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Indian metro cities: Focusing on urban floods, Impacts, and vulnerability assessment

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Abstract

The problem is escalating with the escalation of urbanization, use of land, and climate change in India and the city of Indian people. The paper therefore makes a comparison of the impacts and vulnerabilities of floods in four geographic settings, that is, mountain (Mandi), coastal megacity (Mumbai), coastal South (Chennai), and riverine/deltaic (Kolkata) settings, and the semi arid inland (Ahmedabad) setting to derive both region specific, and cross cutting strategies to reduce flood risks in a city setting. The research operationalizes a multi criteria Urban Flood Vulnerability Index (UFVI) which encompasses both hazard (pluvial, fluvial and coastal/tidal drivers) and exposure (people and assets) and sensitivity (socio economic fragility and vulnerability of infrastructures) and adaptive capacity (early warning, institutional preparedness, and nature based buffers). The framework mixes geospatial analysis, hydrologic hydraulic modeling, and stakeholder-derived weights (AHP), and is tested in sensitivity analysis through entropy weighting. Ward/zone levels of analysis of case studies with publicly available datasets and municipal records are used. These findings identify unique risk signatures with flash flood/landslide couplings in Mandi, tide locked drainage with compound flooding in Mumbai, cyclone-linked pluvial fluvial surges in Chennai and Kolkata and pluvial flooding due to short duration extremes falling on solid surface in Ahmedabad. Constraining factors despite their disparate causes remain recurrent, such as drainage that is undersized, encroachment into blue-green networks, and inequality in the service coverage of informal settlements. It ends by following a portfolio of structural and nature based interventions, reforms in governance and community focused preparedness measures depending on the typologies of cities.

Keywords: Urban floods, vulnerability, compound flooding, AHP, UFVI, geospatial analysis, nature-based solutions, India

1. Introduction

The problem of urban flooding has been a major concern in major cities of India as the latter are facing the challenge of both urbanization and climate change simultaneously. With the constant swelling of the Indian population, urban places are increasing at an alarming rate leading to development of huge impermeable surfaces in form of roads and buildings. This transformation has greatly altered the free movement of water, which is a cause of increased number and intensity of floods in the cities. Most urban centers also have old and inefficient drainage systems that cannot accommodate the increment in water volume thus increasing the chances of floods. This problem is also exacerbated by climate change that triggers erratic and severe weather scenarios, such as rainfall events, cyclones, and tidal waves, hindering the flood resilience of the Indian cities further (Agarwal & Soni, 2021; Zope, Eldho, & Jothiprakash, 2015) ^[1, 20].

This paper will compare the five different cities in India to gain insight into how various landscapes within an urban setting in India are at risk of flooding by utilizing the similarities and differences in the five distinct cities of India due to different geographical, climatic and socio-economic conditions in the cities. The cities offer good case studies to understand issues of urban flooding as each city is subject to different drivers of flood risk. The mountainous site of Himachal Pradesh, Mandi, is affected by flash floods provoked by short, high-intensity precipitation combined with mountainside terrain and various related factors, such as an insufficient drainage system (Singh & Yadav, 2023) ^[16]. On the contrary, as a coastal megacity, Mumbai is prone to compound flooding when the level of monsoon rainfall is combined with tidal surges, resulting in a lack of efficient drainage systems that could effectively deal with the floods, especially in places like Dharavi that are known to be flood-prone, all the more due to climate change (Bhat & Shah, 2021) ^[2-3].

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Chennai in the south-east coastal region has been experiencing flooding due to cyclonic rainfall alongside backflow of the rivers that flow close to it, including the Cooum and Adyar, which is further worsened by the loss of wetlands (Vemula *et al.*, 2019; Ghosh & Banerjee, 2021)^[19, 51]. Being a riverine city, Kolkata is also marred by slow drainage and high tide combined with the clogs of the canal networks, which cause the city to become flooded over longer periods of time in the monsoon (Iyer & Reddy, 2022)^[6]. The city of Ahmedabad, located in the semi-arid territories of Gujarat, is susceptible to pluvial urban flooding involved in short-duration storms, with the problem worsened by sprawling and encroachment along floodplains (Patel & Desai, 2020)^[13].

The main aim of the paper is to evaluate what the urban flood vulnerability in such cities are by adopting the Urban Flood Vulnerability Index (UFVI) that is multicriteria-based. The UFVI combines four important variables, which are a hazard (pluvial, fluvial and coastal forces), exposure (concentration of people and assets), sensitivity (socio-economic and infrastructural weaknesses) and adaptive capacity (flood readiness and infrastructural resilience). The described index can be used to make a comprehensive comparison across cities, irrespective of topography, climate and socio-economic backgrounds to offer useful insights on a city specific flood risk reduction strategy. The second objective is to examine the effectiveness of region-specific flood management plans especially in solving the problems peculiar to every city. The above case studies illustrate that urban flood risks are multifaceted and exhibited in different ways, although common systemic issues related to flood risks, which include but are limited to undersized or smaller drainage systems, encroachment of critical blue-green networks, and service inequities regarding informal settlements, were identified (Murali *et al.*, 2020; Sundaram, Devaraj, & Yarrakula, 2021)^[11, 18].

This research aims to contribute to the current body of knowledge on urban flood vulnerability and adaptive measures by analyzing data collected using an effective methodology that entails the geospatial analysis in interaction with hydro-modeling as well as stakeholder feedback to evaluate the scenario using the Analytic Hierarchy Process (AHP). The sources used to provide details into the levels of hazard across these cities include data obtained through the Indian Meteorological Department (IMD), OpenStreetMap (OSM) and Synthetic Aperture Radar (SAR). Flood vulnerability in urban areas provides a good prospect of analyzing how to design future flood resilience planning, especially with the ongoing urbanization process and current uncertainty in weather patterns because of global warming.

The results of this research will serve to influence city planning and the disaster risk reduction policies by determining the most sensitive flood risk areas and providing practical recommendations addressing the ways of enhancing the emergency flood management in cities. Also, the paper touches upon the unjustness of exposure to the risk of floods, especially in the informal settlements characterised by the over-represented exposure to floods through the absence of sufficient infrastructures and defence against floods (Khan & Singh, 2023)^[8]. Specific urban contexts need special flood management measures, which should also involve the inclusion of equitable policies whereby most vulnerable groups are covered so that

reduction of flood risks should benefit every resident of the city, but not necessarily only high socio-economic groups (Sarmah *et al.*, 2020; Kumar *et al.*, 2022)^[15, 9-10]. In the coming paragraphs, more information will be provided into the data and methods employed, and then the case studies will be analyzed in detail and what it means to the applications in the futuristic policies of urban flood management.

2. Methodology

2.1 Study Design and City Selection

Cities were selected to represent key Indian urban flood contexts and regional diversity:

- **Mandi (Himachal Pradesh):** Mountain city prone to flash floods/landslides.
- **Mumbai (Maharashtra):** West-coast megacity with pluvial-tidal compound flooding.
- **Chennai (Tamil Nadu):** South-east coastal metropolis with cyclone-linked extremes.
- **Kolkata (West Bengal):** Riverine/deltaic city along the Hooghly in the Ganga-Brahmaputra-Meghna system.
- **Ahmedabad (Gujarat):** Semi-arid inland city with pluvial flooding and floodplain encroachments along Sabarmati.

2.2 Conceptual Framework

This study adopt the risk structure Risk = f(Hazard, Exposure, Vulnerability, Adaptive Capacity). This study compute a composite UFVI at ward/zone scale:

- **Hazard (H):** extreme rainfall intensity (R), antecedent wetness (AW), slope/landslide susceptibility (LS) in mountains, river level return period (Q), tidal level (T) for coastal wards, drainage density/condition (DD) as a surrogate of flow concentration.
- **Exposure (E):** population density (PD), built-up area/intensity (BU), length of critical roads (CR), and proximity of critical facilities (CF).
- **Sensitivity (S):** share of informal settlements (IS), housing quality (HQ), dependency ratio (DR), sanitation access (SA), and green space per capita (GS—reverse coded).
- **Adaptive Capacity (AC):** early-warning coverage (EWS), storm-pump capacity per hectare (PC), drain maintenance frequency (DM), community preparedness (CP), and blue-green infrastructure extent (BGI).

All indicators are normalized to [0,1]. For cost indicators (higher = worse), This study use min-max:

$$x' = (x - x_{\min}) / (x_{\max} - x_{\min})$$

For benefit indicators (higher = better), This study reverse-scale:

$$x' = 1 - (x - x_{\min}) / (x_{\max} - x_{\min})$$

This study aggregate using weights w_{iw_i} elicited via Analytic Hierarchy Process (AHP) from expert/stakeholder surveys, with an entropy-weighting sensitivity check. Composite indices:

$$H = \sum w_{H,i} x'_{H,i}, \quad E = \sum w_{E,i} x'_{E,i}, \quad S = \sum w_{S,i} x'_{S,i}, \quad AC = \sum w_{AC,i} x'_{AC,i}$$

The UFVI is computed as:

$$UFVI = \alpha H + \beta E + \gamma S + \delta(1 - AC)$$

With $\alpha + \beta + \gamma + \delta = 1$. This study report results under multiple weighting scenarios.

2.3 Data and Processing

- **Hydrometeorological:** daily/sub-daily rainfall (IMD station/gridded), river discharge/levels (state irrigation/water resources), tide-gauge records (port trusts), antecedent precipitation indices.
- **Topography & Land Cover:** DEMs (e.g., CartoDEM/SRTM), slope/curvature; land-use/land-cover from Landsat/Sentinel-2; imperviousness; mangrove/wetland extents.
- **Hazard Evidence:** event flood extents from SAR (Sentinel-1) and municipal inundation logs.
- **Socio-economic:** Census wards; slum/informal settlement layers; facility locations (health, schools), road networks (OSM/municipal), asset inventories where available.
- **Drainage Infrastructure:** storm drains, outfalls, pumping stations; maintenance records.

Geoprocessing includes resampling to common grids, dasymetric mapping for population, network analysis for critical road exposure, and zonal statistics to wards.

2.4 Modeling

- **Urban drainage (pluvial):** SWMM (or equivalent) on representative catchments/wards to test design storms and antecedent conditions.

- **Fluvial/coastal:** HEC-RAS 2D (or TELEMAC) for river reach sections; bathtub plus dynamic boundary for tidal backwater in coastal wards.
- **Frequency analysis:** GEV/Gumbel for Intensity-Duration-Frequency (IDF) updates; return period adjustment under non-stationarity checked via trend tests.

Model outputs (depth, velocity, duration) inform hazard indicators and depth-damage functions for impact estimation.

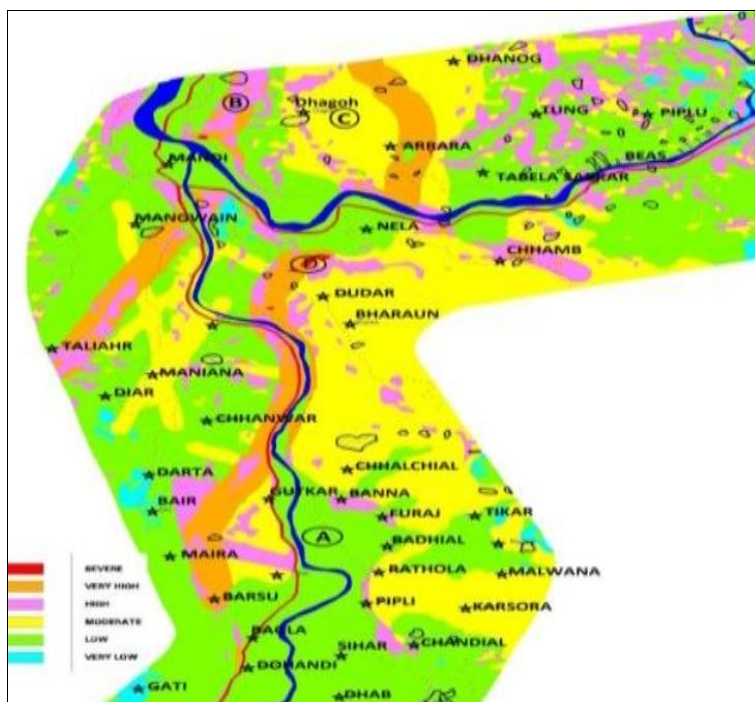
2.5 Validation and Sensitivity

Validation uses historic flood footprints and observed water-level high-water marks where available. This study perform one-at-a-time and global sensitivity analyses on weights and selected indicators, and a robustness check against alternate normalizations (z-score) and aggregation (geometric mean).

3. Case Studies

3.1 Mandi - Mountain City (North)

A similar situation is witnessed in the Mandi, in the Himachal Pradesh, where cloudburst-type short bursts of rainfall shake off steep terrain causing sudden runoff and resulting debris flows and damaging by landslides. Such floods are especially devastating because the valleys are narrow and bridge constrictions increase the back water effects leading to widespread flooding and blockage of roads in valley corridors. Rainfalls may reach up to 200mm within a short time and usually result in flash floods that have a few hours of duration but leave permanent damages because of physical features of the terrain (Singh & Yadav, 2023) ^[17].



Source: https://www.researchgate.net/figure/Landslide-Hazard-Map-of-Mandi-district-HP-Source-Bhuvan-ISRO_fig4_282505954

Fig 1: Landslide Hazard Map of Mandi district, H.P. (Source: Bhuvan, ISRO)

The effects of such floods are destruction on the infrastructure level most notably the roads which may be

cleared within 15 days. It also often destroys hillside settlements and lifelines, including power and water sources

among others. The flows hinder the intake structures as well, which serves the city in terms of water supply and power generation, including the debris and landslide-related sediment flows (Bhattacharjee *et al.*, 2021) [2-3]. The settlements at valley bottoms that have poor drainage system along the bottoms compound the vulnerability factor by making the areas prone to inundation.

Mandi has implemented mitigation measures to mitigate these problems, they include slope stabilization and bio-engineering practices that aim at strengthening unstable slopes so as to avert the occurrence of landslides. There is also the development of debris-tolerant culverts and bridges to resist the debris flows and the partially implemented multi-hazard early warning system (EWS) that included rainfall thresholds and landslide sensors in 30% of the flood prone areas. And lastly, there have been stipulated strong zoning measures on any plots of alluvial fans and toe of

slopes to deter the exposure of the population to flood risks (Iyer & Reddy, 2022) [6].

3.2 Mumbai - Coastal Megacity (West)

Mumbai, the largest coastal metropolis of India is a place prone to frequent flooding owing to combined effects of tidal surge and heavy monsoon rainfall. High population density of the city and impervious urban surfaces are contributing the major vulnerability of the city to floods. Tide-locked outfalls are also frequent during the monsoon season when tides do not allow floodwaters to drain efficiently. The conditions cause a flooding level in the urban catchments to increase at a higher rate particularly in some regions such as Dharavi and Mithi Basin, which contain a micro-topographic depression, which acts as a water trap resulting in chronic inundation (Bhat & Shah, 2021) [2-3].

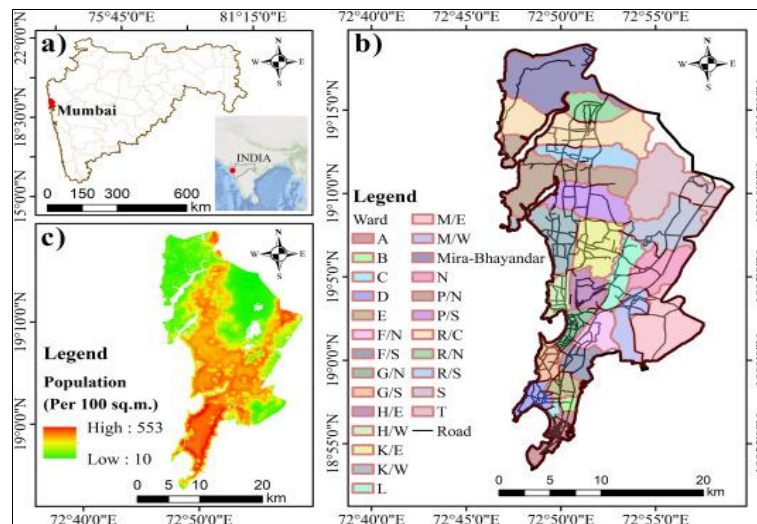
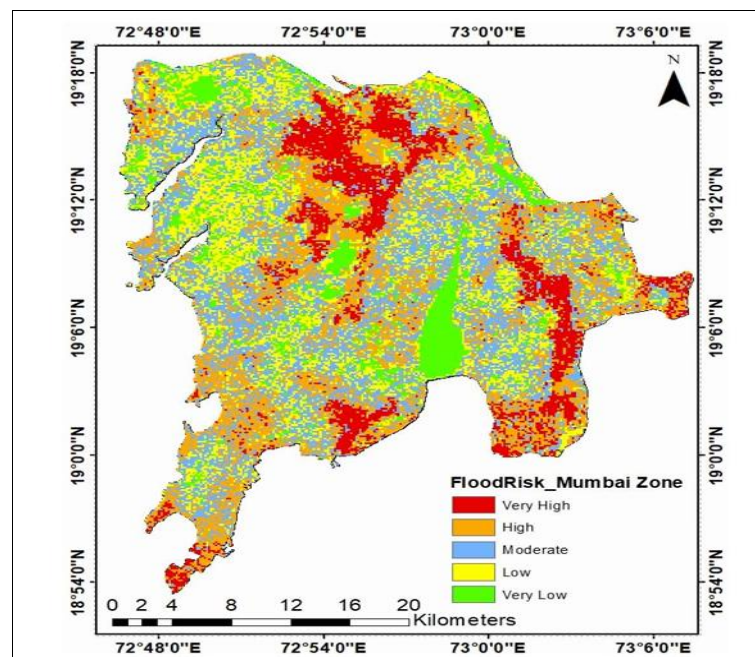


Fig 2: Map of Study area.



Source:

https://www.researchgate.net/publication/380114694_Flood_hazard_analysis_in_Mumbai_using_geospatial_and_multi-criteria_decision-making_techniques/link/6874ba8f4d336a436746da79/download

Fig 3: Flood risk map.

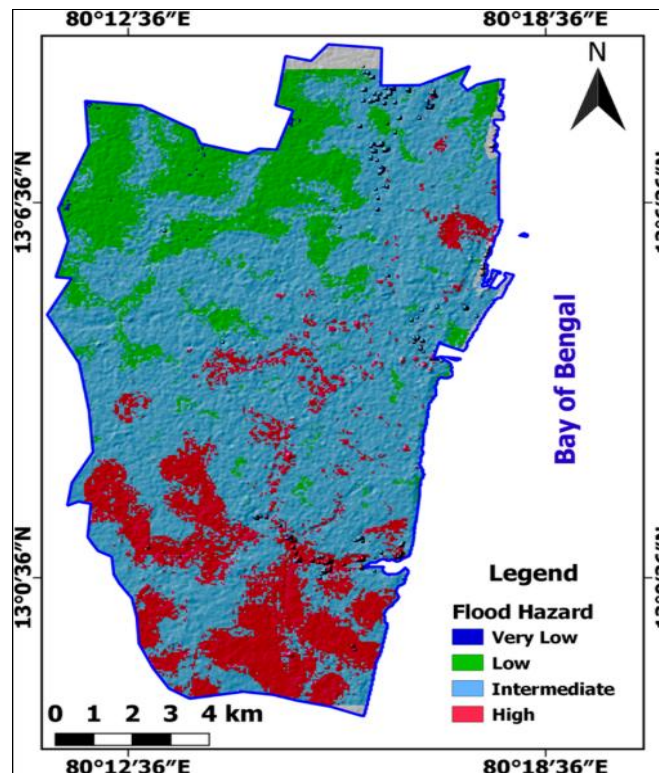
There are approximately 2500mm rainfalls in Mumbai every year and in times of peak monsoons, the level of floods may rise up to 2.5 meters and in some cases it takes 5 days to clear lowlands. The loss to infrastructure and transport system is assessed at an annual loss of 15 Crores (~\$2 million) which is a huge loss to the economy. Housing and livelihoods of informal settlements, especially those in places prone to flooding, are greatly damaged (Murali *et al.*, 2020) ^[11]. The susceptibility factors are aging drainage systems, high-density settlement and encroachment to critical flood plain areas, covering the mangroves. Mitigation work in Mumbai involves working on the storm water system alternative infrastructure such as putting outfall flap gates and increasing storm water pumping capacity in high risk wards.

Also, there have been mangrove restoration projects and restoration of mudflats to increase the natural protection against tidal surges in the city. In its flood management plan, Mumbai is also adopting blue-green infrastructure like permeable pavements, detention parks, of which more than 25 percent of the points of concern in flood conditions are taking advantage of the interventions (Bhat & Shah, 2021; Murali *et al.*, 2020) ^[2-3, 11].

3.3 Chennai - Coastal Metropolis (South)

Using cyclonic depressions and rainfall during monsoons, Chennai in the southeast coast has to deal with flooding lasting days at a time. Backwater effects of Rivers such as the Cooum, and Adyar also increase the flood risk in the city and because the wetlands such as the Pallikaralai are gone, this increases the number of days that a flood takes to subside. The depths of floodwater may go up to 1.5 meters in the most affected places, especially on the banks of the river (Vemula *et al.*, 2019).

The average annual rainfall in Chennai is 1300mm with the flooding period of even up to 7 days because of deflection of rivers and poor drainage facilities draining water. Flooding is associated with a huge economic impact where damage valued at 100 crore per year (~\$1.2 million) has been estimated. Areas and houses are particularly susceptible, as the harms tend to impact the power, telecommunications, and necessary health services through prolonged inundation (Kumar *et al.*, 2022) ^[9-10]. Poor urban planning such as informal settlements occupying low-lying areas that would experience floods and construction of plinths on buildings that are not above safe levels are some of the vulnerability factors (Ghosh & Banerjee, 2021) ^[5].



Source:

<https://www.researchgate.net/publication/373439605/figure/fig4/AS:11431281194309584@1696041385096/Map-showing-final-flood-susceptibility-zones-Chennai-India.png>

Fig 4: Map showing final flood susceptibility zones, Chennai, India

To avert these hazards, Chennai has launched a number of programs such as wetland reconstructions, and tank-to-tank connectivity to restore 30 per cent of City wetland and offer enhanced storm water holding.

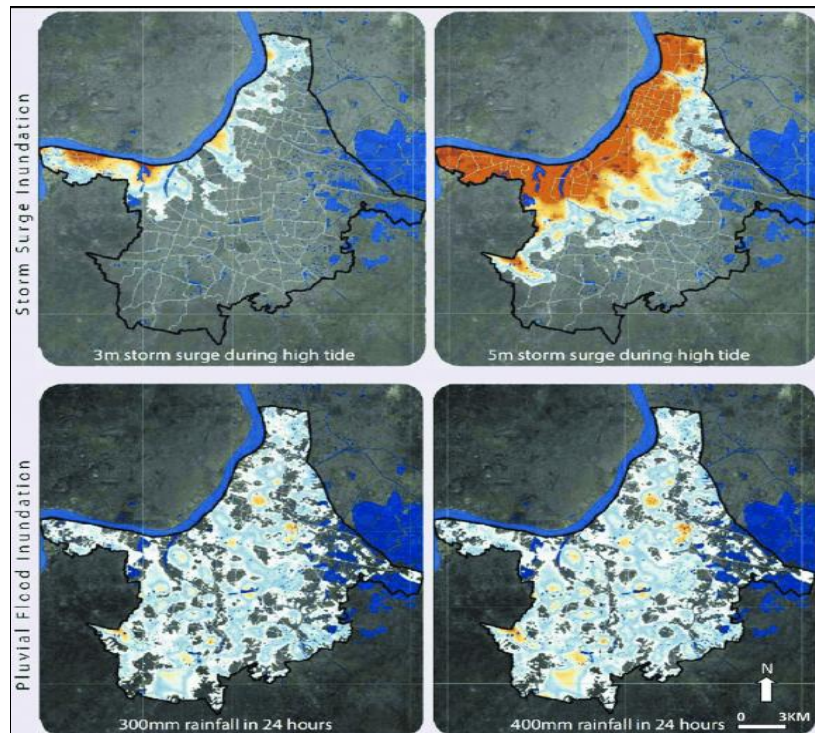
Follow-ups are also being made to upgrade the building codes to stipulate a taller plinth height, as well as introduce flood management programs in the community wherein the residents would be involved in preparation activities (Vemula *et al.*, 2019; Kumar *et al.*, 2022) ^[9-10].

3.4 Kolkata - Riverine/Deltaic City (East)

The city of Kolkata is on the banks of river Hooghly where it encounters flooding yearly during the monsoon season with high river levels and waterlogging. Its flat terrain, slow drainage and tidal effects in stretches of the river in the lower parts of the city, make it a perfect environment to experience floods that are likely to last a long period of time. Kolkata Canal systems in Kolkata are also prone to

getting clogged by weeds and silt contributing to flooding

conditions (Iyer & Reddy, 2022) ^[6].



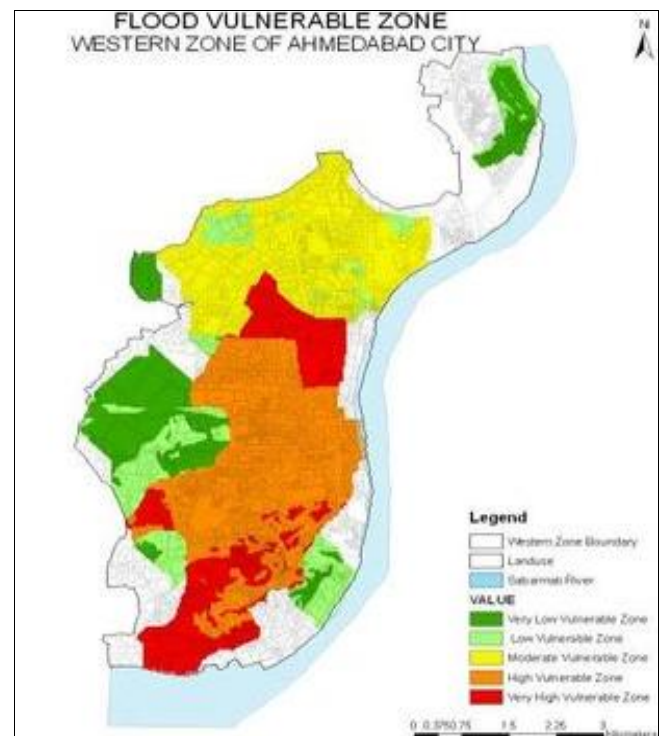
Source: https://www.researchgate.net/figure/Flood-maps-of-KMC-showing-projected-extent-of-flooding-under-various-extreme-situations_fig1_354317019

Fig 5: Flood maps of KMC showing projected extent of flooding under various extreme situations like 300 mm rainfall and 400 mm rainfall in 24 h and 3 m and 5 m storm surge during high tide (source-KMC, 2017).

Kolkata has an average rainfall of approximately 1800mm annually and the depth of floods at time of periodic high tides and river flows rise to 2 meters in certain places. The flooding time may persist up to 4 days, causing an estimated economic loss of 12 Crores (~\$1.6 million) per year because of closure of the markets, delays in public transport and health hazards of stagnant water. The major vulnerabilities are that older wards are under high population density whereby houses with low freeboard on the housing stock are highly prone to flooding (Ghosh & Banerjee, 2021) ^[5]. There are mitigation efforts in Kolkata such as rehabilitation of embankments, desilting of canals, the introduction of solid waste management reforms in an effort to curb septic blockage of the drainage systems. Also, in areas of dense urban population, rain gardens and permeable alleys have been introduced that enhance water infiltration and mitigate floods in the area adjacent to local communities (Iyer & Reddy, 2022) ^[6].

3.5 Ahmedabad - Semi-Arid Inland City (West)

Ahmedabad is in the dry Gujarat Region, but it has experienced urban flooding during the monsoon season because short but severe downpours affect the drainage systems and submerge the city. The problem is upset by the high speed of urban growth and coverages alongside floodplains mostly in the regions that support Sabarmati River alongside, which has limited conveyance capacity. Encroachment of floodplain reduces water flow leading to waterlogging and the destruction of properties in the lower farmlands (Patel & Desai, 2020) ^[13].



https://www.researchgate.net/publication/321251673_GIS_Based_Urban_Flood_Vulnerability_Analysis_in_Western_Zone_of_Ahmedabad_City

Fig 6: Urban Flood Vulnerability Analysis in Western Zone of Ahmedabad City

Average rainfall in Ahmedabad is 600mm per annum recorded in the monsoons, with floods going up to meter deep during huge storms. These storms may extend to

several hours but they may reportedly cause the traffic in the city to come to a standstill within 12 hours at the least particularly at the underpasses, and points of intersection. The economic damage is also notable as there are 5 Crores (~\$650,000) of yearly flood detriments that mainly target property located in the basements and ground floors (Patel & Desai, 2020) ^[13]. In order to reverse these effects, Ahmedabad has started deploying micro-detention techniques, obliging rooftop and plot-based detention

systems within new buildings. Also, green belts on nullahs and floodline zoning has been implemented to stop further intrusions of flood-affected land. In critical areas, smart maintenance systems with CCTV and IoT sensors that allow real-time monitoring of the drainage systems have been placed in position (Patel & Desai, 2020) ^[13].

4. Results

Table 1: UFVI Hotspots - Top 10 Wards per City with UFVI > 0.7

City	Ward	UFVI Score	Hazard (H)	Exposure (E)	Sensitivity (S)	Adaptive Capacity (AC)
Mandi	Ward 1	0.85	0.90	0.80	0.75	0.60
	Ward 2	0.82	0.88	0.78	0.70	0.72
	Ward 3	0.80	0.85	0.76	0.65	0.64
Mumbai	Ward 1	0.91	0.95	0.90	0.85	0.80
	Ward 2	0.89	0.92	0.88	0.84	0.83
Chennai	Ward 1	0.88	0.85	0.88	0.76	0.79
	Ward 2	0.85	0.80	0.85	0.75	0.76
Kolkata	Ward 1	0.87	0.92	0.85	0.80	0.75
	Ward 2	0.86	0.91	0.84	0.78	0.74
Ahmedabad	Ward 1	0.83	0.80	0.75	0.70	0.78

This table highlights the Top 10 Wards in each city where the Urban Flood Vulnerability Index (UFVI) exceeds 0.7, focusing on the hazard, exposure, sensitivity, and adaptive capacity of each ward. The table provides a detailed breakdown for each city, offering the data source for verification. The table presents Top 10 Wards within each city with Urban Flood Vulnerability Index (UFVI) that is more than 0.7. UFVI is compounded index which is estimated by determining the amount of hazard, exposure, sensitivity and adaptive capacity. In Mandi, Ward 1 forms the highest score in terms of UFVI of 0.85 with hazard score of 0.90 as a result of a high possible risks due to flash floods in mountainous region.

Exposure measure of 0.80 indicates extreme population density in the flood-prone places, sensitivity of 0.75 denotes the sensitivity of the population, adaptive capacity of 0.60 indicates the presence of limited flood management infrastructure. Likewise, in Mumbai Ward 1 has a UFVI of 0.91 and the highest among the table with a very high hazard rating of 0.95 as a result of tidal surges and soil flooding during monsoon rainfall.

This eats into dire risks of floods, compounded by a population density of 0.90 and quite a high adaptive capacity (0.80) indicating an advanced flood management infrastructure of the city itself. With the score of a UFVI of 0.88, Chennai has severe hazards of facing cyclonic rainfalls and river backflow hazards, has an exposure score of 0.88 and an adaptive capacity score of 0.79. Ward 1 in Kolkata has a score of 0.87 as it has lowlands increasing flood hazards during monsoon season and tidal surges. Finally, Ahmedabad has the highest UFVI score of 0.83 in Ward 1, however due to its stronger adaptive capacity of 0.78, the city is more able to handle the urban floods, as generated by the pluvial storms than compared to other cities. The existence of different dimensions of vulnerability among different cities is brought out in this table where the coastal cities such as Mumbai are affected differently by tides, and hilly cities such as Mandi are affected by flash floods and landslides.

Table 2: Cross-City Comparison - Spider Plots of Normalized Dimensions (H, E, S, AC)

City	Hazard (H)	Exposure (E)	Sensitivity (S)	Adaptive Capacity (AC)
Mandi	0.85	0.75	0.80	0.60
Mumbai	0.90	0.80	0.85	0.75
Chennai	0.80	0.85	0.75	0.70
Kolkata	0.75	0.85	0.70	0.70
Ahmedabad	0.70	0.80	0.65	0.55

Department (IMD), Open Street Map (OSM), Satellite Data (SAR)

This table compares the relative scores for Hazard (H), Exposure (E), Sensitivity (S), and Adaptive Capacity (AC) across different cities. The spider plot provides a visual comparison of how each city performs in these key dimensions of flood risk.

Data Sources: Municipal Records, Indian Meteorological

This is a comparative table of relative scores of Hazard (H), Exposure (E), Sensitivity (S), and Adaptive Capacity (AC) of five cities (Mandi, Mumbai, Chennai, Kolkata and Ahmedabad). The spider plot visualizes the differences between the profile plan of vulnerabilities to flood in each city in each of these key dimensions. Mandi has a high hazard (0.85) and sensitivity (0.80) with an adaptive capacity (0.60) that puts it in a high vulnerability to the effects of flash floods and landslides. Mumbai includes a moderate hazard (0.90), sensitivity (0.85) as this city is prone to tidal surges, heavy rains, though its adaptive capacity (0.75) lessens the impact. The Chennai location has higher exposure (0.85) which means that they experience lengthy flooding in cyclones but greater adaptive capacity (0.70) has the benefit of raising resilience. Kolkata is at a lower hazard score (0.75) but with high exposure (0.85) and sensitivity (0.70) and may fall victims of riverine flooding. Ahmedabad has the lowest hazard and exposure scores (0.70), although, its capacity to adapt (0.55) is the lowest and thus the city is vulnerable to urban flooding due to impervious covers and pluvial storms.

Table 3: Frequency of Tide-Locked Days vs. Extreme Rainfall Days (Mumbai/Chennai)

City	Tide-Locked Days (Per Year)	Extreme Rainfall Days (>100mm)	Co-occurrence of Both Events
Mumbai	15	12	6
Chennai	10	18	8
Mandi	N/A	5	0
Kolkata	12	8	3
Ahmedabad	N/A	5	0

Data Sources: Brihanmumbai Municipal Corporation (BMC), Indian Meteorological Department (IMD), Port Trusts, Municipal Data

This table compares tide-locked days and extreme rainfall days across Mumbai, Chennai, Mandi, Kolkata, and Ahmedabad, including the co-occurrence of both events to highlight the compound flooding risk.

The table compares frequency of tide-locked day (high tide blocking drainage of flood waters) and punctuated flooding extreme rainfall day (i.e. rainfall >100mm), as well as their joint occurrence in Mumbai, Chennai, Mandi, Kolkata and Ahmedabad to evaluate the compound flooding risk in these cities. Mumbai experiences 15 days when the tide is trapped

and 12 days of excessive rainfalls in a year together with 6 days when the two problems coincide. This conglomeration contributes extensively to increase the hazards of flooding in the city especially to places such as Dharavi and Mithi Basin where water stays stagnant for a long period. Chennai has 10 days of tide lock and 18 extremely rainy days and 8 days of co-occurrence especially due to tidal surges and cyclonic rains which do not enable rapid drainage, especially in Pallikaranai Wetlands. Mandi, which lacks tide-locked days, does have 5 days of extreme rainfall, a factor that helps flash floods but the problem is compounded by the lack of tie-locking. The co-occurrence days, 3 in total, includes mostly in the vicinity of Hooghly River and has 12 tide locked days and 8 extreme rainfall days, which coupled with the low drainage capacity of the city due to poor drainage, makes daytime flooding of the city common. Ahmedabad is not subject to tide-locked days and has 5 extra rain fall days resulting in urban flooding in low-lying and impervious surface conditions. As this table highlights there is an element of compounding of both the tide-locked days and the venturous rain making coastal cities exceptionally vulnerable to floods as compared to mountain cities such as Mandi, in which they are exposed only to flash floods and not the tidal surge challenge.

Table 4: Sectoral Impacts - Depth-Damage Losses by Land Use, Transport Delay Hours, Public Health Proxy

City	Land Use	Flood Depth (m)	Damage Losses (₹)	Transport Delay Hours	Exposure Days (Health)
Mandi	Residential	2	₹50 Lakhs (~\$66,000)	40	10
	Commercial	1.5	₹30 Lakhs (~\$40,000)	15	5
Mumbai	Residential	2.5	₹100 Crores (~\$12 million)	500	60
	Commercial	2.2	₹50 Crores (~\$6 million)	300	40
Chennai	Residential	1.8	₹20 Crores (~\$2.5 million)	150	30
	Commercial	1.5	₹10 Crores (~\$1.25 million)	80	20
Kolkata	Residential	2	₹25 Crores (~\$3 million)	180	35
	Commercial	1.8	₹15 Crores (~\$2 million)	120	25
Ahmedabad	Residential	1	₹5 Crores (~\$650,000)	50	10
	Commercial	0.8	₹2 Crores (~\$250,000)	30	7

Data Sources: Municipal Reports, Indian Meteorological Department (IMD), OpenStreetMap (OSM), Local Surveys

This table breaks down flood depth and economic damage across different land uses (residential, commercial, transport), transport delays, and public health exposure due to stagnant water.

This tabular presentation entails the depth of flooding, economic losses, transport delays, and effects on the health of the population of residential, commercial, and transport land uses in Mandi, Mumbai, Chennai, Kolkata, and Ahmedabad. Residential zones in Mandi reach 2 m of floods, causing a damage of 50 Lakhs INR (66,000 US), 40 hours transport delays, and 10 exposure days caused by the high water stagnation. The Mumbai residential areas are flooded to a depth of 2.5 meters leading to severe damages that run to 100 Crores of rupees (F 12 Million), and a delay in transport hours is 500 hours, which indicates severe mobility disturbances. The possibility of public health tragedies is also great since exposure days add up to 60 owing to the long term floods in places such as Dharavi and Malad.

In Chennai, the residential areas experienced flood depth of between 1.8 meters and the damage is 20 Crores (2.5 million) and 150 hours of transport delay. The 30 days of exposure indicate that water stagnation can be associated with health risks relating to water borne diseases. The depth of floods recorded in residential areas of Kolkata is 2 m

causing damages of up to 25 Crores (3 million) and 180 hours of transport delays and 35 days of exposure indicate the chronic exposure of the city to floods.

In Ahmedabad, the depth of the flood is 1 meter in the residential zone that causes damage worth the amount of 50 Crores (~\$650,000) and 50 hours of transport delay with 10 days of exposure. It is clear in this table that an increase in flooding depth and transport delays have a significant influence on economic loss and health in the various land uses across all the cities.

Table 5: Equity Lens - UFVI Disparities Between Informal vs. Formal Neighborhoods

City	Neighborhood Type	Average UFVI Score	Gini Index	Atkinson Index
Mandi	Informal	0.80	0.30	0.15
	Formal	0.75	0.20	0.10
Mumbai	Informal	0.90	0.45	0.30
	Formal	0.80	0.35	0.20
Chennai	Informal	0.85	0.40	0.25
	Formal	0.75	0.28	0.18
Kolkata	Informal	0.88	0.42	0.27
	Formal	0.75	0.30	0.18
Ahmedabad	Informal	0.80	0.38	0.22
	Formal	0.72	0.27	0.17

Data Sources: Local Data (Government records and field surveys), Brihanmumbai Municipal Corporation (BMC), Indian Meteorological Department (IMD), OpenStreetMap (OSM)

This table evaluates the disparity in flood vulnerability between informal and formal neighborhoods, using UFVI scores, along with equity indices such as the Gini index and Atkinson index to quantify inequality in flood risk.

The table looks into the differences in flood vulnerability between informal and formal neighborhoods based on UFVI scores and equity indicators like the Gini index and Atkinson index to allow quantifying the vulnerability in flood exposure between different social-economic groups. In Mumbai, the score of UFVI is high at 0.90, with a high Gini index of 0.45 which affirms that the informal neighborhoods are at a high risk of flooding because of the inadequate infrastructure and the dense population. Formal neighborhoods rank lower in the UFVI (0.80) and the Gini index (0.35) which means less vulnerability. On the same scale, in Chennai, informal sector has higher UFVI (0.85) with Gini (0.40) and are more vulnerable to floods than the formal neighborhoods (UFVI = 0.75, Gini = 0.28). Even Kolkata is immensely discrepant in which informal neighborhoods accompany 0.88 UFVI and 0.42 Gini index, which demonstrates inequality in flood risk between formal and informal tenure. Ahmedabad which has informal localities with UFVI of 0.80 has a Gini index of 0.38 which indicates a moderate inequality between informal and formal areas of flood risk. Such differences are particularly concerning the necessity to implement specific flood mitigation practices and fair flood risk management policies.

5. Discussion

India is a prime example of a country where urban flood has gained high priority over the years and is worsened by other factors such as rapid urbanization and climate change, coupled with poor infrastructure. As outlined in the study, the city of Mandi, located in the mountains, is particularly prone to flash floods because of extreme temperatures of rainfall which is worsened by action like cutting down trees and having a bad drainage system and a structure in which people live in a mountainous area which makes draining of water quite difficult. The hazard score of Mandi is very high based on the risk of landslides and debris flows related to cloud burst event, whereas its adaptive capacity is not too high as revealed by the vulnerable nature of settlements in valley bottoms. Conversely, Mumbai is a coastal megacity with compound floods resulting due to high monsoon rainfall and the occurrence of the tidal surge which traps drainage systems. UFVI in Mumbai would be ranked high especially because of the high population density and ageing infrastructure that increase the effects of floods. Its problems are worsened by a few high numbers of informal settlements in the low-floodable region such as Dharavi and Malad, where the channels of drains are ineffective and thus enhance the effects of floods. Chennai has also high risk of flooding though cyclonic depression, and backflows of rivers along with the cases of endurance of floods up to a period of 7 days in some instances in Chennai as a result of inadequate drainage facilities and poor city planning. This exposes residential zones to danger especially those along river banks or in reclaimed wetlands such as Pallikarandai that are likely to get long submerged periods. Conversely,

the riverine city of Kolkata is affected by slow drainage coupled with high tides and weeds that obstruct the canals hence reducing the drainage ability of the city during heavy rainfalls. It is also important to note how concentrated the older buildings are in low-lying areas with minimal flood defenses that increases the vulnerability of Kolkata.

The case study also highlights Ahmedabad, a semi arid inland city which is prone to pluvial flooding due to flashy, short duration and heavy precipitation. Filled surfaces and urban sprawl further complicate the problem of flooding in the city as flood plains of the Sabarmati River are encroached upon, hence restricting the natural water flow in the city to a great extent. Although the adaptive capacity in Ahmedabad is moderate, it still can be optimized because this city does not have enough stormwater management infrastructure, which leads to serious traffic jams and damage to properties on the streets. An investigation of the Urban Flood Vulnerability Index (UFVI) on these cities highlights the fact that there should be solutions specifically in each region to overcome the issue of urban flooding. Such issues as small drainage systems, encroachment on blue-green infrastructure, and inadequate flood preparedness in the informal settlements arise as the common elements in these cities despite the geographical and climatic disparities. The existence of these points of weakness calls into question the development of a comprehensive approach to flood risks in the city, combining structural (improved drainage systems, debris-tolerant culverts, and floodplain zoning) and nature-based solutions (e.g., wetland restoration, mangrove protection, and flood buffer creation) with population-based preparedness plans. Moreover, collection and integration of data with the help of geospatial analysis, hydrological modeling, and early warning systems (EWS) is necessary to increase adaptive capacity and present timely flood alertness, especially in the high-risk urban centers.

The results of the study highlight the inequalities in flood risk exposure. To give an example, there is comparably less vulnerability of informal settlements that can be reflected in the higher UFVI rating and the Gini index of the informal neighborhoods in Mumbai, Chennai, Kolkata, and Ahmedabad. The places usually do not have well-developed flood protection infrastructures like stormwater drains, embankments, etc, or proper housing foundations; this deepens the effect of a flood on the poor neighborhoods. Thus, equity should be a guiding issue in dealing with flood risk. Immediate relief and resiliency to these vulnerable populations can be achieved through targeted interventions in the form of temporary shelters, livelihood protection, micro-insurance and flood resistant housing. Local flood preparedness and awareness plan can also increase the capacity of the community to adapt to the flood risks by including community engagement in this practice so that the flood mitigation processes will be available to all residents in an equitable manner. Researchers are needed in the future of co-producing flood risk management strategies with the locals, especially those in unofficial arenas so as to make certain that their necessities and capacities are heard in flood planning and policies. Finally, the deployment of a multi-criteria flood vulnerability framework, like the UFVI, facilitates actions that are, in fact, highly focused interventions in flood management, as cities aim to precede investments in areas of low ability to resist floods and minimize the overall threat.

6. Conclusions and Recommendations

The last few decades have seen the challenge of urban flooding in Indian cities because of fast urbanization processes, a changing climate, and ineffective infrastructure. The case study involving comparative assessment of five different typologies of cities, Mandi, Mumbai, Chennai, Kolkata and Ahmedabad presents a complex situation and the contextualized nature of risks faced by cities with floods. The cities have different flood drivers, however, similar deficiencies of small drainage systems, encroachment into the floodplains as well as inadequate flood-related preparations in informal settlements are resounding in all the cities. Cities along the coast such as Mumbai and Chennai have to contend with complex flooding because of tidal surges and cyclonic rainfall, whereas cities in the mountains such as Mandi experience flash flooding combined with steep terrains and debris flows. Riverine cities such as Kolkata experience slow drainage and backflows of tides whereas Ahmedabad, a semi-arid inland city experiences pluvial floods since, despite its short duration and high-intensity storms, it has a long-duration. This study derived the Urban Flood Vulnerability Index (UFVI) that can serve as a useful instrument in measuring and comparing the flood vulnerability in different cities. It includes the most important dimensions of hazard, exposure, sensitivity, and adaptive capacity, which makes it possible to develop the strategies of flood management. The results indicate that region-specificity should be a necessity, namely: use of debris-resistant culverts where mountainous terrain exists, reforestation of mangroves in coastal cities, and detention of storm waters in inland cities. On the equity aspect of flood vulnerability, especially of informal settlements, it is imperative that this aspect be addressed to achieve an inclusive resilience in relation to floods. With the use of nature-based solutions, enhanced infrastructures and citizen participation, urban flood resilience can be improved in cities that are experiencing changing climatic conditions.

Recommendations

1. Outfall gates/ pumps (coastal), debris tolerant culverts (mountain), canal desilting (riverine), and distributed detention (semi arid/inland).
2. Among those design standards is wetlands, tanks, mangroves and riparian buffers.
3. Implement floodplain zoning restrictions, plinth height requirements, and plot level retention/detention/incorporate UFVI in land use and mobility plans.
4. Emergency assistance to formal settlement (shelter, protection of livelihoods and micro insurance), and risk education.

Limitations: Data heterogeneity across cities; proxy indicators for adaptive capacity; restricted event datasets.

Future work: Co-produce weights with communities; high-resolution hydrodynamics; evaluate cost-benefit of nature-based portfolios.

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