri mountain ranges to the east, the Arabian Sea to the west, the dense forest section of Gujarat to the north, and shares its southern boundary with the economic hub of Mumbai (Figure 1).

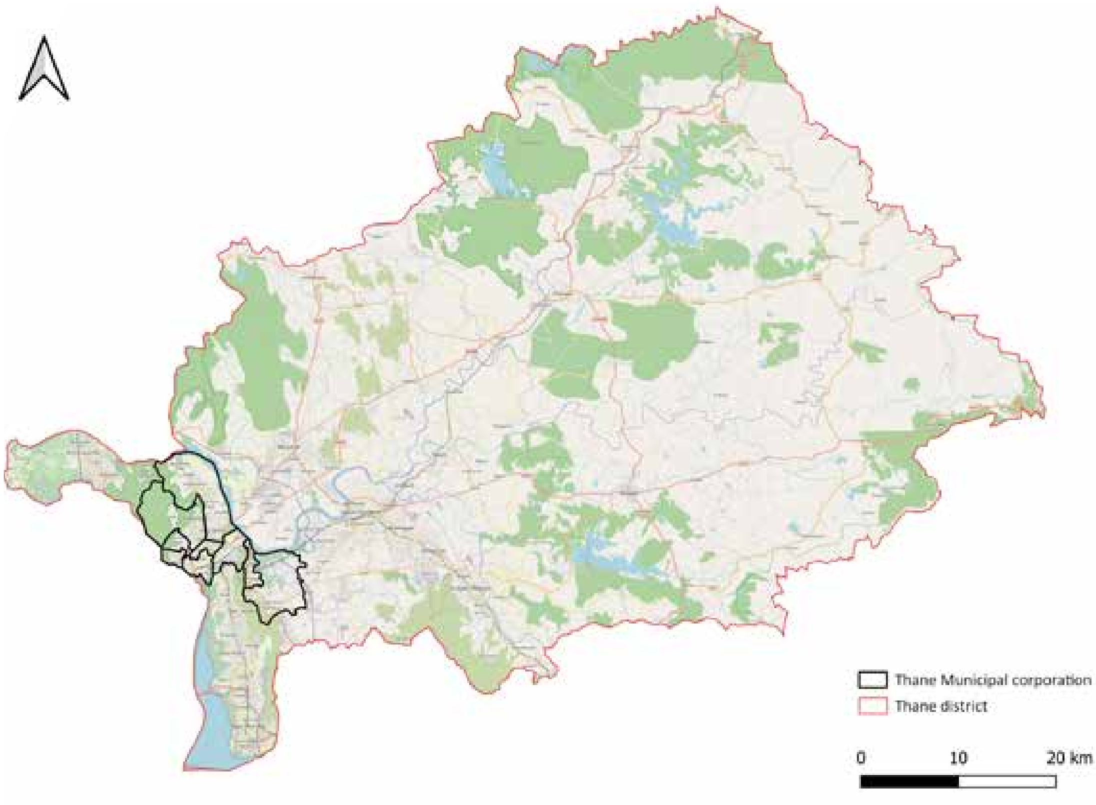
In terms of economy, Thane has witnessed substantial growth in the commercial and real estate sector due to its proximity to Mumbai. The district is the second largest contributor to Maharashtra's economy (13.1 per cent) after Mumbai (22.1 per cent) (ICLEI South Asia 2021). Along with the district, Thane City is emerging as a destination hub for the IT/ITES sector and associated residential and retail developments, including large commercial spaces and malls.

Thane City falls within the sub-district of Thane and exercises jurisdiction over Kalwa, Mumbra, and the central city of Thane (Figure 1). Covering an area of approximately 128.23 sq km, Thane city is situated between east longitude 72.50° and north latitude 19.10° and is subdivided into 9 Prabhag Samitees (administrative wards) and 33 electoral wards. According to the 2011 census, Thane city's population stands at 18,26,649.

The topography of Thane City ranges from 0–7 m above mean sea level, featuring black and sand mixed soil conducive for cultivating rice, vegetables, and orchards. The city's topography is defined by submerged marshland along the Thane Creek and the Ulhas riverbank, complemented by high hills on one side. Thane has a tropical monsoon climate with the average temperature varying between 22°C and 36°C. The average annual rainfall is 2000–2500 mm, and the humidity ranges from 61 to 86 per cent, making it a city with predominantly humid weather.

Thane City's sewerage network extends to 54 per cent of the city's area with a collection efficiency of 22 per cent through underground piped networks. Effectively managed stormwater drains are instrumental for urban flood management strategy. The total length of the constructed *nullah* network in TMC is approximately 278 km, of which 147 km has been completed and 131 km remains to be completed.

Figure 1: Map of Thane district highlighting the area of Thane Municipal Corporation



Source: Authors' compilation

3. Urban floods and the current scenario

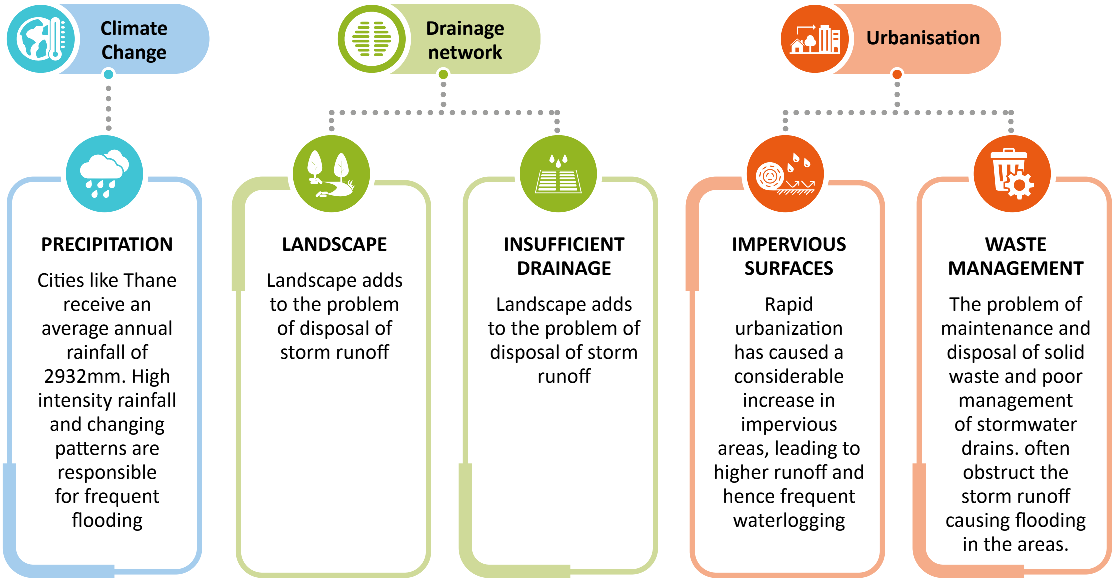
Urban floods occur when a city receives massive amounts of water due to heavy rainfall, rapid snowmelt, storm surges caused by a cyclone or tsunami, or other causes. This excessive water leads to the submergence of parts of or the entire city, and the city's infrastructure is unable to drain the water quickly enough to address it in other ways to prevent inundation.

3.1 Causes of urban flooding

Urban flooding across the globe is caused by a combination of natural and anthropogenic factors (Figure 2), which is a serious problem to manage. The Inter-Governmental Panel on Climate Change (IPCC) report reiterates the dire consequences of human-induced climate change for the Indian subcontinent, including increased dry spells, intensification of extreme rainfall by more than 20 per cent, and an exponential surge in heatwaves and cyclonic events. One of the outcomes of such climate extremes is the increased occurrence of flood hazards.

Insufficient drainage systems in urban areas exacerbate flooding during storm events due to the additional runoff from built-up areas (Ashley et al. 2007). Consequently, climate change–driven intensification of precipitation patterns is leading to more frequent and heavy downpour events that overwhelm urban drainage systems (Wang et al. 2021).

Figure 2: Major factors responsible for urban flooding



Source: Authors' compilation

Rapid urbanisation is yet another major contributing factor to the severity of urban floods. Impermeable materials such as concrete and asphalt are replacing natural surfaces in the cities, making them impervious and reducing infiltration (Thiessen et al. 2013). Urban flooding is further exacerbated by bad zoning and urban planning choices, such as disregarding floodplain laws and encroaching on natural streams (Olshansky et al. 2014). Additionally, the ageing and poor maintenance of the current drainage system further reduces its ability to manage rainwater efficiently (Talebian et al. 2020).

3.2 Status of the drainage system in India

With the expansion of cities and the migration of people from rural areas to urban areas, there has been immense pressure on urban infrastructure and living conditions, and the problem of urban drainage systems in India is worsening (Central Public Health and Environmental Engineering Organisation [CPHEEO] 2019a). Several factors are responsible for the present status of poor urban drainage systems in India. These are:

- Due to high urbanisation, the natural drainage system in most cities and towns is severely compromised. The flooding situation has worsened due to the non-availability of properly engineered stormwater drainage infrastructures (CPHEEO 2019a). Moreover, encroachment and rampant dumping of garbage and solid waste exacerbate the situation in the absence of preventive maintenance of the drainage system.
- Megacities have a long history of municipal drainage since the British era. Most of the underground drainage systems within core clusters are century-old, antiquated brick masonry conduits (CPHEEO 2019a). The existing stormwater system was mainly designed to serve as a combined sewerage and stormwater runoff system. However, many cities have initiated the process of separating the two systems.
- In 2011, the coverage of the stormwater drainage network was just 20 per cent of the road network and its allied catchment areas, which is too inadequate to cater to the present stormwater disposal (CPHEEO 2019a).

3.3 Status of the drainage system in Thane

Thane has a natural stormwater drainage system that includes 72 major *nullahs* and 95 *sub-nullahs,* most of which originate from either the Yeoor Hills of Sanjay Gandhi National Park or Parsik Hills (ICLEI 2021). Drains flowing from Yeoor Hills pass through the city, and those from Parsik Hills pass through Kalwa and Mumbra. The total length of the *nullahs* in the TMC limit is estimated to be approximately 278 km, out of which 147 km is completed and 131 km is yet to be completed (Table 1). Thane is divided into four zones – Thane city, Kalwa, Mumbra, and Diva – based on the catchment areas (Table 2). The TMC began strengthening its stormwater drainage network through the *Integrated Nullah Development Programme* (INDP) in 2006, with three of four phases completed under the INDP as a long-term measure to control water logging in the city (ICLEI, 2021).

Table 1: Length of stormwater drains in Thane Municipal Corporation

Sr. No.	Particulars	Nullah length (km)
1	Total *nullahs* under TMC limit	278
2	Completed *nullahs*	147
3	Remaining *nullahs* to be completed	131

Source: Authors' compilation using data received from the TMC Stormwater Department

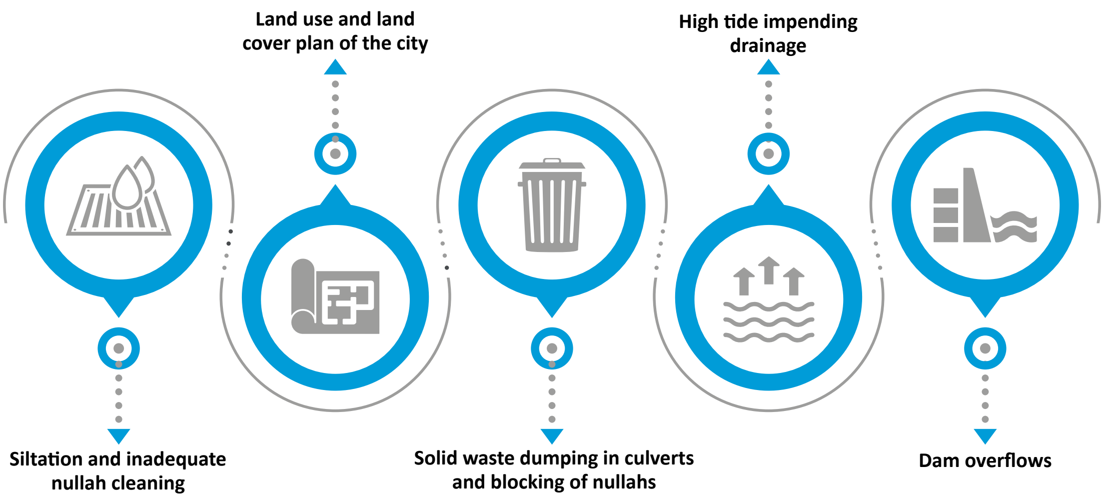
Table 2: Area-wise length of stormwater drains in Thane Municipal Corporation

Sr. No.	Area	No. of nullahs	Length (in km)		Total (in km)
			Constructed	To be constructed	
1	Thane City and Ghodbhunder Road	17	70	71	141
2	Kalwa	9	20	17	37
3	Mumbra	40	41	5	46
4	Diva	17	16	38	54
	Total	**83**	**147**	**131**	**278**

Source: Data received from TMC's Stormwater Department

The construction of new stormwater drains in the TMC is as per the 2019 CPHEEO manual. This incorporates the rapid urbanisation and climate change component to an extent. In addition to the CPHEEO requirements, drains are being designed for 20 per cent increased rainfall intensity as an uplift factor for climate change. Although the TMC has a wide network of drainage systems, it faces issues in terms of both the construction of a new drainage network and the operation and maintenance of the existing drainage network (Figure 3).

Figure 3: Identified pressures on stormwater drainage network in TMC



Source: Authors' compilation

3.4 The need for a comprehensive stormwater management plan

With extreme rainfall events becoming more frequent and intense (Mohanty and Wadhawan 2021), an action plan is needed to prevent them from turning into disasters. The key lies in identifying the cause, evaluating current preparedness, and successfully implementing the solutions outlined in the national, state, or district disaster plans. Disaster plans are policy documents that provide a framework for preparing, responding, recovering, and learning from extreme disasters, including urban floods.

The revised NDMP 2019 focuses on how climate change is exacerbating urban floods across the country. This guideline emphasises effective inter-agency and stakeholder coordination, mapping vulnerable and at-risk populations, the need for early warnings, formulating a stakeholder responsibility matrix, and delineating strategies for monitoring, evaluating, and plan updating (NDMA 2019).

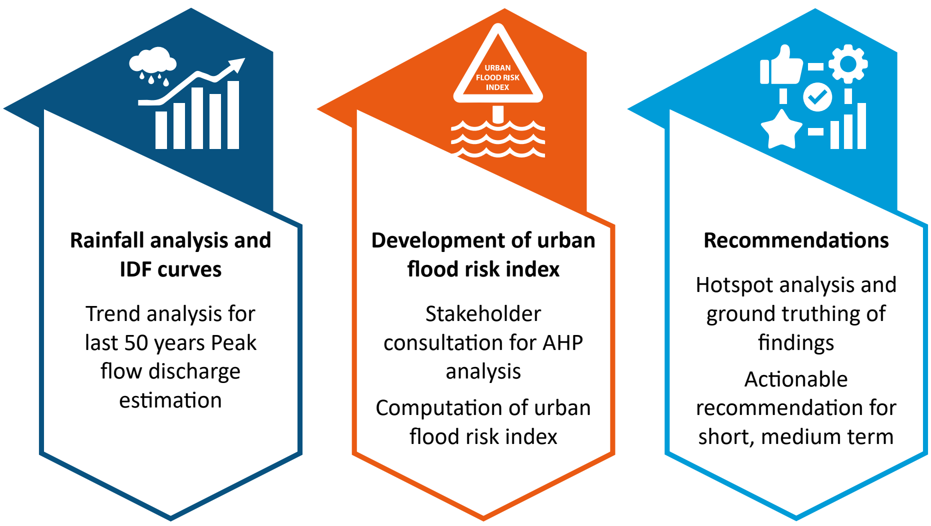
In India, these guidelines have played an important role in the management of urban floods by state governments and district administrations. However, to ensure effective management of these guidelines, it is important to contextualise them at the local level. Currently, only cities such as Mumbai and Chennai have adopted urban flood management under their climate action plan, yet no city has documented a comprehensive urban flood management plan.

This report specifically focuses on the problem of urban floods in Thane, the existing initiatives by TMC, and recommendations to manage them and protect those at risk.

4. Methodology

A detailed methodology was followed to understand the past and current rainfall patterns in Thane, accompanied by IDF analysis of Thane. IDF analysis and peak flow discharge were estimated for a period of 52 years (1970–2021), which helped to understand Thane's hydrological and drainage dynamics. This was followed by developing an urban flood risk index using the IPCC AR 5 assessment framework. Finally, we identified the hotspot regions for urban floods and made recommendations with short-, medium-, and long-term targets (Figure 4).

Figure 4: An overall approach for the development of an urban flood management plan



Source: Authors' compilation

4.1 Intensity duration frequency (IDF)

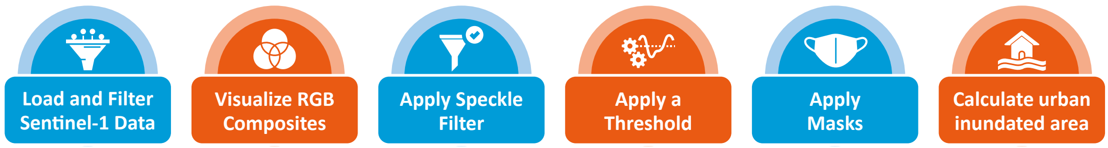
To understand the rainfall trends, occurrence of storm events, and flood peak discharge in TMC, intensity duration frequency (IDF) analysis was undertaken using the methodology presented by Kumar et al. (2022); the details are provided in Annexure 1.

4.2 Flood inundation mapping

Most flood forecasting centres in flood-prone countries lack the ability to run complex flood forecasting models to improve the spatial coverage of flood early warning systems (FEWS) and generate extents, as revealed by the global survey of FEWS conducted by the United Nations University (United Nations 2006). To overcome this, we used the Google Earth Engine (GEE), a planetary-scale platform for earth science data and analysis, which made it possible to develop global-scale products and services using the power of cloud computing and EO data (Sentinel) to generate historical global flood inundation data.

Sentinel data was used for the analysis as it has a higher resolution than other satellites and can penetrate through clouds and capture reflectance value both day and night. The spatial resolution of the data is 10 m, and the temporal resolution varies between 6–12 days, depending on the location. The steps involved in carrying out flood inundation mapping are described in Figure 5.

Figure 5: Steps involved in flood inundation mapping



Source: Authors' compilation

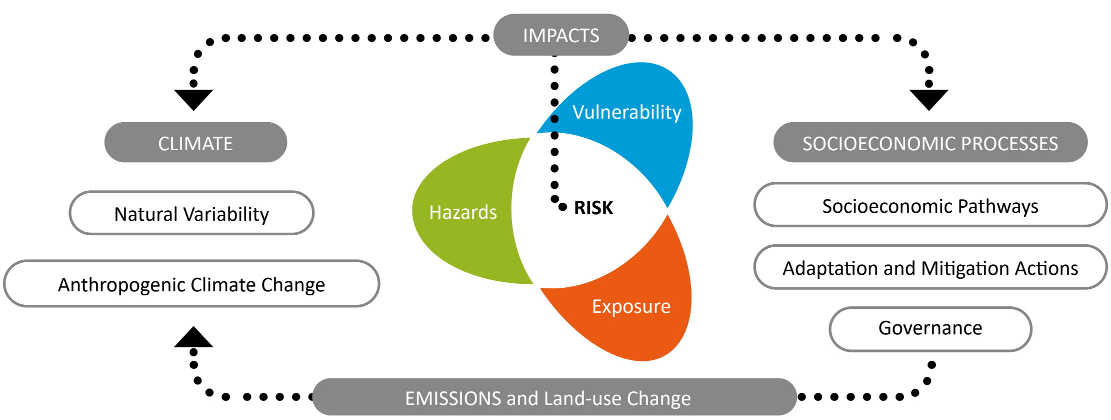
4.3 Development and computation of ward committee–level urban flood risk index

To enumerate the 'where to prioritise action' component of the Thane City APFRM, a ward committee-level urban flood risk index was developed. The index estimated the extent of risk associated with urban floods for each ward committee based on the scores assigned to each of them.

The development of the urban flood risk index in this assessment adheres to the methodology outlined in the IPCC Fifth Assessment Report (AR5), which entails that risk arises from the interaction of three components – hazard, exposure, and vulnerability (Figure 6). The framework defines 'risk' as "the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from the potential impacts of climate change and human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and wellbeing, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species" (Intergovernmental Panel on Climate Change [IPCC] 2014). The components of risk are explained in Annexure 2.

A detailed methodology and a series of steps were undertaken to develop and compute the urban flood risk index at the ward committee level (Figure 7). It involved the selection of indicators based on a detailed relevant literature review and broad-based stakeholder consultation, followed by data collection at the ward committee level. Further, the normalisation of indicators was carried out to bring parity across the indicators and was reclassified based on their relation (direct or indirect) to the outcome. The detailed list of indicators under hazard, vulnerability, and exposure is given in Annexure 3.

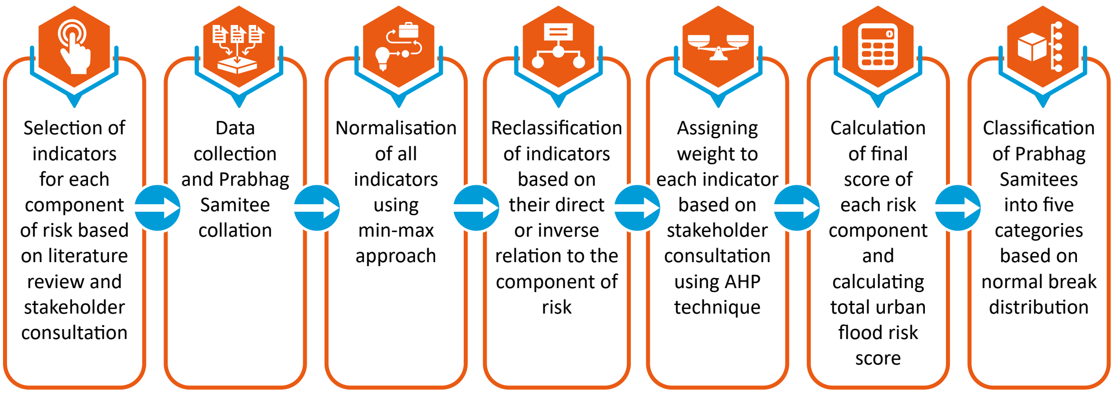
Figure 6: Components of the risk assessment framework and its sub-components



Source: IPCC 2014

After that, the analytical hierarchy process (AHP) was followed to assign weight to each indicator (Figure 8). The details of the process and assigned weights are presented in Annexure 4. Finally, the composite risk scores were computed for each ward committee using the risk equation, and they were classified into the following five categories: very high, high, medium, low, and very low (Figure 9).

Figure 7: Schematic representation of the stepwise approach to compute the urban flood risk index



Source: Authors' analysis

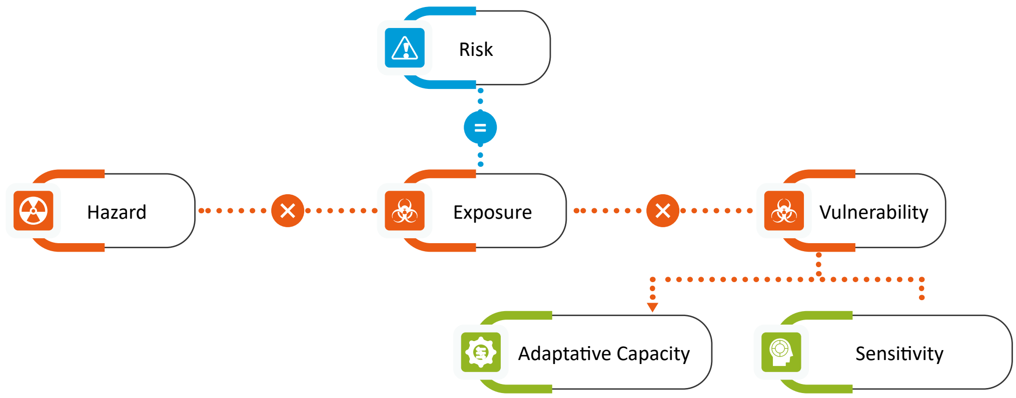
Figure 8: Consultation workshops and meetings with TMC officials

(a) *CEEW team conducting* analytical hierarchy process with *TMC officials for Thane APFRM*

(b) *A two-day workshop on climate action organised with officials from various line departments in February 2024*

Images: CEEW

Figure 9: Risk assessment equation



Source: Authors' compilation using data from IPCC 2014

4.4 Data constraints

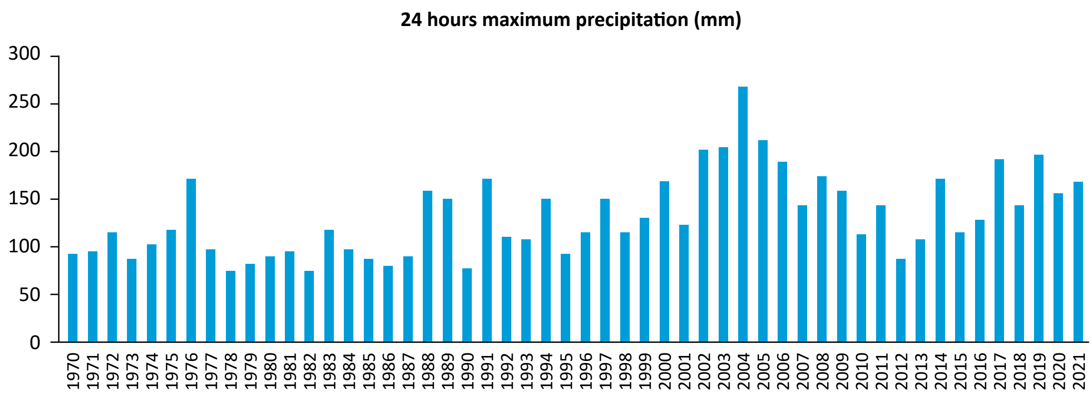
The flood risk index for Thane City was computed based on the IPCC framework comprising three components – hazard, exposure, and vulnerability. However, due to the unavailability of certain data sets, some indicators were excluded from the risk index computation. The list of complete indicators, including those excluded from the risk assessment, is provided in Annexure 3. The data gaps may impact the reliability of the risk assessment. The missing data sets are attributed to various reasons, including limited monitoring infrastructure, insufficient data collection processes, or challenges in accessing certain geographical areas.

5. Results

5.1 IDF Curves

Rainfall in Thane city shows high inter-annual variability. Between 1970 and 2021, the maximum daily rainfall varied from 72 millimetres (mm) to 267 mm (Figure 10). The variability in maximum daily rainfall, as indicated by the coefficient of variation in rainfall, was estimated to be 32 per cent. For Thane which is a hilly coastal city, such variability is substantial. Hence, there is a need to prepare for such extreme events better.

Figure 10: Variations in daily maximum precipitation for Thane City from 1970–2021



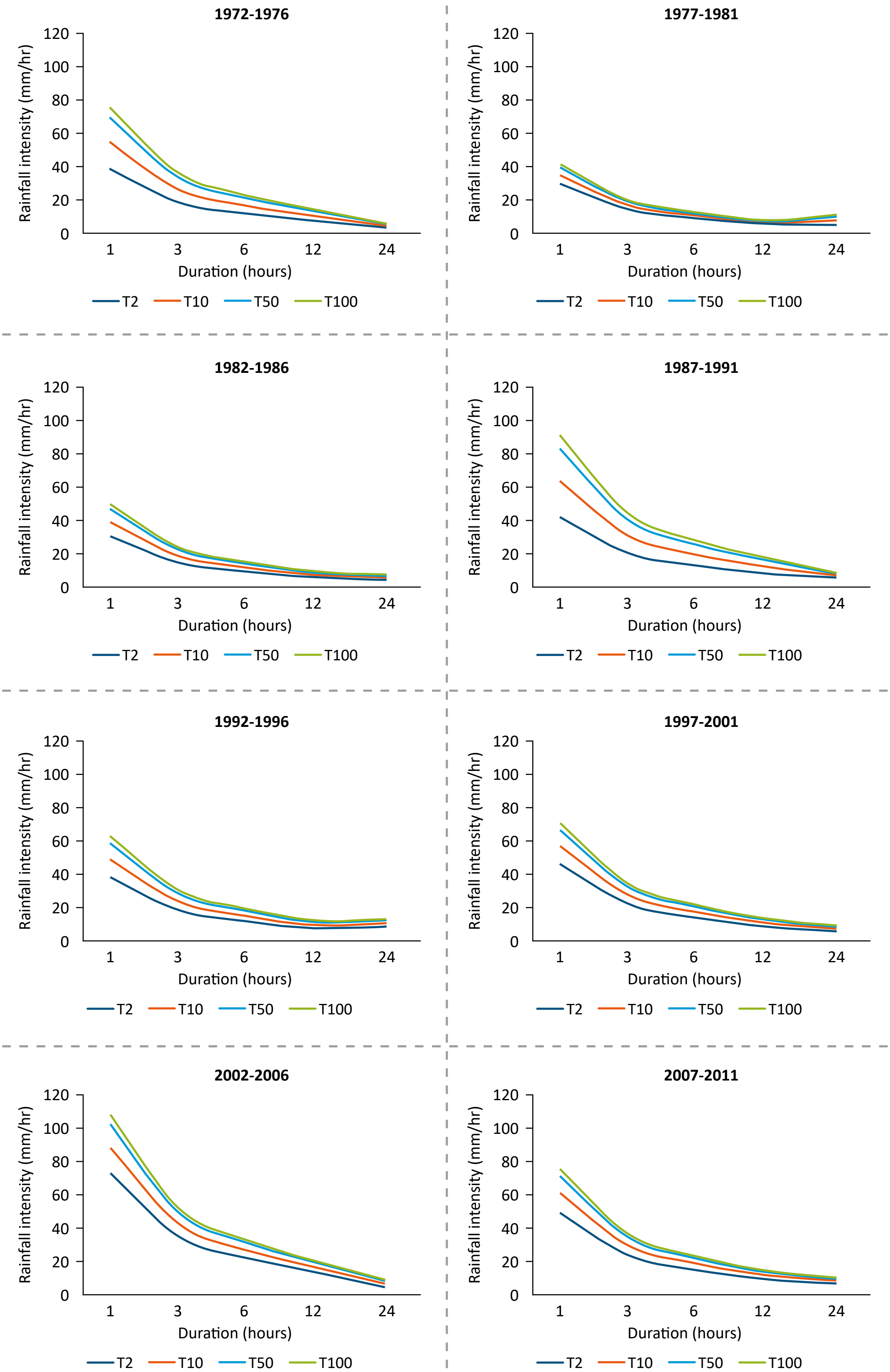
Source: Authors' analysis using IMD rainfall data

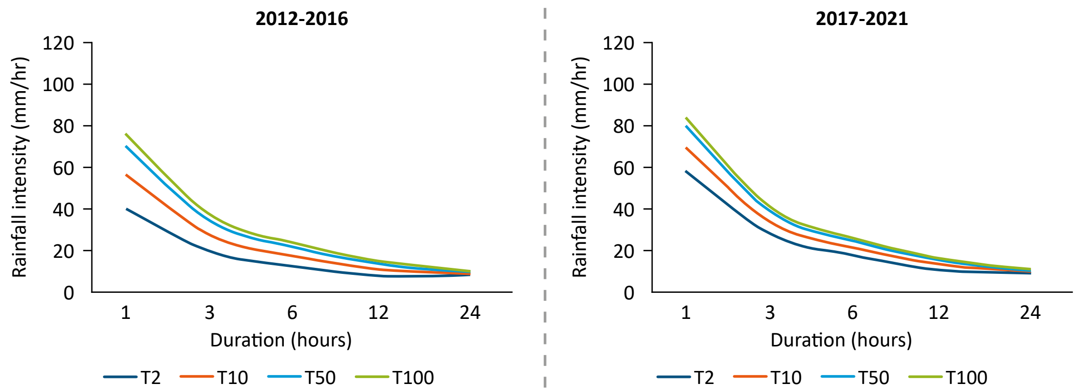
The IDF curves for the analysed time period are presented in Figure 11. Each IDF curve considered five years of daily maximum rainfall. The average rainfall intensity for the entire period was 42.88 mm/hr for a one-hour duration of a two-year return period. Similarly, the average rainfall intensity was 64.98 mm/hr for a one-hour duration of a ten-year return period. It can be observed that every IDF curve behaves differently, with some time periods having lower values than others. The historical flood of 2005 is reflected in the very high rainfall intensity in the graph for the period 2002–2006.

The maximum rainfall intensity was 63.64 mm/hr for a one-hour duration of a two-year return period in 2002–2006. Similarly, the rainfall intensity was 90.86 mm/hr for a one-hour duration of a ten-year return period for 2002–2006.

For the last five years of the analysis (2017–2021), the rainfall intensity was 51.29 mm/hr for a one-hour duration of a two-year return period and 69.96 mm/hr for a one-hour duration of a ten-year return period.

Figure 11: Intensity duration frequency graphs for rainfall in Thane City





Source: Authors' analysis using IMD rainfall data

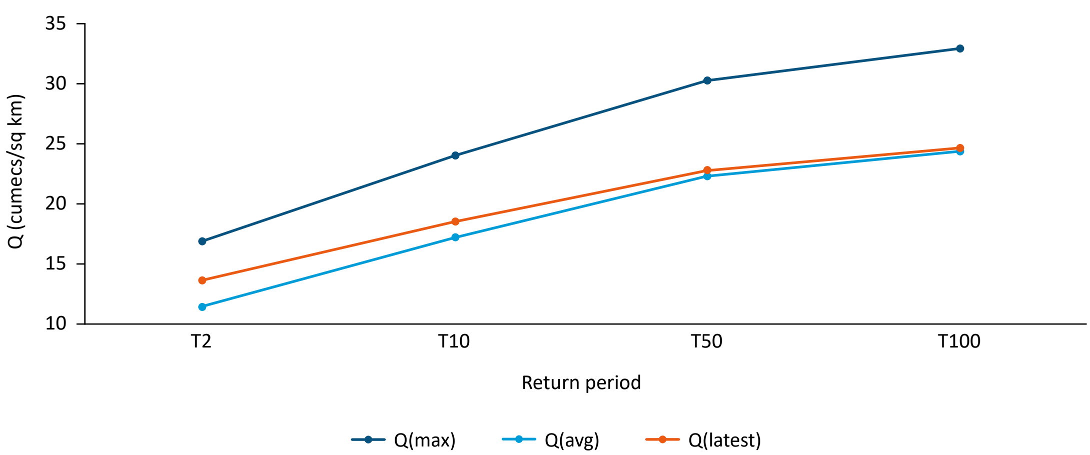
5.2 Peak flow discharge estimation

Following the IDF analysis, the peak flow discharge was estimated. This estimation helps to understand the amount of discharge generated during different events and return periods.

The concentration time was estimated as 1.3 hours, which is the time needed for water to flow from the most remote point in a watershed to its outlet. The rainfall intensity corresponding to 1.3 hours and a return period of 2, 10, 50, and 100 years was considered for estimating the peak flood flow from the total area. For estimation, the entire area under the TMC was considered a watershed. The coefficient of runoff was considered to be 0.72.

The peak flow discharge for the entire TMC area was estimated to be 973.28 cumecs for a two-year storm return period event and 1757.28 cumecs for a ten-year storm return period event. For a more nuanced understanding, peak flow discharge was considered per unit area. Q (avg) refers to the peak flow discharge estimated using the entire period of analysis. Q (max) refers to 2002–2006 when the maximum discharge was observed, and Q (latest) peak discharge refers to 2017–2021, the last five years of the analysis (see Figure 12 and Table 3).

Figure 12: Peak flow discharge estimation for areas under Thane Municipal Corporation for different scenarios



Source: Authors' analysis using IMD rainfall data

Table 3: Peak flow discharge estimation for areas under Thane Municipal Corporation for different scenarios

Return period	Q (max) 2000–2004	Q (average) 1970–2021	Q (latest) 2017–2021
T2	16.77	11.30	13.52
T10	23.95	17.13	18.44
T50	30.24	22.23	22.75
T100	32.90	24.39	24.58

Source: Authors' analysis using IMD rainfall data

The current design capacity of stormwater drains in Thane is approximately 16.37 cumecs per sq km. From Table 3, it is evident that if we consider any of the discharge estimated for an event with a ten-year return period, the current capacity is not sufficient for any scenario, and these events will result in flooding. Additionally, even if we consider the maximum discharge for an event with a two-year return period, the current capacity is insufficient, indicating a high probability of floods in Thane.

Therefore, there is an urgent need to upgrade the current stormwater drainage system in Thane. The TMC plans to upgrade its drainage system through the INDP programme and other interventions.

5.3 Extent of flood inundation in TMC

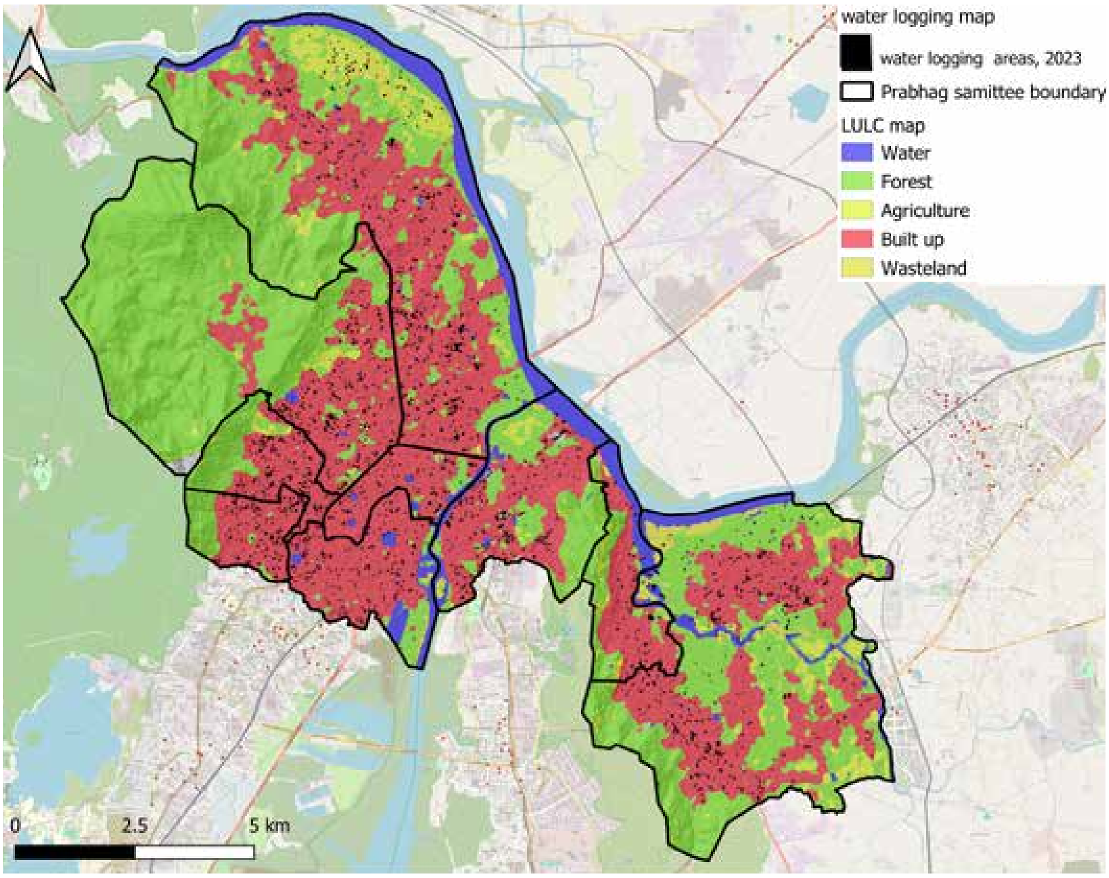
The ward-wise inundated area was estimated for the highest rainfall event each year, considering the past five years for which data was available with TMC (Table 4). Additionally, the major flood event of 28 June 2023 was also mapped; nearly 5 per cent of the total area under TMC was waterlogged in this event (Figure 13).

Table 4: Flood inundated areas in the last five years in a single event

Prabhag Samitee	Ward-wise area inundated (in per cent)					
	05/07/2023	20/09/2022	09/06/2021	08/07/2020	02/07/2019	07/07/2018
Lokmanya-Sawarkar Nagar	8.23	7.50	6.56	7.42	5.38	6.31
Majivade-Manpada	2.95	2.76	1.91	4.76	6.12	1.60
Vartak Nagar	5.40	5.23	3.96	4.71	3.77	2.42
Kalwa	3.49	3.45	2.52	2.88	2.67	2.42
Uthalsar	4.65	5.10	3.39	3.85	3.51	3.69
Mumbra	1.88	1.62	1.45	1.03	2.25	0.65
Diva	2.27	2.12	2.45	2.18	6.37	1.44
Naupada	4.35	4.15	3.59	2.98	3.62	3.39
Wagle	6.22	6.26	5.16	5.54	4.99	5.43

Source: Authors' analysis

Figure 13: Water logging areas in Thane Municipal Corporation following a rainfall event on 28 June 2023



Source: Authors' analysis

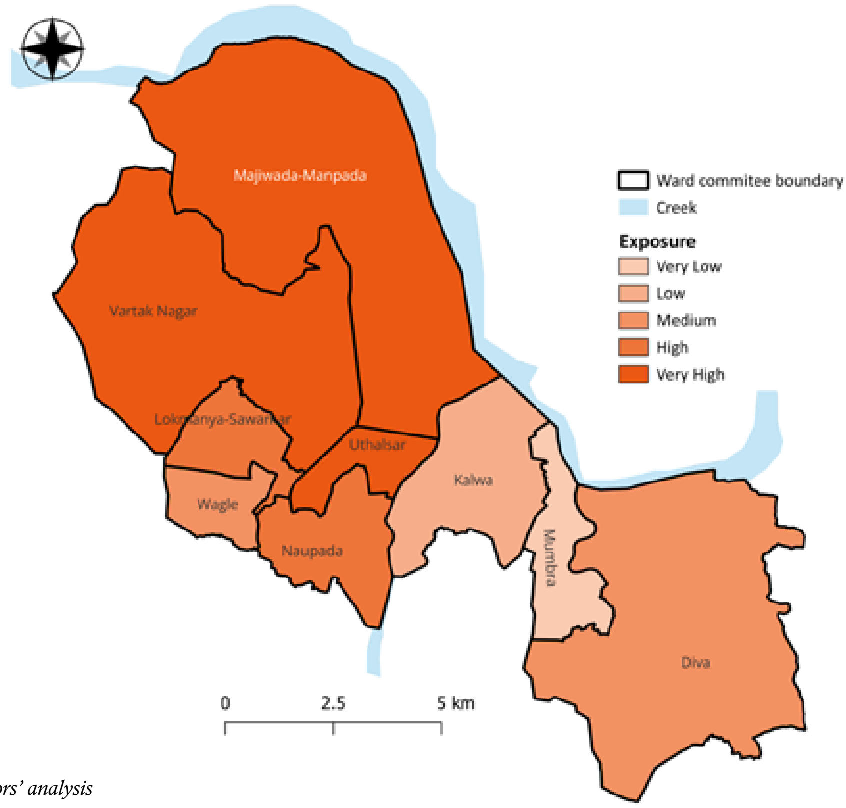
5.4 Urban flood risk index

The urban flood risk index was computed at the *Prabhag Samitee* or administrative ward level for TMC. Based on scores, five categories were created using the natural breaks: very high, high, medium, low, and very low risk. The risk maps and the sub-indices maps are presented in Figure 14.

The computations revealed that Majiwada-Manpada PS was under very high risk, followed by Diva and Naupada PS, which fell in the high-risk category. They were followed by Kalwa, Wagle, and Uthalsar, all falling in the moderate risk category. Lokmanya-Sawarkar Nagar and Mumbra PS were in the low-risk category, followed by Vartak Nagar PS, which exhibited very low risk. The PS-level urban flood risk profiling will help the TMC prioritise the interventions and identify the relevant stakeholders and types of interventions needed for managing floods.

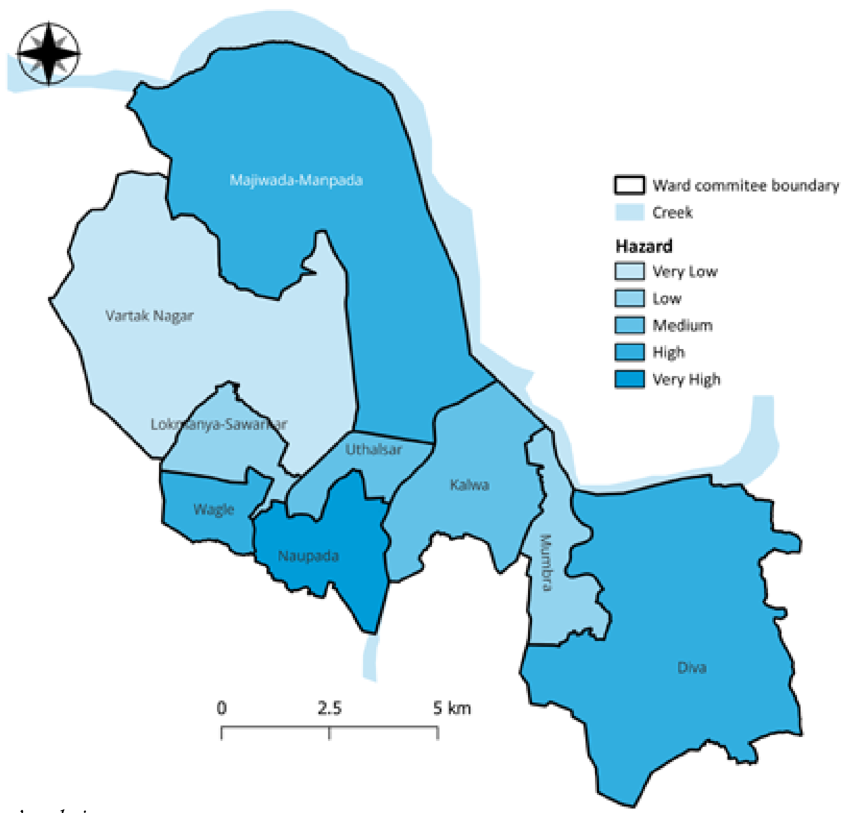
Figure 14: Findings from the urban flood risk index for Thane City: a) hazard, b) exposure, c) vulnerability, and d) risk

(a)



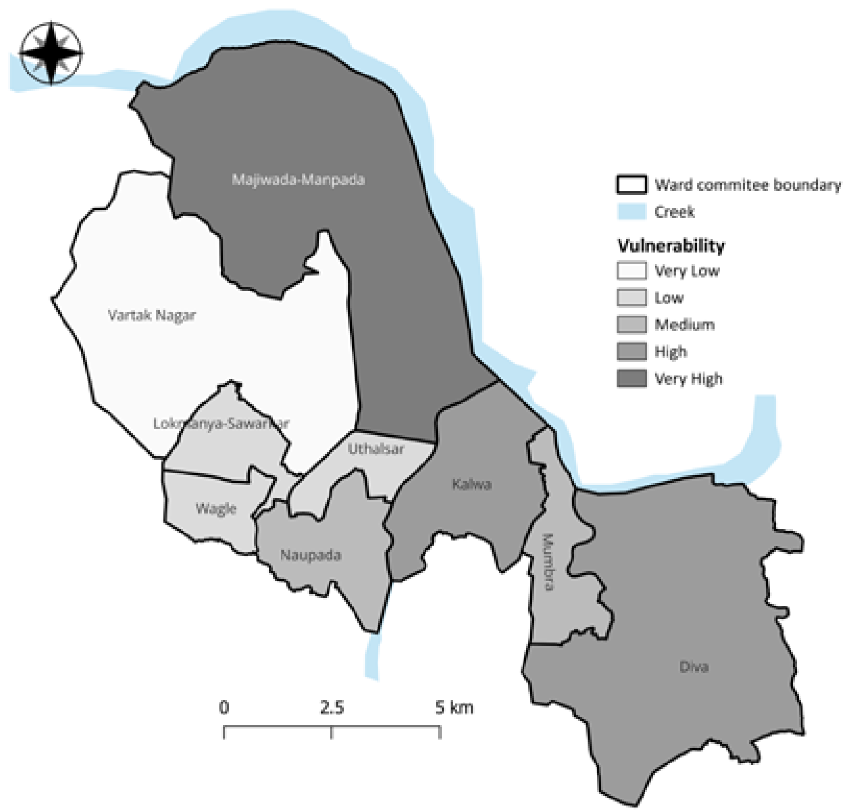
Source: Authors' analysis

(b)



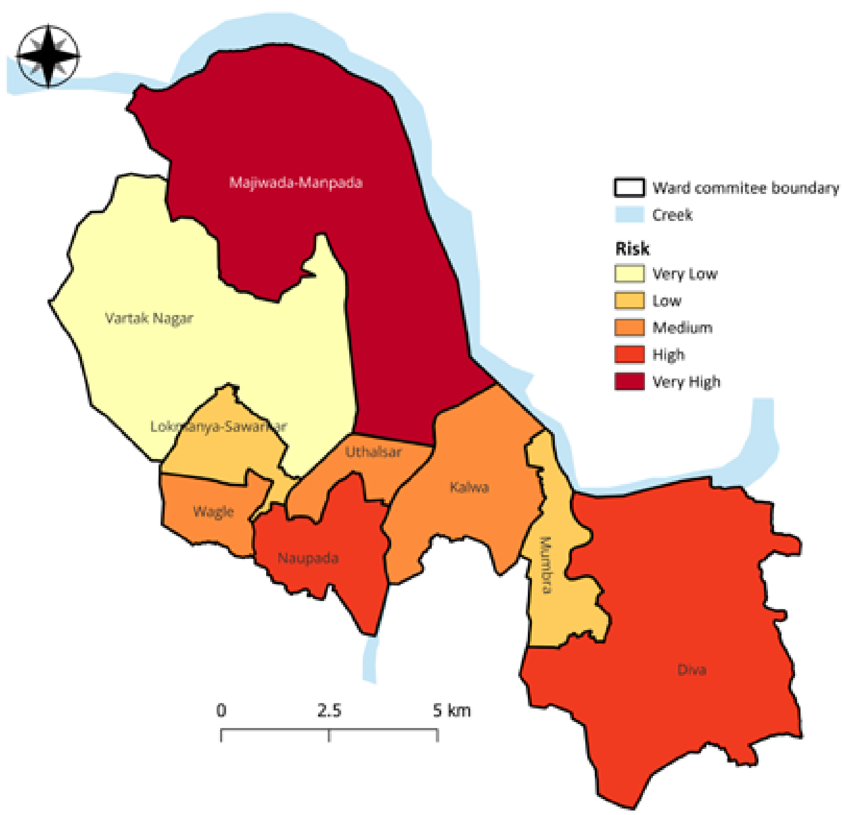
Source: Authors' analysis

(c)



Source: Authors' analysis

(d)



Source: Authors' analysis

Further, we identified the factors (indicators) responsible for high hazard, exposure, and vulnerability scores for each PS (see Table 5). This information offers government stakeholders the necessary details to address potential causes of urban flood risks in specific *Prabhag Samitees* and take targeted actions to enhance urban flood resilience.

Table 5: Factors contributing to urban flood risk in each Prabhag Samitee

Indicators	Majiwada-Manpada	Diva	Naupada	Kalwa	Wagle Estate	Uthalsar	Lokmanya -Sawarkar Nagar	Mumbra	Vartak Nagar	Relation to risk
Hazard										
Instances of water logging events (in the last five years)			■			■				Direct
Proportion of flood inundated area (highest annual flood event in last five years)	■	■								Direct
Exposure										
Population density					■			■		Direct
Stormwater network coverage	■								■	Inverse
Sewage network coverage								■	■	Inverse
Slope					■			■		Direct
Built-up area to the geographical area			■			■				Direct
Vulnerability										
Distance from the estuaries/creek (note: create buffer zones)	■	■								Direct
Households with access to water supply within the premises	■		■			■				Inverse
BPL households	■		■	■				■		Direct
Population with special needs/ disability		■				■				Direct
Proportion of kaccha houses		■						■		Direct
Medical care		■								Inverse
Forecasting and early warning	■				■					Inverse
Response and relief measures	■			■				■		Inverse

Color					
Legend (Risk category)	Very High	High	Medium	Low	Very Low

Source: Authors' analysis

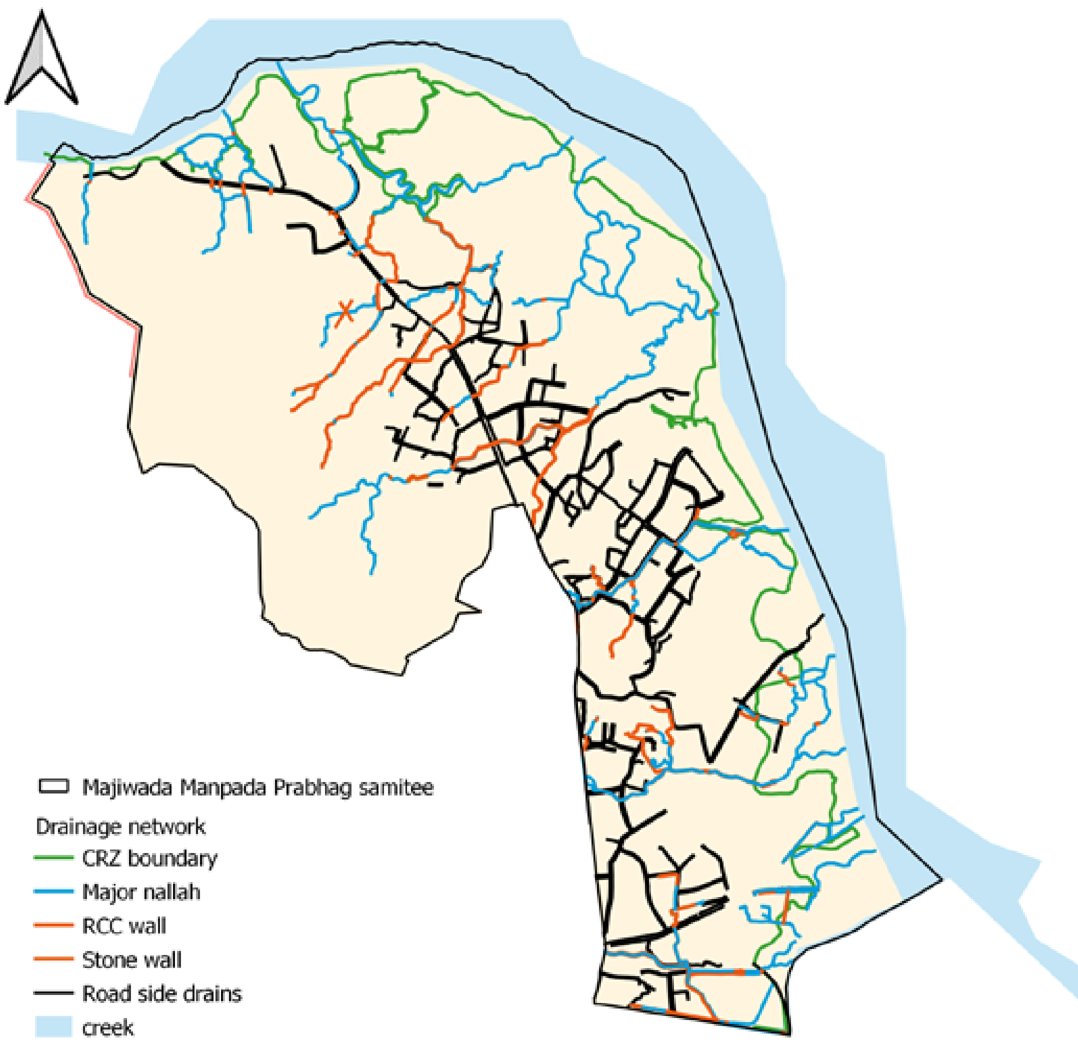
Note: The shaded boxes indicate Prabhag Samitees with the highest risk with respect to that particular indicator

5.5 Hotspot analysis

Hotspot analysis was carried out for two *Prabhag Samitees* falling under the high and very high-risk categories. The urban flood hotspots were identified based on stakeholder consultations and data on past flood events obtained from TMC officials. Further, stormwater drainage network maps, water-logged maps, and slope maps were created to understand the factors contributing to the occurrence of hotspots (Figure 15). These maps can help the officials and relevant authorities plan and intervene in a more informed manner to undertake actions in both pre- and post-flood events, especially in the PS exhibiting a high to very high risk of flooding.

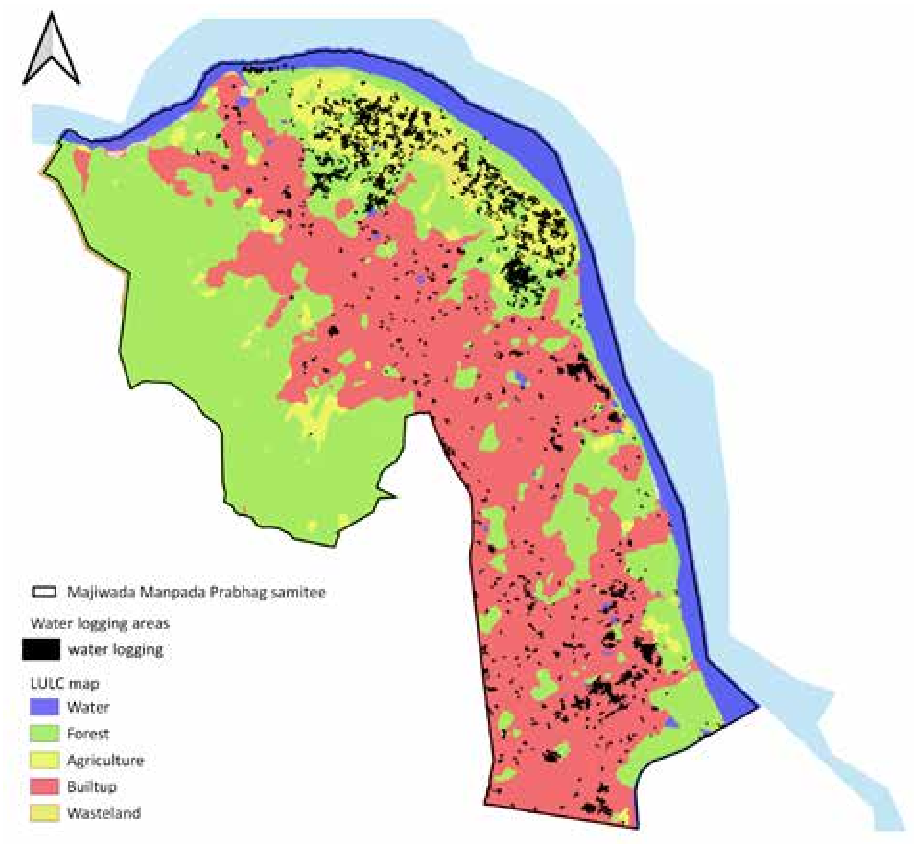
Figure 15: Hotspot analysis for Majiwada-Manpada and Naupada Prabhag Samitees, Thane

(a)



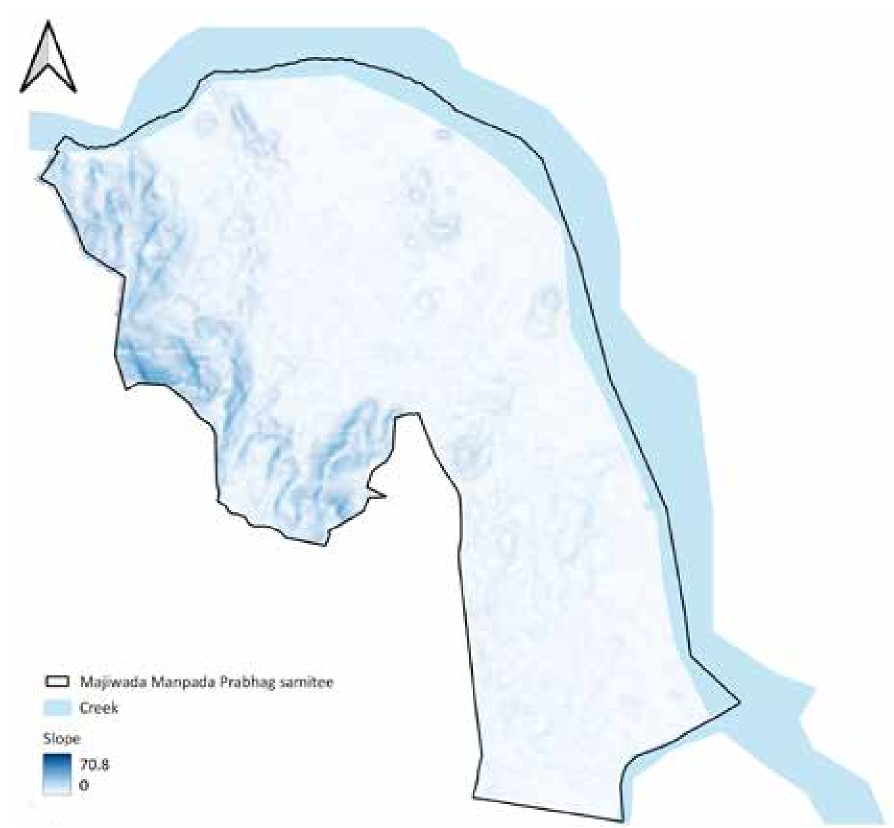
Source: Authors' analysis using TMC data.

(b)



Source: Authors' analysis

(c)



Source: Authors' analysis

(d)

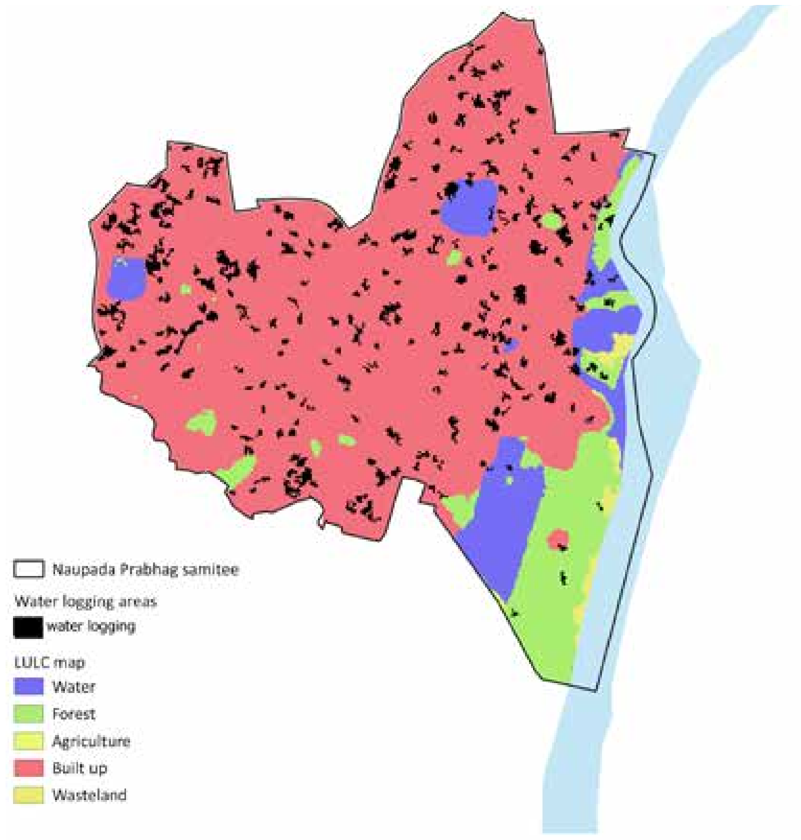
Source: Authors' analysis using TMC data

Naupada

(e)

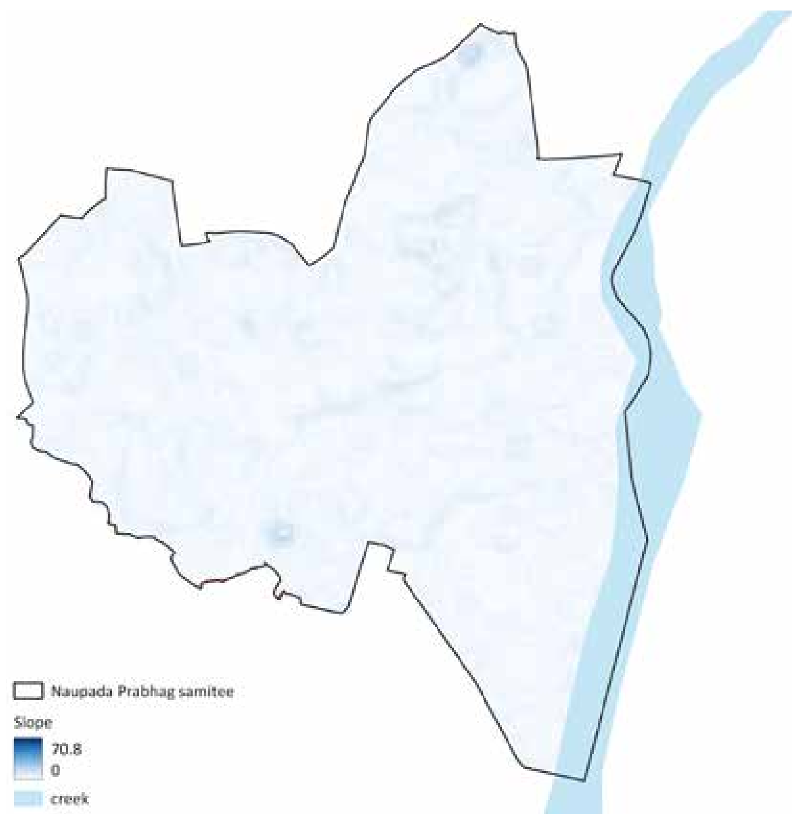
Source: Authors' analysis using TMC data

(f)



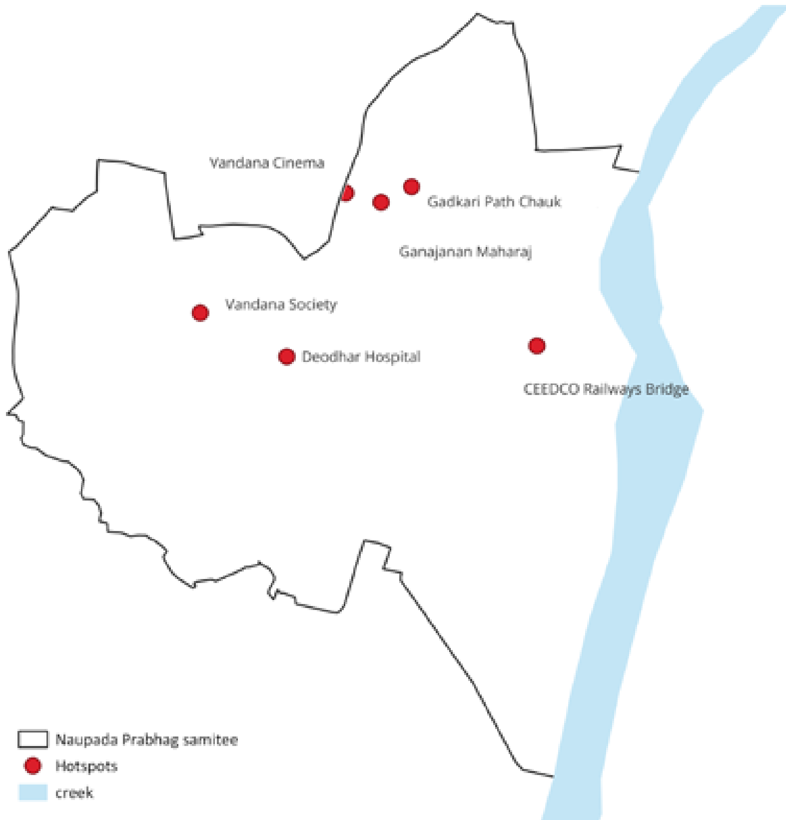
Source: Authors' analysis

(g)



Source: Authors' analysis using satellite imagery

(h)



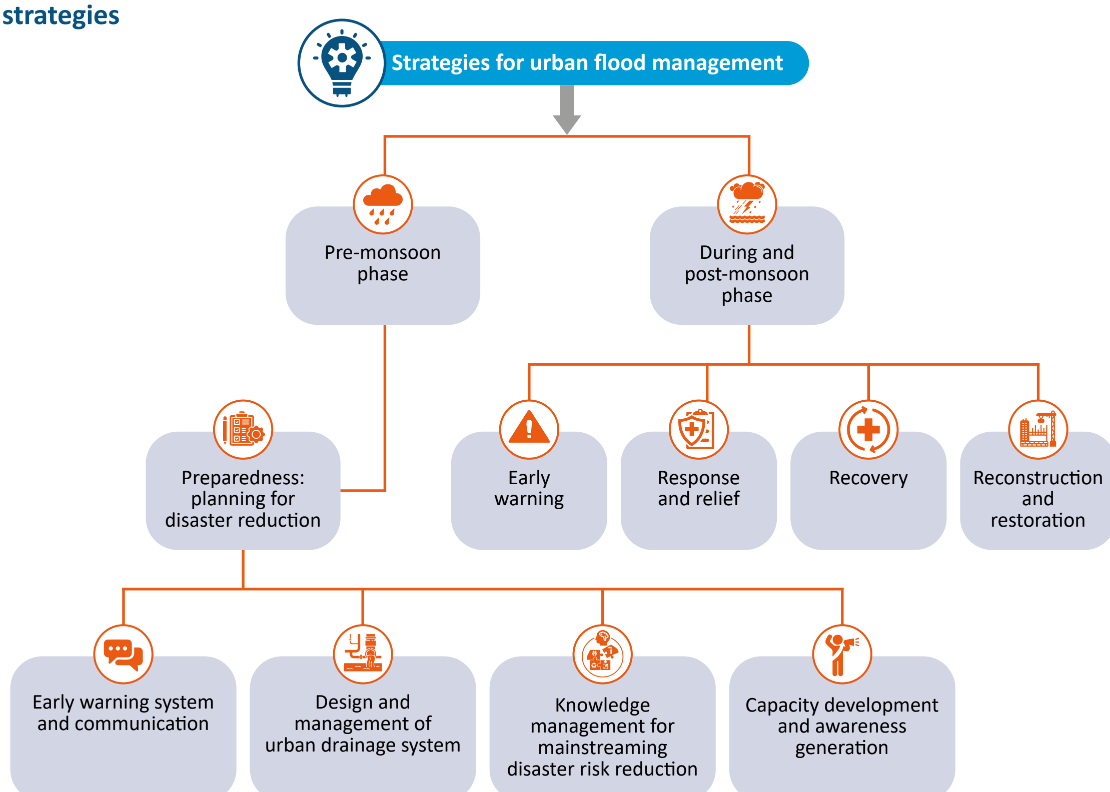
Source: Authors' analysis using TMC data


APARTMENT
COFFEE
AUTO Machine
ECO BUS

6. Urban flood management plan

In the previous section, the scores for each flood risk component – hazard, exposure, and vulnerability – along with the composite score for urban flood risk at the ward committee level were presented. Following this, the Prabhag Samitees were placed under different risk categories based on the composite score. In this section of the action plan, a set of actionable recommendations has been provided, which, once implemented, can play a pivotal role in strategising risk mitigation and adaptation at the ward committee level. The plan (Figure 16) adopted a two-pronged approach where the pre-monsoon phase (December-May) underlined the preparedness phase, and recommendations were made for short-, medium-, and long-term actions. In the second phase, during monsoon (June-September) and post-monsoon (October-November), the hub-spoke model is followed. During the second phase, an Emergency operation centre (EOC) will coordinate the activities of each relevant department. The responsibility of each department during this phase is divided into four major heads: early warning, response and relief, recovery, and reconstruction and restoration.

Figure 16: An effective urban flood management underlines the importance of phase-wise strategies



Source: Authors' compilation

6.1 Pre-monsoon phase

This phase is crucial for preparedness and planning purposes, as both structural and non-structural measures must be implemented to effectively mitigate and adapt to flood risks. These measures need to be duration-specific (short, medium, and long term), and their progress trackable and accountable.

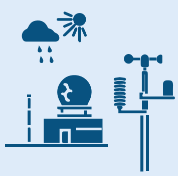
6.1.1 Short-term recommendations

The short-term (0–2 years) recommendations address four major themes: early warning system and communication, design and management of urban drainage system, knowledge management for mainstreaming flood risk reduction, and capacity development and awareness generation (Tables 6 to 9).

Table 6: Recommendations for strengthening local early warning system and communication in the short-term

Theme 1: Early warning system and communication		
Sub-thematic area	**Existing capacity**	**Recommendations**
Local network for forecasting, monitoring, and early warning	Considering the high and very high-risk status of specific ward committees, the network of automatic weather stations (AWS) is currently available at: Majiwada-Manpada: 1 Naupada: 0 Diva: 1	Prioritise the installation of AWS in high and very high-risk ward committees. As per the World Meteorological Organisation (WMO) norms, there should be at least one AWS for 10–20 sq km (IMD n.d). Based on that, the following quantities of AWS networks in high and very high-risk ward committees would be ideal for precise long-term localised forecasting and issuance of timely early warning alerts: Majiwada-Manpada: 2 to 4 Naupada: 1 Diva: 2 to 3

Source: Authors' analysis



After the 2005 Mumbai floods, the Brihanmumbai Municipal Corporation mainstreamed the installation of AWS, which has now reached a total of 120. This effort has enabled the monitoring of rainfall in real-time and has immensely benefited disaster managers in mobilising rescue and relief to flood-affected areas.

Table 7: Recommendations for improving the design and management of urban drainage systems in the short-term

Theme 2: Design and management of urban drainage system		
Sub-thematic area	**Existing capacity**	**Recommendations**
Operation and maintenance of stormwater drains	• Currently, drains are not being cleaned and desilted enough. • Trenching and de-silting of the *nullahs* are done at a small scale. • Restoration of *nullahs* and construction of walls are also done on a small scale.	a. Complete pre-monsoon desilting of all major drains by March 31 each year. b. Additionally, schedule the periodicity of cleaning drains based on the local conditions. c. Do not allow waste removed from the major and the minor drains to remain outside the drain for drying. Dispose of waste promptly.
		d. Follow the Manual on Solid Waste brought out by the CPHEEO (Manual on Storm Water Drainage Systems 2019b) in cleaning shallow surface drains. e. Implement interventions such as traps, comminutors, and trash racks in the drainage system to reduce the amount of solid waste going into the storm sewers. f. Replace ageing stormwater and sewerage systems on an urgent basis.
Special design consideration	Yet to be mainstreamed.	g. Mill the existing layers of the road during re-levelling works or strengthening overlay works to prevent an increase in road levels.
Rainwater management	TMC has mandated rainwater harvesting (RWH) in all new upcoming urban infrastructure. The RWH scheme proposed by the developer needs to get approval from the consultant, who has expertise in geohydrology and is based in the Environment Management Cell of the TMC. This initiative has been undertaken to harness the runoff.	h. Incorporate the concept of rain gardens when planning public parks and on-site stormwater management for larger colonies and sites. Encourage stakeholders to adopt such concepts even on sites that have already been developed.

Source: Authors' analysis using NDMP (2019) and the National Disaster Management Guidelines: Management of Urban Flooding (2010).

Table 8: Recommendations for mainstreaming flood risk reduction through knowledge management in the short-term

Theme 3: Knowledge management for mainstreaming flood risk reduction (Based on the global goal on adaptation)		
Sub-thematic area	**Existing capacity**	**Recommendations**
Vulnerability risk assessment Ward-level hazard risk vulnerability analysis (HRVA)	The disaster management cell conducts exercises on hazard assessment, but a full-fledged HRVA is not undertaken.	a. Prepare and document micro-scale hazard vulnerability and zoning maps, especially for high and very high-risk ward committees, to prioritise the development of appropriate mitigation plans. b. Undertake institutional mapping and capacity assessment of stakeholders (government and community-based) at the ward level to manage flood risk.
Economics of financing flood risk reduction	Yet to be mainstreamed.	c. Prepare estimates of damages from past flooding events based on relevant flood characteristics (flood depth, flow velocity, water quality, duration, and sediment load) to develop a baseline for damage assessment. d. Prioritise ward committees falling under high and very high-risk categories to estimate the financial requirements for flood risk reduction. e. Formulate a comprehensive flood loss damage assessment framework incorporating direct and indirect losses.

Source: Authors' analysis using NDMP (2019), Ministry of Home Affairs (MHA) and National Disaster Management Guidelines: Management of Urban Flooding (2010).

Bhubaneswar's hazard risk vulnerability analysis (HRVA) has been carried out under the GoI-UNDP project 'Enhancing Institutional and Community Resilience to Disasters and Climate Change'. It aims to integrate disaster risk reduction measures into development programmes and under mitigation and adaptation activities based on scientific analysis.

Table 9: Recommendations for capacity development and awareness generation in the short-term

Theme 4: Capacity development and awareness generation		
Sub-thematic area	**Existing capacity**	**Recommendations**
Formation of task force/volunteer group (TF/VG)	NGOs and civil societies are roped in during the response and relief phase, but no comprehensive guidelines exist for mainstreaming their participation in the overall flood management cycle.	a. Encourage residents to constitute and be a part of task force/volunteer groups on floods. This can include residents, ex-servicemen, retired police, or paramilitary personnel. b. Encourage resident welfare associations (RWAs) to head the task force as they hold influence over residents. Involve women and youth organisations such as the National Service Scheme (NSS), National Cadet Corps (NCC), accredited social health activist (ASHA), and auxiliary nurse midwives (ANMs). This would lead to better outreach at the grassroots level and ensure ready availability for immediate assistance on the ground in the event of any disaster.

Theme 4: Capacity development and awareness generation		
Sub-thematic area	**Existing capacity**	**Recommendations**
		d. Develop dedicated training modules for VG/TFs and conduct mock drills at frequent intervals with the support of civil defence, the Thane Disaster Response Force (TDRF), the State Disaster Response Force (SDRF), and the National Disaster Response Force (NDRF).
Mock drills and exercises	Its frequency varies across different wards.	e. Prioritise ward committees that are in high and very high-risk zones. f. Schedule emergency mock drills involving local administration/staff and community-based organisations. g. Convene TF/VG meetings at regular intervals.

Source: Authors' analysis using NDMP (2019) and National Disaster Management Guidelines: Management of Urban Flooding (2010).

6.1.2 Medium-term recommendations

The medium-term (3–5 years) recommendations also span across the four themes: early warning system and communication, design and management of urban drainage system, knowledge management for mainstreaming flood risk reduction, and capacity development and awareness generation (Tables 10 to 13).

Table 10: Recommendations for strengthening early warning systems and communication in the medium-term

Theme 1: Early warning system and communication		
Sub-thematic area	**Existing Capacity**	**Recommendations**
Upscaling of flood early warning system	Under the Thane *Urban Flood Alert Network* (TUFAN), early warning systems based on Internet of Things (IoT) are installed at six locations. It includes four ultrasonic and two radar-based water-level sensors and 1 AWS.	a. Install similar IoT-based early warning systems on the *nullahs* that are in close proximity to flood hotspots identified by the Stormwater Department and in this action plan.
Establishment of an Urban Flood Management Cell	The presence of an Integrated Command and Control Centre (ICCC) under Thane Smart City Limited	b. Transform the existing Integrated Command and Control Centre (ICCC) into an urban flood management cell, which would serve as the technical hub for monitoring and forecasting. It would also integrate data with social media platforms and other broadcasting mediums to disseminate early warning alerts for wider outreach. In future, it can further transform into multi-hazard data management centre.

Source: Authors' analysis using NDMP (2019) and National Disaster Management Guidelines: Management of Urban Flooding (2010).

The Mumbai Integrated Flood Warning System (IFlows) is designed with a modular structure that includes information on potential possible flood-prone areas, estimated floodwater levels, and identification of location-wise problem areas across all 24 wards. This information is used to assess the vulnerability and risk of elements exposed to flood.

Table 11: Recommendations for improving the design and management of urban drainage systems in the medium-term

Theme 2: Design and management of urban drainage system		
Sub-thematic area	**Existing capacity**	**Recommendations**
Preparation of stormwater drainage inventory using geographical information system (GIS) mapping	Drainage maps exist for TMC but are scattered.	a. Undertake GIS mapping of drainage system considering slope, land use land cover (LULC), and sewer network. b. Complete separation of stormwater from sewerage system.
Contour mapping	Low spatial resolution mapping	c. Undertake high spatial resolution contour mapping
Drainage mapping based on run-off coefficient for long-term planning	Currently, it is used as 0.72	d. Designing of stormwater drainage system considering the run-off coefficient up to C = 0.95 or land use changes and estimated peak flood flow volume for every alternate year.
Replacing ageing infrastructure	Not structured well	e. Renovate existing structures identified by the officials.
Runoff management using nature-based solutions	• Under Thane Smart City Limited, waterfront development and creek line restoration interventions are undertaken. The latter focuses on protecting creek bio-diversity as a measure for flood risk management. These are carried out based on coastal regulation zone guidelines (CRZ). Further, activities that relate to responsible tourism are also promoted. • Thane has several lakes; however, they are not managed to enable ecosystem services and benefits such as flood regulation.	f. Mainstream storage-oriented approach: • Run-off retention: Recharge wells, porous pavements, rain gardens, and natural lakes. • Run-off detention: Detention ponds, artificial lake/reservoir/ponds, natural wetlands, including lakes. (Refer to Annexure 5 for nature-based solutions)

Source: Authors' analysis using NDMP (2019) and National Disaster Management Guidelines: Management of Urban Flooding (2010).

Table 12: Recommendations for mainstreaming flood risk reduction through knowledge management in the medium-term

Theme 3: Knowledge management for mainstreaming disaster risk reduction (Based on the global goal on adaptation)		
Sub-thematic area	**Existing capacity**	**Recommendations**
Planning and implementation of urban flood risk reduction measures	A preliminary study has been carried out for *Climate Resilient City Action Plan Thane.*	a. Constitution of expert advisory committee for operationalising the components of the action plan and its revision in the future. b. Members of the Expert Advisory Committee can include representatives of: • Municipal Commissioner (Chairman) • Stormwater Department • Water Supply Department • Parks and Garden Department • Town Planning Department • Sewerage Department • Regional Disaster Management Cell (RDMC) • Health Department c. External experts should be from the domain of: • Disaster risk reduction (DRR) strategies and planning • Financing DRR • Social experts • Water resources and hydrology d. Prioritise the ward committees in high and very high-risk zones. e. Harness HRVA analysis for the development of a ward-wise risk assessment inventory. f. Inventorise ward-wise land use patterns by integrating proposed development plans. g. Prepare a ward-specific flood risk reduction plan constituting mitigation and adaptation measures (structural and non-structural) for a complete disaster management cycle.
Disaster risk transfer (relief and insurance)	There are no specific guidelines on flood risk transfer.	h. Map ward-wise vulnerable urban population. Use the urban flood risk index (UFRI) developed by CEEW for Thane, which is presented in this action plan. i. Research how floods impact vulnerable populations to devise a realistic relief package. j. Explore appropriate public-private partnership (PPP) models for delivering micro-insurance and micro-credit services, especially for flood-affected vulnerable sections, to ensure effective risk transfer. k. Avail assistance from private/public insurance companies and community-based organisations (CBOs) for awareness generation and public sensitisation on available schemes and interventions by the TMC.

Source: Authors' analysis using NDMP (2019) and National Disaster Management Guidelines: Management of Urban Flooding (2010).

Table 13: Recommendations for capacity development and awareness generation in the medium-term

Theme 4: Capacity development and awareness generation		
Sub-thematic area	**Existing capacity**	**Recommendations**
Institutional capacity development needs to be carried out on a regular basis	A common training module has been developed for all disasters but not exclusively for floods.	a. Make RDMC a nodal department, and prepare a comprehensive training module dedicated to urban flooding with well-defined roles and responsibilities for each relevant department. b. Draft department-specific capacity development charter. For instance, the SWM department needs to be provided training on the operation and maintenance of *nullahs*. c. Ensure close coordination between the disaster management cells of the State Administrative Training Institute (ATI) and RDMC of ULBs for robust multi-layer capacity development.
Strategising for the wider outreach of early warning alerts	Early warning alerts are sent out through the TUFAN app. (Annexure 6 presents the current sensor locations)	d. Make ICCC the brain and nerve for data monitoring, forecasting, and sharing warning alerts. e. Embed it with social media and other broadcast mediums such as SMS alerts and community radio for wider outreach with Dos and Don'ts guidelines.

Source: Authors' analysis using NDMP (2019) and National Disaster Management Guidelines: Management of Urban Flooding (2010).

Flood Control Centre, Bangkok

The Bangkok Metropolitan Authority has adopted a data-informed decision-making approach, establishing a Flood Control Centre (FCC). The FCC acts as the master station and receives data from 69 remote sites covering 1000 sq km. It plays a pivotal role across all phases. During the pre-monsoon phase, it provides evidence-based data for improving planning regulations to protect green areas that have the potential to retain flood water. During the monsoon phase, it monitors the flood and drainage situation in real-time. Further, the alert system is embedded with social media to ensure wider outreach.

6.1.3 Long-term recommendations

Long-term (more than five years) recommendations are focused on one theme – the design and management of urban drainage systems (Table 14).

Table 14: Recommendations for improving the design and management of the urban drainage system in the long run

Theme 2: Design and management of urban drainage system		
Sub-thematic area	**Existing capacity**	**Recommendations**
Complete coverage and separation of drainage system	TMC has a *nullah* network of a total of 278 km, of which 147 km is completed	a. Complete the separation of stormwater from sewerage systems in a phased manner by prioritising the high and very high-risk ward committees.
Floodproofing of evacuation infrastructure		b. Floodproof bus yards, metro terminals, railway stations, and airports by providing efficient drainage for high-intensity rainfall.

Source: Authors' analysis using NDMP (2019) and National Disaster Management Guidelines: Management of Urban Flooding (2010).

6.2 Monsoon and post-monsoon phase

In this phase, swift and prompt action is needed for effective flood response. The strategy that needs to be followed during the monsoon (June-September) and post-monsoon phases (October-November) across four major heads of early warning, response and relief, recovery, and reconstruction and restoration are discussed using a hub-spoke model. During this phase, an Emergency Operation Center (EOC) takes charge of the activities and coordinates with relevant departments to ensure an effective response to minimise adverse flood impacts. The EOC acts as a hub for relevant departments during the monsoon and pre-monsoon phases (Figure 17). The roles and responsibilities of various stakeholders are presented in Table 15.

Figure 17: During the monsoon and post-monsoon phase, an Emergency operation centre (EOC) would serve as a coordination hub for various departments

Source: Authors' compilation

Table 15: Stakeholder responsibility matrix across each phase during the monsoon and post-monsoon period

Phases / Departments	Early warning	Response and relief	Recovery	Reconstruction and restoration
Regional Disaster Management Cell	• Setting up an Emergency operation centre (EOC). • Coordinate with ICCC to continuously monitor the flood situation, issuing warnings, and sending out alerts to citizens. • Activate ward-level disaster management plan in consultation with relevant departments.	• Deploy rescue teams with all necessary tools and equipment. • Coordinate with EOC, NDRF, SDRF, and civil defence for an inventory check of the necessary equipment in each ward, such as dewatering pumps, emergency vehicles, stand-by boats etc. • Coordinate with Assistant Municipal Commissioner (AMC) in each ward committee to set up temporary shelters with a safe water supply, food packets, and essential medicines. • Coordinate with the Transport Department and Traffic Police to ensure connectivity.	• Set up relief camps and temporary rescue zones. • Provide relief material, including food, water, and other consumables • Coordinate with local task forces/ volunteer groups/ NGOs/youth organisations to generate awareness for various relief interventions being carried out.	• Compile department-wise action reports and, in coordination with the Urban Flood Management Cell, carry out damage assessment and prepare realistic relief packages, especially for vulnerable sections.
Stormwater Department	• Activate emergency de-silting and drain cleaning action plan for critical drains. • Install high-capacity pumps in low-lying areas. • Keep spare pump sets ready for all locations.	• Coordinate with the EOC to quickly identify affected drains and water-logged areas. • Coordinate with the ICCC to monitor flooding spots and critical drains continuously.	• Repair and monitor maintenance of damaged drain and drainage networks in the flood-affected ward committees. • Pump out water from submerged low-lying areas.	• Restore and refurbish damaged drain and drainage networks. • Prepare zone-wise action reports, update network maps, and submit them to the Urban Flood Management Cell.

Phases / Departments	Early warning	Response and relief	Recovery	Reconstruction and restoration
Public Health Department	• Alert field staff with proper equipment and kits. • Issue alerts to private and public sector hospitals for support. • Maintain an adequate number of ambulances and mobile dispensaries on standby.	• Coordinate with the EOC to quickly identify affected zones for surveillance and response. • Establish makeshift health facilities at disaster/ relocation sites. • Establish temporary morgue facilities at temporary shelters.	• Deploy field staff as needed in the wards/zones. • Ensure adequate supply of medicines, disinfectants, and equipment. • Coordinate with EOC for vector control and fogging.	• Undertake disinfecting measures in contaminated zones. • Coordinate with Police for early disposal of dead bodies. • Prepare and maintain crisis/ epidemic management reports and submit the final report to the Urban Flood Management Cell.
Public Works Department	• Depute the designated officials to EOC to coordinate all activities at the ward committee level. • Identify an adequate number of temporary shelters/sites based on the risk categories of ward committees. • Prepare a disaster response map identifying safe routes and exits in coordination with the Traffic Police.	• Undertake checks to ensure infrastructure remains in operational condition during flooding. • Monitor dilapidated structures and update the list of collapsed structures to coordinate with EOC.	• Provide emergency access in areas where communication links are severely lost/damaged during the event. • Construct emergency structures (levees, among others) to control flood risk.	• Undertake detailed damage assessment of critical infrastructure. • Prioritise repair and restoration work for critical infrastructures. • Prepare an action report and submit it to the Urban Flood Management Cell.

Phases / Departments	Early warning	Response and relief	Recovery	Reconstruction and restoration
Water Supply Department	• Ensure an adequate number of water tankers for emergency supplies. • Identify and map emergency groundwater resources resistant to disasters. • Install water supply outlets (taps/hand pumps/other) above flood level at identified hotspots. • Identify temporary shelter sites to serve as emergency potable water sources. • Deploy mobile toilet vans at temporary shelters.	• Mobilise resources for extracting water from identified emergency groundwater resources. • Make on-site arrangements for potable water supply through tankers.	• Provide safe drinking water supply in temporary shelters, hospitals, etc. • Provide water to mobile toilets for transit and relief camps.	• Restore all services to the pre-disaster phase and maintain quality checks. • Prepare an action report and submit it to the Urban Flood Management Cell.
Fire Department	• Communicate with EOC and different agencies for vital inputs during the warning period. • Keep communication devices in a state of readiness • Ensure the availability and maintenance of equipment and vehicles.	• Evacuate stranded persons from the affected area. • Coordinate with the Transport Department, Public Works Department, Police, and Traffic Police during rescue and evacuation		• Coordinate with other agencies in the restoration stage.

Phases / Departments	Early warning	Response and relief	Recovery	Reconstruction and restoration
Traffic Police	• Depute the designated officials to EOC to coordinate all activities in ward committees. • Prepare an emergency traffic plan, including detailed mapping focusing on strategic routing and safe holding terminals. • Activate a flood contingency plan that maps out exit routes for safe evacuation. It must be prepared in consultation with the development authority, Transport Department, and PWD.	• Deploy traffic staff to help identify and redirect traffic through safe routes. • Give directions whenever necessary to ensure free passage for fire brigade ambulance, police vehicles, and vehicles of other respondents. • Provide information about traffic flow through the media, public address system, signboards, and display boards.	• Control and monitor traffic movements. • Clear roads or pathways of uprooted trees in coordination with PWD.	• Prepare operational and management reports and submit them to the Urban Flood Management Cell.
Power supply	• Activate flood preparedness plan based on alert received from EOC. • Identify sensitive locations around high-risk power installations. • Switch the power supply of critical infrastructure to an alternate and secure power source.	• Ensure emergency power supply lines for medical camps and temporary relief shelters. • Ensure mobile diesel generator sets/solar-powered batteries are on standby for emergency supply.	• Restore power supply in phases as per safety.	• Undertake total restoration in all power supply zones/ any damaged infrastructure. • Prepare a detailed action report and submit it to the Urban Flood Management Cell.

Phases / Departments	Early warning	Response and relief	Recovery	Reconstruction and restoration
Police	• Depute the designated police officials to EOC to coordinate all activities in the zones/wards of the city. • Activate an emergency plan with a focus on the deployment of police personnel.	• Deploy police personnel with rescue equipment. • Assist persons with special needs in evacuation shelters, such as small children, pregnant women, and mothers with nursing infants. • Plan for active patrolling during disasters to maintain law and order.	• Maintain law and order and ensure crowd management. • Ensure safe transportation of personnel, resources, and relief goods to and from the affected area. • Undertake efforts to identify missing persons and notify relatives.	• Ensure law and order for all restoration efforts. • Prepare a detailed action report and submit it to the Urban Flood Management Cell.
Parks and Garden Department		• Assist PWD and Traffic Police in clearing uprooted trees. • Provide clearance for the removal of trees to create safe exit routes.		• Carry out damage assessment for trees and other green cover. • Formulate a plan for restoring damaged trees (if possible) and compensatory afforestation needed post-disaster.
Tele-communication	• Identify high-risk transmission towers. • Ensure the provision of secure communication lines to EOC and other relevant departments. • Ensure the provision of necessary communication channels such as hotlines and ham radio, as well as linking with EOC.	• Deploy portable communication channels at temporary shelters. • Provide portable communication devices to the rescue teams. • Set up an integrated flood relief helpline service (immediate rescue information/ Fire/ Ambulance/ Police and others).	• Inspect and repair communication lines in flood-affected areas.	• Coordinate with the Parks and Garden Department to restore telecom towers damaged by falling trees. • In general, prioritise the restoration of suspended lines and telecom towers.

7. Areas of future work

The Thane City Action Plan for Flood Risk Management is the first of its kind document prepared for the city. A comprehensive assessment was undertaken to suggest flood management interventions, yet some nuances need detailing and should be considered while revising the plan in the future. These include:

- Climate change is expected to further impact the rainfall pattern and intensity in Thane. While the analysis is based on past and present rainfall trends, future revisions should model the projected changes in rainfall due to climate change and its impact on flood risk.
- Thane is a city that is rapidly expanding its urban landscape, resulting in significant changes in land use. The built-up area in the city will increase, which might further block the natural drainages. As the city grows in size and population, the need for sewerage infrastructure will also increase. While the need for separating stormwater drains and sewerage channels has been identified, other city-specific plans, such as a drainage master plan, need to be aligned with the findings and recommendations of this action plan.
- This action plan has identified the urban flood hotspots in administrative wards that are in the high-risk category. Critical infrastructure such as hospitals, schools, fire stations, roads, and electrical substations in these hotspots are likely to get inundated during floods. There is a need to prepare a separate spatial inventory of such critical infrastructure so that they can be protected through the actions undertaken following the recommendations in this plan.
- Effective implementation of urban solid waste management policy in Thane is crucial to support the flood-mitigating activities identified under the plan. The policy should highlight the importance of involving the community and include provisions to raise awareness about the adverse impact of solid waste accumulation in the drains, which leads to blocked drains that exacerbate flooding locally.
- A financial feasibility assessment is necessary to determine the ease of implementing the suggested recommendations. Further, the sources of funds, whether from the central, state, or local administration, need to be determined. Probable sources of funding include the *National Mission on Sustainable Habitat* (NMSH), the *Atal Mission for Rejuvenation and Urban Transformation 2.0* (AMRUT 2.0), and various initiatives of the National Disaster Management Authority (NDMA).

Annexures

Annexure 1: Methodology to estimate IDF curve and peak flood flow

The methodology to estimate the IDF curve and peak flood flow is adapted from Kumar et al. (2022). The intensity of flood-causing rains and the peak flood volume were estimated using historical data on rainfall. For this, the intensity-duration-frequency (IDF) curve of rainfall was developed using the maximum daily rainfall data from 1970 to 2021 for Thane City. This data was accessed from the daily rainfall available from IMD (see Table A1).

Using Gumbel distribution, the statistical analysis of daily and hourly rainfall data was performed. The maximum daily precipitation in a particular year was identified for all the 52 years considered, and ranking was done based on the rainfall values. Using the daily precipitation figures, hourly rainfall depth corresponding to 1, 3, 6, and 12 hours was estimated using the IMD empirical reduction formula presented in equation A1.

$$P_t = P_{24}\sqrt[3]{\frac{t}{24}} \qquad \text{.................(equation A1)}$$

Where, P_t is the required rainfall depth in mm at t-h duration, P_{24} is daily rainfall in mm, and t is the duration of rainfall in h. This method is widely used for short-duration rainfall events.

Gumbel's probability distribution was used to determine the return period (frequency) of storms of different intensities and durations (Chow et al. 1988). As a first step, the frequency factors (K_T) for the desired return periods (T) were computed using equation A2. For this purpose, the return period of 2,10, 50, and 100 years were considered.

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \text{In}\left[\text{In}\left(\frac{T}{T-1}\right)\right]\right\} \qquad \text{.......................(equation A2)}$$

In the second step, the rainfall intensity corresponding to the different durations and their return period was estimated using equation A3, which is based on Chow et al. (1988).

$$X_T = X + K_T S \qquad \text{...............................(equation A3)}$$

Where, X_T is rainfall intensity at a given return period, X is the mean of a particular time, and S is the standard deviation. From the estimated rainfall intensity of different durations and frequencies, the peak flood flow for the city was estimated using equation A4 based on Rodriguez-Iturbe et al. (1979).

$$Q_T = 0.278 * I_T * A \qquad \text{...............................(equation A4)}$$

Where, QT is the design peak discharge in m^3/s, with a return period of T years; I_T is the average rainfall intensity of design rainfall in mm/h, with a return period of T years and with rainfall duration being equal to the time of concentration, and A is the catchment area in sq km.

Table A1: 24-hour maximum precipitation in mm for the period (1970–2021), TMC

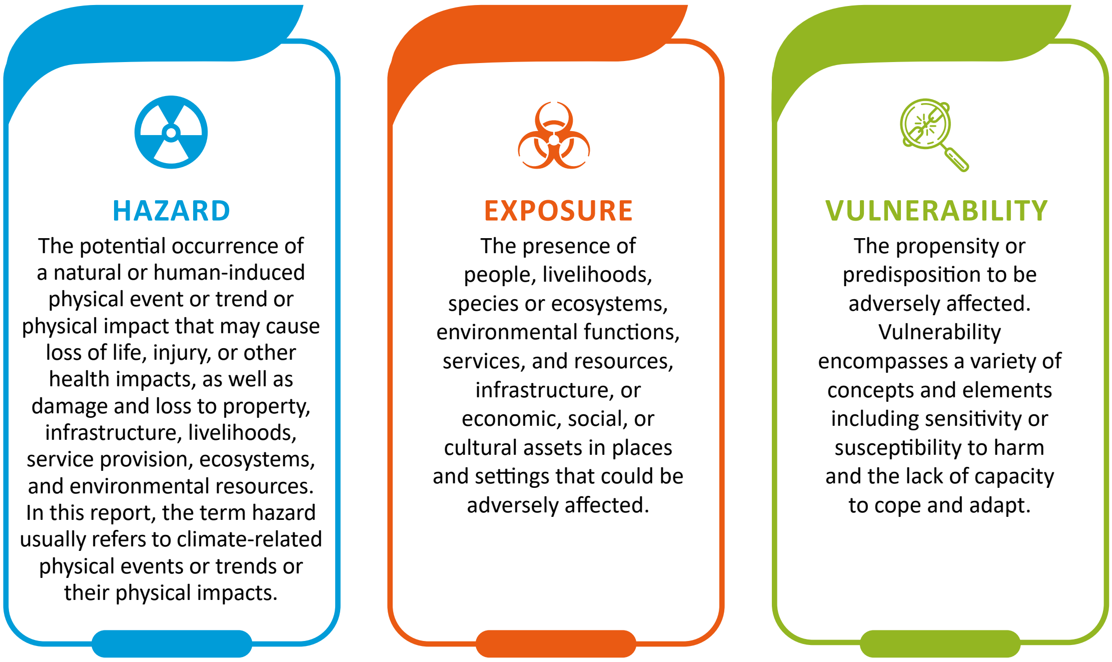
Year	Rainfall (mm)	Year	Rainfall (mm)
1970	90.86	1996	114.11
1971	94.86	1997	149.58
1972	113.48	1998	114.35
1973	85.29	1999	127.34
1974	99.75	2000	166.53
1975	115.58	2001	122.46
1976	169.63	2002	202.32
1977	97.85	2003	202.90
1978	73.43	2004	267.64
1979	81.03	2005	211.23
1980	88.90	2006	187.60
1981	94.26	2007	143.29
1982	72.98	2008	173.68
1983	116.25	2009	157.39
1984	97.12	2010	111.97
1985	86.92	2011	142.10
1986	80.21	2012	85.96
1987	87.73	2013	107.77
1988	157.42	2014	170.12
1989	148.77	2015	115.32
1990	74.54	2016	127.08
1991	169.78	2017	189.91
1992	108.88	2018	142.11
1993	105.60	2019	195.51
1994	148.50	2020	155.38
1995	90.12	2021	168.78

Source: Authors' compilation

Annexure 2: Components of the risk assessment framework

In its AR5, the IPCC highlights three major components of risk: hazard, exposure, and vulnerability. The framework of urban flood risk assessment of the system deals with the flood hazard, exposure of the system to the flood hazard, and vulnerability of the community to disruptions caused by flood hazards. It also highlights that vulnerability is an endogenous characteristic of a system and is determined by its sensitivity and adaptive capacity (in this analysis, a system is equivalent to ward committees). The risk components are defined in Figure A1.

Figure A2: Methodology for developing climatic projections



Source: Authors' compilation using data from IPCC 2014.

The vulnerability component of the risk assessment framework includes the following two sub-indices:

- **Sensitivity,** which refers to the degree to which a system or species is negatively or positively affected by climate variability or change.
- **Adaptive capacity,** which refers to the ability of systems, institutions, humans, and other organisms to adjust to potential damage, seize opportunities, or respond to consequences arising from climatic or anthropogenic causes.

Annexure 3: Selection of indicators for hazard, exposure, and vulnerability assessment

The degree of risk induced through floods depends on various social, physical, institutional, economic, and environmental factors that vary from one locality to another (in this analysis, ward committees). Hence, the degree of risk induced by flooding is expected to vary significantly across each ward committee in TMC.

To determine indicators reflecting the three dimensions of risk—hazard, exposure, and vulnerability, a comprehensive review of literature, both national and global, along with other flood action plans and a handbook of urban flood risk assessment, were undertaken (Ferguson et al. 2023, Osman and Das 2023, Hagos et al. 2022, Rincón, Khan, and Armenakis 2018, Zhao et al. 2023, Muis et al. 2017, Shanableh et al. 2018, Tayyab et al. 2021, Sridhar, Johnson, and Mosuro 2020, Tiwari et al. 2018, ("Report of Sub-Committee for Development of "National Sustainable Habitat Parameters on "Urban Stormwater Management'" n.d., Zhou et al. 2019, Zimmermann et al. 2023, "United Nations Office for Disaster Risk Reduction: 2018 Annual Report | UNDRR" 2019, "Urban Stormwater Management -Potential and Challenges,"). Following that, a series of consultations and discussions were held with various departments and relevant stakeholders within TMC. While the hazard indicators were based on the extent of variability in rainfall and storm events, the final indicator list of exposure and vulnerability (sensitivity and adaptive capacity) reflected the socio-economic, physiological, climatological, and behavioural variables impacting the risk either directly or inversely. A detailed list of indicators, along with their description and data sources, is provided in Tables A2–A4.

Table A2: List of hazard (and associated events) indicators

Categories	Indicators	Description	Correlation	Source
Natural	Frequency of occurrence of extreme rainfall, i.e., magnitude exceeding 100 mm over 24 hours (1970–2021)	Higher magnitudes of rainfall will lead to higher chances of flood occurrences	Direct	Disaster Management Cell and Stormwater Department, Thane Municipal Corporation
	The proportion of flood inundated area (highest annual flood event in last five years) (2018–2023)	The greater the extent of flood inundated area, the greater the hazard it will create	Direct	CEEW analysis based on Normalised Difference Vegetation Index (NDVI) from Sentinel satellite imagery with 10m resolution
	Instances of water logging events or frequency of flooding (in the last five years) (2018–2023)	The municipal corporation keeps a record of the number of complaints reported by civilians in their neighbourhood	Direct	Disaster Management Cell, Thane Municipal Corporation

Source: Authors' compilation

Table A3: List of exposure indicators

Categories	Indicator		Rationale	Correlation	Source*
Social	Population density	-	The higher the population density, the higher the proportion of the population exposed to flood impacts.	Direct	Thane Municipal Corporation, UHC-wise data
Physical	Stormwater network coverage	Existence of a stormwater network	The presence of a stormwater network will lead to reduced exposure to floods.	Inverse	Stormwater Department, Thane Municipal Corporation

Categories	Indicator		Rationale	Correlation	Source*
		Area under stormwater network coverage	A comprehensive stormwater drainage network will ensure systematic disposal of stormwater and minimise the incidents of water logging and the impact of floods.	Inverse	Stormwater Department, Thane Municipal Corporation
	Sewerage network coverage	Sewerage network coverage	A higher proportion of the area covered with the sewer network will minimise the recurring events of water logging, especially during the rainy season, and reduce flooding in the ward.	Inverse	Sewerage Department, Thane Municipal Corporation
		The existence of separate sewage and stormwater network	During a flood, runoff will be channelled through separate systems, thus preventing sewage from mixing with stormwater and preventing the overflowing of sewerage drains. This will improve the adaptive capacity of the region.	Inverse	-
	Slope	Elevation	A higher proportion of the area covered with the sewer network will minimise the recurring events of water logging, especially during the rainy season, and reduce flooding in the ward.	Direct	-
		Slope	The slope influences the direction and amount of surface runoff or subsurface drainage reaching a site. The slope has a dominant effect on the contribution of rainfall to stream flow.		
	Percentage of built-up area to the total area of the ward	-	Built-up areas reduce the surface roughness and enhance the surface runoff coefficient, thereby increasing the risk of flooding and making the area more exposed. Whereas areas having a higher proportion of blue-green spaces would ensure higher run-off detention and promote infiltration in surrounding soil	Direct	CEEW analysis based on Land Use Land Cover Analysis from Sentinel 2A at 10 m

Source: Authors' compilation
Note: *indicators for which the source is not mentioned were not considered for computation.

Table A4: List of vulnerability indicators

Categories	Indicator		Rationale	Correlation	Source*
Physical	Distance from the estuaries/ creek (note: create buffer zone)	-	The relative location of a place from the stream is very important in determining whether this area will be affected by flood or not and to what extent it will be affected. If the distance from the river of an area is greater, it is less likely to be flood-affected. According to studies, the areas most affected by floods are those near these rivers as a consequence of overflow.	Direct	CEEW analysis, based on a topographical map using Google Maps
	Households (HHs) with access to water supply within the premises	-	During flood events, access to common water discharge points will be restricted. Therefore, the presence of a water supply within the premises will enhance their adaptive capacity and lower their vulnerability.	Inverse	Health Department, Thane Municipal Corporation, 2023
	HHs with access to safely managed sanitation services	-	During floods, access to common toilets located outside the dwelling premises will be restricted. Therefore, access to individual toilets within the premises will lower the vulnerability of the HHs and enhance their adaptive capacity.	Inverse	-
Socio-economic	Proportion of the population living below the poverty line	-	During flood events, poor people are generally more vulnerable as they lack access to resources, have low educational attainment, and often lack awareness of flood response measures; hence, their adaptive capacity would be poor to cope with such extreme events.	Direct	Health Department, Thane Municipal Corporation, 2023
	Population with special needs/ disability	-	During flood events, populations with special needs/disability often lack access to basic services due to the absence of disabled-friendly infrastructure, which hampers their mobility and increases their dependency. Hence, they are highly vulnerable to such extreme shock events and have poor adaptive capacity.	Direct	Health Department, Thane Municipal Corporation, 2023

Categories	Indicator		Rationale	Correlation	Source*
	Proportion of people living in *kaccha* houses	-	The higher the proportion of the population living in kaccha houses, the higher their vulnerability and more sensitive they will be towards the flooding impacts	Direct	Revenue Department, Thane Municipal Corporation, 2023
	Literacy rate	-	The higher the literacy rate, the better the population will be prepared to respond to disasters	Inverse	-
Medical	Medical care	Availability of healthcare centres	The higher the number of health care centres in proportion to the population of each ward, the more effective response measures such as medical services first-aid can be activated and the higher the adaptive capacity	Inverse	Health Department, Thane Municipal Corporation, 2023
		Water-borne cases in the last five years	The higher the cases reported (indicating the presence of more breeding sites), the higher the vulnerability and lower the adaptive capacity will be	Direct	Health Department, Thane Municipal Corporation, 2023
Institutional	Forecasting and early warning	Number of functional automated weather stations (AWS)/ automated rain gauge (ARG) in each ward	Functional AWS/ARG would strengthen the early warning system during flood events. This would further help strategise response and relief measures much better in advance, thus enhancing the adaptive capacity of that ward.	Inverse	Disaster Management Cell, Thane Municipal Corporation
		Presence of a dedicated Emergency Operation Center (EOC) connected to the automated rain gauge station (ARG)/AWS in each ward	The presence of EOC will ensure prompt response to the events of urban flooding and thus strengthen the adaptive capacity of that ward.	Inverse	Disaster Management Cell, Thane Municipal Corporation

Categories	Indicator		Rationale	Correlation	Source*
	Response Measures	Identification of suitable sites for temporary shelters for effective evacuation ward-wise	Identifying ward-wise suitable sites for evacuation as the preparatory measure will make the response measure during the event more organised and smooth and thus improve the adaptive capacity.	Inverse	Disaster Management Cell, Thane Municipal Corporation
		Training and orientation programmes conducted to strengthen the ability to manage and cope with disasters involving multi-stakeholder participation, such as government officials, RWAs, SHGs, and NGOs	Capacity-building programmes involving multi-stakeholders enhance the overall adaptive capacity of the wards to cope with extreme events as they ensure better coordination and responsibility sharing.	Inverse	Disaster Management Cell, Thane Municipal Corporation
	Research and documentation	-	Research and documentation are related to flood vulnerability because they help identify and reduce risks. Research aids in locating susceptible communities, infrastructure, and locations, and documentation documents historical occurrences and their effects	Inverse	Disaster Management Cell, Thane Municipal Corporation

Source: Authors' compilation
Note: *indicators for which the source is not mentioned were not considered for computation.

Normalisation and reclassification of indicators

All the indicators were normalised by bringing them to a common scale. For this, the min-max normalisation technique was used to make them unit-free. The normalisation is based on the functional relationship of indicators. For positively related indicators, i.e., where risk increases with an increase in the value of the indicator, the following formula was used:

$$X_{ij}^{P} = \frac{Xij - Min_i\{Xij\}}{Max_i\{Xij\} - Min_i\{Xij\}}$$

For negatively related indicators, i.e., where risk decreases with an increase in the value of the indicators, the following formula was used:

$$X_{ij}^{N} = \frac{Max_i\{Xij\}-Xij}{Max_i\{Xij\} - Min_i\{Xij\}}$$

The indicators after normalisation ranged between 0 and 1, where 1 corresponds to a ward committee with maximum risk, and 0 corresponds to a ward committee with minimum risk.

Annexure 4: Analytical hierarchy process (AHP)

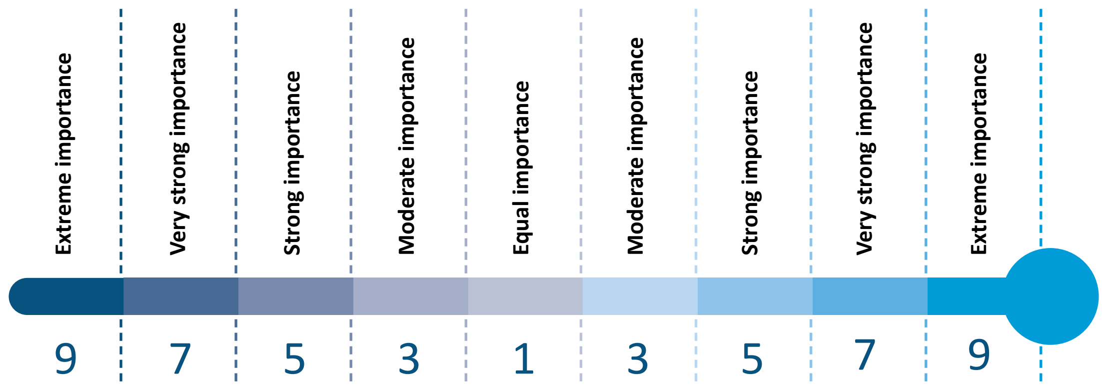
Weightages were assigned to all the indicators using the analytical hierarchy process (AHP). The AHP is a multi-criteria decision modelling tool widely applied within vulnerability and flood risk assessment studies (Hasanuzzaman et al. 2022, Mohanty and Wadhawan 2021, Hoque et al. 2019, Danumah et al. 2016). It is a semi-quantitative approach that allows for stakeholder engagement in determining the relative weights of the indicators being compared. The AHP undertaken for the APFRM involved the following steps:

- **Hierarchy:** The AHP uses a hierarchical structure consisting of a main goal or objective, criteria (or components), and sub-criteria (or indicators). The indicators chosen under each risk component (except hazard) underwent pairwise comparison to arrive at different weightages based on stakeholder judgement. Some indicators for exposure and vulnerability components were clubbed to minimise response fatigue while executing the AHP. As a result, 14 indicators were considered in the AHP analysis. Hazard indicators were considered to have equal weightage and, hence, were not included in the AHP.

- **Pairwise comparison through stakeholder consultation:** To compute weights for the indicators in the AHP, an n x n matrix was developed, where n is the number of indicators within a particular risk component (Pacetti et al. 2022). Within the matrix, indicators were quantitatively compared based on a predetermined scale in sets of two. This scale, developed by Saaty, uses a scale of preference with values ranging from 1–9 (Figure A2 and Table A5) to rate the relative importance of two indicators (Saaty 1987). Data is collected through experts' judgements, called pair-wise comparisons, where stakeholders are asked to assign a value to their subjective judgements. Based on priorities assigned by comparison, indicators are ranked according to their importance, and a weight is assigned to each indicator.

  For the APFRM, pairwise comparison was undertaken at a stakeholder consultative meeting with representatives from eight concerned line departments of TMC, including the Disaster Management Cell, Drainage Department, Environment Department, Health Department, Mechanical Department, Stormwater Department, Town Planning Department, and Water Supply Department. Additionally, input from two subject experts was also obtained. The stakeholders were asked to complete a structured questionnaire to collect individual pairwise comparisons of indicators related to exposure sensitivity and adaptive capacity. The hazard index indicators were not included in the pairwise comparison process as we assumed equal importance for all indicators within the hazard component; all indicators received equal weightage. Similarly, all three risk components (hazard, exposure, and vulnerability) were assigned equal weightage due to their equal importance in contributing to urban flood risk.

Figure A2: Satty scale used for pairwise comparison of indicators



Source: Authors' compilation

Table A5: Relative importance based on Saaty scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two indicators are equally important with respect to the objective
3	Moderate importance	As per experience and judgement, one indicator is slightly more important
5	Strong importance	As per experience and judgement, one indicator has strong importance with respect to the objective over another
7	Very strong importance	One indicator has a much stronger importance than the other
9	Extreme importance	The evidence signalling the importance of one indicator over another is of the highest possible order of affirmation

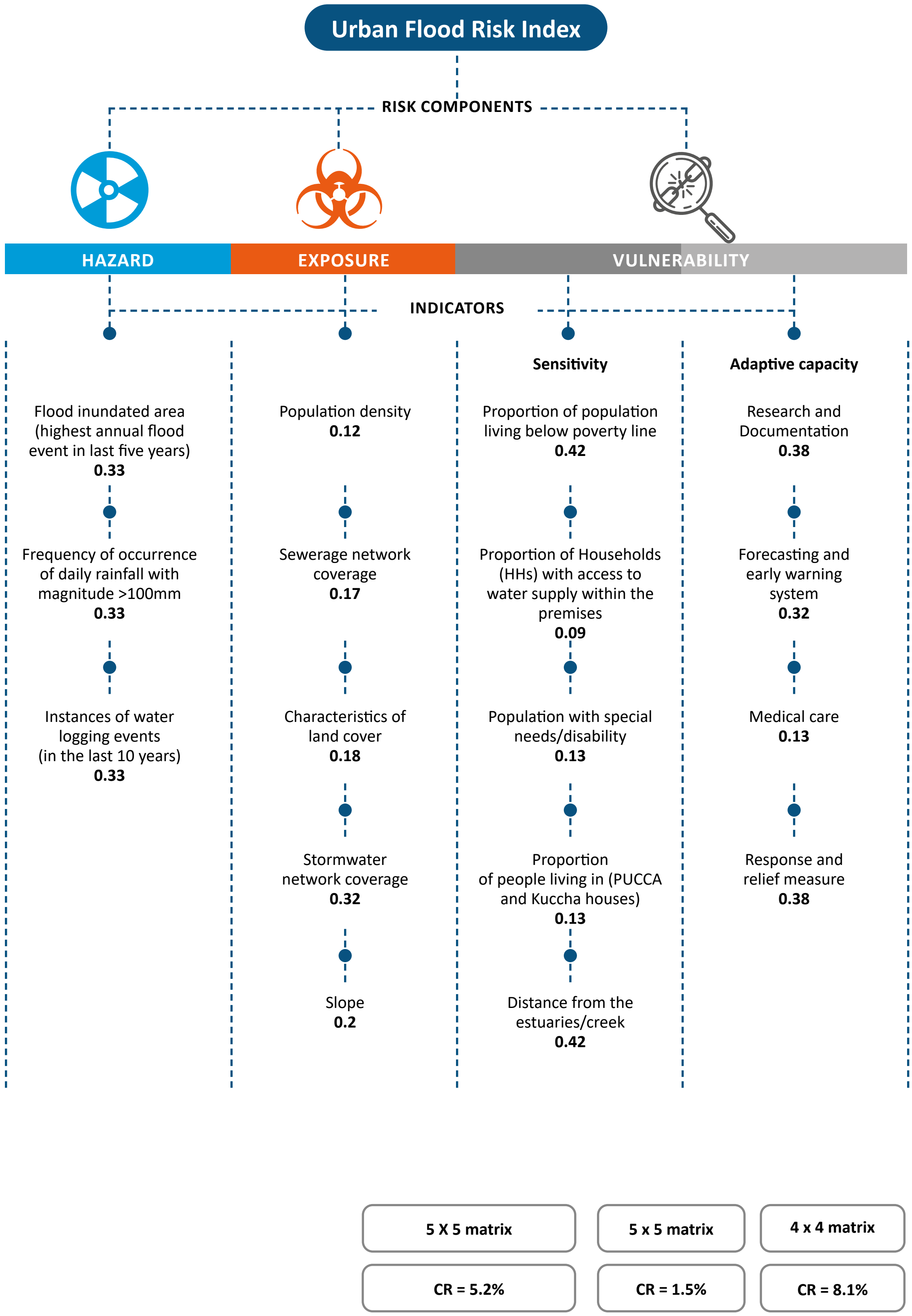
Source: Joerin and Shaw 2011

- **Computation of weights:** Matrices developed from individual stakeholder responses were aggregated to calculate the percentages weights assigned to each indicator relating to the three components. The ten responses were aggregated through the geometric mean method to derive a consolidated preference matrix. The final weights of indicators lay within the range of 0–1 (Figure A3). Finally, the consistency ratio (CR) was calculated to check for consistency in stakeholder judgements using equation A5. For a matrix to be consistent, the CR value should lie below 10 per cent or less than 0.1. The CR of all the consolidated matrices was under 10 per cent.

$$CR = \frac{(\lambda - 1)}{(n - 1)} \qquad \text{.............................(equation A5)}$$

Where λ= maximum eigenvalue of the matrix n= number of indicators. An AHP template (Goepel 2013) was employed to aggregate and analyse the pairwise comparison matrix collected from stakeholders.

Figure A3: AHP approach and results



Source: Authors' analysis

Questionnaires developed for AHP are provided in Tables A6 to A8.

Table A6: Exposure questionnaire

Indicator A	Indicator B	Equal	Relative importance scale				Rationale
		Equal importance (1)	Moderate importance (3)	Strong importance (5)	Very strong importance (7)	Extreme importance (9)	
Stormwater network coverage (SWNC) (The larger the coverage of **SWNC, the lower** the exposure risk)	**Sewerage Network (The larger** the coverage of the **sewerage network,** the **lower** the exposure risk)						
SWNC (The larger the coverage of **SWNC, the lower** the exposure risk)	**Slope (The lower** the **slope** value, the **higher** the exposure risk)						
SWNC (The larger the coverage of **SWNC, the lower** the exposure risk)	**Characteristics of LULC (Higher** the proportion of built-up area, **higher** the exposure risk)						
SWNC (The larger the coverage of **SWNC, the lower** the exposure risk)	**Population Density (The higher** the population density, the **higher** the exposure risk)						
Sewerage Network (The larger the coverage of the **sewerage network,** the **lower** the exposure risk)	**Slope (The lower** the **slope** value, the **higher** the exposure risk)						
Sewerage Network (The larger the coverage of the **sewerage network,** the **lower** the exposure risk)	**Characteristics of LULC (Higher** the proportion of built-up area, **higher** the exposure risk)						

Indicator A	Indicator B	Equal	Relative importance scale				Rationale
		Equal importance (1)	Moderate importance (3)	Strong importance (5)	Very strong importance (7)	Extreme importance (9)	
Sewerage Network (The larger the coverage of the **sewerage network,** the **lower** the exposure risk)	**Population Density (The higher** the population density, the **higher** the exposure risk)						
Slope (The lower the slope value, the **higher** the exposure risk)	**Characteristics of LULC (Higher** the proportion of built-up area, **higher** the exposure risk)						
Slope (The lower the slope value, the **higher** the exposure risk)	**Population Density (The higher** the population density, the **higher** the exposure risk)						
Characteristics of LULC (Higher the proportion of built-up area, **higher** the exposure risk)	**Population Density (The higher** the population density, the **higher** the exposure risk)						

Source: Authors' analysis

Table A7: Sensitivity questionnaire

Indicator A	Indicator B	Equal	Relative importance scale				Rationale
		Equal importance (1)	Moderate importance (3)	Strong importance (5)	Very strong importance (7)	Extreme importance (9)	
Distance from estuaries/ creeks (The lesser the distance from estuaries/ creeks, the more sensitive the area is to flooding)	**Households (HHs) with access to water supply within the premises** (The larger the proportion of HHs with access to water supply within the premises, the lower their sensitivity towards flood risk will be)						

Indicator A	Indicator B	Equal	Relative importance scale				Rationale
		Equal importance (1)	Moderate importance (3)	Strong importance (5)	Very strong importance (7)	Extreme importance (9)	
Distance from estuaries/ creeks (The lesser the distance from estuaries/ creeks, the more sensitive the area is to flooding)	**Proportion of people living in pucca houses** (The higher the proportion of the population living in pucca houses, the lesser will be their sensitivity towards flooding impacts)						
Distance from estuaries/ creeks (The lesser the distance from estuaries/ creeks, the more sensitive the area is to flooding)	**Proportion of the population living below the poverty line** (The higher the proportion of the population living below the poverty line, the higher their sensitivity towards flooding impacts will be						
Distance from estuaries/ creeks (The lesser the distance from estuaries/ creeks, the more sensitive the area is to flooding)	**Population with special needs/ disability** (The higher the proportion of the population with special needs and disability, the more dependent they are and the higher their sensitivity will be)						

Source: Authors' analysis

Indicator A	Indicator B	Equal	Relative importance scale				Rationale
		Equal importance (1)	Moderate importance (3)	Strong importance (5)	Very strong importance (7)	Extreme importance (9)	
Households with access to water supply within the premises (The larger the proportion of HHs with access to water supply within the premises, the lower their sensitivity towards flood risk)	**Proportion of people living in pucca houses** (The higher the proportion of the population living in pucca houses, the lesser will be their sensitivity towards flooding impacts)						
Households with access to water supply within the premises (The larger the proportion of HHs with access to water supply within the premises, the lower their sensitivity towards flood risk)	**Proportion of the population living below the poverty line** (The higher the proportion of the population living below the poverty line, the higher their sensitivity towards flooding impacts						
Households with access to water supply within the premises (The larger the proportion of HHs with access to water supply within the premises, the lower their sensitivity towards flood risk)	**Population with special needs/ disability** (The higher the proportion of the population with special needs and disability, the more dependent they are and the higher their sensitivity)						

Indicator A	Indicator B	Equal	Relative importance scale				Rationale
		Equal importance (1)	Moderate importance (3)	Strong importance (5)	Very strong importance (7)	Extreme importance (9)	
Proportion of people living in pucca houses (The higher the proportion of the population living in pucca houses, the lesser will be their sensitivity towards flooding impacts)	**Proportion of the population living below the poverty line** (The higher the proportion of the population living below the poverty line, the higher will be their sensitivity towards flooding impacts)						
Proportion of people living in pucca houses (The higher the proportion of the population living in pucca houses, the lesser will be their sensitivity towards flooding impacts)	**Population with special needs/ disability** (The higher the proportion of the population with special needs and disability, the more dependent they are, and the higher their sensitivity)						
Proportion of the population living below the poverty line (The higher the proportion of the population living below the poverty line, the higher will be their sensitivity towards flooding impacts)	**Population with special needs/ disability** (The higher the proportion of the population with special needs and disability, the more dependent they are, and the higher their sensitivity)						

Source: Authors' analysis

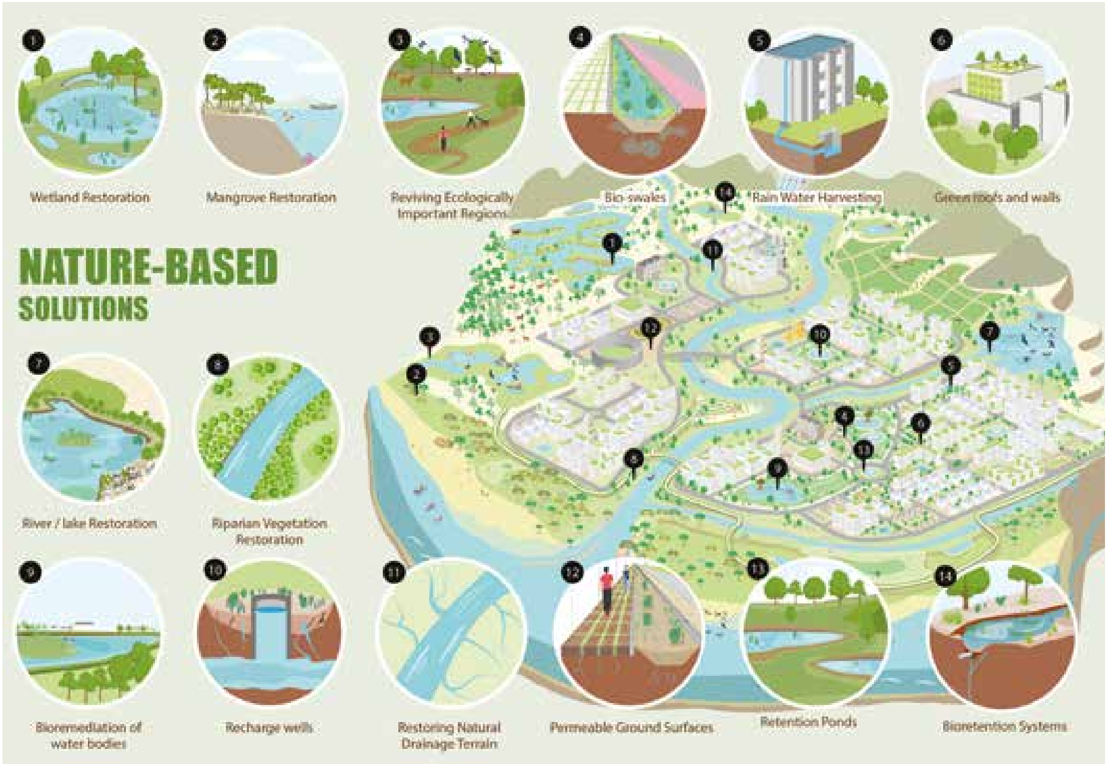
Table A8: Adaptive capacity questionnaire

Indicator A	Indicator B	Equal	Relative importance scale				Rationale
		Equal importance (1)	Moderate importance (3)	Strong importance (5)	Very strong importance (7)	Extreme importance (9)	
Medical care (The higher the coverage of medical care facilities, the better will be the adaptive capacity to respond to flood impacts)	**Forecasting and early warning system** (The more advanced the flood forecasting and early warning system, the more accurate and timely information dissemination will be. Hence, better will be their adaptive capacity)						
Medical care (The higher the coverage of medical care facilities, the better will be the adaptive capacity to respond to flood impacts)	**Research and documentation** (Detailed research and documentation of disaster events and their impacts much improved the institutional understanding for future events and hence better their adaptive capacity)						
Medical care (The higher the coverage of medical care facilities, the better will be the adaptive capacity to respond to flood impacts)	**Response and relief measures** (The better the preparedness and planning for R&R measures, more the promptness in the response action and hence better their adaptive capacity)						

Indicator A	Indicator B	Equal	Relative importance scale				Rationale
		Equal importance (1)	Moderate importance (3)	Strong importance (5)	Very strong importance (7)	Extreme importance (9)	
Forecasting and early warning system (The more advanced the flood forecasting and early warning system, the more accurate and timely would be the information dissemination. Hence, better will be their adaptive capacity)	**Research and documentation** (Detailed research and documentation of disaster events and their impacts much improved the institutional understanding for future events and hence better their adaptive capacity)						
Forecasting and early warning system (The more advanced the flood forecasting and early warning system, the more accurate and timely would be the information dissemination. Hence, better will be their adaptive capacity)	**Response and relief measures** (The better preparedness and planning for R&R measures, more the promptness in the response action and hence better their adaptive capacity)						
Research and documentation (Detailed research and documentation of disaster events and their impacts much improved the institutional understanding for future events and hence better their adaptive capacity)	**Response and relief measures** (The better the preparedness and planning for R&R measures, more the promptness in the response action and hence better their adaptive capacity)						

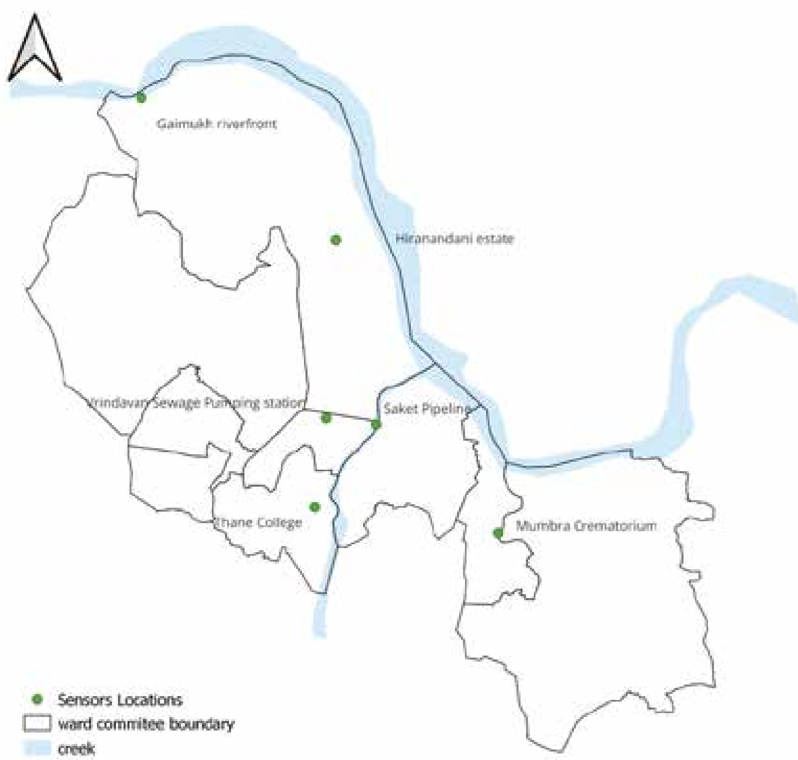
Source: Authors' analysis

Annexure 5: Nature-based solutions under runoff management



Source: NIUA, World Bank, and GFDRR, 2022

Annexure 6: Map of installed sensors in Prabhag Samitees in TMC



Source: Authors' compilation

Acronyms

AHP	analytic hierarchy process
AMC	assistant municipal commissioner
ANM	auxiliary nurse midwife
AR	assessment report
ASHA	accredited social health activist
AWS	automated weather stations
BPL	below poverty line
CBO	community-based organisation
CPHEEO	central Public Health and Environmental Engineering Organisation
CR	consistency ratio
CRZ	coastal regulation zone
DRR	disaster risk reduction
EOC	emergency operation centre
FEWS	flood early warning system
GEE	Google Earth Engine
GIS	geographic information system
HH	households
HRVA	hazard risk vulnerability analysis
ICCC	integrated command and control centre
IDF	intensity duration frequency
IoT	internet of Things
IMD	Indian Meteorological Department
INDP	Integrated Nullah Development Programme
IPCC	Intergovernmental Panel on Climate Change
LULC	land use and land cover
NCC	National Cadet Corps
NDMA	National Disaster Management Authority
NDRF	National Disaster Response Force
NDVI	normalised difference vegetation index
NGO	non-governmental organisation
NSS	National Service Scheme
PPP	public-private partnership
PWD	public works department

RDMC	regional disaster management cell
SDRF	state disaster response force
TDRF	Thane Disaster Response Force
TMC	Thane Municipal Corporation
TUFAN	Thane Urban Flood Alert Network
APFRM	Action Plan for Flood Risk Management
UFRI	urban flood risk index
ULB	urban local bodies
ICLEI	International Council for Local Environmental Initiatives
WMO	World Meteorological Organization

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Notes

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