REPORT

Climate resilient cities

Assessing differential vulnerability to climate hazards in urban India

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Foreword

Cities in India are increasingly focused on addressing the risks posed by the climate crisis. Throughout the country, many urban governments are engaging in different forms of climate action, including the creation and implementation of adaptation, resilience, and disaster risk reduction plans. These plans rely on accurate assessments of climate vulnerability that consider how both climate hazards and social factors influence the ways in which urban communities respond and adapt to emergent climate threats.

The Climate Hazard and Vulnerability Assessment (CHVA) is a tool that officials and planners can use to holistically understand climate vulnerability in their cities and urban areas. Beyond focusing on climate hazards, this tool pays particular attention to how social factors create differential vulnerability within urban communities. By focusing on differential vulnerability, the CHVA highlights the urban poor in underserved, risky, and often inaccessible locations. These locational factors deepen exclusion and marginalization, intensify climate hazards such as flooding and urban heat, and structure the unequal distribution of vulnerability in cities.

Capturing differential vulnerability is not an easy task, though it is increasingly necessary as we learn more about the ways in which social, economic, and political factors constitute climate vulnerability. Methods for assessing climatic and environmental hazards have advanced significantly over the past several years, and we must work to correspondingly improve our ability to understand how the social landscapes of cities interact with hazards and create differential impacts.

The CHVA is designed with the needs of urban planners and resilience practitioners in mind, and is grounded in the latest research on climate vulnerability. This report builds on experiences assessing vulnerability in cities such as Mumbai, Bengaluru, and Kochi and equally on WRI's existing tools, such as the Urban Community Resilience Assessment (UCRA) and the Inclusive Climate Action Planning (ICAP) frameworks. Striking a balance between depth and accessibility, the CHVA primarily relies on readily available data to assess climatic hazards and the socioeconomic aspects of vulnerability. Further, the CHVA outlines methods for community engagement and direct data collection, ensuring that the voices of the most vulnerable and marginalized are prioritized during the vulnerability assessment process. The CHVA is also an iterative tool. By making vulnerability assessment a process rather than a one-time event, the efficacy of interventions can be readily measured, ongoing plans can be fine-tuned, and cities can be more readily compared with one another.

Understanding the problems posed by climate change is key to creating solutions that are effective, equitable, and just. Our efforts over the years have focused on analyzing data and evidence on climatic and environmental hazards, as well as sensitivity and adaptive capacity, to drive practical and needs-based adaptation actions and solutions in Indian cities. The CHVA builds on this institutional knowledge and ongoing efforts within the development and environmental ecosystem. With this report, the hope is that Indian cities will focus more intensely on addressing climate risks from an equity lens to create more just, equal, and resilient cities.

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Executive summary

The effects of the climate crisis are becoming increasingly clear in Indian cities. Understanding the vulnerability of urban populations to these changes is critical for creating adaptation- and resilience-focused interventions that can help residents adapt to the changing climate. This Climate Hazard and Vulnerability Assessment framework is an accessible tool that focuses on the hazards and social factors that create differential vulnerability to climate change in cities.

HIGHLIGHTS

- Cities in India are growing quickly and facing emerging and intensifying climate hazards. But how those hazards and other environmental and ecological factors are experienced by different people and communities within cities varies greatly depending on a range of social, economic, political, and cultural factors.
- The Climate Hazard and Vulnerability Assessment (CHVA) helps urban planners, policymakers, and practitioners understand the interactions between climate hazards and socioeconomic factors.
- Existing vulnerability assessments often fail to capture the forms of sociopolitical and economic inequality that determine the differential nature of climate vulnerability. The CHVA fills this gap.
- To analyze differential vulnerability, the CHVA is divided into three parts: Hazard Identification and Assessment, Exposure Analysis, and Vulnerability Assessment.
- Using official city-level data that can in some cases be supplemented with alternative local data sources, the CHVA assesses both hazards and the vulnerability of people and critical infrastructure to give a robust and in-depth understanding of urban vulnerability.
- Although this tool helps diagnose forms of vulnerability, changes in approaches to governance and community participation together with broader planning efforts are likely needed to bring about transformational adaptation in Indian cities.

CONTEXT

Indian cities are rapidly expanding while simultaneously facing new and intensifying climate hazards and risks. Increasing temperatures, less predictable weather patterns, sea level rise, floods, droughts, and other problems threaten urban populations (IPCC 2022). India's urban population continues to grow by at least a million people every year (based on decadal census data between 2001 and 2011), compounding the social and environmental concerns of cities (Khosla and Bhardwaj 2019).

Within urban populations, how climate hazards are experienced differs significantly because of forms of socioeconomic inequality and political and cultural factors. The sensitivity of individuals, families, and communities to climate hazards and how they are able to cope with or adapt to them depends on their access to a range of social and economic resources and various cultural, political, and contextual factors (Cutter et al. 2000; IPCC 2022; Thomas et al. 2019). In India, high levels of socioeconomic inequality within cities, uneven urban development, and enduring forms of marginalization interact with intensifying hazards to structure the landscape of urban climate vulnerability.

Existing vulnerability assessments largely focus on exposure to hazards, overlooking socioeconomic factors that primarily determine the vulnerability of people and communities. Although an accurate understanding of hazards is important, socioeconomic and political factors need to be analyzed to fully understand how those hazards affect people and communities (IPCC 2022,1050–59). In India, official data remain indispensable for measuring these aspects of vulnerability, though additional diverse experiential and primary data collected by nongovernmental and community-based organizations add important context and nuance.

The CHVA addresses this gap by building on the concept of differential vulnerability. This concept helps make clear that vulnerability to climate change varies significantly due to non-climatic factors (see IPCC 2022, 928–30, 1050–51, 1180–81; Thomas et al. 2019). By focusing on both exposure to hazards and socioeconomic forms of vulnerability, the CHVA can help orient climate action toward the drivers of vulnerability in particular communities.

ABOUT THIS REPORT

This report describes the CHVA in detail. It gives an overview of gaps in existing vulnerability assessments and outlines how the CHVA addresses them. Using examples from WRI India projects and building on the WRI Urban Community Resilience Assessment (Rangwala et al. 2018), this report gives a detailed overview of how the CHVA can be conducted and explains how the results of the CHVA can be applied within cities.

This report answers the following three questions. Why do cities need to conduct vulnerability assessments to inform resilience planning? How can cities assess and visualize these differential vulnerabilities and use these findings to impact resilience capacities? How can cities conduct and integrate the findings from a vulnerability assessment into planning processes?

This report highlights case examples of how the CHVA was conducted in Mumbai, Bengaluru, Kochi, Chhatrapati Sambhajinagar, Nashik, and Solapur. In addition to discussing the CHVA process in these cities, this report also details actions and interventions that were carried out based on information provided by the CHVA. For example, landslide preparedness workshops were conducted in Mumbai after an assessment of landslide-prone locations and slum settlements in the city showed that over 70 percent of Mumbai's landslide-prone areas fall within informal or slum settlements.

This framework is intended for urban planners and officials, policymakers, and other practitioners interested in addressing urban climate vulnerability. The spatially informed approach of the CHVA will help users better understand differential vulnerability in their cities and how climate hazards interact with socioeconomic factors. Policymakers and practitioners will then know where to allocate attention and resources, and the focus of the CHVA on differential vulnerability will help users go beyond infrastructural fixes to also address the social drivers of climate vulnerability.

WHAT IS THE CHVA?

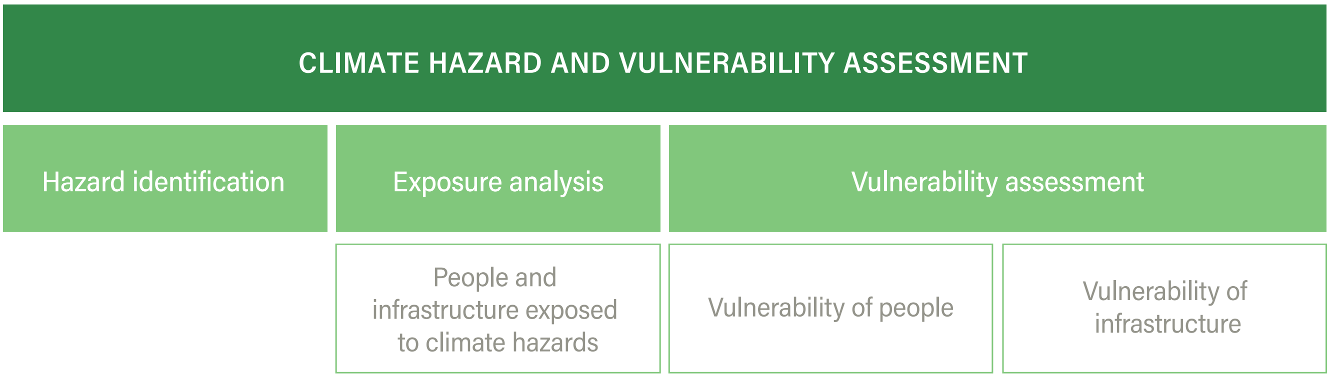
The CHVA is a tool to analyze differential vulnerability in Indian cities. It is intended for use in any Indian city, using accessible data and methodologies. The Census serves as the primary data source, as it is the most comprehensive and reliable public dataset used by government and nongovernmental agencies to produce comparable and robust analyses. Census data can also be disaggregated at the ward level for several important indicators, allowing for a reading of differential vulnerability. However, given the dynamic nature of climate hazards and the associated vulnerabilities it produces, the census dataset (updated every decade) may be inadequate for representing the extent of temporal vulnerability. This report discusses the limitations of the census data for capturing the temporal nature of vulnerability, given the uncertainties associated with climate hazards and the vulnerabilities that they produce. Census data can be supplemented by a range of optional sources. The CHVA encourages participatory forms of data collection, which helps ground the assessment in local and contextual forms of knowledge, close the data gaps, and resolve the inconsistencies in official data. This report addresses the problems with data collection that are present in many Indian cities, and the CHVA itself allows for flexibility in contexts where institutional barriers or data gaps impede assessment efforts.

The CHVA comprises three parts: the Hazard Identification and Assessment (HIA), the Exposure Analysis (EA), and the Vulnerability Assessment (VA). The first part provides information on the types and intensities of the hazards faced by a city, the second part links those hazards with urban populations and critical urban infrastructure to assess the potential for compounding and cascading risks, and the third part considers forms of socioeconomic vulnerability. Together, these features of the CHVA provide a robust assessment of urban vulnerability (see Figure ES-1).

The HIA considers meteorological, hydrological, geological, and environmental hazards. Within these groups, the HIA outlines specific indicators to analyze the impacts of particular hazards on cities and neighborhoods.

Vulnerability is analyzed using the lenses of sensitivity and adaptive capacity, following international standards (IPCC 2022). *Sensitivity* refers to how affected a community is by climate hazards, whereas *adaptive capacity* refers to the ability of a community to cope with exposure to hazards. The VA part of the CHVA uses indicators specific to the urban Indian context, many of which can be assessed through census data. Additionally, analyzing the vulnerability of critical infrastructure provides a complete picture of vulnerability in a city. This is assessed using a questionnaire.

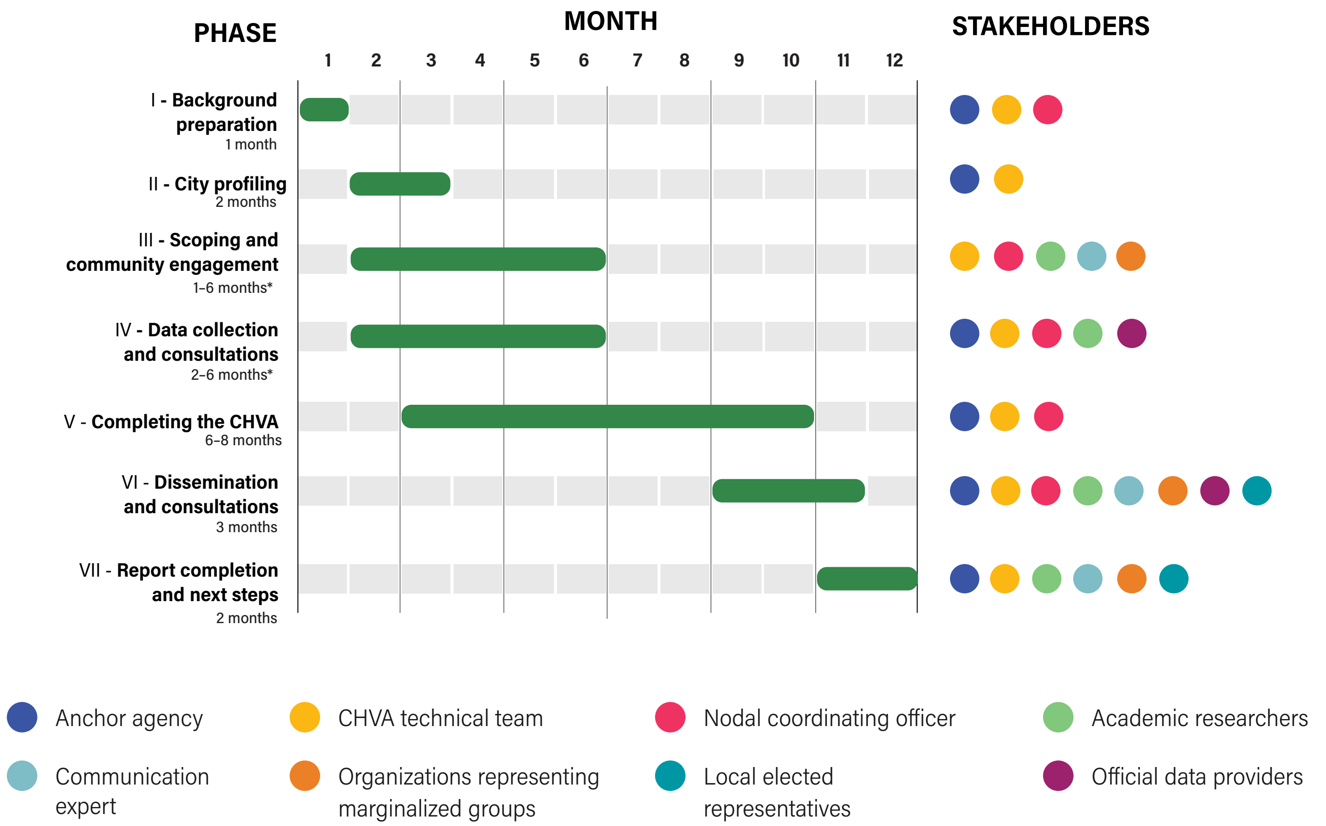
FIGURE ES-1 | Climate Hazard and Vulnerability Assessment Framework



Note: See the detailed illustration in Chapter 2, Figure 2.

Source: Authors.

FIGURE ES-2 | Seven-phase process for conducting the Climate Hazard and Vulnerability Assessment



Note: The above timeline is suggestive and would differ based on a city's context, needs, and resources.

Source: Authors.

This report details how all parts of the CHVA can be conducted. The six steps of the CHVA are outlined in Figure ES-2. This report not only describes in detail the technical elements of the CHVA but also provides guidelines and suggestions for approaching such assessments within the governance context of Indian cities. Although some cities may have environment departments, other nodal agencies may need to be identified and designated in many cases in order to anchor the CHVA process to aspects of the city such as capacity, authority, and existing institutional arrangements and duties. Often, external practitioners or consultants can support this process, working with city government officers. This report also discusses the steps that can be taken after the completion of the CHVA, such as finer-grained assessments of vulnerability at the neighborhood level, the creation of climate action and resilience plans, and concrete interventions to address the identified acute forms of vulnerability.

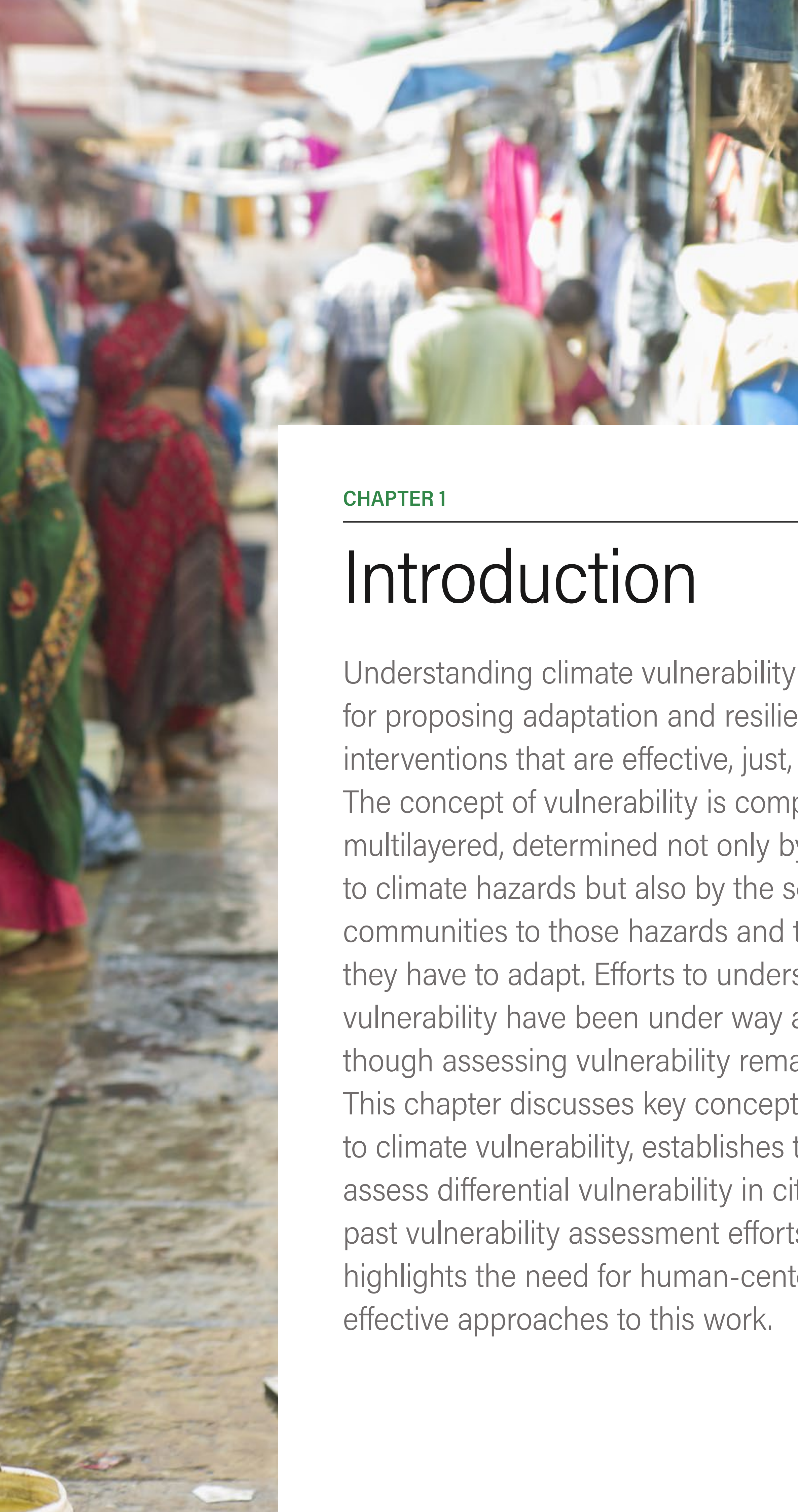
The approach taken by the CHVA is spatial, iterative, and flexible. A spatial perspective and approach is necessary for understanding differential vulnerability (Cutter et al. 2001), as is mapping exposure to hazards at the ward level with indicators of sensitivity and adaptive capacity such as access to resources and basic services. Further, the CHVA is designed as an iterative tool, intended to be conducted every few years. Figure ES-2 shows the CHVA process, which is flexible and encourages cities to adapt the process to suit their needs, timelines, and available resources. The Scoping and Community Engagement Phase of the process will guide the CHVA team in collecting more localized forms of information to supplement the official data collected. The iterative process will allow practitioners and policymakers to understand how vulnerability evolves over time as hazards change and interventions are implemented. It will also show how the CHVA process can evolve with changes in capacities, institutional readiness, public participation, and political will.

In conclusion, by focusing on differential vulnerability, the CHVA fills a gap left in existing urban vulnerability assessment frameworks. By measuring and spatially analyzing socioeconomic factors, incorporating forms of participatory planning, and engaging in iterative forms of measurement and assessment, the CHVA allows policymakers and practitioners to better understand the relationship of climate hazard vulnerability with social equity, economic development, urban and environmental planning, infrastructure planning and development, and governance of cities. Such disaggregated understanding helps in crafting sectorally initiated but integrated resilience solutions. This approach to differential vulnerability can also address ongoing concerns over maladaptation and help promote climate justice.

RECOMMENDATIONS FROM THIS REPORT

The CHVA framework can serve as a powerful foundation for resilience- and adaptation-focused plans, moving away from incremental solutions to more transformational forms of resilience and adaptation that address the underlying nature of historic marginalization, inequality, and climate injustice. Finally, this report lays out the following five recommendations for practitioners and policymakers on how they can create an enabling ecosystem to undertake this assessment and translate it into meaningful action:

- Improve access to high-quality data by enabling well-maintained and open-source data repositories that are coordinated across national and state-level agencies.
- Conduct robust city-level baselines, promote community-based assessments to ground-truth city-level datasets, and tap into local resources and knowledge pools.
- Institutionalize the CHVA through capacity-building programs, governance interventions for better interdepartmental coordination, and coordination with local and global organizations to move beyond ad hoc efforts to holistic and coordinated adaptation actions.
- Prioritize and accelerate adaptation action in high-risk areas and within vulnerable communities by promoting community-level needs assessments through deeper forms of engagement, allowing for exchanges between vulnerable groups and policymakers.
- Incorporate quantitative and qualitative assessments of the social drivers of vulnerability into ongoing planning and implementation processes by working with marginalized and highly vulnerable groups to avoid maladaptation.



CHAPTER 1

Introduction

Understanding climate vulnerability is essential for proposing adaptation and resilience interventions that are effective, just, and equitable. The concept of vulnerability is complex and multilayered, determined not only by exposure to climate hazards but also by the sensitivity of communities to those hazards and the resources they have to adapt. Efforts to understand climate vulnerability have been under way across India, though assessing vulnerability remains difficult. This chapter discusses key concepts related to climate vulnerability, establishes the need to assess differential vulnerability in cities, reviews past vulnerability assessment efforts in India, and highlights the need for human-centered, just, and effective approaches to this work.

Cities in India and throughout the world are increasingly exposed to a broad range of climate hazards, which—by interacting with compounding forms of inequality and marginalization—threaten to aggravate the climate vulnerability of urban communities. Along with slow-onset concerns such as sea level rise, cities are threatened by erratic weather patterns and extreme heat, floods, and droughts.[1] As anthropogenic climate change continues to intensify such hazards in an increasingly urbanized world, attention needs to be paid to addressing climate vulnerability in cities. It is imperative that practitioners focusing on this task understand the interplay between emergent climate threats; forms of social, economic, and political inequality; and other social features that influence the vulnerability of people, communities, and infrastructure to climate change.

Exposure to climate hazards may or may not be uniform across a city or urban area, but how these hazards are experienced by people is almost always uneven, dynamic, and contextual (Rosenzweig et al. 2018). Vulnerability to climate change is largely a function of social factors (Cutter et al. 2000; IPCC 2022; Pelling 2011; Tierney 2014). Forms of inequality, differential levels of development, and a range of sociopolitical factors can exacerbate the experience of climate hazards, creating differential vulnerability to the effects of climate change (IPCC 2022, 928–30, 1180–81; Thomas et al. 2019).

Assessing differential vulnerability is particularly important in unequal cities and is a key task for practitioners focused on bringing an equity lens to urban resilience, adaptation, and mitigation (Chu et al. 2019). Indian cities are often sites of extreme inequality, where—even within a single neighborhood—households may have markedly different levels of vulnerability to climate threats. The interplay of mostly unplanned large-scale urbanization in India with inadequate provision of basic infrastructure and municipal services coupled with increasing climate-related extreme weather events underscores the urgent need to address vulnerability to climate change in cities and make resilience planning a routine feature of urban planning (Babu and Chaturvedi 2022; Khosla and Bhardwaj 2019). Vulnerability assessments can help capture the often highly differential forms of climate vulnerability present in cities in order to support effective and just climate action and resilience plans. This can be achieved by considering how socioeconomic, political, institutional, and cultural factors influence the sensitivity of urban dwellers to climate threats and their adaptive capacity in the face of those threats (Bulkeley et al. 2013; Kuhl et al. 2021).

This means that vulnerability assessment—and plans created on the basis of such assessments—must take an increasingly nuanced approach, attending not only to climate hazards but also to a range of social drivers of climate vulnerability. Failing to take differential vulnerability into account when creating urban resilience plans threatens to inadvertently increase forms of vulnerability, perhaps redistributing vulnerability between areas of cities or increasing other forms of inequality (Fraser et al. 2016).

This report aims to answer three questions: why do cities need to conduct vulnerability assessments to inform resilience planning? How can cities assess and visualize these differential vulnerabilities and use these findings to impact resilience capacities? How can cities *conduct a vulnerability assessment and integrate its findings* into plans, projects, and strategies?

This introduction reflects on the first question and focuses on the need for assessing differential vulnerability at the urban level and the benefits of considering climate vulnerability from a spatial perspective. By describing the context of climate action in India, the evolution of vulnerability assessments, and their integration in planning in India, this chapter draws attention to the need to center vulnerable people in resilience plans and broader climate action.

DEFINING CLIMATE VULNERABILITY IN AN URBAN CONTEXT

In an urban context, a range of factors such as climatic, infrastructural, and social factors influence how vulnerable communities are impacted by climate change (Fraser et al. 2016). Reducing vulnerability to climate change is the central goal of resilience planning and a key part of broader climate action plans. How vulnerability is conceptualized and framed shapes these plans (Cutter 2016). Unlike mitigation plans, which focus on a quantitative reduction of greenhouse gas (GHG) emissions, vulnerability assessments and resilience efforts rest to some extent on qualitative assessments and normative judgments of current and future social well-being (see Bhushan et al. 2018; Kuhl et al. 2021; Scoville-Simonds et al. 2020). This means that vulnerability assessments and the subsequent plans are inextricably connected with—and potentially co-constitutive of—the current and future social fabric of cities.

Vulnerability is a broad term. Its use has evolved since its original inclusion in climate discourse, and debate continues over how it should be framed. This report relies on how the IPCC frames the concepts of vulnerability and risk, while also considering how other researchers approach these concepts and how practitioners working in Indian cities define (or use) such terms.

As defined in the most recent IPCC report, vulnerability is "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and a lack of capacity to cope and adapt" (IPCC 2022, 2927). In the IPCC's Fourth Assessment Report (IPCC 2007), vulnerability was understood to stem from a combination of exposure to climate hazards, sensitivity to those hazards, and adaptive capacity. This framing is still used in much of the academic and practitioner-focused literature (see the review by Thomas et al. 2019). However, the IPCC has moved away from including the concept of exposure in vulnerability, in part to highlight the social nature of vulnerability (IPCC 2014, 171, 79). More recently, in the Sixth Assessment Report, the concept of risk is increasingly centered, and vulnerability is understood as "a component of risk, but also an important focus independently" (IPCC 2022, 133).

For this report, we follow this recent guidance from the IPCC, separating exposure to climate hazards from the concept of vulnerability, which we understand as constituted by sensitivity and adaptive capacity. Sensitivity is the "degree to which a system or species is affected, either adversely or beneficially, by climate variability or change" (IPCC 2022, 2920), whereas adaptive capacity is the "ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences" (IPCC 2022, 2899). This framing aligns our report with the most recent IPCC literature and helps emphasize the social nature of vulnerability.

A range of social factors determine the sensitivity and adaptive capacity of communities (Cutter et al. 2000; IPCC 2022; Smit and Wandel 2006; Pelling 2011; Thomas et al. 2019), and these factors can also be measured across scales, such as at the individual or household level. Put simply, the more economic, social, and political resources a community has, the lower its sensitivity to hazards and the higher its capacity to adapt to current or projected hazards. Because of this, the vulnerability of a community depends not only on its exposure to climate hazards but also on a range of social factors, such as differential access to resources, power differentials between individuals and groups, aspects of governance and politics, and a range of cultural factors.

Within cities, forms of inequality, uneven development, and power imbalances create an irregular terrain of differential vulnerability to climate change. This report centers on this concept. We use the term *differential vulnerability* to make clear that when a particular urban community is exposed to the same set of hazards as another community, how those hazards are experienced can vary significantly based on social factors. This term is invoked, both explicitly and implicitly, in a wide range of literature focusing on vulnerability and adaptation. Conceptually, differential vulnerability builds on the notion that risk is socially constructed (see Freudenburg et al. 1995; Kasperson et al. 1988; Tierney 2014), and the term has been used explicitly to foreground the notion that social factors structure how climate hazards are experienced. The term was used in passing at least as far back as the IPCC's Third Assessment Report in 2001. However, with the focus turning toward adaptation as a necessary response to climate change (see Orlove 2022), the term has become more commonly used in recent IPCC reports (e.g., IPCC 2022, 928–30, 1180–81). Although the term is not foregrounded in IPCC reports and does not appear in the glossary, the notion that the impacts of climate change are differentially experienced has become a key baseline understanding in IPCC reports.

In this report, we build on literature that directly evokes the concept of differential vulnerability (Adams et al. 2023; Birkmann 2013; Cutter and Emrich 2006; Thomas et al. 2019; Tierney 2014) and recent literature that, although not directly focusing on the concept, provides valuable insight into how vulnerability is unevenly distributed (e.g., Chu et al. 2019; Eriksen et al. 2015, 2021; Kuhl et al. 2021; Scoville-Simonds et al. 2020). This concept is particularly germane for cities, where high population density and high levels of socioeconomic and political inequality can exacerbate climate vulnerability (Bulkeley et al. 2013; Fraser et al. 2016).

In short, for this framework, we follow the convention set over the previous two cycles of the IPCC and frame vulnerability as a largely social phenomenon. To conceptualize vulnerability (as dependent on interactions between social factors) and exposure (to climatic phenomena), we focus on the identification and assessment of hazards faced

by cities in India, such as extreme temperatures, sea level rise, storms, cyclones, floods, droughts, and less predictable weather patterns. The concept of exposure helps identify risk-prone areas of the city and populations (or communities) living in those areas. For this framework, we recommend using spatial analysis to assess exposure to climate hazards and a combination of socioeconomic and geographic information system (GIS) analysis to assess vulnerability as constituted by two social elements, sensitivity and adaptive capacity.

The IPCC increasingly emphasizes the concept of risk, which has been framed, since AR4 (IPCC 2007), as a combination of hazards, exposure, and vulnerability, visually represented as a "propellor" (see IPCC 2022, 6, 132). Even with this increased focus on risk, the IPCC continues to hold that vulnerability is a key concept and that it is "an important focus independently [of the concept of risk]" (IPCC 2022, 133). For the Climate Hazard and Vulnerability Assessment (CHVA) framework, we use the term *vulnerability*—and focus on assessing differential vulnerability—to emphasize the social aspects of climate impacts. Further, the vulnerability literature, beyond IPCC reports, is used to define key terms, associations, and indicators of the CHVA framework, to align with the terminology used by urban adaptation practitioners in India.

Understanding and accurately assessing vulnerability is a critical first step for climate action in cities, including for the creation of climate action plans and resilience plans. Although these terms (see Glossary) are different, they are—along with concepts such as adaptation—often used flexibly in practice. In this report, building on existing work establishing the importance of adaptation in cities (Chu et al. 2019), we suggest that understanding and assessing differential vulnerability is a key task for practitioners focused on resilience and adaptation and the creation of broader climate plans. As we discuss below, much planning to date has given too much attention to questions of exposure and the related infrastructural fixes while overlooking questions of sensitivity and adaptive capacity, thus excluding the social interventions required to address these.

CONTEXT OF CLIMATE ACTION IN INDIA

In India, efforts toward climate change mitigation and adaptation in cities, in the form of climate action plans, urban adaptation or resilience plans, or city resilience strategies, have grown in scope over the past two decades. Additionally, sectoral plans have been created that address heat (such as heat action plans) and flood risks (such as flood mitigation plans), often guided by the National Disaster Management Agency (NDMA) to encourage localized, contextual hazard risk mitigation strategies for Indian cities. These are city-level efforts aligned with national and/or subnational climate goals and are framed within the broader field of climate policy and action.

In this broader field and in international forums, India has historically played a major role in negotiations over responses to climate change such as in the United Nations Framework Convention on Climate Change (UNFCCC) and other settings. The country has maintained a strong stance predicated on the concept of differentiated responsibility, which suggests that countries with high levels of historical emissions and high per capita emissions should bear the cost of climate action (Dubash and Ghosh 2019; Sengupta 2019). Although India's current annual emissions are significant, historical emissions remain low and per capita emissions are a fraction of those of Global North countries. This differentiated responsibility standpoint holds that mitigation action should not slow development or economic growth and that finance for adaptation and the nascent question of loss and damage should be provided by wealthy nations. Although these conversations largely operate beyond the purview of particular cities, these factors influence national- and state-level plans. Further, such discourse potentially influences state actors, NGOs, and other non-state actors that work on urban-level climate-related plans in India.

In 2008, before the highly anticipated 2009 UNFCCC negotiations, India began the process of creating a National Action Plan on Climate Change (NAPCC). This process marked a notable shift at the national level, where addressing climate change more clearly became a part of the national agenda (Dubash and Ghosh 2019). To further the goals and assist in the implementation of the NAPCC, the central government in 2009 directed Indian states to create State Action Plans on Climate Change (SAPCCs). The creation of these SAPCCs has been a highly heterogenous process with mixed results (see Dubash and Jogesh 2019; Gogoi 2019), though elements of these SAPCCs have, in limited cases, been incorporated into climate-relevant planning in cities.

Beyond this, urban climate action has not been a primary focus of higher levels of government, beyond limited instances. For example, the ClimateSmart Cities Assessment Framework (CSCAF) was incorporated into the Smart Cities Mission in 2020 (NIUA 2020). This work has primarily been an exercise in assessing climate-relevant parameters using a relatively simple framework that relies on readily available data. Although the CSCAF initiative has helped to put the issue of climate vulnerability on the urban agenda, its scope remains limited. Further, this initiative—planned by the Ministry of Housing and Urban Affairs (MoHUA)—highlights an ongoing tension within the field of urban climate action in India. The Ministry of Environment, Forest, and Climate Change (MoEFCC)—the nodal ministry for climate issues—is not tasked with handling urban issues, and the MoHUA is similarly not regularly asked to address climate-related concerns in urban plans and programs.

Given the relative lack of support from the central government, much urban climate action planning to date in India has instead occurred in concert with international networks and through leveraging different modes of financial assistance. Such efforts rely on often-complex cross-scalar networks, involving urban local governments and a range of NGOs and other non-state actors such as consultants, experts and academics, national and international donors, and formal international consortiums of cities (Khosla and Bhardwaj 2019). This began with efforts through ICLEI – Local Governments for Sustainability and the Rockefeller-Foundation-funded Asian Cities Climate Change Resilience Network (ACCCRN) (D. Sharma and Tomar 2010). ACCCRN operated from 2008 to 2015 and was involved in seven second-tier cities in India (Chu 2016, 2018; D. Sharma et al. 2014); however, it was largely a planning exercise, with limited implementation. The ACCCRN program helped establish an initial, albeit limited, focus on climate change in cities and on the need to address emerging forms of vulnerability.

Following ACCCRN, the Rockefeller Foundation began the 100 Resilient Cities (100RC) program, which ran from 2013 to 2019 and involved four Indian cities. Although implementation efforts remained limited with the 100RC program as well, the focus was placed on institutionalizing climate change as a planning priority within municipal corporations. Currently, six Indian cities participate in the C40 Cities Climate Leadership Group and are developing (or have recently published) their city climate action plans to meet the C40 leadership standards. Although the experiences of cities have varied, such participation has encouraged new climate-focused action, including vulnerability assessments and ongoing work to create climate action plans for the participating cities.

VULNERABILITY ASSESSMENT FRAMEWORKS USED IN INDIAN CITIES

Historically, vulnerability assessments have been carried out using a range of different frameworks, tools, and methodologies. This is in part due to both the complex and contextually specific nature of vulnerability and the available tools, norms, and standards. In this section, we provide the historical context in which our proposed CHVA framework is situated. In roughly chronological order, we review the specific frameworks used in India, noting their strengths and limitations.

As part of the ACCCRN platform, participating cities were allowed to choose a vulnerability assessment framework, but the findings and processes were meant to align with adaptation strategies that aim to reduce vulnerability and increase resilience. In contrast, the 100RC network required participating cities to use the City Resilience Index, developed by the consulting firm ARUP. This index attempts to tackle the complex aspects of urban systems that contribute to vulnerability, such as health, well-being, the economy and society, infrastructure, ecosystems, and leadership and strategy. Although it acknowledges the social drivers of vulnerability, it provides little guidance to cities on translating findings into resilience or adaptation strategies for reducing vulnerability. The City Resilience Index has been further critiqued for treating vulnerability in an overly simplistic and technocratic manner that fails to fully account for local context, conditions, and forms of knowledge (see Leitner et al. 2018; Webber et al. 2021).

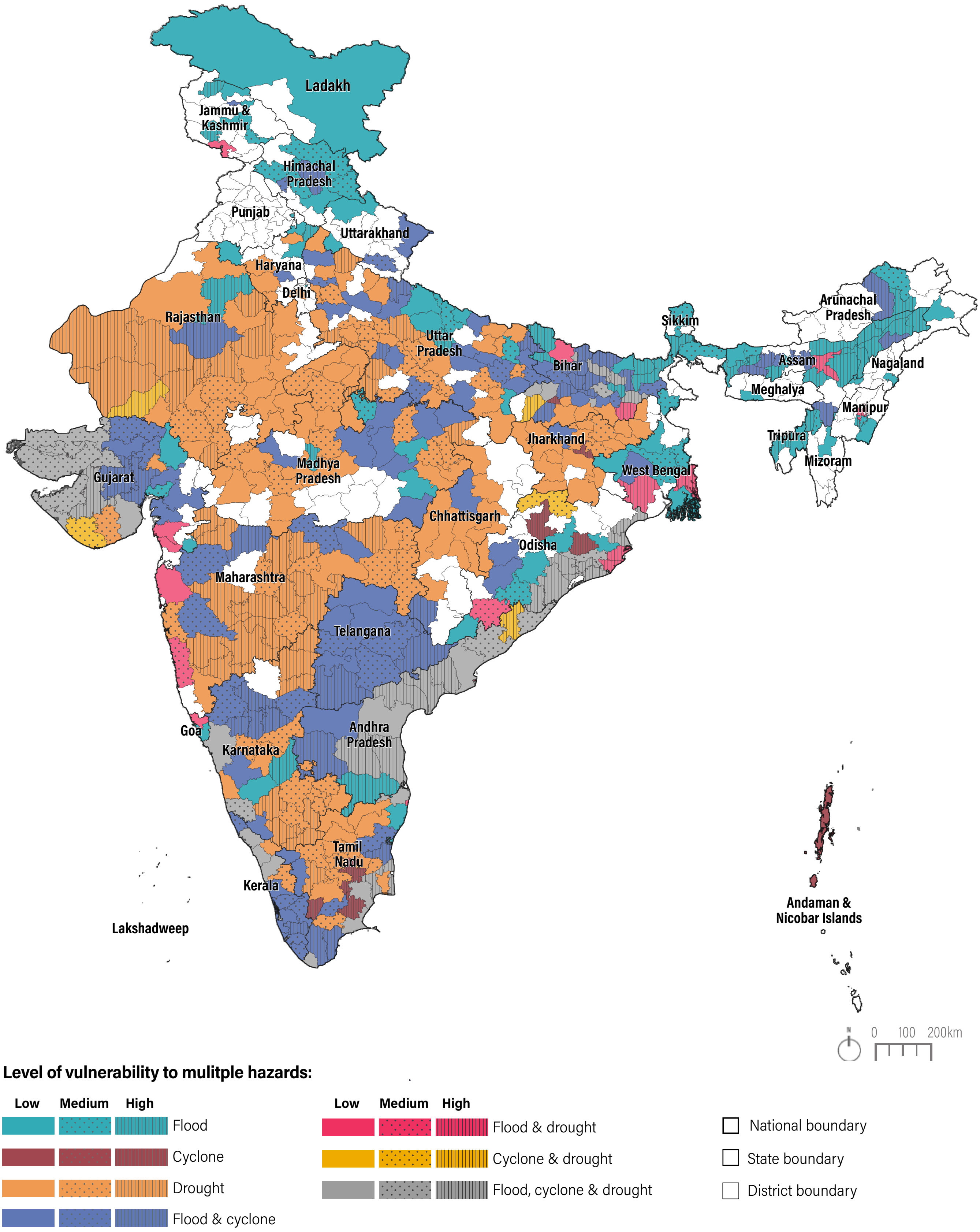
Even larger in scope and ambition than ACCCRN or 100RC, the international C40 Cities Network and Global Covenant of Mayors for Climate & Energy (GCoM)[2] require that all participating cities publish climate action plans (CAPs) as part of their leadership commitments. C40-compliant CAPs include both mitigation and adaptation strategies, and all cities are required to fill out a checklist of indicators based on their Climate Change Risk Assessment (CCRA) framework (C40 Cities Climate Leadership Group, C40 Knowledge Hub n.d.). Like many other vulnerability assessment (VA) frameworks in use, the CCRA focuses on the current and future climate hazards and their potential impacts on people, assets, and services. However, the CCRA builds on C40's Inclusive Climate Action (ICA)[3] framework by strongly recommending that cities spatialize these assessments to identify critical hotpots for intervention in the action plans. C40's Knowledge Hub provides a range of tools for cities to use. Further, C40 acknowledges the limitations of city governments in accessing and analyzing data, especially for underserved areas of the city, and the often-limited technical capacities of urban governments to produce coherent assessments.

Vulnerability assessments have also been proposed in India. In 2014, the Government of India (GoI) and United Nations Development Programme (UNDP) published a city-level climate risk and vulnerability assessment for the city of Bhubaneshwar in Odisha. This was one of the first assessments of this type published in India. The report included a multi-hazard analysis to map risk exposure and produce a composite vulnerability assessment addressing physical, social, and environmental aspects, and their impact on human health with an assessment of capacities (UNDP 2014). This effort resulted in several targeted actions such as ward-level disaster preparedness plans, school and hospital safety, crowd management during disasters, incident response systems, first aid and disaster survival skills, and collapsed structure search-and-rescue preparedness. Although these efforts are vital in a disaster-prone state, they are solely focused on disaster risk reduction (DRR) (BMC n.d.). That is, a focus on DRR alone does not adequately address the social determinants of vulnerability, and the approach has not been sufficiently comprehensive for resilience planning at a city scale.

More recently, in 2021, the Department of Science and Technology (DST) published the *Climate Vulnerability Assessment for Adaptation Planning in India Using a Common Framework* report, acknowledging that assessment of vulnerability is the first step toward addressing climate risks. Although India's National Communication (NATCOM) to the UNFCCC and Biennial Update Reports (BUR) have been highlighting vulnerability at different scales across non-urban sectors such as agriculture, forests, and water, this was one of the first official comprehensive efforts to use a common framework to create a national climate vulnerability assessment highlighting the most vulnerable states and districts in India. The report shows that all districts and states in India are to some degree vulnerable to climate risks (PIB Delhi 2021). The focus is on assessing "current weaknesses of a natural or socioeconomic system along with drivers of such weaknesses" by using 14 socioeconomic, biophysical, institutional, and infrastructural vulnerability indicators. Vulnerability insights and adaptation priorities from this report focus on sectors such as agriculture, forests, and health (IIT Mandi and IIT Guwahati 2019), revealing a gap in addressing differential adaptation needs in complex urban environments.

In alignment with one of the key recommendations highlighted in the DST's report, the Council on Energy, Environment, and Water (CEEW) published a report creating a Climate Vulnerability Index (CVI) for states and union territories by mapping exposure, sensitivity, and adaptive capacity using spatiotemporal analyses. This study looks at the combined risk of hydrological and meteorological disasters (floods, droughts, and cyclones) and their compounded impacts on vulnerability. The report suggests that more than 80 percent of India's population lives in districts that are highly vulnerable to such disasters, as seen in Figure 1 (Mohanty and Wadhawan 2021). The CEEW report can provide necessary direction to subnational governments for targeted adaptation action at the district level, but has limited insights for urban local bodies, which require a more disaggregated understanding of needs and hazard risks in the most vulnerable areas (or communities) in a city. Therefore, the ability of some of these national-

FIGURE 1 | Composite Disaster Vulnerability Index of India



Note: Vulnerability is analyzed for floods, cyclones, and droughts exclusively, sequentially, or in combination, as applicable.

Source: Re-created by the authors based on Mohanty and Wadhawan (2021).

level assessments in India to influence city-level climate action or resilience plans is currently limited. However, these assessments have been vital in highlighting the issue of increasing vulnerability in India across regions, sectors, and occupations.

City-level vulnerability assessments can help identify high-risk areas and focus on climate hazards that are relevant to a particular city. Assessing the differential vulnerabilities to climate hazards from a systems approach can address the risks associated with cascading problems and failures given the interdependencies of infrastructural and social systems (C40 Cities and AECOM 2017). Adaptation action in Indian cities is often focused on preparatory actions and capacity building for disaster management. However, a more integrated approach is required for response and preparedness planning that requires first understanding the present and anticipated forms of vulnerability while addressing the issues of exposure, sensitivity, and adaptive capacity. The Hazards, Infrastructure, Governance and Socioeconomic (HIGS) framework for climate responsive urban development is a foundational work that adopts an integrated systems approach in reducing hazard vulnerability across infrastructure, governance, and socioeconomic conditions (Parikh et al. 2014). The CHVA framework in this report builds on the HIGS framework and provides a spatialized assessment of vulnerability for Indian cities, focusing on demographic differences and people's ability to access critical infrastructure networks and urban services, both routinely and during disasters.

INTEGRATING VULNERABILITY ASSESSMENTS INTO CLIMATE PLANNING EFFORTS IN CITIES

Vulnerability assessments are only one—although important—part of broader climate action. Resilience and adaptation plans depend on assessments of vulnerability, and how the "problem" of vulnerability is defined shapes the solutions proposed in these plans.[4] More broadly, CAPs may or may not involve adaptation or resilience, though given the climate risks faced by almost all cities globally, the need for taking vulnerability into account in CAPs is growing. In this section, we consider how vulnerability assessments are translated into more action-focused plans.

In 2014, eight Indian cities—Coimbatore, Tirunelveli, Tiruchirappalli, Vadodara, Ahmedabad, Rajkot, Siliguri, and Udaipur—were identified to be part of the "Capacity Building for Low-carbon and Climate Resilient City Development in India (CapaCITIES)" project[5] (CapaCITIES n.d.). In its first phase, the project aimed to enhance the capacities of city authorities to plan and implement climate change mitigation and adaptation measures at the city level using the "comprehensive Climate Resilient Cities (CRC) methodology" (CapaCITIES and SDC n.d.). This was one of the first methodologies developed for Indian cities to create action plans that promote low-carbon and climate resilient city development. Following this, the CSCAF created a simplified framework of indicators aligned with the Smart City Mission. It was meant to build capacities through a training program and encourage cities to create CAPs (MoHUA and NIUA 2022).[6]

Building an evidence base and conducting a baseline assessment is an essential first step in climate action planning for any city, state, or country. Along with mitigating GHG emissions, CAPs can be used by cities to prepare, adapt, and plan for climate hazards and address risks that affect people, assets, and systems in cities (C40 Cities 2020). Adaptation actions in CAPs are usually based on climate risk and vulnerability assessments that evaluate physical, environmental, economic, and social vulnerabilities and focus on the most vulnerable groups in the city (UN-Habitat 2015). Nine Indian cities, supported by NGOs and other non-state actors, have conducted hazard, risk, and vulnerability assessments, following a key recommendation under the CSCAF's Cities Readiness Report to integrate spatial mapping and geospatial analysis for data-informed decision-making. As many as 96 out of 126 cities are still at early stages of developing CAPs and need to initiate vulnerability assessments and GHG inventory preparation (MoHUA and NIUA 2021).

When vulnerability assessments are factored into city CAPs, cities are better able to address present and future climate hazards and make a compelling case for statutory amendments, institutional reforms, and climate proofing critical infrastructure. Through the C40 Cities leadership platform, the Brihanmumbai Municipal Corporation (BMC) published its first CAP in 2022, which integrates a detailed spatial climate and air pollution risks and vulnerability assessment to plan for adaptation and climate-proofed mitigation measures. Although Mumbai has one of India's most well-equipped and modern disaster management departments, the department's knowledge, data, and expertise are rarely used to inform long-term land use planning, for developing building regulations, or to identify locations for new infrastructure projects. The Mumbai CAP encourages several interdepartmental alignments to address the city's vulnerability to climate change and the adaptation potential of integrated and holistic solutions (BMC 2022).

As part of the city climate action planning processes in Mumbai, Bengaluru, Solapur, Nashik, Chhatrapati Sambhajinagar, and Kochi, WRI India teams have worked with city authorities to assess climate-related risks and hazards, differential exposure, and vulnerabilities. The approach for these assessments was built on WRI's Urban Community Resilience Assessment (UCRA) framework, which operationalizes the principle of putting vulnerable people at the center of climate action and helps cities acknowledge differential vulnerability across localities, within localities, and within households. The city-based assessments completed so far differ between cities and by different risk criteria, based on the availability of data and the kinds of challenges and interdependencies between risks, hazards, and vulnerabilities in each city.

Through this report we highlight the importance of integrating vulnerability assessments in planning efforts related to climate change in cities, both people's vulnerability and that of infrastructure and its impact on people.

PUTTING VULNERABLE PEOPLE AT THE CENTER OF CLIMATE ACTION

The resilience and climate planning efforts that we outline above have largely overlooked questions of differential vulnerability. Recently, C40's ICA framework has highlighted the necessity of focusing on vulnerable urban populations and addressing their needs in CAPs. However, inadequate access to data for underserved communities makes using the ICA tools difficult and uncertain in helping city governments develop just and equitable CAPs. Conversely, focusing on differential vulnerability and using the CHVA framework to develop spatial maps of differential vulnerability can help governments identify "differential adaptation needs" across cities, creating room for granular implementations of the ICA or similar approaches.

More broadly, although the concept of differential vulnerability has become increasingly mainstream in international discourse on adaptation and resilience, operationalizing it is challenging. Within India, the concept remains relatively marginal, and there is a need to make vulnerability assessments in cities more focused on differential vulnerability and the needs of people and communities. This is an important gap to address. As we have illustrated in this chapter, vulnerability in cities is shaped to a great extent by social factors and different forms of inequality (Bulkeley et al. 2013; Cutter et al. 2008; Fraser et al. 2016; Kuhl et al. 2021; Thomas et al. 2019). Addressing differential vulnerability thus requires a social analysis of needs, deprivations, resources, and service gaps that make exposed populations sensitive to climate hazards and less able to cope with climate risks.

The approach that we outline in this report for assessing differential vulnerability to climate change builds on WRI's UCRA framework (Rangwala et al. 2018) and the ICA framework (Mahendra et al. 2019). The CHVA framework aligns with the IPCC's approach to the concept of vulnerability (see IPCC 2022, 2927), grounded in the assumptions outlined above that social factors significantly impact vulnerability to climate change. The UCRA is intended to overcome concerns with top-down methods of assessing vulnerability by suggesting a more bottom-up approach that directly incorporates place-based concerns (see Cutter et al. 2008). This is done by broadening the range of stakeholders who are included in vulnerability assessments and by focusing explicitly on the incorporation of local knowledge into the assessment process. By involving more voices in the vulnerability assessment process—coupled with taking a strongly spatial approach to understanding vulnerability—the UCRA helps operationalize the principle of putting vulnerable people at the center of climate action.

Further developing these features of the UCRA framework, this report uses the concept of differential vulnerability to underscore this people-centric approach. There is no precise science for assessing vulnerability, and such assessments must strike a balance in their approach between focusing on climatic exposure, infrastructural concerns, and the social determinants of vulnerability. To date, many vulnerability assessments have strongly focused on questions of exposure, framing the problem of vulnerability as one of exposure to climate hazards. The resulting resilience plans thus focus on primarily infrastructural fixes to reduce the impact of such exposure. Although infrastructural fixes are without doubt a key element in many cases, they do not address the question of differential vulnerability and the many social factors that constitute sensitivity and adaptive capacity. Putting people at the center of vulnerability assessments highlights the social underpinnings of vulnerability. This reframing means that it is not only infrastructural interventions that are important to resilience plans; explicit attention to the social, economic, and political factors that drive differential vulnerability is also necessary.

This infrastructural bias of vulnerability assessments is in many ways related to logistical and resource constraints. Collecting and analyzing data on exposure is often easier, faster, more quantitatively clear, and less politically fraught than handling social data on sensitivity and adaptive capacity. Similarly, infrastructural interventions can be framed as technical fixes that can often be converged with other policy priorities, whereas addressing differential vulnerability demands more complex solutions.

The framing of differential vulnerability in this report has an explicit focus on hazards and the social drivers of vulnerability using accessible data and methodologies. By helping to bring people to the center of climate action, the framework that we outline in this report can serve as the basis for adaptation plans and interventions that can build resilience in cities and help create more just and equitable climate action and development. In the following chapters, we discuss in detail this framework, methods for conducting a vulnerability assessment, and the potential applications of assessment findings. In Chapter 2, we discuss the methodology used to create this framework, also highlighting the framework's scope and limitations. Chapters 3 and 4 present the framework itself in two parts, one, identification and assessment of hazards and exposure and, two, assessment of differential vulnerabilities, through the lenses of sensitivity and adaptive capacity, respectively. Chapter 5 focuses on the methods suggested for conducting a vulnerability assessment and the necessary tools and data sources. Chapter 6 outlines how to conduct a vulnerability assessment. Finally, Chapter 7 provides recommendations and suggestions for practitioners and policymakers to address urban vulnerability.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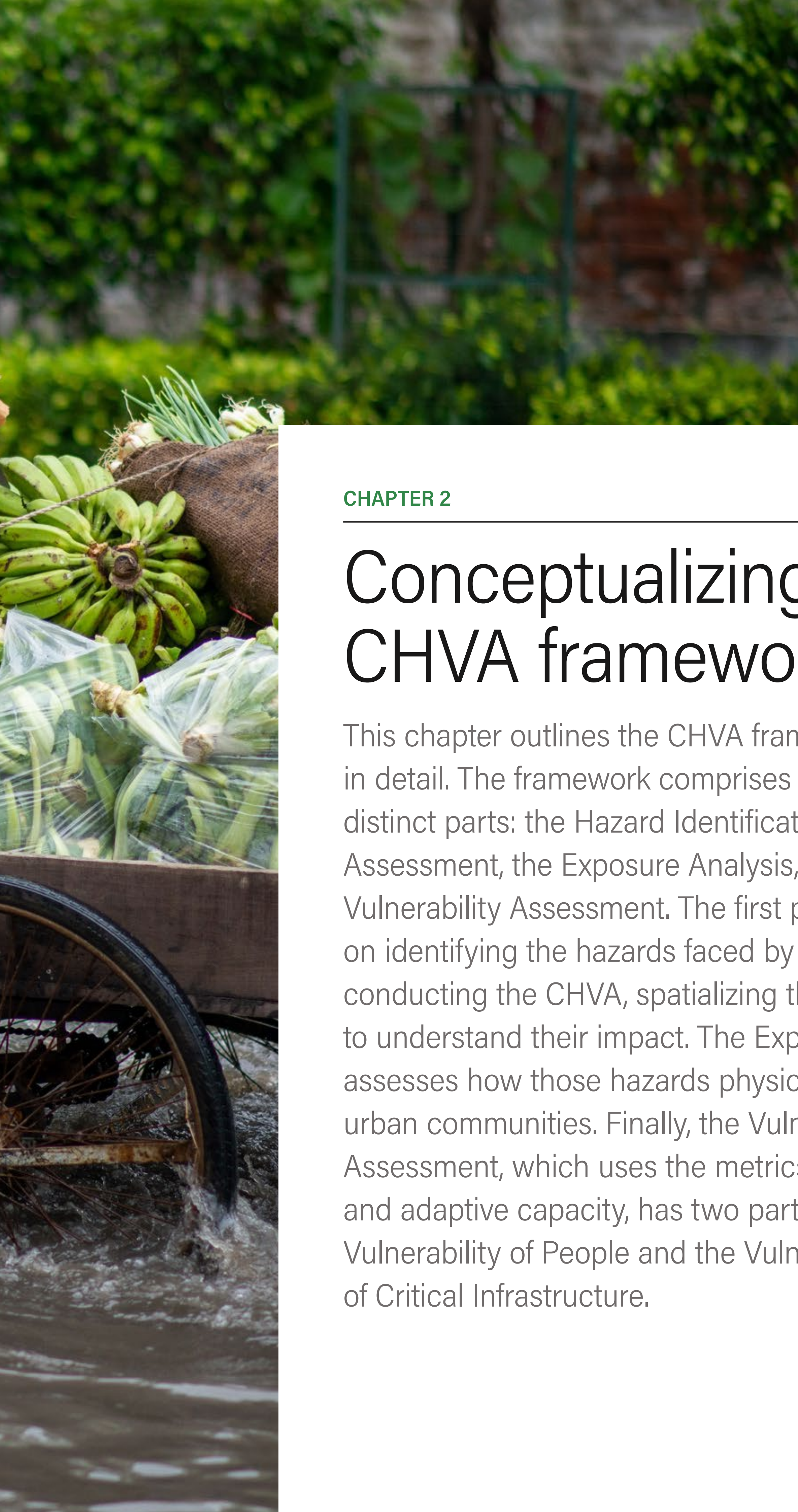


CHAPTER 2

Conceptualizing the CHVA framework

This chapter outlines the CHVA framework in detail. The framework comprises three distinct parts: the Hazard Identification and Assessment, the Exposure Analysis, and the Vulnerability Assessment. The first part focuses on identifying the hazards faced by the city conducting the CHVA, spatializing those hazards to understand their impact. The Exposure Analysis assesses how those hazards physically impact urban communities. Finally, the Vulnerability Assessment, which uses the metrics of sensitivity and adaptive capacity, has two parts: the Vulnerability of People and the Vulnerability of Critical Infrastructure.

As part of city climate action planning processes in Mumbai, Bengaluru, Solapur, Nashik, Chhatrapati Sambhajinagar, and Kochi, WRI India teams have worked with city authorities to assess climate-related risks and hazards, differential exposure, and vulnerabilities. Building on these learnings, the CHVA (as seen in Figure 2) is structured in three parts: first, the Hazard Identification and Assessment (HIA); second, the Exposure Analysis (EA); and third, the Vulnerability Assessment. The Vulnerability Assessment is composed of two parts: the Vulnerability of People and the Vulnerability of Critical Infrastructure in the city. This framing allows the social and physical determinants of vulnerability to be assessed. We further disaggregate social vulnerability to engage with the social, economic, and political factors that drive differential vulnerability within the framework in the hope that resilience plans and adaptation strategies will address these dimensions that drive differential vulnerability.

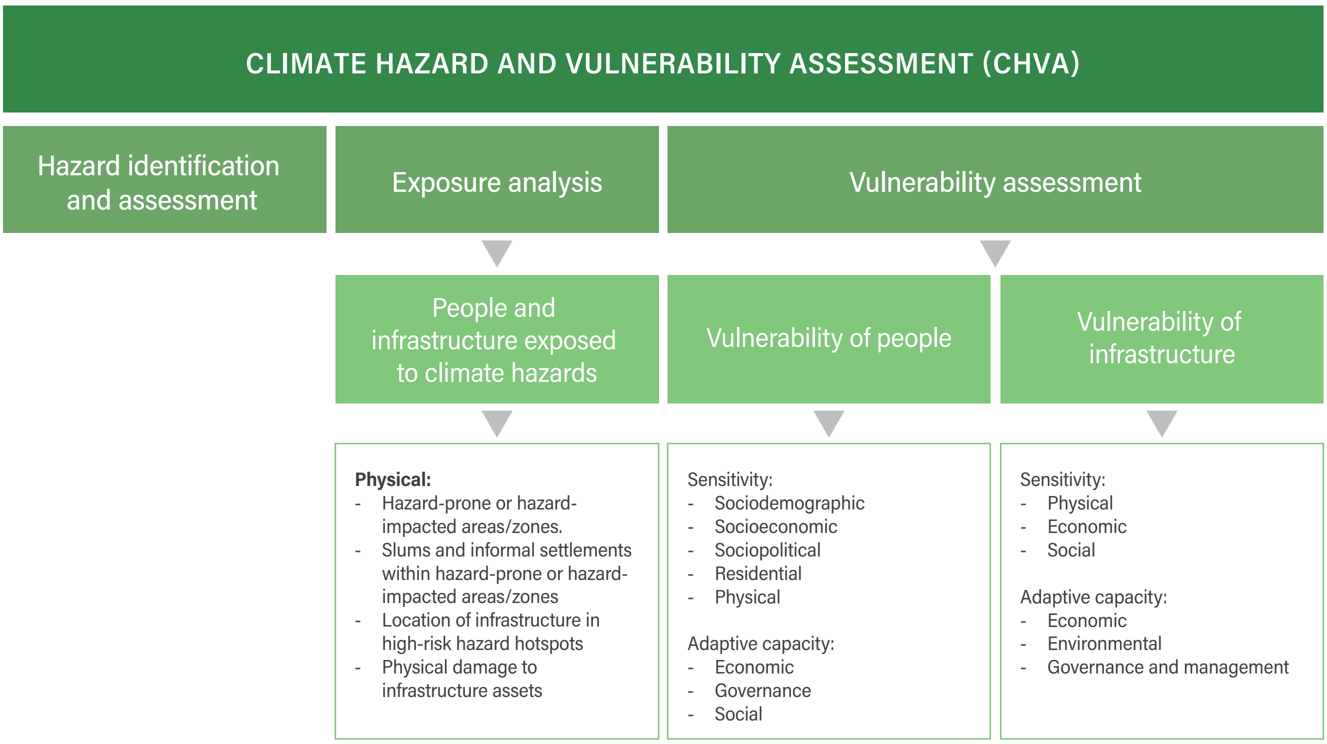
This chapter situates the CHVA within the context of the risk and vulnerability literature and discusses the scope and limitations of the framework. Following this, Chapters 3 and 4 present the operational description of the framework by outlining the vulnerability indicators. Chapter 5 briefly describes methods, data required to conduct the assessments, and analytic approaches. These four interconnected chapters together provide an overview of the CHVA.

DEFINING THE FRAMEWORK

The CHVA was developed to identify and assess climate hazards, analyze exposure in risk-prone areas, and visualize differential vulnerability in Indian cities. The framework can be used by urban local bodies, development authorities, Smart City Offices, environment departments, and other relevant agencies in India to conduct a climate hazard and vulnerability assessment. For specific transborder hazards, the risk assessment will need to be conducted at the regional level, such as the watershed or airshed level for certain parameters of drought, riverine flooding, or air pollution. In addition, regional air and water flows or activities outside city boundaries may influence the air quality and water quality and availability within a city or urban area.

Using this assessment framework, hazard trends, areas exposed, and vulnerability can be compared over time,

FIGURE 2 | The Climate Hazard and Vulnerability Assessment framework explained



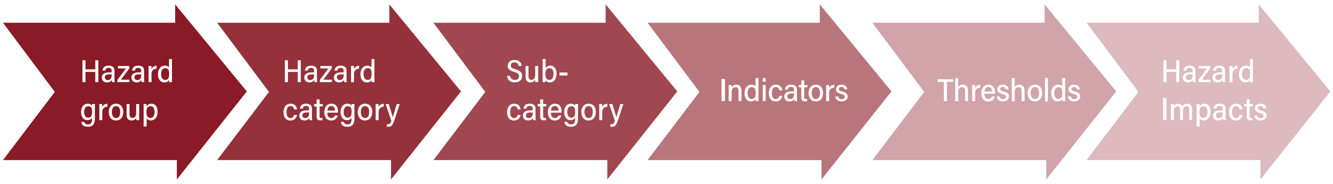
Source: Authors.

depending on the availability of historical data in a particular city. Cities can conduct a Vulnerability Assessment to understand the impact of climate hazards on people, urban infrastructure, and services to establish a baseline against which progress on climate action in a city can be measured. The CHVA can also be used to monitor the implementation and outcomes of adaptation and vulnerability reduction programs and undertake midcourse corrections as needed. The CHVA relies on historical weather data and satellite imagery for the temporal assessment of climate hazards and exposure. Due to inconsistencies in the quality of the data available at the granular level to suit city-specific needs, it is difficult to accurately model future climate risks. However, the CHVA can help cities visualize differential vulnerability based on past and current data to inform spatial planning processes and the implementation of climate actions to meet future needs.

Step 1: Hazard Identification and Assessment

The first step of the framework focuses on identifying and assessing the extent and propensity of climate- and environment-related hazards that potentially impact urban populations. Figure 3 explains the various attributes used to identify and assess the nature of the hazards (based on their group, category, and sub-category), and Table 1 presents the definitions, which are further explained in Chapter 3.

FIGURE 3 | Levels of the Hazard Identification and Assessment framework



Source: Authors.

TABLE 1 | Definitions of the various levels of the Hazard Identification and Assessment

TERM	DEFINITION
Hazard croup	Hazards are grouped on the basis of their origin, causes, natural or anthropogenic processes, and associated phenomena. The grouping used in the framework includes meteorological, hydrological, geological, and environmental hazards.
Hazard category	Hazard groups are further subdivided on the basis of the causal sequence or aspect of the natural or anthropogenic process that drives the hazard.
Sub-category	Hazard categories are further subdivided based on the precise event in the causal sequence of hazard occurrences.
Indicators	Hazards are characterized by their location, intensity, frequency, magnitude, and likelihood. These are measurable indicators that can be computed exclusively, sequentially, or in combination.
Thresholds	The thresholds for each hazard sub-category are defined as follows. Each threshold is a metric used to categorize the intensity of extremity of hazards according to national and international standards. A threshold can be a point beyond which variations cannot be attributed to weather variability and that impact the effective functioning of key climatic and environment systems (Jones 2020). They might otherwise be a departure beyond permissible or acceptable limits.
Hazard impacts	The impacts of hazards primarily refer to their effects on natural and human systems due to changes in climate trends and/or the occurrence of extreme weather and climate or environmental events.

Source: IPCC 2014.

TABLE 2 | Defining the hazard groups

TERM	DEFINITION
Meteorological and hydrological hazards	Meteorological and hydrological hazards are those resulting from the state and behavior of Earth's atmosphere. These hazards include weather and climate patterns or events that interact with land, oceans, and the atmospheric cycles.
Geological hazards	Geological hazards can be attributed to seismogenic and volcanogenic activity; that is, Earth's internal geophysical processes, or the impact of meteorological or hydrological hazards that lead to changes in surface or near-surface formations (some type of land mass movement).
Environmental hazards	Environmental hazards arise through urbanization pressures and degradation of the natural systems and ecosystem services on which humanity depends.

Source: UNDRR 2020.

The first step assesses hazards and their potential impact on various elements of a city (people and society, economy, infrastructure, services, and natural systems), within a climate context made variable by local pressures and global climate change.

The grouping of meteorological, hydrological, geological, and environmental hazards is contextualized to align with the definitions of hazards and climate patterns provided by multiple agencies of the GoI. The theoretical definition of these identified hazard groups is provided in Table 2 (as defined by the United Nations Office for Disaster Risk Reduction, International Science Council [UNDRR and ISC]). Some of the hazards listed in the table are interlinked due to their fundamental nature, which means that they often trigger a domino effect in the form of sequentially experienced or concurrent events, or contribute to long-term change along with the post-disaster impacts (UNDRR 2017). For example, an increase in sea surface temperature leads to cyclone formations, resulting in high-intensity rainfall events or unseasonal rainfall events that may cause localized floods, landslides, disease outbreaks, and so on. Therefore, when analyzing hazard events for a location, hazards can be regrouped to match the local context.

This framework will not cover extraterrestrial hazards such as asteroid and meteorite impacts, chemical hazards such as gas leaks, biological hazards such as disease outbreaks and epidemics, technological hazards such as technological disruptions and failures, and societal hazards such as war and armed conflict. Additionally, the impact on agricultural and nutritional security is also beyond the scope of this framework; complex analysis is required to ascertain the risk posed by climate change on these factors in the urban context (UNDRR 2020).

Step 2: Exposure Analysis

The second step focuses on analyzing the extent (spatial area, people, and infrastructure) of exposure in a city, based on the identification of high-risk areas, or risk hotspots. Figure 4 depicts the structure of the Exposure Analysis framework that helps spatialize the extent of exposed areas, people, and infrastructure in a city.

FIGURE 4 | Levels of the Exposure Analysis framework

Source: Authors.

TABLE 3 | Definitions of the various levels of the Exposure Analysis

TERM	DEFINITION
Exposure domains	Exposure is mainly a function of location and hence is defined by the physical domain.
Elements exposed	Exposure is assessed for two elements; namely, the people and infrastructure exposed to climate hazards.
Exposure index	Each site of exposure is defined by indices that group related indicators. For example, two indices are used for exposure of people: hazard-prone locations or areas in the city and slums or informal settlements located in hazard-prone or high-risk areas in the city.
Indicators	These are specific measurable attributes that are assessed to determine the city's population, communities, and infrastructure exposed to climate hazards.
Percentage exposed	When the indicators of exposure are spatialized on a map, the percentage exposed in a city can be determined.

Source: Authors.

The Exposure Analysis framework focuses on the physical domain and helps identify the areas, communities, and critical infrastructure that are most exposed to specific climatic and environmental hazards. The objective is to identify, one, the percentage of the population that lives in hazard-prone or risk hotspots in a city and, two, the exposure of critical infrastructure—such as mass transportation networks and infrastructure for water management, sanitation, power generation and supply, fire services, and health services—located in hazard-prone areas in the city. Table 3 defines aspects of the Exposure Analysis framing; more details are provided in Chapter 3.

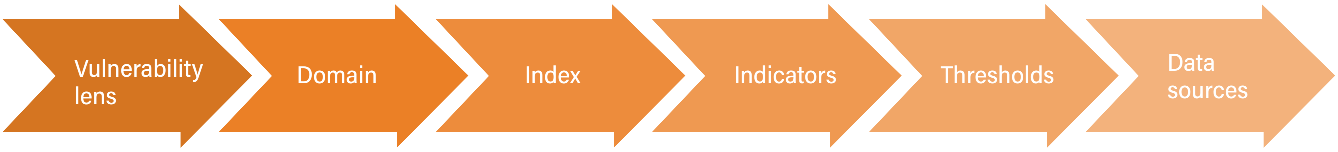
After completing the Hazards and Exposure Analysis, cities will have the information they need to conduct a Vulnerability Assessment, which is described in the next section.

Step 3: Vulnerability Assessment

The Vulnerability Assessment framework is structured in two parts: first, assessment of the vulnerability of people, and second, assessment of the vulnerability of critical infrastructure. In this report, we focus on the social drivers of vulnerability, based on the IPCC's Sixth Assessment Report, which frames vulnerability as one of three components that drive risk, alongside exposure and hazards (IPCC 2022,133). The CHVA is intended to help cities understand and act on vulnerability. It will help cities understand how vulnerability is differentially distributed given socioeconomic, political, and demographic drivers. Here, vulnerability is defined by two lenses: sensitivity and adaptive capacity; alongside the Exposure Analysis, these components are determined as "necessary for identifying climate adaptation strategies and actions" (Thompson et al. 2015). The lenses are further defined and operationalized for this framework in Chapter 4.

- **Vulnerability of people:** This framework will help identify the socioeconomic aspects that drive vulnerability in communities, neighborhoods, and wards that are exposed to the climate hazards assessed in the Exposure Analysis. The structure of the framework (as illustrated in Figure 5) clarifies the differential vulnerabilities of various people and communities based on their levels of socioeconomic sensitivity and adaptative capacities. For sensitivity, people's demographic and socioeconomic conditions are assessed and their access to infrastructure and urban services in underserved neighborhoods is mapped. For adaptive capacity, people's access to financial schemes and insurance is assessed, in addition to the reach of early warning systems and information communication technologies. This composite reading of various factors can help cities map differential vulnerability and thus act on it.
- **Vulnerability of infrastructure:** This part of the framework will help assess the sensitivity of infrastructure projects, in terms of economic and social factors, such as revenue or asset losses, and the adaptive capacity of infrastructure systems and agencies by checking the associated disaster relief protocols, emergency relief funds, and potential for climate proofing.

FIGURE 5 | Levels of the Vulnerability Assessment framework for people



Source: Authors.

FIGURE 6 | Levels of the Vulnerability Assessment framework for infrastructure

Source: Authors.

TABLE 4 | Defining key terms in the Vulnerability Assessment framework

TERM	DEFINITION
Vulnerability lens	Sensitivity and adaptive capacity are the two lenses through which vulnerability is viewed.
Domain	The vulnerability lens looks at different vulnerability "domains" such as physical, sociodemographic, economic, and environmental.
Index and indicator	These are specific, measurable attributes that are to be assessed by this framework to understand the different types and extent of vulnerability in the city. When spatialized on a map, they help determine differential vulnerabilities across localities in the city and differences due to socioeconomic sensitivities and lack of access to essential services.
Thresholds	These are specific critical values that are used to assess the vulnerability indicators. For both the vulnerability of people and of infrastructure, these thresholds are sourced or determined based on a scientific and consultative approach. ▪ For the vulnerability of people: Thresholds are determined scientifically on the basis of literature studies on socioeconomic, cultural, and political systems, including service delivery and access benchmarks and standards at the global, national, or city level. These thresholds vary from city to city, depending on a city's inherent geographic and social conditions and encompassing its cultural, demographic, economic, and governance systems. ▪ For the vulnerability of infrastructure: The nature, quality, and resolution of the datasets used in the assessment will determine the thresholds. The consultative process for establishing vulnerability thresholds is discussed in Chapter 6.
Information Needs	Finally, the framework suggests using datasets sourced from public and government agencies, which are likely to be available on public platforms. However, most Indian cities lack good-quality publicly accessible administrative data collected by the city itself. The primary suggested data source is the Government of India's decadal Census, the limitations of which are discussed later in this section.

Source: Authors.

Figure 6 shows the structural flow of the framework from the vulnerability lens to information needs. The terms in the figure are defined in Table 4. Information needs comprise a list of data points that need to be collected from a city authority or a private entity that manages the specific system. These data points and sources will differ for different cities.

LIMITATIONS OF THE FRAMEWORK

Like other tools used to assess vulnerability to climate change, the framework outlined in this report has a number of limitations. It is important that practitioners and users of this framework understand these limitations so that vulnerability is not incorrectly conceptualized or measured. The limitations in large part stem from external factors, such as problems with data and logistical or political factors inherent in local governance, though the framework does have some conceptual limitations.

Data

This framework primarily relies on data from the Census of India, which is advantageous because of its accessibility, depth of coverage of issues related to populations by age and gender, and decennial continuity. Census data provide details down to the ward level within cities, in a standardized format that makes it easy to compare different locations. However, because census data are collected on a decadal basis, they become outdated quite quickly. The use of outdated data raises concerns about the accuracy with which the rapid demographic change evidenced in many Indian cities can be captured and may result in skewed results. Census data attempt to but do not fully capture certain populations of migrants, informal workers, and unhoused people. The Census and existing sources of official data in general do not account for the degree of mobility and migration patterns that prevail in India. Moreover, administrative boundaries within cities might not correspond directly to census boundaries, necessitating additional analysis.

The CHVA framework also relies on and can be supplemented by departmental and other government data, though such data also have limitations. For example, such data are rarely uniform. Cities collect different data for different purposes, depending on their capacity, needs, and priorities. Even in cities with higher levels of capacity and more resources, data collection is often challenging, irregular (both spatially and temporally), and at times unfeasible. Data for this framework need to be drawn from multiple sectors, and due to the lack of interdepartmental collaboration and coordination, collecting relevant data from multiple departments can be a daunting task. The data collection phase of conducting a CHVA (see Chapter 6) may take up to six months or more, considering the degree of inter-agency coordination needed. Moreover, data collected by municipal governments can be of poor quality and difficult to verify. Because data gaps are common, with, for example, data from certain years missing, longitudinal analysis becomes difficult.

In addition to census and urban departmental data, this framework actively employs publicly available, geospatial data derived from satellites, monitoring stations, and sensors, among others. However, it requires a relatively high level of expertise to process and analyze large geospatial datasets.

Additional data—for example, from community groups, NGOs, or other local organizations—can be used to supplement this framework. Such data can be helpful for adding nuance and context to official data, allowing those conducting the CHVA to pinpoint especially vulnerable neighborhoods and communities. However, because of the particular nature of such data, they can be heterogenous, variable, and difficult to verify, and they might represent a relatively limited area or community and are unlikely to be comparable within a city or between cities. All of these data also suffer from inherent gaps in measurement and focus, because each agency conducting such surveys has its own purpose, projects, methods, tools, and formats for data collection. Unfortunately, no existing standard framework can be used as a model for the quality, scope, and format that such community- or crowd-sourced datasets will need for compatibility with a holistic national-level framework such as the CHVA. Such data may also not be available from cities that lack strong local community platforms and public forums. Further, the collection of such data is often resource intensive and logistically challenging. Cities will have to make tactical choices given their limited resources and use the available research instead of conducting new surveys. These community-sourced data can be valuable, though, for filling in what might be missing in the census and other official data sources or for validating such data, and can be especially useful in determining the vulnerability of localities and neighborhoods that show up as highly exposed and hazard prone.

However, the CHVA primarily relies on the Census and other official data because these data are standardized, comparable between cities, and accepted by bureaucrats and politicians. Other government data and satellite and geospatial data also provide similar quantitative data that are comparable between places and iterations of the CHVA. The gaps in these datasets for assessing the qualitative determinants of vulnerability can be addressed through consultations with local agencies. As outlined in Chapter 6, consultative processes and community engagement at various levels of the CHVA can help in striking a balance between official government data and qualitative data.

Capacity

Although this framework has been developed to focus on accessible data, using it requires a certain level of capacity. Actors working with this framework—including urban government employees, consultants, and other practitioners—will need some technical expertise. In particular, the prerequisites for using the framework are knowledge and expertise in geosciences, remote sensing, GIS, and data computation. Urban governments may also face challenges in hiring or engaging with experts or consultants in a timely manner, which is essential for the assessment.

Apart from questions of expertise, the cost of performing the assessment may be out of reach for many cities. A lack of budgetary allocations for conducting vulnerability assessments is another obstacle. Within Indian cities, the political will of the local leadership or a directive from higher levels of government are important drivers for vulnerability assessments and climate action planning. The sustainability of such efforts is a challenge, but one that can be mitigated by engaging with donors and participating in networks that advocate for and support climate vulnerability mitigation efforts. Such support in India has included the previously mentioned ACCCRN, 100RC, and C40 initiatives. However, such support has trade-offs; it can impact local ownership of interventions and deter local capacity development efforts.

Qualitative aspects of vulnerability assessments

In addition to these logistical challenges, vulnerability assessments have conceptual limitations. As outlined in Chapter 1, vulnerability—especially within cities—is a relatively complicated concept that is defined in many ways by difficult-to-measure variables which depend greatly on sociopolitical contexts (see Fraser et al. 2016). Vulnerability assessments—including the framework proposed here—attempt to provide a degree of standardization that allows for a straightforward assessment of vulnerability that can be compared across contexts. However, aspects of climate vulnerability can be quite location specific. In short, as discussed in Chapter 1, it is important to understand that vulnerability is in many ways qualitative and contextual, making standardized assessments of vulnerability in some ways inherently limited (see Leitner et al. 2018). This does not mean that such assessments should be ignored; there is great value in measuring vulnerability and in quantifying aspects of vulnerability, wherever possible. However, practitioners need to acknowledge the qualitative and complex nature of vulnerability and understand the contextual features—including social, cultural, and political particularities—that impact the vulnerability of people to climate threats (Pelling 2011; Thomas et al. 2019).

This limitation of vulnerability assessments illustrates the importance of ensuring that assessments are well designed and executed. How vulnerability is defined and assessed in a particular place undergirds subsequent resilience or adaptation interventions. That is, how the "problem" of vulnerability is defined determines resilience-focused "solutions" (Cutter 2016). Treating vulnerability only as a function of hazards produces plans that are often overly technocratic and infrastructurally focused. Conversely, if people are centered in vulnerability assessments, subsequent solutions are more likely to address the root sociopolitical causes of vulnerability, as outlined in Chapter 1.

Potential for maladaptive outcomes

Incorrectly identifying forms of vulnerability or overlooking aspects of vulnerability creates the potential for maladaptation; that is, interventions that increase rather than decrease overall climate vulnerability (Pelling 2011; Thomas et al. 2019). Researchers have identified different pathways through which maladaptation can occur (Atteridge and Remling 2018; Juhola et al. 2016). Avoiding maladaptation can be particularly challenging in cities, where the density of urban populations means that forms of vulnerability often overlap. Interventions that might decrease vulnerability for one community could have negative consequences for another community.

In the context of questions of climate justice within cities, researchers have raised concerns over the possibility that vulnerability-focused interventions might primarily benefit the wealthy while shifting forms of vulnerability to the poor (Anguelovski et al. 2019; Shokry et al. 2020), and exacerbating forms of "green gentrification" and "bourgeois environmentalism" in Indian cities (Aggarwal 2013; Baviskar 2002; Wagh and Indorewala 2022). In India, these questions are related to ongoing concerns regarding uneven urban planning and the general focus of planning efforts on middle-class or wealthy neighborhoods while often neglecting the poor (see Roy 2009). This raises concerns of how urban governments will respond to the findings of a vulnerability assessment and how unintended consequences can be prevented. For example, the identification of hazards and vulnerability in an informal settlement might be used to justify slum clearance in a risky location instead of pursuing environmental improvements within the location. Such inequitable actions are almost certainly maladaptive.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CHAPTER 3

Hazard Identification and Exposure Analysis

To promote sustainable development, cities need to reduce the risks and vulnerabilities of people, places, services, and infrastructure to the impacts of climate hazards. This chapter discusses discrete hazards and uses a framework of related indicators to help determine the exposure of people and infrastructure.

The first step toward determining exposure is the accurate identification of hazards and their underlying indicators based on past trends and future scenarios. Using spatial maps and data analytics, the second step is to identify the areas, communities, and infrastructure that are most exposed to these climate (and environmental) hazards. Exposure Analysis helps determine the percentage exposure for people and infrastructure in a city.

HAZARD IDENTIFICATION AND ASSESSMENT

Indian cities are impacted by a range of hazards, which often occur sequentially or concurrently. Table 5 captures many of these hazards. Cities will have to identify the hazards relevant to them based on their physiography and hydro-meteorological conditions and understand what elements of the city are impacted (see Table 5). The process used in the assessment is discussed in Chapter 6.

TABLE 5 | Indicators for Hazard Identification and Assessment

HAZARD GROUP	HAZARD CATEGORY	SUB-CATEGORY	INDICATORS FOR ANALYSIS[A]
Meteorological	Thermal stress	Air Temperature	Annual air temperature trend analysis and deviations
			Long-term trends of temperature across seasons and timescales
			Frequency of extreme temperature days and nights
			Long-term trend of the frequency of extreme temperature days and nights
			Projected changes in temperature
		Land Surface Temperature (LST)	Short-term trends of LST
			High or low LST hotspots within city
		Thermal Comfort	Temporal trends in heat stress
			Temporal trends in cold stress
		Sea Surface	Temporal trends in sea surface temperature close to the coastline
	Precipitation Change	Rainfall	Temporal trends in rainfall patterns
			Spatial trends in rainfall
			Frequency of extreme rainfall days
			Temporal trends of frequency of extreme rainfall days
			Projected changes in rainfall
		Snowfall	Temporal trends in snowfall

TABLE 5 | Indicators for Hazard Identification and Assessment (cont'd.)

HAZARD GROUP	HAZARD CATEGORY	SUB-CATEGORY	INDICATORS FOR ANALYSIS[A]
Meteorological	Windspeed		Temporal trends of wind speed
	Weather Events	Cyclone	Frequency of cyclones
			Temporal trends of cyclone strength and accumulated cyclone energy
		Thunderstorms	Frequency of lightning strikes
			Temporal trends in frequency of lightning strikes
	Sea Level Change	Sea Level Rise and Fall	Long-term trends in sea level
			Temporal trends in tide levels
		Storm Surge	Temporal trends in storm surges
			Frequency of storm surge events
Hydrological	Flood	Waterlogging	Urban flood hotspot identification
		Riverine Floods	Identification of riverine flood hotspots
			Riverine flood risk mapping
		Coastal Floods/Storm Surge	Identification of areas under risk because of storm surges or associated events
		Glacial Lake Outburst	Identification of upstream glacial lakes
	Drought	Hydrological Drought	Spatiotemporal assessment of baseline water stress in the study area
			Spatiotemporal assessment of baseline water stress in the watershed
		Meteorological Drought	Spatiotemporal assessment of meteorological drought frequency in the study area
			Spatiotemporal assessment of meteorological drought frequency of the watershed
		Groundwater Exploitation	Spatial patterns in groundwater recharge potential
			Temporal patterns in groundwater recharge potential
			Spatiotemporal trends in stage of groundwater development
Geological	Land Deformation	Land Subsidence	Spatiotemporal patterns in land subsidence
		Coastline Change/Sea Level	Spatiotemporal changes to coastline
	Ground Movement	Landslide	Landslide hotspots
			Landslide susceptibility
		Avalanche	Avalanche susceptibility

TABLE 5 | Indicators for Hazard Identification and Assessment (cont'd.)

HAZARD GROUP	HAZARD CATEGORY	SUB-CATEGORY	INDICATORS FOR ANALYSIS[A]
Environmental	Air Quality Degradation	Indoor Air Quality	Indoor PM2.5 concentration
		Outdoor Air Quality	Spatiotemporal trends in concentration of major/criteria pollutants: physical and gaseous pollutants
			Space observations
	Water Quality Degradation	Surface Water Quality	Quality criteria based on physical, chemical, and biological parameters
		Groundwater Quality	Quality criteria based on physical, chemical, and biological parameters
	Soil Quality Degradation	Soil Quality	Quality criteria based on physical, chemical, and biological parameters
	Vegetation Change	Density of Green Vegetation	Spatiotemporal trends in Normalized Difference Vegetation Index (NDVI)
	Fire	Forest Fire	Spatiotemporal trends in satellite-observed fire hotspots within forested areas
		Other Fires	Spatiotemporal trends in satellite-observed thermal anomaly hotspots

Note: a. Methods for analyzing these indicators along with the corresponding datasets and data sources needed are discussed in Chapter 5. For indicator-wise details on computation and thresholds used in assessment, see Appendix B.

Source: Authors.

Many of the indicators listed in Table 5 are derived from natural and climatic phenomena whose variations and trends are analyzed with the objective of understanding their relevance to future trends, climate change, and their impacts. These phenomena become hazardous if their deviation from the long-term averages is significant (Turrentine and Denchak 2021). For example, temperature trends identify whether conditions are becoming warmer or colder, and rainfall trends identify whether the region is becoming drier or wetter. Often, extreme or long-term variations in these phenomena become hazard events when they cross certain thresholds.

Each hazard indicator has a different threshold that may vary depending on the study area,[7] seasonality, and the dataset used for the analysis. Thresholds are the tipping points beyond which the intensity of a hazard and its occurrence changes, and impacts are the long-term climatic and environmental balances of that geography. Over time, cities will be able to assess and integrate the changing profile of hazard occurrences in them as a result of climate change and influence disaster preparedness and resilience planning processes. Thresholds are defined for each hazard sub-category as explained in Table 4. See Appendix B for details on the thresholds for each hazard sub-category.

Identified hazards—alone, in combination (multi-hazard), or as a compounded effect of one another—can negatively impact human and natural systems. Exposure, sensitivity, and adaptive capacity in zones at risk from multiple hazards (determined based on risky locational characteristics, sensitivity to past hazards, or projected trends) have to be studied for impact on population and places. Hazard impacts include (but are not limited to) loss of life, health implications, asset and property loss, resource and environmental destruction, ecological damage, disruption of social order, shifts in livelihood options, and threats to the normal functioning of civic services and amenities. Table 6 offers a short checklist that cities can use to determine which elements within the urban system are likely to be impacted by different kinds of hazards.

The impact is relative and can be prolonged, short-term, and/or immediate based on the magnitude of the hazards and the underlying vulnerability conditions. After identifying hazards, their interactions with each other in multi-hazard-prone areas are mapped. The Exposure Analysis framework described in Table 7 helps identify who and what are most exposed to climate hazards and likely to be impacted. For the CHVA framework, we focus on assessing the vulnerability of people and infrastructure; hence, the Exposure Analysis focuses on elements such as people, jobs, and infrastructure (as detailed in Table 6).

TABLE 6 | Elements in a city that may be impacted due to hazards

IMPACTED ELEMENTS	METEOROLOGICAL					HYDROLOGICAL		GEOLOGICAL		ENVIRONMENTAL				
	TS	Pr	Wn	WE	SL	Fl	Dr	LD	GM	AQ	WQ	SQ	Vg	Fr
Population														
Natural environment														
Built environment														
Jobs and livelihood														
Infrastructure														
Access to services														
Amenities														
Housing														
Food systems														

Notes: TS = Thermal Stress; Pr = Precipitation Change; Wn = Wind; WE = Weather Events; SLC = Sea Level Change; FL = Flood; Dr = Drought; LD = Land Deformation; GM = Ground Movement; AQ = Air Quality Degradation; WQ = Water Quality Degradation; SQ = Soil Quality Degradation; Vg = Vegetation Change; Fr = Fire.

Housing: Residential, including formal and informal. Services: Water, energy, solid waste, sanitation, fiber/Internet. Amenities: Health, open spaces, blue-green infrastructure, education, social services, emergency and disaster management services, roads and rail, public/mass transport, public information systems, heritage buildings, and important monuments.

Source: Authors.

EXPOSURE ANALYSIS

This step considers people in specific physical settings as well as infrastructure systems that could suffer loss and damage due to hazards and thereby impact people through disruption of services. The Exposure Analysis operates in the physical domain and deals with locational characteristics of elements that deepen vulnerabilities upon interaction with hazards. It measures differential exposure within the city by identifying such elements within hazard-prone areas. Table 7 describes the Exposure Analysis in detail. The spatial mapping helps determine the extent of hazard exposure, including variation of hazard exposure within the city.

Exposure for the "People" element focuses on those living in hazard-prone areas, especially those living in slums or informal settlements. The latter is a function of sensitivity, because the common characteristics of the informal built environment often leave people more exposed than those who live in formal housing in the same neighborhood. This can be attributed to the nature of the building materials used in informal settlements, access to resources and services, and lack of adaptive capacity among the resident households (as described in Chapter 6 through case examples of WRI India's climate action planning work in Indian cities.)

Infrastructure located in hazard-prone areas of the city is vulnerable to system failures, loss, and damage. Infrastructure and service disruptions pose a significant risk to human life, sometimes increasing exposure to different hazards with potentially cascading effects. Conversely, climate-proofed, resilient infrastructure can significantly mitigate the potential for harm and reduce urban vulnerability. Infrastructure Exposure Analysis requires first identifying and mapping infrastructure assets and networks within hazard-prone areas or hotspots that are likely to be impacted by a hazard (either respective to a particular hazard or to the interaction between multiple hazards). Beyond identifying the assets at risk, it requires a thorough qualitative assessment of the nature of the physical damage or loss the infrastructure system could suffer due to a hazard occurrence.

In infrastructure Exposure Analysis, the data requirements for hazard zone mapping are based on the results of Hazard Identification and Assessment, as discussed in

TABLE 7 | Framework for analyzing exposure to hazards

INDEX	INDICATOR	PERCENTAGE EXPOSED
Element exposed: People		
Variation in population density Slums or informal settlements Variation in jobs (density) located ▪ Formal ▪ Informal ▪ Outdoor	Within or in close proximity to hazard-prone or hazard-impacted areas, such as: ▪ Thermal stress: Zones with land surface temperature (LST) ≥ threshold ▪ Flooding hotspots/Flood impact zones/Flood-susceptible zones/Area within high flood line (HFL) ▪ Land deformation/Landslide-prone locations or zones/sites of past landslides ▪ Areas prone to extreme weather events or impact areas from previous hazards ▪ Low-lying areas ▪ Coastal Regulation Zones (CRZs) ▪ Areas with air pollutant concentrations higher than the daily permissible limits ▪ Areas within threshold distance of polluted waterbodies/ environmentally sensitive areas, such as dumping grounds, and sewage treatment plants ▪ Areas prone to forest fires or other fire hazards ▪ Areas prone to multiple hazards	Percentage of urban area exposed Density of population exposed No. of slums exposed Percentage of jobs (formal/ informal/outdoor) exposed
Element exposed: Infrastructure		
Infrastructure systems and networks to be assessed include (but are not limited to): ▪ Roads and transport network/stations/ terminals/hubs/ports ▪ Water supply: Resource, treatment facility, supply, and distribution ▪ Sanitation and sewage: Network and treatment facility ▪ Solid waste: Network, management systems, and treatment facilities ▪ Storm water management network and systems ▪ Power generation: Distribution and supply ▪ Emergency, safety, fire, and disaster relief services ▪ Digital and communications/information, early warning systems ▪ Urban agriculture and food systems: Markets, warehousing, public distribution systems ▪ Social infrastructure: Healthcare, schools, heritage buildings, and important monuments ▪ Blue-green infrastructure: Forests, wetlands, public green open spaces, other open vegetation, lakes, canals, and natural drains ▪ Housing and other built infrastructure	Within or in close proximity to hazard-prone or hazard-impacted areas, such as: ▪ Thermal stress: Zones with LST ≥ threshold ▪ Flooding hotspots/Flood impact zones/Flood-susceptible zones/Area within High Flood Line (HFL) ▪ Land deformation/Landslide-prone locations or zones/ previous landslide locations ▪ Areas prone to extreme weather events or impact areas from previous hazards ▪ Low-lying areas ▪ CRZs ▪ Areas with air pollutant concentrations higher than the daily permissible limits ▪ Areas within threshold distance from polluted waterbodies/ environmentally sensitive areas, such as dumping grounds, sewage treatment plants, etc. ▪ Areas prone to forest or other fire hazards ▪ Areas prone to multiple hazards	Percentage of physical infrastructure exposed (spatial exposure)
Qualitative analysis of nature and extent of damage to infrastructure assets (see Appendix D for details)		

Source: Authors.

Chapter 5. Qualitative analysis of damage to infrastructure can be based on documentation available from the city and nodal agencies of historical instances of damage to infrastructure due to different hazards. The agencies responsible for conducting the CHVA can also support the qualitative assessment by using the leads detailed in Appendix D, which will give cities flexibility in approaching the assessment.

Indicators for Exposure Analysis may not be able to spatialize intracity differential exposure extents for all hazards due to data limitations or because certain hazards may expand to affect the larger region around the city. Therefore, given the objective of the exercise, differential exposure can be determined provided the spatial assessment of hazards recognizes areas with greater likelihood of hazard occurrence that are comparable at the neighborhood level. Otherwise, the densities of elements such as population, informal settlements, jobs, and infrastructure disaggregated at the ward, or smallest spatial assessment unit, level can be used as priority determinants of varied vulnerability, as explained in Chapter 4. The next step, as described in Chapter 4, is to establish differential vulnerability for different hazards and the resulting impact.

BOX 1 | Defining exposure indicators

Variation in population density: It is essential to assess variation in population density within hazard-prone or hazard-impacted areas of the city to fully understand exposure. This assessment will help practitioners and policymakers prioritize efforts and plan interventions and resources efficiently and effectively.

Slums or informal settlements: Slum populations living within or near hazard-prone or hazard-impacted areas are among the most vulnerable and sensitive groups, with limited access to household and civic services, temporary housing materials and structures, and lack of financial and social protections. Assessing and identifying low-income communities and informal settlements in hazard-prone areas will help make a case for improving service provisioning, help understand high-priority intervention areas, explore resilience measures, and enable deeper engagements and analysis in those areas.

Note: The above indicators are taken from the long list of indicator rationales in Appendix A and presented here for reference.
Source: Authors.


A.C
RESTAURA
TRIPTI
(HOTEL)
Lodge
MONEY
EXCHANGE
अशोक
मेहंदी आर्ट
PENCo
EXCLUSIVE PEN STORE
आरक्षण केन्द्र
TICKET • TAXI BOOKING
PACKAGE
साड़ी
घर

CHAPTER 4

The Vulnerability Assessment framework

The Vulnerability Assessment framework recognizes the systemic nature of risk, where the degree of impact depends on and is accelerated by the complex interactions of cultural, social, fiscal, political, and environmental factors. Deep-rooted structural vulnerabilities, which manifest as lack of access to essential infrastructure and resources for the urban poor and underserved communities, can further deepen vulnerabilities unless equity considerations are mainstreamed in resilience planning.

The CHVA framework, with its strong focus on uncovering differential vulnerability within unequal cities, puts equity front and center of vulnerability assessments and climate action and across the vulnerability domains under each vulnerability lens (see Figure 7). The data for each indicator within the framework discussed below are collected and analyzed at both spatial and temporal scales, and the Vulnerability Assessment is conducted at the city scale, possibly downscaled to the ward level depending on the availability of citywide disaggregated data.

The Vulnerability Assessment focuses on two elements, people and infrastructure, and both elements are described by the lenses of sensitivity and adaptive capacities as illustrated in Figure 7.

PEOPLE'S VULNERABILITY: THE SENSITIVITY LENS

Among the population exposed to hazards, the sensitivity lens within the Vulnerability Assessment framework details "the conditions determined by built, social, economic and environmental factors or processes which increase the susceptibility [sensitivity] of an individual, a community, or the city to the impacts of hazards" (The Secretary General 2016). Table 8 presents the sensitivity aspect of vulnerability and highlights various demographic groups that are disproportionately impacted due to their identities, the nature of their work, and the quality of their residential or workplace environments. Indicators need to be systematically disaggregated to take into account gender and forms of social inclusion. The sensitivity lens is derived from UNISDR's Sendai Framework, SDG 2030, and recommendations from CEDAW (UNISDR IAP 2018) and is adapted to data practices in India. The social domain of vulnerability is further disaggregated into the following sub-domains:

- Sociodemographic domain, which considers population groups disproportionately impacted by hazards.
- Socioeconomic domain, which considers forms of occupation and labor.
- Sociopolitical domain, which considers legal access to housing and tenure.[8]
- Residential domain, which considers factors in the living environment of people that deepen their sensitivity to the impacts of hazards.

FIGURE 7 | Structure of the Vulnerability Assessment framework for people and infrastructure

	Sensitivity	Adapative Capacity	*Vulnerability Lens*
People	▪ Sociodemographic ▪ Socioeconomic ▪ Sociopolitical ▪ Residential ▪ Physical	▪ Economic ▪ Governance ▪ Social	*Domain*
Infrastructure	▪ Physical ▪ Economic ▪ Social	▪ Economic ▪ Environmental ▪ Governance and management	

Source: Authors.

TABLE 8 | The sensitivity lens of vulnerability in relation to people

DOMAIN	INDEX	INDICATOR	DATA SOURCE
Sociodemographic	Population groups disproportionately impacted	▪ Women and trans communities ▪ Illiterate[a] women ▪ Scheduled Caste (SC)/Scheduled Tribe (ST) communities ▪ Vulnerable age groups: <6 years of age >60 years of age ▪ Non-workers ▪ Illiterates[b]	Census
		▪ People with disabilities ▪ Migrant women, women from Dalit, Adivasi, and other minority communities ▪ Religious and ethnic minorities ▪ Low-income communities/Poverty ▪ Migrants	Primary survey, secondary sources, and reports
Socioeconomic	Populations in adverse working conditions	Outdoor workers, temporary or informal workers: ▪ Construction laborers ▪ Street vendors ▪ Sanitation workers ▪ Courier delivery workers ▪ Door-to-door salespersons ▪ Traffic police ▪ Firefighters ▪ Transportation workers ▪ Utility workers ▪ Emergency responders ▪ Informal daily wage labor, etc. ▪ Migrant workers ▪ Domestic workers (maids, security guards, drivers)	Surveys by grassroots organizations/ NGOs/educational institutions, Directory of Establishments (DoE), Economic Census, trade organizations, Annual Survey of Industries (ASI), International Labour Organization (ILO), World Bank reports on informal labor in cities
	Populations involved in high-risk livelihood activity	People/communities involved in climate-sensitive livelihoods and activities , such as: ▪ Rainfed smallholder agriculture ▪ Fisheries ▪ Seasonal agriculture such as tea, coffee, and cocoa ▪ Pastoralism ▪ Tourism ▪ Agroforestry ▪ Mangrove-related	
Sociopolitical	Lack of home ownership, limited tenure, and houselessness	Households that do not own the property they reside in	Census
		Population living in notified slums with settlement boundaries	Census, the slum department of municipal corporations, city slum board surveys and reports, Pradhan Mantri Aawas Yojna (PMAY) reports, slum clearance/redevelopment/rehabilitation authority reports or surveys by grassroots organizations/ NGOs/educational institutions
		Population living with limited tenure/other than notified slums with settlement boundaries: ▪ No ownership documents ▪ No rental agreement ▪ No rent receipts	

TABLE 8 | The sensitivity lens of vulnerability in relation to people (cont'd.)

DOMAIN	INDEX	INDICATOR	DATA SOURCE
		Houseless population	Government night shelters, slum board reports, tags by corporation for footpath dwellers (those traveling for work such as roadwork that may be seasonal), labor organizations, the Public Works Department (PWD)
Residential	Inadequate housing conditions (temporary building materials as a proxy for built/ structural conditions of the house and socioeconomic condition of the residents)	Material of roof ▪ Temporary roofing[c] ▪ Material of wall ▪ Temporary wall[d]	Census
	Inadequate household-level essential services	**Not having** access to treated drinking water facility within the house premises: ▪ Location of drinking water source - Near the premises - Away from the premises ▪ Source of drinking water - Tap water from untreated source - Covered well - Uncovered well - Handpump - Tube well, borehole - Spring - River, canal - Tank, pond, lake - Other sources	Census Additional sources for household-level data: data on community taps available with the water department or emergency water supply available with the fire services department or disaster management authority Zone-wise or disaster management authority (DMA) household-level supply data and supply network shape file from the respective water departments
		Not having access to sanitation services ▪ Latrine location not within the house premises - Public latrine - Open ▪ Unhygienic sewage disposal method if latrine is within the household premises - Pit latrine without slab/open pit - Night soil disposed into open drain - Service latrine: Night soil removed by human - Service latrine: Night soil serviced by animal ▪ Unhygienic wastewater disposal method - Wastewater outlet connected to open drainage - Wastewater outlet connected to no drainage/ unregulated - No access to solid waste management services	Census Additional sources for household-level data: data on community toilets available with sanitation department, Swachh Surveskshan reports Data on zone-wise household-level connections and sewage network shape file from the respective sewage, sanitation, or drainage department
		Main source of lighting **not connected** to grid or renewable energy ▪ Kerosene ▪ Other oils ▪ No lighting	

TABLE 8 | The sensitivity lens of vulnerability in relation to people (cont'd.)

DOMAIN	INDEX	INDICATOR	DATA SOURCE
		Use of polluting cooking fuels ▪ Kerosene ▪ Firewood ▪ Crop residue ▪ Cow dung cake ▪ Coal, lignite, or charcoal ▪ Other	
		Not having access to information dissemination assets based on household ownership of ▪ Radio or transistor ▪ Landline, cell phone, or both ▪ Personal computer with Internet ▪ Television	Census
Physical	Lack of access to public infrastructure and amenities (based on road network)	Access to healthcare	Municipal corporation: health department or urban community development department
		Access to education	Municipal corporation: education department or urban community development department
		Access to mass transit or public transport	Metro, rail, bus transport agency, roads and transport department of municipal corporation
		Access to public green open spaces	Municipal corporation/garden department
		Access to emergency or disaster relief shelters	City disaster management department, district DMA, fire department, municipal corporation

Note: Indicators highlighted in blue should be included if possible, though they are not necessary. Tentative datasets, sources, and additional reports have been listed under the "Data source" column. It is suggested to define the indicators listed in the tables wherever possible using government standards such as the 2011 Census of India (Census 2011).

a. This term and others used as indicators come directly from the Census. We use these terms to stay close to and accurately represent the data. However, when conducting the CHVA and especially when working with vulnerable groups, practitioners can consider using more sensitive terms such as "women who cannot read and write" rather than "illiterate women."

b. This term and others used as indicators come directly from the Census. We use these terms to stay close to and accurately represent the data. However, when conducting the CHVA and especially when working with vulnerable groups, practitioners can consider using more sensitive terms such as "persons who cannot read and write" rather than "illiterates."

c. Unstable roof materials: grass, thatch, bamboo, wood, mud, etc.; plastic, polythene; galvanized iron, metal, or asbestos sheets; tiles, etc.

d. Unstable wall materials: grass, thatch, bamboo, wood, mud, unburnt bricks, etc.; plastic, polythene, stone not packed with mortar; galvanized iron, metal, or asbestos sheets; tiles, etc.

Source: Authors.

BOX 2 | Defining Vulnerability Assessment indicators

Women and trans communities: Gender equality and empowering women (SDG 5) is another significant factor enhancing resilience (UN n.d.-b). In addition, limited participation in decision-making and other social responsibilities make women more vulnerable (UNFCCC n.d.). Women and girls are disproportionately impacted due to distorted access to resources and services and the need to fill the caregiver role after a disaster.

Outdoor workers and temporary or informal workers: These workers include construction labor; domestic workers such as maids, security guards, and drivers; street vendors; courier delivery workers; door-to-door salespersons; traffic police; firefighters; transportation workers; utility workers; emergency responders; informal daily wage laborers, and so on. Information on these workers can be obtained from surveys by grassroots organizations, NGOs, educational institutions, Directory of Establishments (DoE), Economic Census, trade organizations, Annual Survey of Industries (ASI), the International Labour Organization (ILO), and World Bank reports on informal labor in cities.

Access to public green open spaces: Public parks and playgrounds serve the residents of a city in multiple ways. They function as recreational areas, safeguard and enhance the nature component of the city by improving its air quality and enhancing its biodiversity. The open spaces and blue-green networks of the city also act as sponge spaces during hazard occurrences, and even otherwise. The WHO mentions that vulnerable communities, in particular, benefit more from these spaces as they help them destress and rejuvenate themselves (WHO 2016).

The Urban and Regional Development Plans Formulation and Implementation (URDPFI) guidelines of 2015 recommend 10–12 square meters of open green (recreational) space per person.

Note: The above are taken from the long list of indicators in Appendix A. They can be referenced and adapted to the local context when selecting appropriate indicators for the CHVA.

Source: Authors.

PEOPLE'S VULNERABILITY: THE ADAPTIVE CAPACITY LENS

Adaptive capacity is the potential or ability of a system, region, or community to anticipate and prepare for changes and uncertainties in climate. It also includes understanding climate variability and extremes and adapting to the effects of climate change. When higher adaptive capacities are built through governance and infrastructural systems, the city not only promotes sustainable development but also reduces the vulnerability of populations and infrastructure to climate-change-induced hazards and other hazards (IPCC 2001). Conversely, when the adaptive capacity is low relative to exposure and sensitivity, vulnerability increases. A key part of adaptive capacity is social capital; that is, relationships and ties with neighbors, friends, and kin in a community (Nyahunda and Tirivangasi 2021). However, unlike in rural areas, the idea of community in urban areas, particularly in slums with large migrant populations, is not necessarily as strong or homogeneous. Often, externally mediated platforms are crucial for community engagement, cooperation, and participation for addressing community challenges such as climate change. These associational activities inside an urban community or neighborhood or ward could be a proxy indicator of social capital because they foster a sense of civic engagement and drive collective action to solve difficult problems such as those posed by climate change (Aldrich and Meyer 2015). In discussing adaptive capacity in relation to people, under the social domain, we use the indicator of citizen engagement as a proxy of social capital. The vulnerability domains considered for adaptive capacity are economic, governance, social, and environmental domains.

For the indicators listed in Tables 8, 9, and 10, the latest available datasets should be used for the assessment. In case ward-level datasets are not available, or better granular information is available that is approved by the government agencies, cities can select the datasets that are comprehensive, comparable, and relevant across the city. However, these are critical indicators for vulnerable groups. Depending on the scope set by the CHVA team (see Phase 3, Chapter 6), cases or examples of community surveys in the form of anecdotal granular information can be used to supplement and optimize official datasets such as the Census and thus enrich the overall results of the CHVA.

TABLE 9 | The adaptive capacity lens of vulnerability in relation to people

DOMAIN	INDEX	INDICATOR	DATA SOURCE
Economic	Employment and livelihood	Job security of formal and informal jobs at the onset of or after hazard events ▪ Loss in workdays/working hours ▪ Loss in income ▪ Loss of employment security	Economic Census, Directory of Establishments, Department of Labour, factories, and shops, or any other government-approved dataset on employment location, industry type, and size
		Level of dependence on high-risk livelihood activity and adverse working conditions	
		Livelihood diversification ▪ Opportunity for reskilling and skill upgradation ▪ Availability of small business loans ▪ Access to credit	
Governance	Social security	Access to secure housing	Slum surveys
		Access to social welfare/protection schemes	NGO and government reports
	Level of decentralization	Prevalence of zone-, ward-, and community-level governance and management to monitor the status of, and maintain, basic infrastructure and services	Surveys/questionnaires
	Disaster preparedness and response	Access to early warning systems, disaster training, and capacity building	Surveys/questionnaires City's Disaster Management Plan District's Disaster Management Plan
		Access to open spaces to support emergency response	
		Prevalence of community-based disaster resilience and management practices	
	Disaster mitigation and risk reduction	▪ Protocols for managing different categories of hazards ▪ Plans and policies for directing future population growth while protecting the environment	Other protocols followed by civil society organizations (CSOs) in vulnerable neighborhoods, if available
Social	Citizen Engagement	Frequency of neighborhood-, ward- and zone-level meetings to inform, involve, and engage with people. Presence of sociocultural and religious institutions that undertake group-based welfare activities	Secondary reports and assessments of civic participation, if available. Primary surveys commissioned by cities/ CSOs

Note: Indicators highlighted in blue should be included if possible, though they are not necessary. Tentative datasets, sources, and additional reports have been listed under the "Data source" column. It is suggested to define the indicators listed in the tables wherever possible using government standards such as the 2011 Census of India (Census 2011).

Source: Authors.

VULNERABILITY OF INFRASTRUCTURE

Access to regular services and infrastructure is a boon immediately after a disaster event, and resilient infrastructure can enhance both people's and infrastructure's ability to adapt to extreme situations. For example, climate-proof design strategies and materials such as elevating critical utilities, passive flood barriers, and gates can reduce the risk of service disruption and ensure asset security (FEMA 2022). Hence, assessing infrastructure's sensitivity and adaptation potential is critical to building climate-resilient infrastructure; Table 10 describes this framework. The indicators detailed in the table are to be evaluated in tandem with Appendix D, which provides an exhaustive listing of potential leads for infrastructure Vulnerability Assessment.

TABLE 10 | Vulnerability of infrastructure through the lenses of sensitivity and adaptive capacity

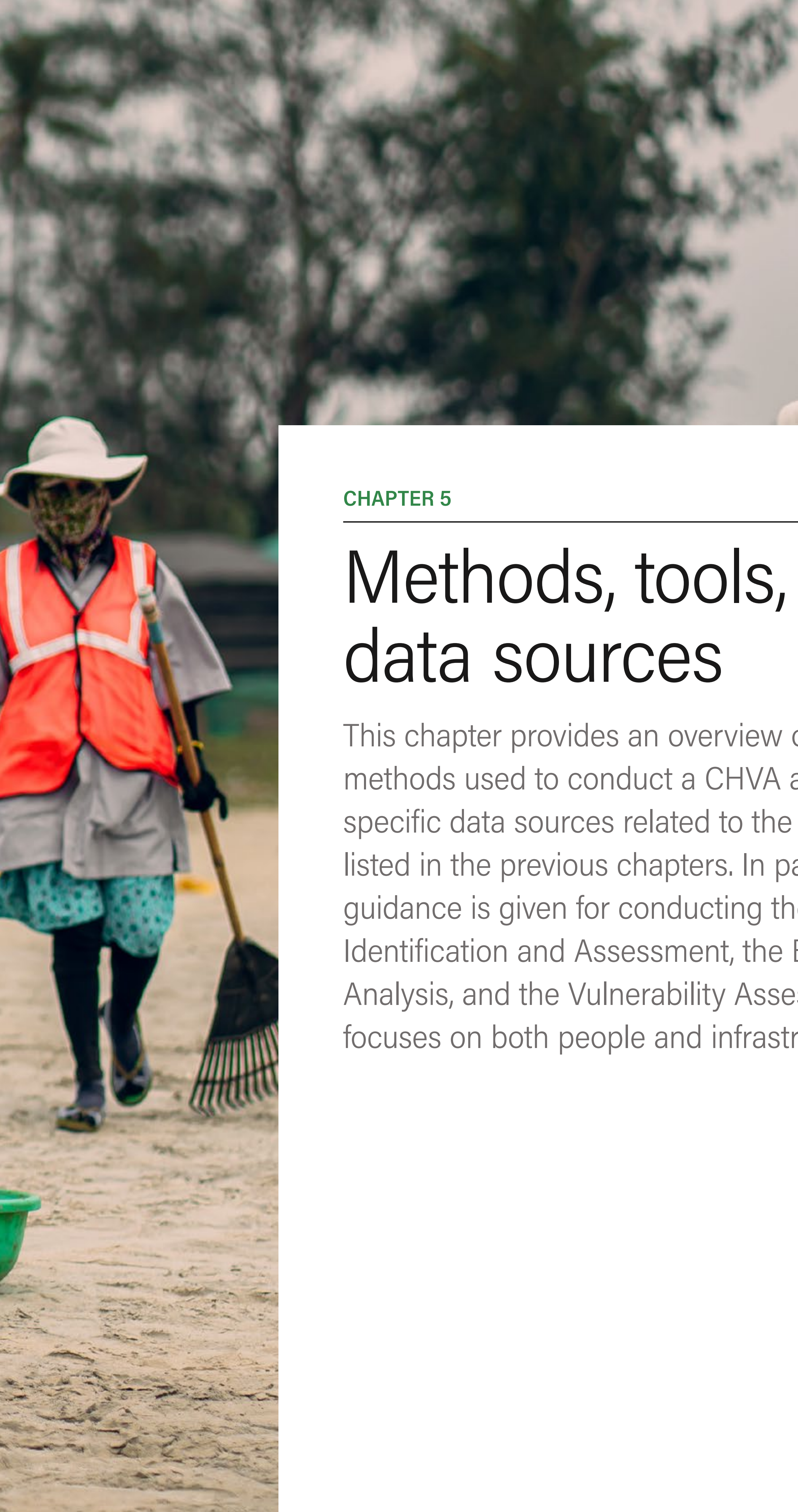
VULNERABILITY LENS	DOMAIN	INDICATORS
Sensitivity	Physical	Reduction in service area due to "lack of" physical access to infrastructure and amenities during and immediately after hazard events, such as for • Livelihoods or jobs • Healthcare • Education • Mass transit or public transport • Public green open spaces • Emergency or disaster relief shelters
	Economic	Losses in revenue, livelihoods, and days of work due to disrupted services
		Revenue losses due to damage to physical assets
	Social	Death and injury
		Disease outbreaks due to damage to infrastructure
Adaptive capacity	Economic	Emergency funds, disaster relief funds
		Insurance
		Climate-proofing funds
	Environmental	Early warning systems
		Disaster management plans at the city level, and for infrastructure and essential services
		Climate-proofing assets: design, construction material and techniques, and maintenance
	Governance and management	Organization structure
		Level of decentralization
		Coordination and communication mechanisms
		Response protocols
		Staff capacity and training

Source: Authors.

As stated in Chapter 3 (in the section on the Exposure Analysis), the infrastructure to be assessed can be (but is not limited to) roads and transport; water resource and supply; sanitation and sewage; stormwater management; solid waste management; power generation and distribution; emergency and disaster relief; digital communications; social infrastructure; blue-green infrastructure; urban agriculture and food systems; and housing and other built infrastructure. Depending on the city's willingness and capacities, physical surveys in select vulnerable communities (references for these kinds of assessments are included in Chapter 7) may be conducted to also assess the dependence, reliability, and safety of small community-built infrastructure such as small bridges on stilts, shading devices, and so on, for disaster preparedness.

Thresholds for the vulnerability of people and infrastructure are defined in Table 4. Thresholds can be subjective empirical evidence accounted in both quantitative and qualitative formats. Cities need to consider the scientific guidance available for some of the indicators and also deliberate with stakeholders and teams of experts while fixing the thresholds for vulnerability of people and infrastructure. Scientifically, these can be fixed based on the city's characteristics, service operations, infrastructure coverage, ease of accessibility, disaster preparedness, climate proofing of assets, and so on. The processes underlying the consultative approach are explained in Chapter 6.

Chapter 5 describes the methodologies used to identify hazards and assess differential vulnerability using specific indicators, thresholds, and data sources that are described in detail in Appendix B.



CHAPTER 5

Methods, tools, and data sources

This chapter provides an overview of the diverse methods used to conduct a CHVA and points to specific data sources related to the indicators listed in the previous chapters. In particular, guidance is given for conducting the Hazard Identification and Assessment, the Exposure Analysis, and the Vulnerability Assessment, which focuses on both people and infrastructure.

As explained in the previous chapters, the CHVA is a three-step process that includes methods to identify and assess hazard trends, future hazard projections, degrees of exposure to hazards, and an assessment of differential vulnerability based on socioeconomic and political drivers. Table 11 illustrates the methods used for each step of the CHVA. Examples from similar assessments in different cities are included to illustrate these methods. The assessment is also caried out at different levels—from the city, ward, to local neighborhood levels—depending on data accessibility.

The next chapter provides a step-by-step guide for cities on how to conduct a CHVA. Some of the detailed methods and tools described here will be cross-referenced to steps in Chapter 6 to help cities understand their relevance and how to complete a CHVA for their city.

Table 12 provides an overview of analytical methods linked to different aspects of the CHVA framework outlined in Chapters 3 and 4. The CHVA is conducted using publicly available and government-owned data, and it is recommended that an iterative and flexible process be used to identify proxy indicators (or data sources) to complete the assessment. See Appendix B for indicator details, definitions, thresholds, and primary and supplementary datasets and sources.

The next two sections provide detailed methods, data sources, and case examples explaining the use of these methods in similar cases. Case examples are referenced from past city vulnerability and other related assessments that were conducted by WRI India as part of city climate action plans and other resilience projects. Some methods are commonly used to assess similar indicators across different aspects; hence, each method's subsection includes a box highlighting pertinent indicators (across aspects) that can be traced back to the framework in Chapters 3 and 4.

TABLE 11 | Assessment methods used for the Climate Hazard and Vulnerability Assessment

TERM	DEFINITION
Hazard Identification and Assessment	A. Trend (spatiotemporal) analyses for different hazards B. Spatial identification of area impacted due to climate and environmental hazards C. Hazard impact checklist (including multi-hazard mapping)
Exposure Analysis	A. Spatial assessment of population impacted due to climate and environmental hazards B. Spatial assessment of infrastructure impacted due to climate and environmental hazards
Vulnerability Assessment	A. Rapid social analysis (RSA) by mapping primary, secondary, and open-source government data and stakeholder consultations, including needs assessment, social vulnerability mapping, and social protection analysis B. Accessibility analysis through service area delineation (pedestrian- and vehicular-speed-based proximity analysis) and plausible service area reductions due to infrastructure at risk of failure or service disruption C. Evaluating loss of life, productivity, and additional expenditure incurred due to disrupted services and physical damage to essential public infrastructure D. City preparedness analysis through a gap analysis of the policy landscape

Source: Authors.

TABLE 12 | Summary table of assessment typologies

ASPECTS OF THE CLIMATE HAZARD AND VULNERABILITY ASSESSMENT (CHVA)	ASSESSMENT METHODS	DESCRIPTION
A. Hazard Identification and Assessment (HIA)		
▪ Establishing weather trends for a city region based on local, regional, and global datasets; climate models; and satellite imagery to assess the frequency and intensity of extreme weather events, and climate uncertainty ▪ Establishing areas or zones prone to or impacted by different or multiple hazards in the city ▪ Identifying potential impact areas for different hazard groups	A. Trend (spatiotemporal) analyses for different hazards B. Spatial identification of area impacted due to climate and environmental hazards C. Hazard impact checklist (including multi-hazard mapping)	Combining remote-sensing techniques and monitored weather data, climate change trends such as extreme temperature, precipitation anomalies, landslide susceptibility, tropical cyclone incidents, change in sea surface temperature, sea level rise, seismic activities, groundwater movement, etc., are analyzed[a] to understand the changes in climate patterns, extreme weather events, and environmental conditions for both the historical and projected epochs (see Table 5, Chapter 3). This includes identification of hotspots and analysis to identify areas and zones prone to different hazards based on the occurrences and extent of potentially impacted areas. Hazard assessment is concluded by identifying various scenarios for elements that may be impacted, using a checklist of various hazards relevant to the study area (see Table 6, Chapter 3).
B. Exposure Analysis		
▪ Exposure of people, focusing on populations living in slums or informal settlements within hazard-prone or hazard-impacted areas and zones ▪ Exposure of critical infrastructure located in hazard-prone areas in the city	A. Spatial assessment of population impacted due to climate and environmental hazards B. Spatial assessment of infrastructure impacted due to climate and environmental hazards	Quantifying and identifying populations, vulnerable communities (informal settlements and informal workers) and populations more at risk due to preexisting vulnerabilities, and infrastructure (services and built networks) critical for the city's day-to-day operations and functions located along, within, and near areas identified in the HIA as being exposed to various hazards (see Table 7, Chapter 3).
C. Vulnerability Assessment: Sensitivity Analysis		
▪ Identifying population groups more sensitive to hazards due to their underlying socioeconomic status, working and living conditions, individual determinants such as age, gender, ability, and differential access to various resources ▪ Identifying plausible infrastructure failures or disruption of services due to climate hazards ▪ Assessing socioeconomic and public health costs associated with physical damage of assets and infrastructure network failures	A. Rapid social analysis (RSA) by mapping primary, secondary, and open-source government data and consulting with stakeholders[b] B. Accessibility analysis: ▪ Service area delineation (pedestrian and vehicular-speed-based proximity analysis) ▪ Mapping plausible service area reductions due to infrastructure at risk of failure or service disruption C. Evaluating loss of life, productivity, and additional expenditure incurred due to disrupted services and physical damage to essential public infrastructure	Secondary data analysis is used to identify populations, groups, and infrastructure elements that are potentially sensitive to climate and environmental hazards and their impacts. Secondary data analysis helps examine the inherent conditions leading to differential vulnerabilities, such as analyzing the spatial distribution of various socioeconomic demographic systems and access to essential services and infrastructure at the household (residential domain) and neighborhood levels (see Table 8, Chapter 4). The sensitivity of critical infrastructure and systems is assessed based on the reduction of service area and infrastructure access, by considering plausible impact scenarios and local insights using hotspot and high-risk area mapping for each relevant hazard indicator. Further socioeconomic losses associated with interruption in day-to-day service delivery, mobility, workdays, public infrastructure asset repair and recovery, fatalities (including disease outbreaks) during or immediately after hazard events are also calculated to understand how differential vulnerabilities are amplified by hazard implications (see Table 9, Chapter 4, and Appendix D).

TABLE 12 | Summary table of assessment typologies (cont'd.)

ASPECTS OF THE CLIMATE HAZARD AND VULNERABILITY ASSESSMENT (CHVA)	ASSESSMENT METHODS	DESCRIPTION
D. Vulnerability Assessment: Adaptive Capacity Analysis		
▪ People's adaptive capacity is assessed based on the prevailing dynamics of employment and livelihood along with overarching governance mechanisms enabling social security and disaster management ▪ Infrastructure vulnerability significantly depends on the distinct features of governance systems and institutions that provide guidance for hazard management, a financial cushion for recovery, easy and proactive communication channels within agencies, and the performance of critical infrastructure (infrastructure elements).	A. RSA by mapping primary, secondary, and open-source government data and consulting with stakeholders B. City preparedness analysis through a gap analysis of the policy landscape	As adaptive capacity indicators are often situational, complex, and entangled, they cannot be measured in isolation. These indicators depend on various internal and external factors that are highly contextual and operate as part of systems that must also be reviewed. Assessment requires identification of sectoral gaps within policies and the regulatory environment. This should include assessing gaps in institutional arrangements that might impact climate action or planning, especially that which might have implications for risk reduction or adaptation action (see Tables 8 and 9, Chapter 4, and Appendix D).

Notes: a. The scale of analysis will be determined by the resolution of the available datasets and the nature of the hazard. For example, data from monitoring stations for the air temperature analysis are both spatial and temporal in nature and can be attributed to the location of the monitoring stations or considered representative of the entire city. However, datasets of groundwater development and landslide susceptibility are area-level indicators, which, depending on the anticipated exposure, could be analyzed at the local or regional level.
b. RSA is a method used for assessing the needs and vulnerabilities of particularly marginalized and vulnerable groups for supporting decision-making and is used in the context of disasters. See Mahendra et al. (2019) and S.V. Sharma et al. (2020).

Source: Authors.

METHODOLOGIES FOR HAZARD IDENTIFICATION AND ASSESSMENT

Trend (spatiotemporal) analyses for different hazards

Analysis of temporal changes, using both historical datasets and projected or modeled outputs, in long- and short-term epochs is termed temporal trend analysis. Meteorological trends such as weather patterns and extreme event occurrences, spatially mapped geological trends such as land subsidence and coastline changes, trends plotted using monitoring and observation stations' data such as air pollutant concentrations, groundwater levels, and so on, help in deriving key recommendations for the city and communities at large, targeting risk mitigation and preparedness strategies.

Hazard mapping generates spatiotemporal trends by combining historical datasets obtained from monitoring stations and satellite-derived insights, allowing areas prone to a hazard or areas impacted during or after a hazard event to be identified and prioritized.

Methods

Temporal trend analysis done for most indicators plots temporal linear fit trends (unless otherwise stated) based on the time series reports to determine monthly, seasonal, and inter-annual trends.

- **Spatiotemporal Trends:** can be derived using data from multiple on-ground and satellite-monitored sources, such as observation wells, station data, radar data, historical maps, aerial photographs, and satellite imagery of varying resolutions, to uncover both temporal and spatial patterns and changes such as variation in heat stress and shrinking of blue-green cover over time.
- **Magnitude:** Temporal trends determine the rate of change (slope) from statistical significance tests such as the Mann–Kendall test (Wang et al. 2020) which determines whether an overall positive (upward) or negative (downward) trend exists over time, or Sen's slope test,[9] which can be used to determine the magnitude (slope) of the temperature trend. Trend analysis of temperature and precipitation data can be performed using historical data from monitoring stations.

- **Baseline Comparison:**[10] Identifying anomalies in historical trends and magnitude of change for projected trends.
- **Change Point[11] Detection:** To identify the location in the time series where the statistical properties change significantly, marking an abrupt shift in the overall trend. Pettit's test (Pettitt 1979) examines the presence of a statistically significant location parameter (a period on the timeline) where a change or abrupt shift in trend likely occurs.

Potential hazard categories that can be evaluated using temporal trend analysis

- **Meteorological:** Thermal stress (air temperature, land surface temperature, thermal comfort, sea surface temperature), precipitation change (rainfall, snowfall), windspeed, weather events (cyclone, thunderstorms), and sea level change (sea level rise and fall, storm surge)
- **Hydrological:** Drought (hydrological, meteorological, groundwater exploitation)
- **Geological:** Land deformation (land subsidence, coastline changes)
- **Environmental:** Air quality degradation (indoor, outdoor air quality), water quantity and quality (surface and groundwater), soil quality, vegetation change (density of green vegetation), and fire (forest fires, other fires)

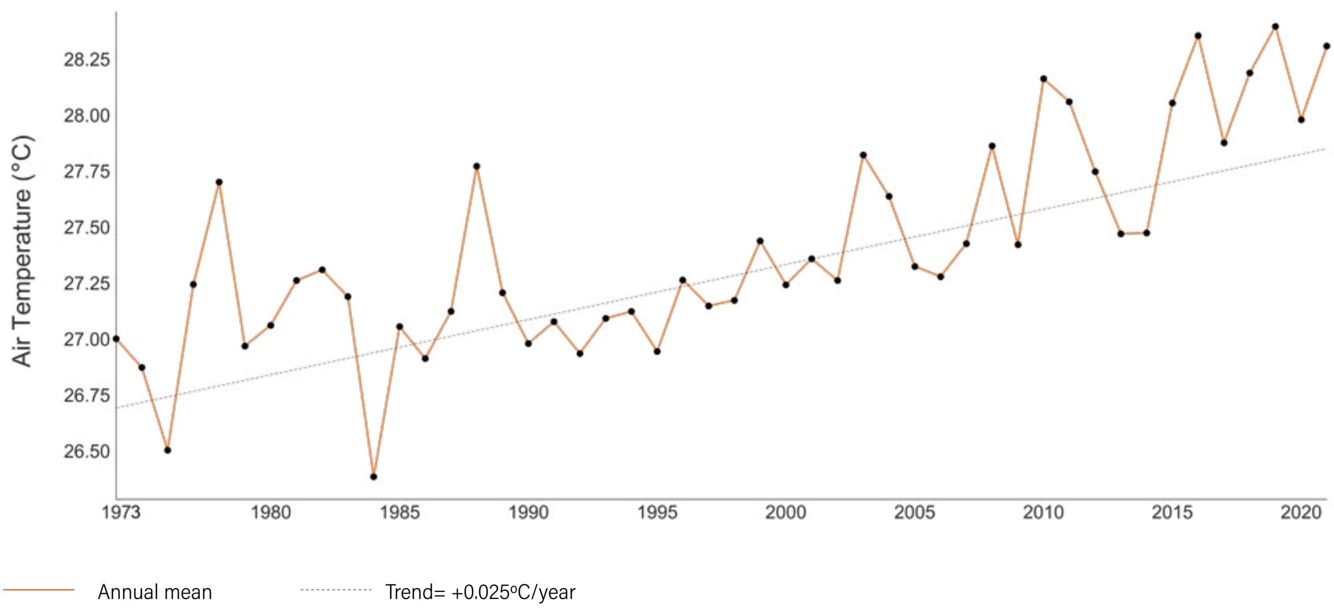
Data sources

Observational meteorological datasets comprise monitored weather data from sources such as the Indian Meteorological Department (IMD), automatic weather station data, data from air quality monitoring stations, coastal data from the Indian National Center for Ocean Information Services (INCOIS), and satellite imagery for various parameters. Weather station datasets represent continuous, multivariate time series data comprising changes in parameters such as wind speed, precipitation, air temperature, dewpoint temperature, and pressure.

Case examples

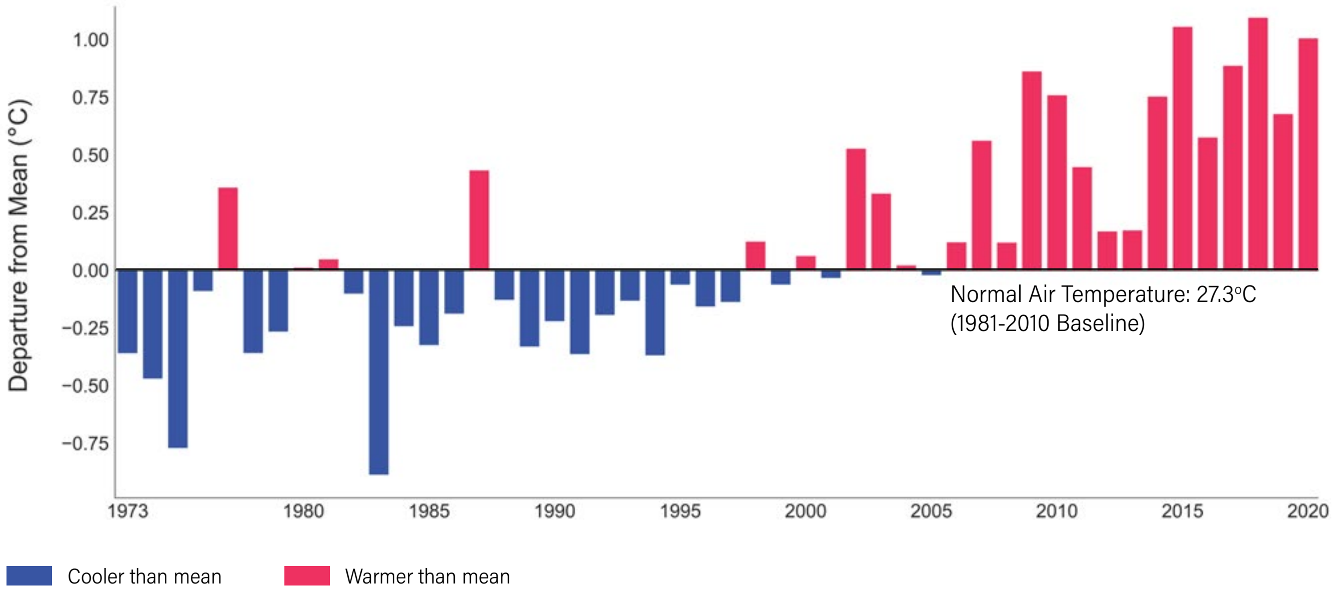
- **Linear trend and baseline comparison analysis:** For the Mumbai Climate Action Plan, long-term air temperature trends and anomalies from the baseline were compared and assessed using the parameter urban heat risk (thermal stress). These observations revealed

FIGURE 8 | Linear trend analysis showing inter-annual air temperature trends for Mumbai



Source: Brihanmumbai Municipal Corporation 2022.

FIGURE 9 | Inter-annual air temperature anomalies from the long-term baseline for Mumbai



Source: Brihanmumbai Municipal Corporation 2022.

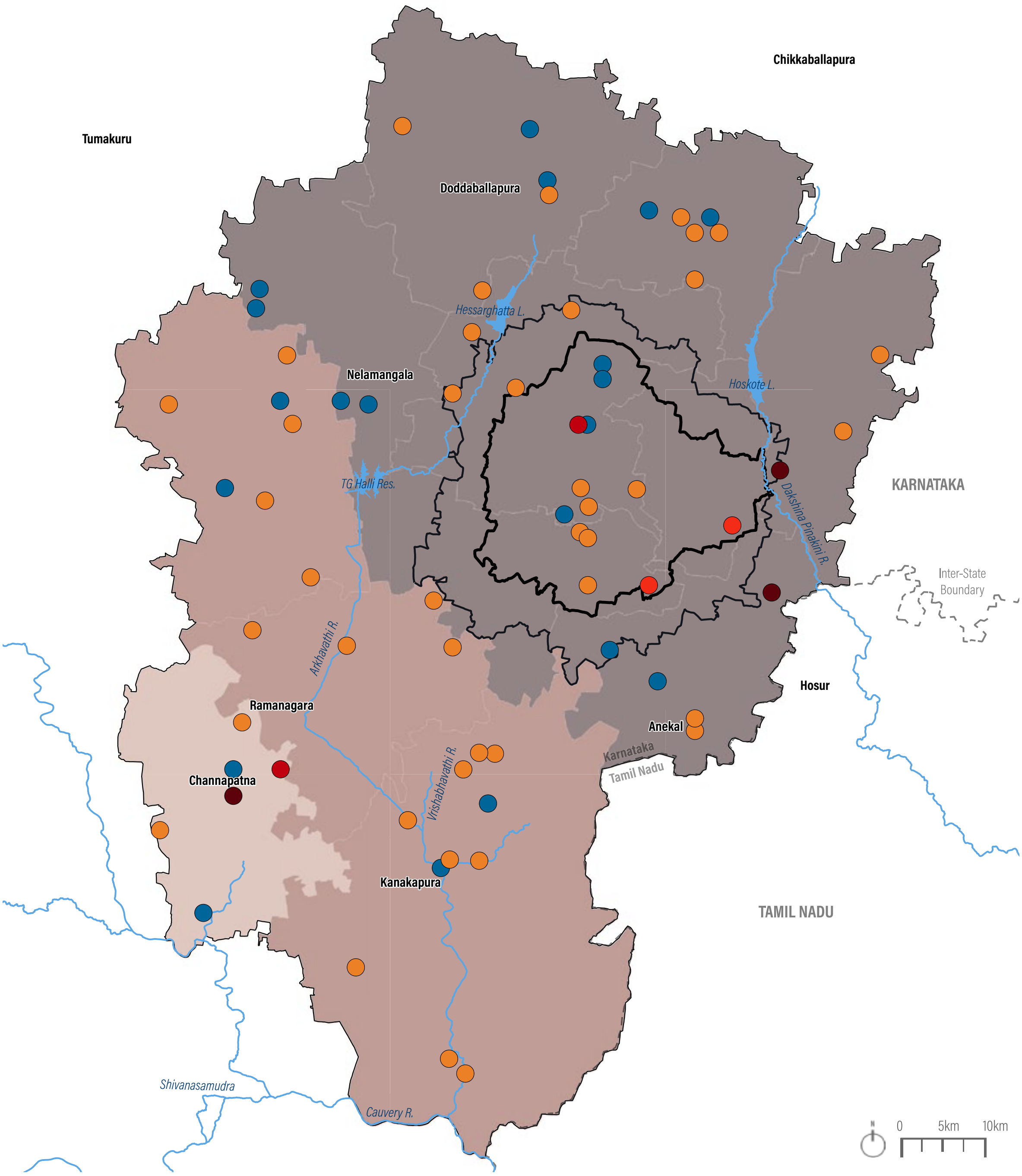
that air temperature in the city has been consistently rising at an annual average of 0.25°C in the last 40 years (see Figure 8). In particular, since 2015, annual air temperature anomalies show a departure of nearly 1°C (see Figure 9) (Ramesh et al. 2022).

- **Spatiotemporal trend analysis:** For the Bengaluru Climate Action Plan, long-term trends of seasonal groundwater fluctuations were analyzed using the Water Resource Information System (WRIS) and Central Ground Water Board (CGWB) data. These observations helped identify a greater decline in groundwater levels during the pre-monsoon season across 70 percent of the wells, especially for the area outside the major urban core (see Figure 10). Taluk-level information on the stage of groundwater development also indicated that these areas denoted greater dependence on groundwater.[12]

Impact assessment: Spatial identification of areas impacted due to climate and environmental hazards

Hazards are often distributed spatially conforming to varied extents and intensities. This differential variability of hazards, based on the available data, can be analyzed either at the study-area level using trends analysis or at a further granular level to identify areas that are more prone to hazards. With the rapid development of GIS mapping tools and remote-sensing-based technologies, readily available location-level datasets can be collated from various sources to identify areas with hazard occurrences as well as areas

FIGURE 10 | Spatiotemporal trend analysis of pre-monsoon groundwater levels and stage of groundwater development across the Bangalore Metropolitan Region Development Authority (BMRDA) region



Groundwater trends 1993-2021 (Pre-monsoon):

Groundwater level change (meter/year): -2.5 Decrease — 0 +0.3 Increase

Average stage of Groundwater development (2020): Over-exploited, Critical, Semi-critical

Observation well | Water body

Bruhat Bengaluru Mahanagara Palike | Bangalore Development Authority | Bangalore Metropolitan Region Development Authority

Source: Prepared for Bengaluru Climate Action Plan. Groundwater level trends analyzed using groundwater observation wells data from Water Resource Information System (WRIS); Stage of groundwater development derived from 'Dynamic Ground Water Resources of Karnataka, March 2020', Groundwater Directorate, Mini Irrigation and Groundwater Development Department, Government of Karnataka and Central Ground Water Board – South Western Region, Bangalore.

that are more vulnerable to hazards. These "impacted" areas for corresponding hazards may have varying spatial resolutions and enable spatial planning frameworks to identify which vulnerable communities are more exposed to hazards, both historically and based on modeled datasets.

Methods

The following are the methods for geospatial analyses that use ground observations or monitoring station data:

- **Spatial aggregation:** This technique summarizes (aggregates) hazard indicator datasets by ward or the smallest available unit of analysis to derive varying levels of hazard manifestation at spatially refined levels (Esri n.d.-c). For example, data layers such as waterlogging incidents, fire incidents, poor air or water quality, and landslide occurrences are used with slum boundaries to derive which slums are at immediate threat of landslides.
- **Hotspot analysis:** This technique can be used to analyze areas with relatively higher (hotspots) or lower (cold spots) values (ESRI n.d.-b) than threshold values. Thus, it can be used to depict which areas have a higher rate of occurrences of, or are contained within zones characterized by, extreme climatic/environmental conditions. Spatial autocorrelation tools and statistical methods can also be used to define these thresholds (apart from the definitions provided in Chapter 2). Indicators such as concentration of air pollutants, areas with drastic changes in vegetation, biodiversity hotspots, flood locations or low-lying area or areas from CRZs, and heat clusters or urban heat islands from land surface temperature (LST) can be spatially identified for targeted actions.
- **Buffer tool:** Based on the type and magnitude of a hazard or event along with the characteristics of the area close to the hazard occurrence, an area is earmarked using the buffer tool as part of the proximity analysis to determine an area likely to be impacted (Esri n.d.-d). The buffer tool allows the user to determine and generate buffer area extents using multiple options, such as a circular (i.e., radius-based) buffer from a point or a linear (i.e., distance-based) buffer from a point that uses the road network as the base. These buffers can be decided by the analyst based on the purpose and scope of the analysis and the nature of the hazard. For example, an instantly impacted area due to waterlogging, given its localized nature, may differ from an area impacted by a rise in air temperature, which is a larger observed phenomenon.
- **Correlations:** By overlaying hazard-prone areas with land use typologies such as land use land cover type, roofing material, and vegetation cover to prioritize areas that tend to be more susceptible to hazards such as heat or floods, areas with limited adaptive capacity can be identified.

Satellite-derived geospatial insights

The following are the methods using satellite-derived geospatial techniques:

- **Spatiotemporal analysis:** Same as "Spatiotemporal trend analysis" in the section titled "Trend (spatiotemporal) analyses for different hazards" above.
- **Feature delineation:** Classification algorithms such as the random forest classification algorithm can be used to delineate land use land cover features. Supervised classification techniques can delineate various classes such as vegetation, water, and non-built and built areas using available satellite imagery.
- **Change detection:** This method can be used to classify satellite imagery using algorithms to delineate the current extent of land use land cover and observe temporal changes in feature boundaries such as the loss and regeneration of mangrove cover and changes in coastline such as erosion and deposition.
- **Spatial geostatistics:** This branch of statistics helps explore and describe spatial variability with interpolation techniques such as kriging, which allows values to be estimated with limited available datasets from monitoring stations and turned into spatially spread rasters such as heatmaps (Esri n.d.-e).

Multi-parameter modeling using both satellite-derived insights and ground observations

The following are the methods to create multi-parameter modeling using both satellite-derived insights and ground observations:

Models simulate real-time environments based on multiple geospatial, meteorological, and other informative layers, and factors suitable for identifying the interdependencies of these multiple layers and their functions. Multiple iterations can be run using various analytical processes to determine patterns in historical data. These techniques can help estimate and fill gaps in historical data and also create real-world-like situations for future projections, for example, by using General Circulation Models (GCMs) to project precipitation and air temperature trends.

Potential hazard categories that can be evaluated using spatial identification of area impacted by hazards

- **Meteorological:** Thermal stress (localized identification based on LST), precipitation change (rainfall)
- **Hydrological:** Flood (waterlogging, riverine floods, coastal floods, glacial lake outburst), drought (groundwater, water stress)
- **Geological:** Land deformation (land subsidence, coastline changes), ground movement (landslide, avalanche)
- **Environmental:** Air quality degradation (outdoor air quality), vegetation change (vegetation), fire (forest fires, other fires)

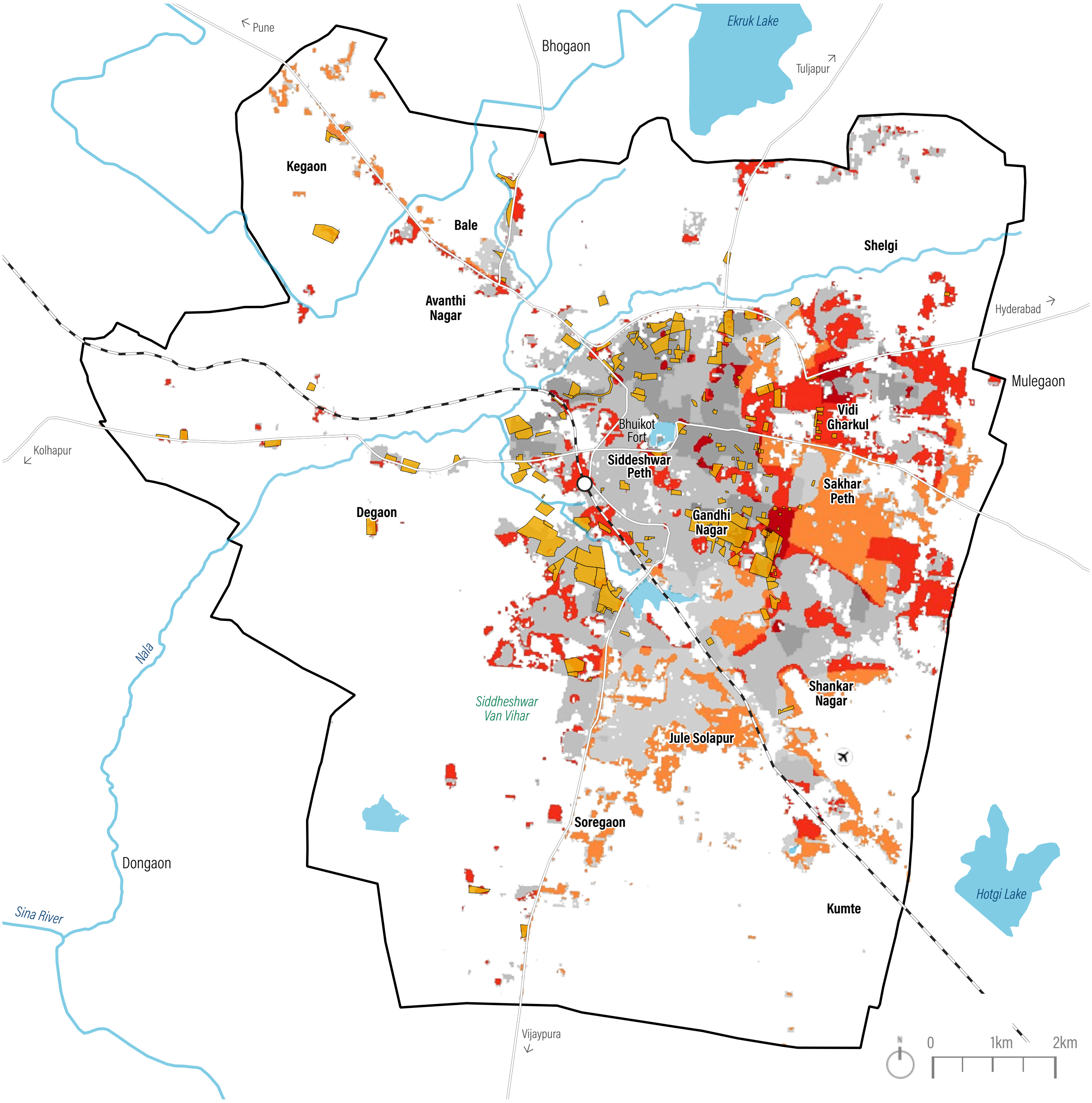
Data sources

- **Satellite imagery (source):** Landsat, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Shuttle Radar Topography Mission (SRTM) (United States Geological Survey [USGS]/National Aeronautics and Space Administration [NASA]); National Remote Sensing Centre (NRSC); Sentinel (EU Copernicus); and Moderate Resolution Imaging Spectroradiometer (MODIS) (Land Processes Distributed Active Archive Center [LPDAAC])
- **Data products:** Aqueduct (World Resources Institute [WRI]) and World Settlement Footprint (WSF) (German Aerospace Center [DLR], European Space Agency [ESA])
- **Fire Information for Resource Management System (FIRMS) and hotspot data:** Disaster management department or authority and allied departments, municipal corporation, public health department, fire department, and other relevant agencies and departments.

Case examples

- **Hotspot analysis:** For the Solapur Climate Action Plan, areas facing intensified urban heat island stress were determined by using the annual average LST. Built settlements with LST higher than the annual average (threshold) were considered hotspots, as shown in Figure 11. This helped identify areas with greater risk of thermal discomfort and prioritized them based on the underlying vulnerability aspects overlayed with the hotspots.[13]
- **Buffer analysis:** In Bengaluru, the Karnataka State Natural Disaster Monitoring Centre (KSNDMC) reported 1,167 flood events between 2013 and 2020, based on which 372 flood hotspots were identified (see Figure 12). The flood impact area—that is, the buffer of a 250-m radius from the flood hotpots—occupies 19 percent of the total built settlement of the city. The impact radius is assumed given that floods and waterlogging limit the physical movement of both people and goods.
- **Feature delineation:** For the Mumbai Climate Action Plan, the mangrove area assessment identified the transformation of the area under mangroves based on the delineated areas between the 2008 and 2021, as shown in Figure 13. Features were delineated as mangroves with increased and decreased density on the basis of erosion, sedimentation, intertidal mud, built expansion, creek invasion, and so on (Ramesh et al. 2022).
- **Correlations:** For the Kochi guidance document for a comprehensive disaster management plan, surface temperatures over different land use types were compared to provide evidence on how LST varies with built form, land cover type, and anthropogenic use or human activities in the area, as illustrated in Figure 14. Analysis showed that natural land uses dampen the UHI effect and are associated with a lower average LST. On the other hand, urban land uses (industrial and commercial) with large concretized surfaces absorb heat and release mechanical heat due to anthropogenic activities, and are associated with a higher observed average LST (Narayanan et al. 2022).
- **Multi-parameter approach and modeling using both satellite-derived insights and ground observations:** For the Bengaluru Climate Action Plan, the natural drainage zones of the city or the flood plains at risk of inundation were modeled. The modeled flood plains helped determine the flood susceptibility of areas, with a special focus on flood plains with unchecked development sprawl, as seen in Figure 15. Further, the population residing within the flood plains that might be at risk of floods was estimated.[14]

FIGURE 11 | Distribution of population density and informal settlements at risk of urban heat in Solapur



Population density within LST hotspots (per 1,000 sq.m): ≤10 10–30 30–60 >60

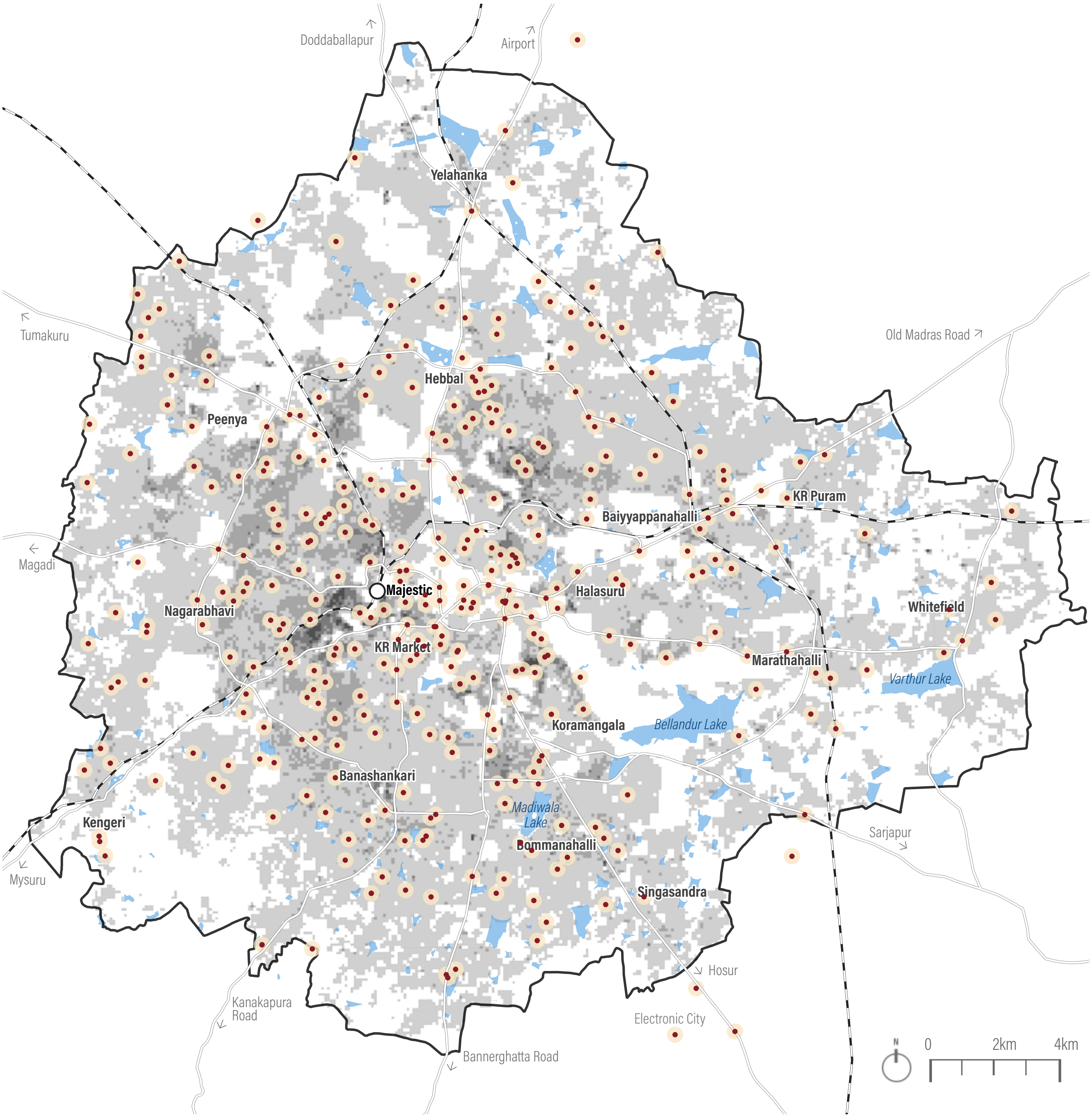
Population density outside LST hotspots (per 1,000 sq.m): ≤10 10–30 30–60 >60

Airport Railway station Railway Major road Water body Informal settlements City boundary

Note: Built settlements with an annual average land surface temperature (LST) higher than the city's annual average have been identified as urban heat hotspots. The average LST value for Solapur is 33°C, calculated using cloud-free thermal band images from Landsat 8 between 2019 and 2021.

Source: Prepared for the Solapur Climate Action Plan. LST retrieved using Landsat 8 processed in Google Earth Engine; population density derived using Census (2011) and World Settlement Footprint (WSF) 2015, European Space Agency (ESA); slum boundaries obtained from the Solapur Municipal Corporation (SMC).

FIGURE 12 | Plausible flood impact area derived using buffer tool for Bengaluru



Railway station | Railway | Major road | City boundary

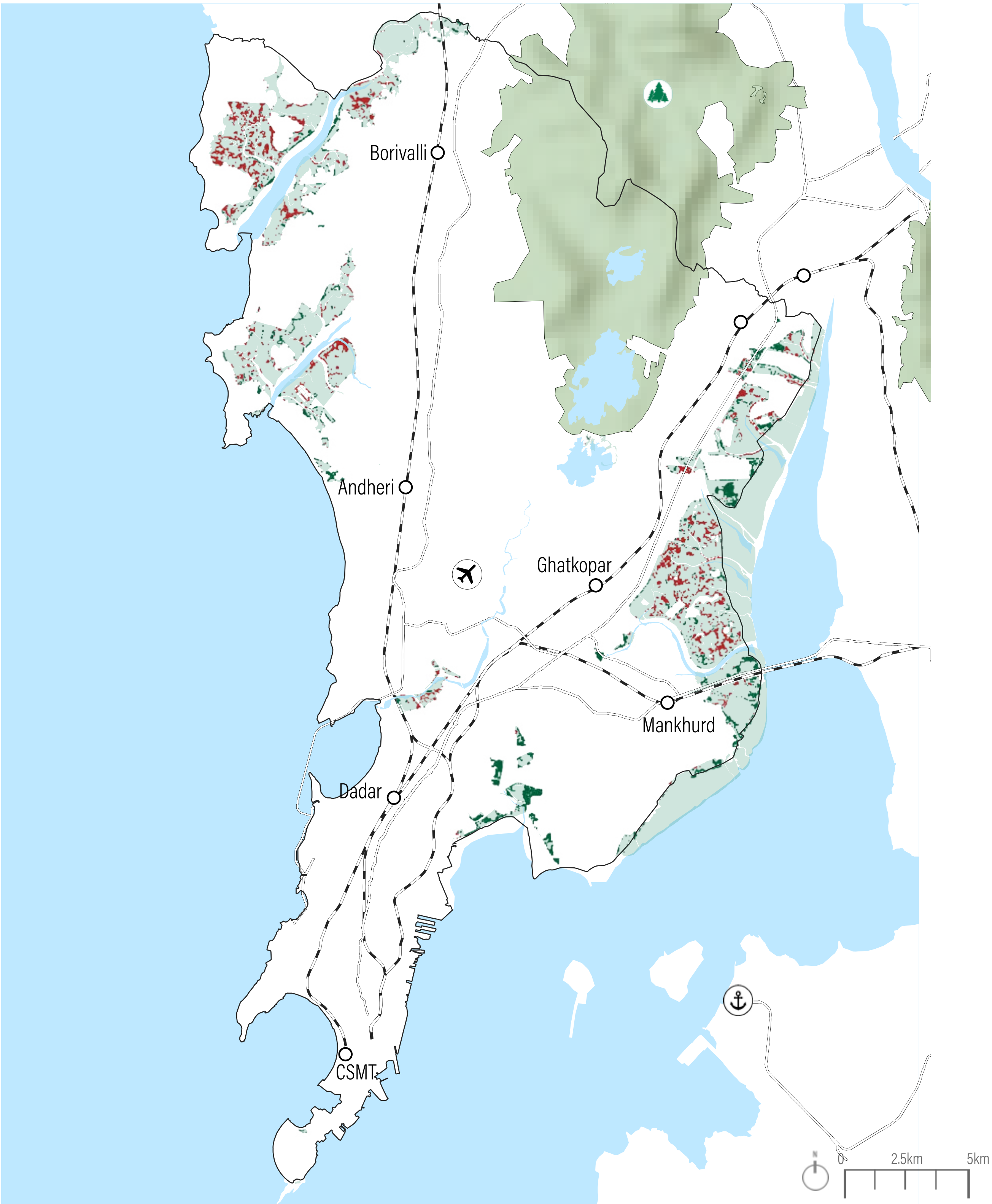
Flood hotspots | Flood impact area | Water body

Population density (per hectare): ≤400 | 400–800 | 800–1,200 | >1200

Note: Areas within a 250 m radius from flood-vulnerable areas are assumed to be potentially at risk due to floods.

Source: Prepared for the Bengaluru Climate Action Plan. Distribution of population density at risk of floods analyzed using "Flood Vulnerable Areas (2013-2020)" from the Karnataka State Natural Disaster Monitoring Centre (KNDMC); Census (2011); and "Building Footprints" data from Bruhat Bengaluru Mahanagara Palike (BBMP).

FIGURE 13 | Mangrove area assessment using landcover delineation for Mumbai

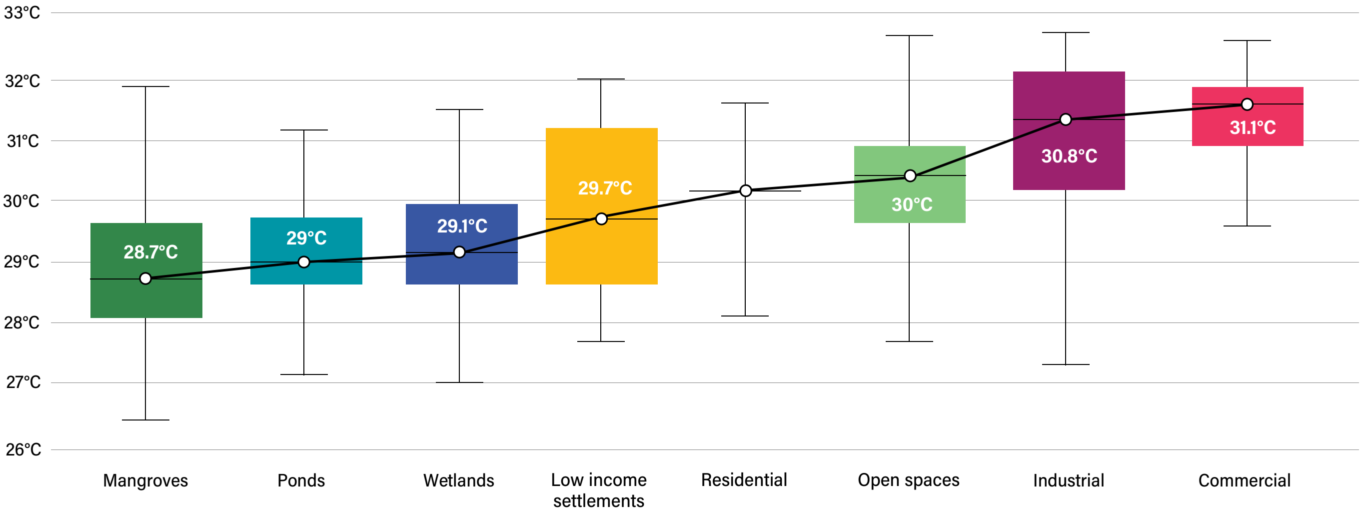


Decreased mangrove density | Mangrove | Increased mangrove density | Water body

Airport | Railway station | Railway | Major road | City boundary

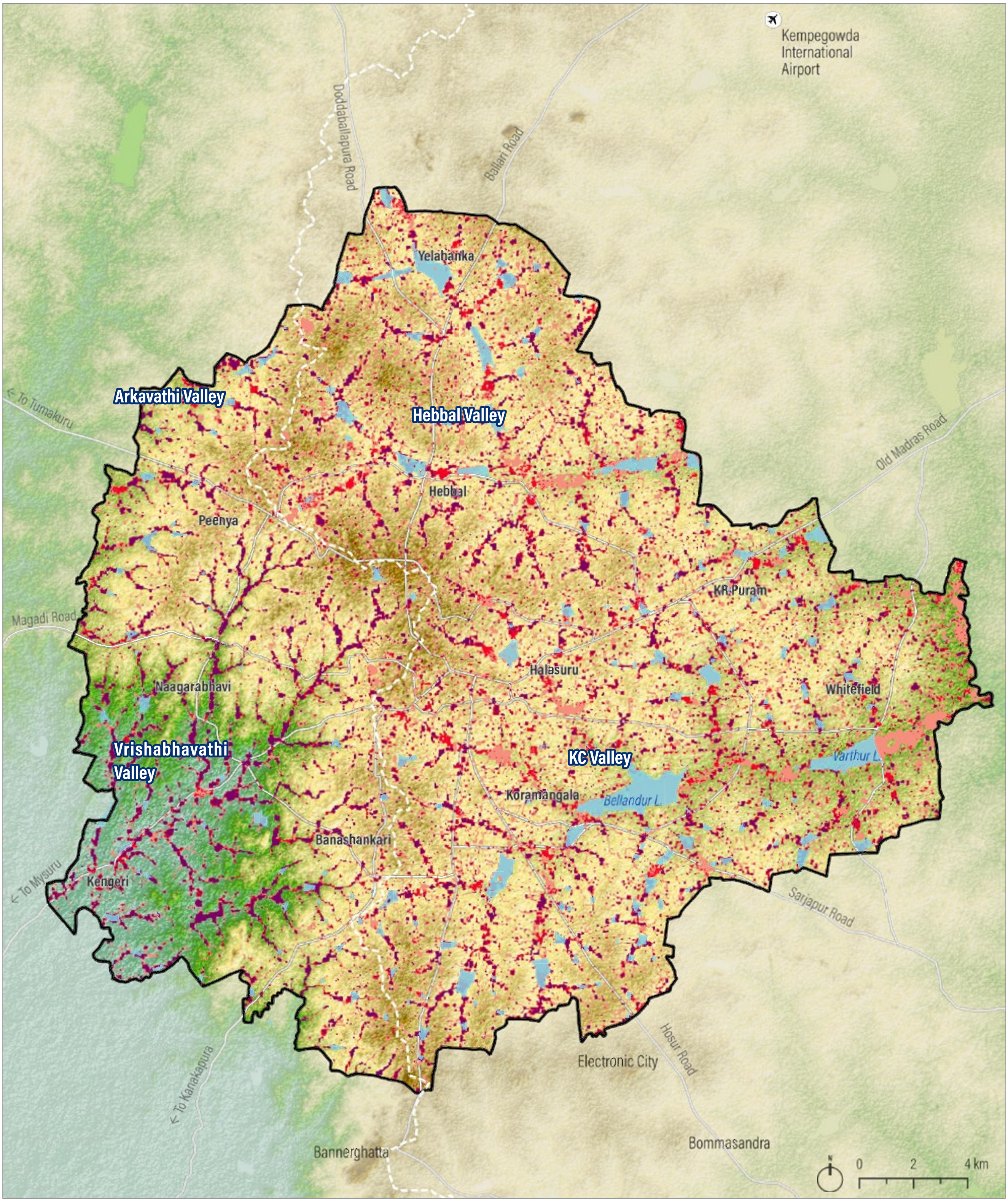
Source: Re-created from Mumbai Climate Action Plan, 2022; Brihanmumbai Municipal Corporation 2022.

FIGURE 14 | Exploring land use land cover correlation with the land surface temperature for Kochi



Source: Narayanan et al. 2022.

FIGURE 15 | Flood risk categories derived using flood modeling for Bengaluru



Airport | BBMP boundary | Major road | River basin boundary | Water body

Flood risk category: Low | Medium | High

Elevation above mean sea level: ≤ 800m – ≥ 1000m

Source: Prepared for the Bengaluru Climate Action Plan. Flood risk derived using different combinations of rainfall return periods from IMD-gridded rainfall data for the period 1985–2020; elevation derived using the Shuttle Radar Topography Mission (SRTM), United States Geological Survey (USGS).

Impact assessment: Hazard impact checklist (including multi-hazard mapping)

The HIA concludes with a checklist that summarizes various climate and environmental hazards that may potentially impact several elements in the city. Table 6, Chapter 3, presents a checklist comprising the common hazard groups relevant to the Indian context together with indicators to help assess the factors driving these hazards that can potentially impact various elements in a city. Cities can use Table 6 to highlight potential elements that may be impacted by specific hazards, helping the CHVA team create a broad scope for acknowledging and assessing these elements (see Chapter 6 for more details on the scoping phase).

Methods

- **Checklist matrix:** This technique is used to collect initial impressions of potential impact elements based on different hazards relevant to the city. Cities can fill out this checklist using secondary data and reports describing the likelihood of hazards based on past trends and future projections (at the state or national level). Elements impacted may be partially (physically or operationally) or fully impacted depending on the type and extent of the hazard and its indicators.
- **Multi-hazard mapping:** Table 7, Chapter 3, helps quantify multi-hazard-prone areas. This technique is a form of composite mapping based on simple GIS tools such as overlay and intersection for all relevant hazard maps. Once spatial extents for hazards are identified, they can be overlaid and compiled as multi-hazard zones. Further, socioeconomic, demographic, and infrastructure data can be overlaid on these to assess differential vulnerability in the study area. Risk can be concurrent with multidimensional vulnerability, where hazards may also interact and be interdependent (Angeli De et al. 2022).

Data sources

- **Satellite imagery (source):** Landsat, ASTER, SRTM (USGS/NASA); NRSC; Sentinel (EU Copernicus); and MODIS (LPDAAC)
- **Data products:** Aqueduct (WRI) and WSF (DLR, ESA)
- **FIRMS and hotspot data:** Disaster management department or authority and related departments, municipal corporation, public health department, fire department, and other relevant agencies and departments.

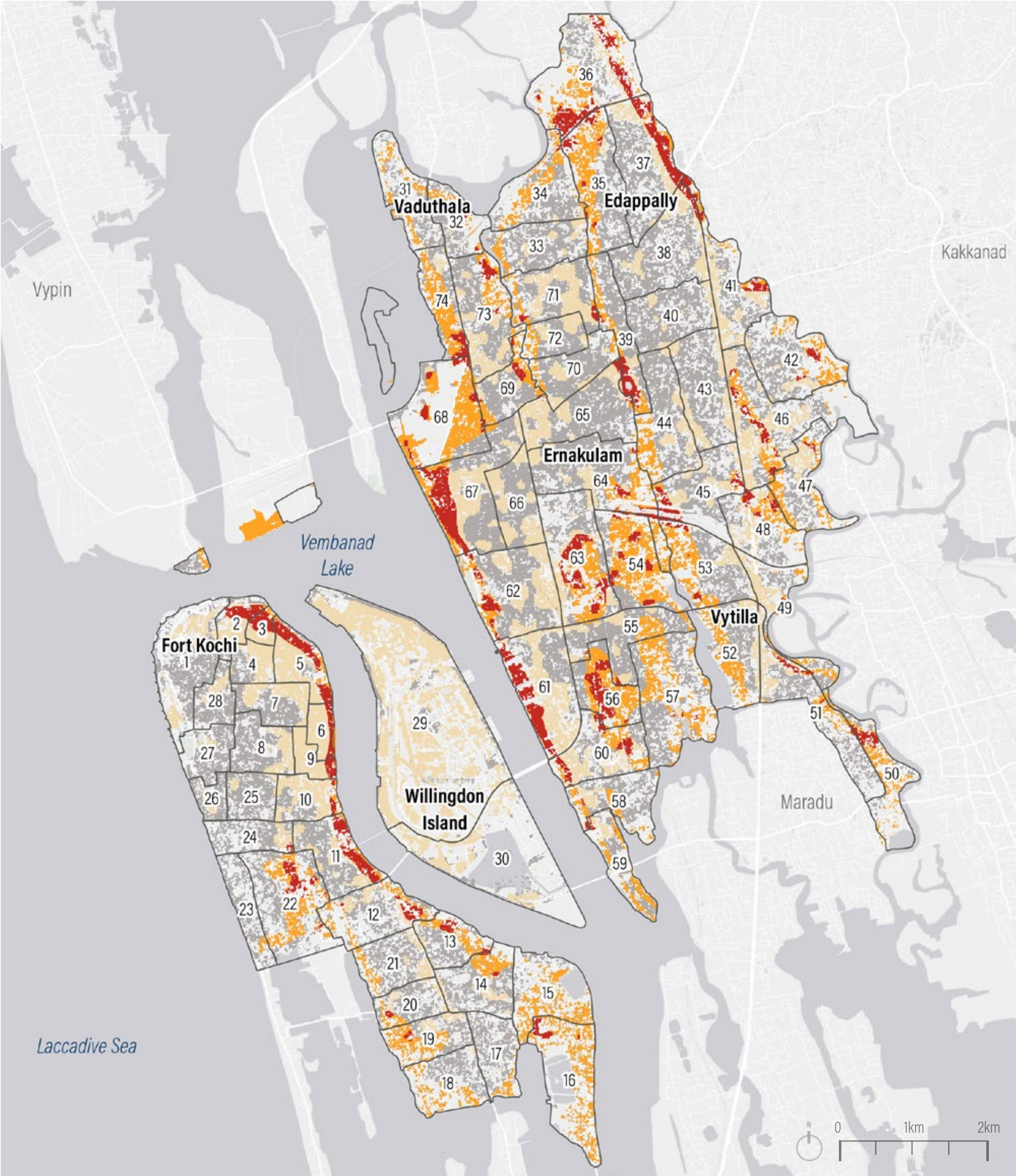
TABLE 13 | Elements impacted corresponding to significant hazards analyzed for Mumbai

IMPACTED ELEMENTS	METEOROLOGICAL					HYDROLOGICAL		GEOLOGICAL		ENVIRONMENTAL				
	TS	Pr	Wn	WE	SL	Fl	Dr	LD	GM	AQ	WQ	SQ	Vg	Fr
Population	✓	✓		✓	✓	✓		✓		✓			✓	
Natural environment	✓	✓		✓	✓	✓		✓		✓			✓	
Built environment	✓	✓		✓	✓	✓		✓						
Jobs and livelihood	✓	✓		✓	✓	✓		✓		✓			✓	
Infrastructure	✓	✓		✓	✓	✓		✓						
Access to services	✓	✓		✓	✓	✓		✓						
Amenities	✓	✓		✓	✓	✓		✓		✓				
Housing	✓	✓		✓	✓	✓		✓						
Food systems														

Note: TS = Thermal Stress; Pr = Precipitation Change; Wn = Wind; WE = Weather Events; SLC = Sea Level Change; FL = Flood; Dr = Drought; LD = Land Deformation; GM = Ground Movement; AQ = Air Quality Degradation; WQ = Water Quality Degradation; SQ = Soil Quality Degradation; Vg = Vegetation Change; Fr = Fire.

Source: Authors.

FIGURE 16 | Multi-hazard mapping: Areas of Kochi susceptible to floods and excessive heat



Settlements vulnerable to both heat and floods | Settlements vulnerable to floods | Settlements vulnerable to heat (above 30°C)

Percentage of households: 7% | 25% | 35% | 48% | Settlements | Ward boundary | City boundary

Source: Narayanan et al. 2022.

Case examples

- **Hazard impact checklist:** In Mumbai, from the secondary literature and relevant studies, the team deduced that excessive heat, floods caused by extreme precipitation, and deteriorating air quality were some of the key hazards in the city. In Table 13, each gray cell denotes the intersection of elements and hazards that were quantified and analyzed for Mumbai city.
- **Multi-hazard mapping:** Assessment of the multiple hazards in Kochi revealed that 25 percent of the total urban settlement (built settlement area) is vulnerable to flood risk and 35 percent is vulnerable to heat risk. Further, 7.3 percent of the settlement is at risk of both hazards (Narayanan et al. 2022). These areas were prioritized for complementary actions to reduce the risk of both the identified hazards (see Figure 16).

METHODOLOGIES USED TO CONDUCT EXPOSURE ANALYSIS

Spatial assessment of population exposed to climate and environmental hazards

For assessing the spatial distribution of populations exposed to hazards, the primary spatial approximation of population density using population statistics available at the smallest administrative unit is needed. Population density can be apportioned to rasterized versions of built-up, building footprint, paved or concretized spaces, or any other available settlement data. The population assessment units can be visualized, and estimates can be made of persons per standard unit area.

Population data can be overlaid with the multi-hazard maps produced during the HIA to identify the percentage of the city's population that lives in hazard-prone areas. Moreover, overlaying shape files of slum settlement boundaries or point locations (coordinates or addresses) of slum settlements on multi-hazard maps helps identify the most vulnerable communities in the city.

Spatial assessment of infrastructure exposed to climatic and environmental hazards

Overlaying the point locations of transit stations or built assets and line networks of infrastructure and amenities listed in Table 7 over multi-hazard maps helps identify infrastructure that is vulnerable to one or more hazards in the city. The impacts of infrastructure and service disruptions are also assessed as part of the sensitivity and adaptive capacity analysis.

Potential indicators that can be evaluated to map the exposure of people and infrastructure are listed as indices or indicators in Table 7. For assessment of exposure of infrastructure, the details of indicator items include (but are not limited to) all critical infrastructure, amenities, and service distribution lines located within or near hazard-prone areas along with an assessment of loss and damage of infrastructure and assets, year-wise, by hazard type. See Appendices C and D for an exhaustive list of potential infrastructure assets/networks and leads for a qualitative assessment of infrastructure and services, respectively.

Data sources

- **Latest administrative boundaries:** These include wards and zones, ward-wise population based on the Census and building footprints, preferably with floor space and building height (municipal corporations or other line agencies).
- **Land use:** Residential (urban development authority, municipal corporation, or other line agencies); built settlement footprint; establishments, industries, shops, and economic clusters, preferably with employee data (DoE, Economic Census, labor department, or any other government-approved dataset on location of employment, industry type, and employment size).
- **Slum boundaries:** Preferably with slum population, including notified and non-notified slums (slum board, municipal corporation, or other line agencies).
- **Infrastructure networks including amenities and utilities:** Roads, rail, metro and monorail stations and networks, public transport (bus stops and terminals), hospitals, emergency and fire stations, disaster relief shelters, schools, stormwater networks, solid waste management sites, power distribution (major) lines and

stations, public green open spaces, public toilets, night shelters, sewage networks, sewage treatment plants, water supply networks, water treatment plants, fiber and Internet networks, and public information systems (municipal corporation or other line agencies).

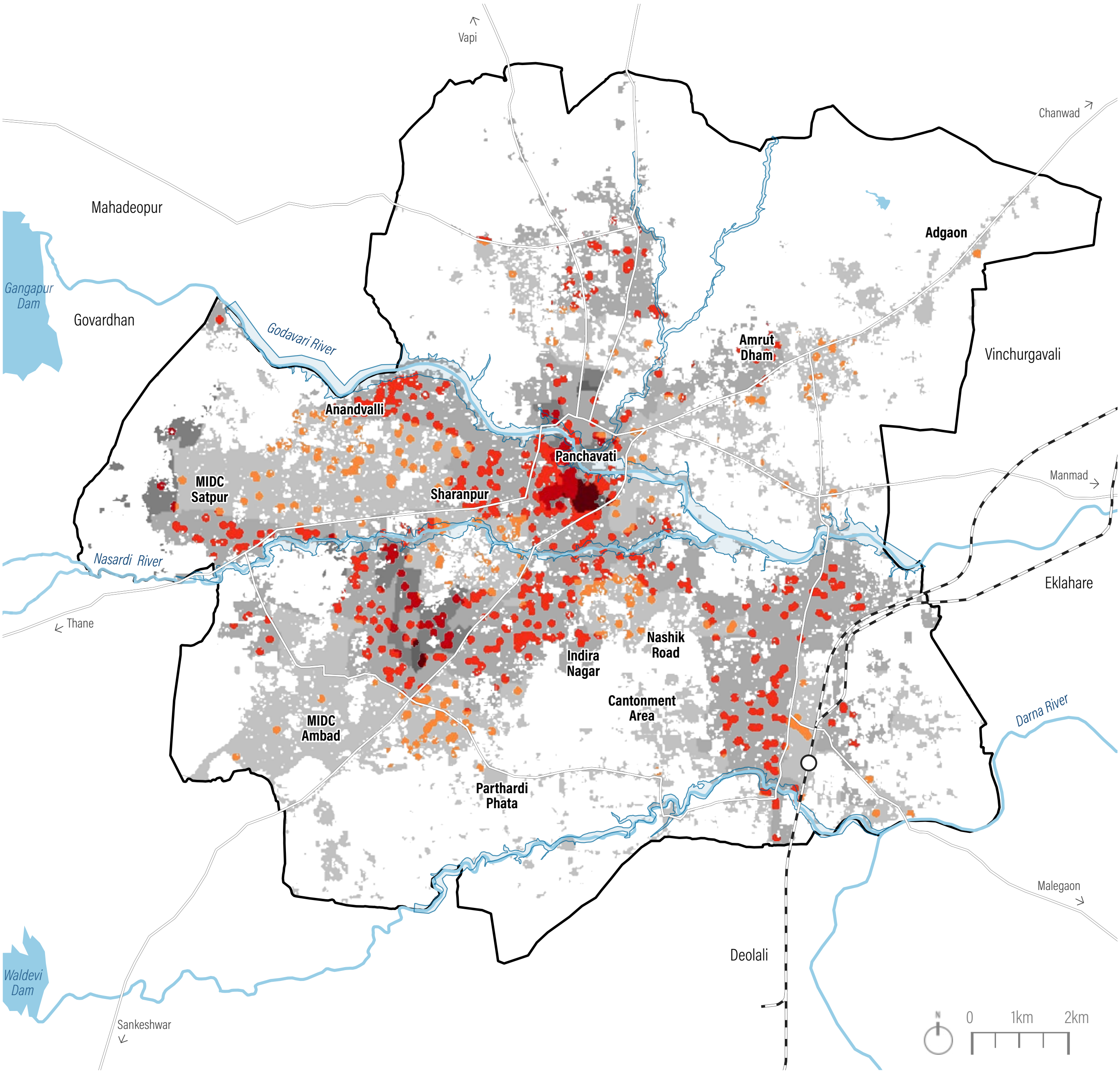
- **Documentation on previous hazard occurrences and the associated infrastructure losses:** Preferably with the nature and extent of damage to specific assets and the location of affected assets by each hazard category.

Case examples

- **Exposure of people (overall population density):** For the Nashik Climate Action Plan, flood impact areas were determined using recurring flood and waterlogging complaints data. Analysis showed that the complaint points cluster along the River Godavari in the city and around the neighborhoods along the minor streams and *nullahs* flowing into Godavari, as seen in Figure 17. Nearly 23 percent of the city's overall population resides within the flood impact area. The population figures were analyzed at the ward and zone level, as well, to facilitate discussions and actions at the smallest administrative units.[15]

- **Exposure of infrastructure (mass and public transport stations and networks):** Heavy rainfall and flooding affect the transport infrastructure in a city by impacting its safety, operation costs, travel time, and service regularity. This further disrupts access to the most essential and critical civic services. Based on the flood hotspot influence zone analysis, 33 percent of Mumbai's mass transit network—including its lifelines, the suburban rail network, metro line, and monorail—are heavily impacted by inundation, which limits physical access to transit stations (see Figure 18) (Ramesh et al. 2022).

FIGURE 17 | Population exposed to potential risk of floods in Nashik



Population density at risk due to flooding (per 1,000 sq. m): ≤10 | 10–30 | 30–60 | >60

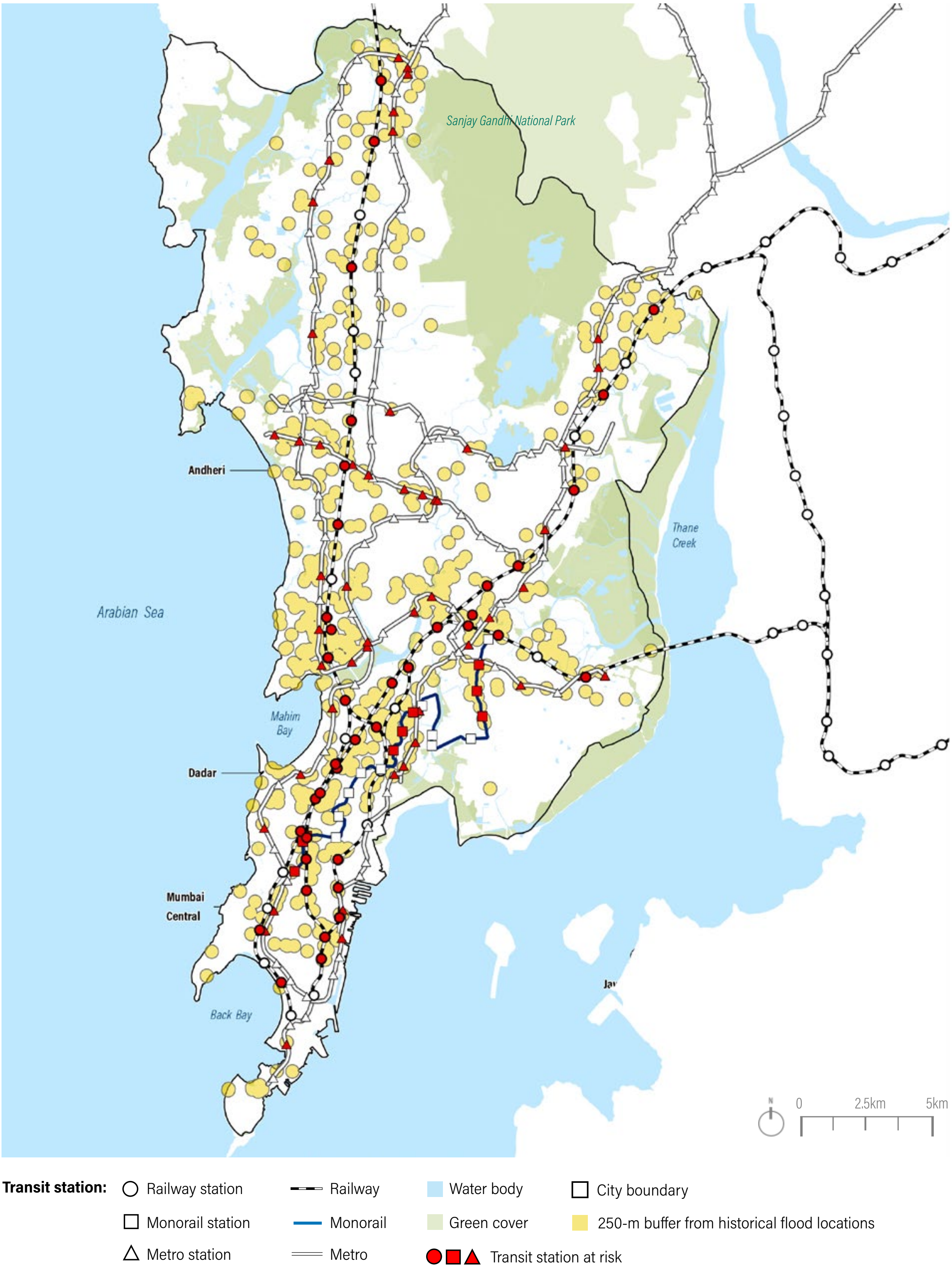
Population density (per 1,000 sq.m): ≤10 | 10–30 | 30–60 | >60

Railway station | Railway | Major road | Water body | City boundary | Floodplain using high flood line

Note: Population lying within a radius of 100 meters of points obtained from flooding locations using complaints data from 2017-2020 are considered to be potentially at risk of flooding.

Source: Prepared for Nashik Climate Action Plan. Population density derived using Census 2011 and 'World Settlement Footprint (WSF)' 2015, European Space Agency (ESA); Flood lines and historic flood locations data from Nashik Municipal Corporation (NMC).

FIGURE 18 | Transit stations exposed to potential risk of flooding in Mumbai



Source: Brihanmumbai Municipal Corporation 2022.

METHODOLOGIES FOR THE VULNERABILITY ASSESSMENT OF PEOPLE AND INFRASTRUCTURE

Rapid social analysis (RSA) by mapping primary, secondary, open-source government data and consulting with stakeholders

RSA is used to assess the first four domains of sensitivity (as discussed in Chapter 4), to assess differential vulnerability based on the population's sociodemographic characteristics at the ward level. RSA is an analytical approach, a process of collecting, interpreting, and applying information to identify vulnerable populations, groups, and persons and understand and explain gaps, disparities, power dynamics, opportunities, and constraints based on social dynamics (including gender dynamics, inequalities, and social exclusions) (Rangwala et al. 2018). RSA begins by looking at government data on social indicators at the city and ward level. For the CHVA, RSA will investigate the preexisting inequalities triggered and intensified by climate change and how the city's response to it deepens inequities owing to social, economic, and political barriers. Beyond desk reviews, multi-stakeholder consultations are recommended with identified representatives of vulnerable groups, civil society organizations working on social inclusion programs at an urban scale, and city officials. Guidelines for incorporating such data into the CHVA process are detailed in Chapter 6. Including these forms of data, which go beyond official data, helps make the CHVA more dynamic and better able to consider the historical factors that have contributed to forms of social vulnerability in particular communities.

RSA for the CHVA uses three types of methods to assess socioeconomic sensitivities: needs assessment, social vulnerability mapping, and social protection analysis.

Methods

- **Needs assessment of impacted groups:** The WRI and C40's inclusive climate action planning guidance, as illustrated in Figure 19, defines needs assessment as identifying "both the communities that are most vulnerable to climate change and those that are the most sensitive to climate actions. Contextualizing climate actions in terms of who will be most impacted helps the city ensure that selected climate actions have the widest economic, environmental, and social impact" (Mahendra et al. 2019).

  To understand the needs of communities and populations disproportionately impacted by climate-change-induced hazards and to assess whether development and climate actions are delivering benefits to them, cities may consider gathering data that are disaggregated by population group and spatial distribution.

- **Social vulnerability maps:** Mapping different socioeconomic, political, residential, and locational or physical indicators of vulnerability at the ward or neighborhood resolution using census data on essential services required at the household level highlights the differential vulnerability of populations across the city. It helps identify and prioritize communities for targeted climate actions, including building the adaptive capacity of impacted populations and places.

Apart from mapping the underlying sociodemographic aspects, the domains focus heavily on ease of physical access and availability of both household and city-level infrastructure and services using ward-level census data and the economic and mobility networks available in the city.

- **Social protection analysis:** It is important that different levels of government and other organizations map social protection programs as part of the post-disaster response and recovery efforts following a major climatic event, because it is important for understanding the coping and adaptive capacity of vulnerable groups. These programs could be cash transfers, food and in-kind transfers, school feeding programs, skilling and capacity building for livelihood diversification, public works, fee waivers, and targeted subsidies, among others.

  The World Bank Social Protection and Labor Strategy for 2012–22 defines social protection as "social protection and labor systems, policies, and programs help individuals and societies manage risk and volatility and protect them from poverty and destitution—through instruments that improve resilience, equity, and opportunity" (GFDRR and The World Bank 2019).

FIGURE 19 | Unpacking inclusion in the context of climate action planning and conducting Vulnerability Analysis

INCLUSIVITY FOCUS	IMPACTED GROUP	DEFINITION
Income level	Low-income communities	Groupings or thresholds connected to earnings of labor and/or capital. Categories typically are defined as related to the local/national economy.
Migrant status	Migrants	Refers to the legal and immigration status of a person who changes their place of residence. Categories include locals, expatriates, documented, and undocumented migrants, refugees, and asylum seekers.
Gender	Women	The socially constructed characteristics of women and men—such as norms, roles, and relationships of and between groups of women and men. Categories typically include lesbian, gay, bisexual, transsexual, and inter-sex, and traditional biological sex categories of male and female.
Social class	Scheduled Caste (SC) and Scheduled Tribe (ST)	The Scheduled Castes (SCs) and Scheduled Tribes (STs) are officially designated groups of historically disadvantaged or marginalized people in India recognized as per Article 341 and 342 of the Constitution of India. Each decennial Census in India enumerates SC and ST population, including their relevant socio-economic and demographic characteristics following the ascertained lists of SCs and STs, as amended from time to time for each State/Union Territory.
Religion	Religious minorities	Religious or spiritual belief of preference, regardless of whether or not this belief is represented by an organized group, or affiliation with an organized group having specific religious or spiritual tenets.
Informality status	Informal communities (residents & workers)	Relationship of individuals, household activities, or firms to the formal or informal economy, typically with respect to production, employment, consumption, housing, or other services.
Disability	People with disabilities	Persons with disabilities include those who have long-term physical, mental, intellectual, or sensory impairments that in interaction with various barriers may hinder their full and effective participation in society on an equal basis with others.
Age	Elderly, youth and children	Chronological grouping based on years lived.
Working conditions	Outdoor, temporary and transitioning industry workers	Working conditions cover a broad range of topics and issues from working time (hours of work, rest periods, and work schedules) to remuneration, as well as the physical conditions and mental demands that exist in the workplace and job stress for workers in transitioning industries (e.g., fossil fuels)

Source: Based on Mahendra et al. (2019) and modified by the authors.

Three interrelated goals for social protection are identified:

- Resilience for the vulnerable by insuring them against the impact of drops in well-being from a range of shocks.
- Equity for the poor by protecting them against destitution and promoting equality of opportunity.
- Opportunity for all by promoting human capital in children and adults and "connecting" men and women to more productive employment.

Potential indicators that can be evaluated using one of the three RSA methods

Sensitivity of people

- Disproportionately impacted population groups
- Populations in adverse working conditions
- Populations involved in high-risk livelihood activity
- Lack of home ownership, limited tenure, and houselessness
- Inadequate housing conditions such as temporary building materials
- Inadequate household-level essential services

Adaptive capacity of people

- Employment and livelihood
- Social security

Data sources

The latest administrative boundaries including wards and zones with census statistics (Primary Census Abstract and House listing and housing tables), population density computed preferably using building footprints or settlements based on ward-wise population statistics from the latest Census, locations and spatial boundaries of major outdoor workers and temporary or informal worker hubs such as street vending zones can be obtained from municipal corporations, labor departments, and other line agencies.

Slum boundaries, preferably with slum population including notified and non-notified slums, can be obtained from slum boards, municipal corporations, and other line agencies.

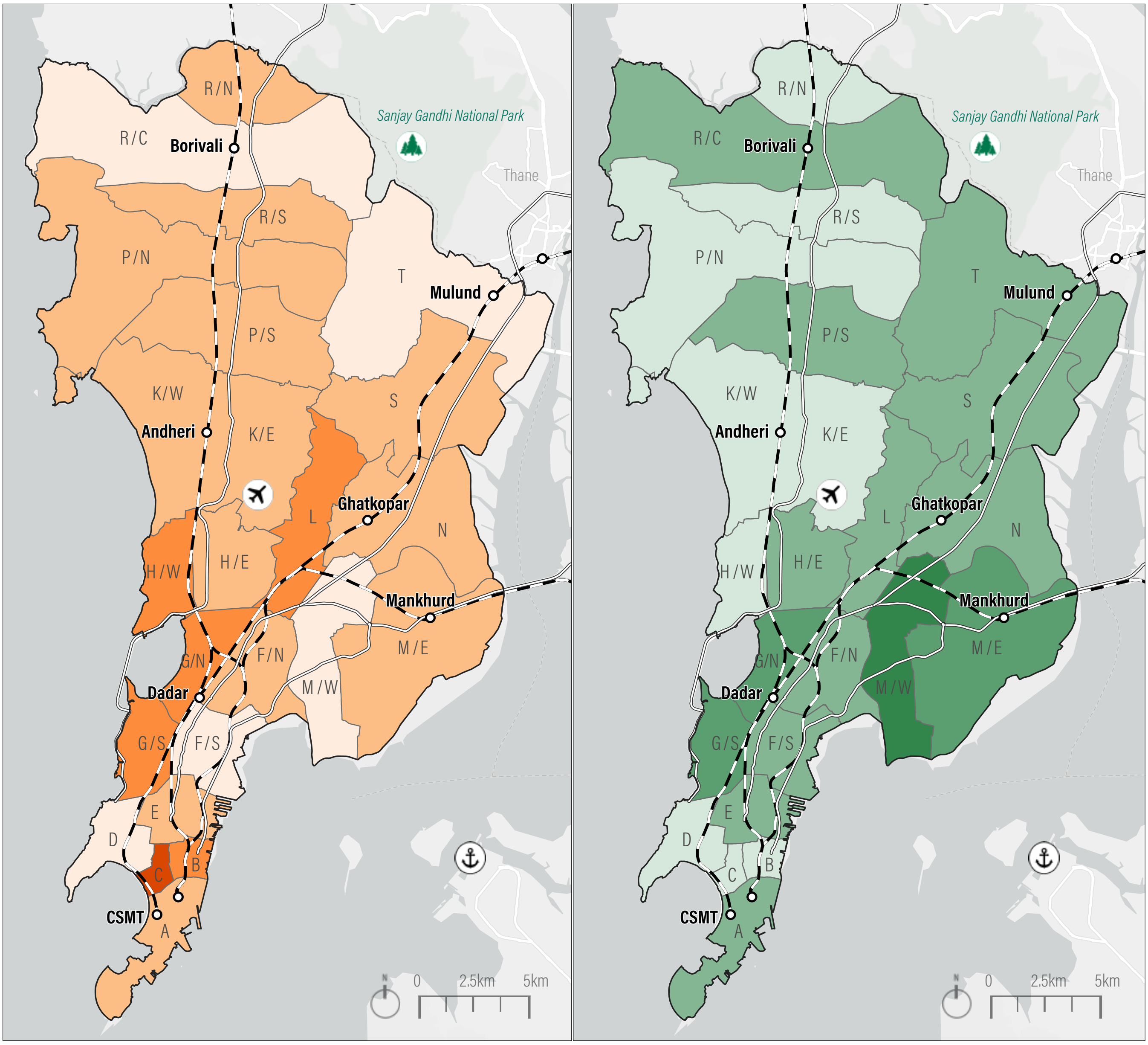
Infrastructure networks, including amenities and utilities, comprise road networks; rail, metro, and monorail stations and networks; public transport, including bus stops and terminals (including frequency and operational status); government and private hospitals; emergency and fire stations; disaster relief shelters and schools, both government and private; public green open spaces; and public toilets. Average vehicular speeds for peak hours can be obtained from city mobility plans and traffic or transport surveys. Country-level aggregate data can be found in the World Social Protection Database by ILO, which is based on SSI; ISSA/SSA, Social Security Programs Throughout the World; ILOSTAT, United Nations Economic Commission for Latin America and the Caribbean (ECLAC), IMF, WHO, WB, UNDP, and UNICEF, completed with national data sources. Other sources are national and state government databases on social protection.

Other community data sources can supplement these official data sources. These sources could be generated by making participatory timelines, creating slum atlases, strengthening official city-level data, tapping into open, crowd-sourced community data, and conducting student-led surveys and mapping. However, because these sources of data are not standardized, their inclusion in the CHVA process should be carefully considered. This sort of approach follows evidenced methods for incorporating local knowledge into climate responses; for example, as outlined through participatory rural appraisals (Omondi 2023; Uddin and Anjuman 2013).

Case examples

- **Social vulnerability maps for Mumbai:** Figure 20 shows ward maps of Mumbai's gender distribution and caste composition (Ramesh et al. 2022). Wards with the highest and lowest number of females per thousand men were identified. The population of Scheduled Castes and Scheduled Tribes (SC/ST) with respect to the overall ward-level population was also mapped. Social vulnerability maps at the ward level, showing the percentage of residents living in households with inadequate access to essential household-level services, were created for the Chhatrapati Sambhajinagar Climate Action Plan (see Figure 21). The study concluded that nearly 43 percent of households in the city have drinking water facility outside their house premises and 18 percent of households do not have access to treated drinking water facility in the city, according to Census (2011) data.

FIGURE 20 | Social vulnerability maps showing the (left) gender and (right) caste composition in Mumbai



Gender distribution (Number of females per 1,000 males):

690–750 | 750–820 | 820–890 | 890–950

Percentage of Scheduled Caste & Scheduled Tribe population:

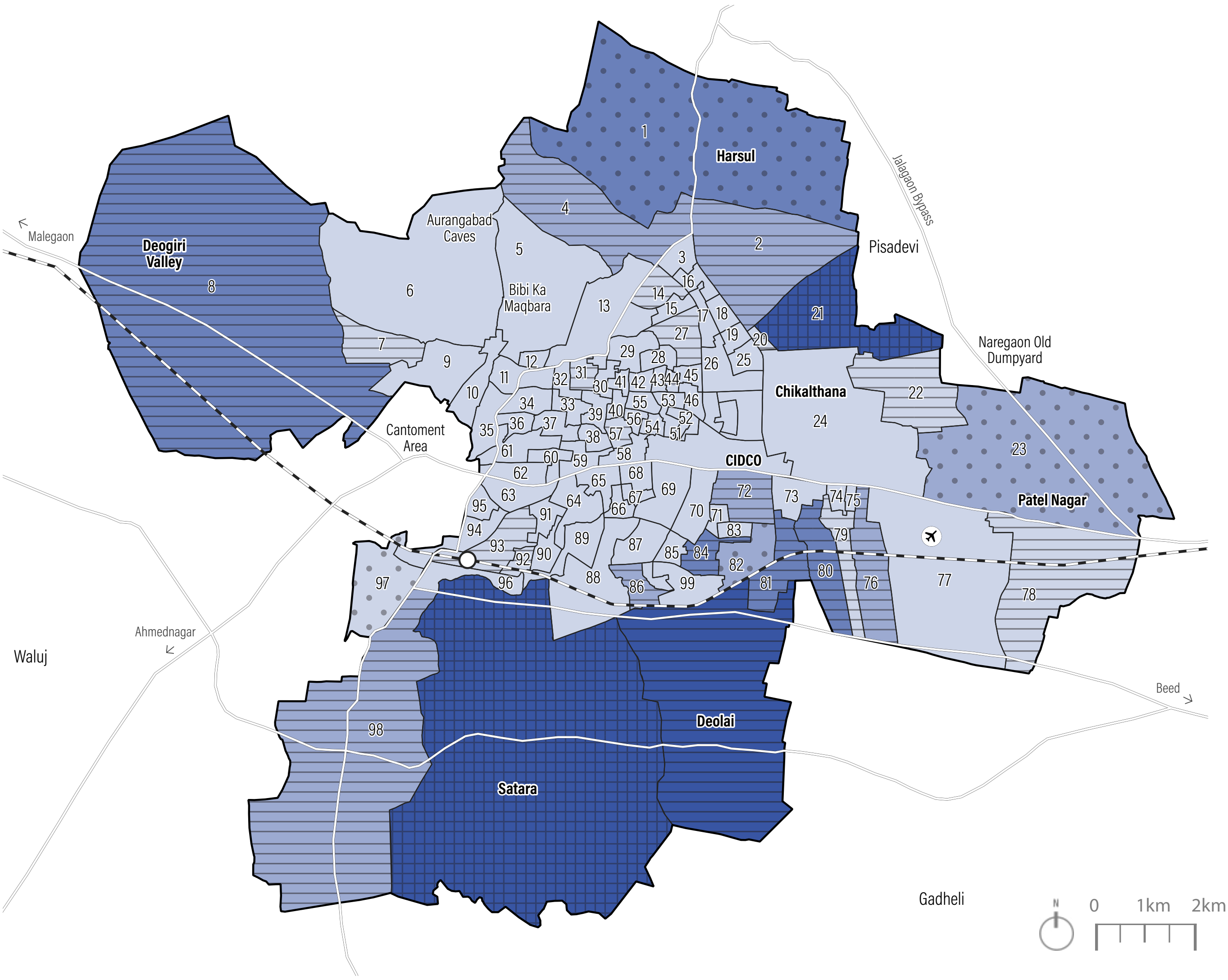
1–6 | 6–10 | 10–14 | 14–19

Airport | Sea port | National park | Railway station | Railway | Major road

Ward boundary | City boundary

Source: Brihanmumbai Municipal Corporation 2022.

FIGURE 21 | Social vulnerability map showing ward-wise access to household-level water supply in Chhatrapati Sambhajinagar



Percentage of households without drinking water inside premises: 0–18 18–35 35–53 >53

Percentage of households without access to treated drinking water: 0–25 25–50 50–75 >75

Airport Railway station Railway Major road Ward boundary City boundary

Notes:

1. Households without access to treated drinking water include those whose drinking water sources include untreated tap water, covered wells, uncovered wells, hand pumps, tubewells or borewells, springs, rivers or canals, tanks, ponds, lakes, and other sources.
2. Households without drinking water inside the premises include both those with drinking water near and away from the premises.

Source: Prepared for the Chhatrapati Sambhajinagar Climate Action Plan. Derived using Census (2011) data.

BOX 3 | Social protection programming example

The MUKTA Yojana in Odisha cities is a labor-intensive social protection program that leverages urban development through public works in Odisha. The program is promoted by the state government and aims to address the rising unemployment in the state in the wake of the COVID-19 pandemic, when extensive reverse migration to the home state occurred. MUKTA is designed as a bottom-up, people-centered integrated urban public works program that includes drain desilting, rainwater harvesting, building community centers, citywide sanitation activities, and public space development. Many of these projects support the implementation of the slum-upgrading activities under the Jaga Mission. MUKTA seeks to provide sustainable livelihood to the poor; improve the living conditions of vulnerable and marginalized populations in urban centers; protect the environment; create climate resilient community assets; and build trust-based partnerships with community organizations through community-centric and community-led development. The public works under MUKTA will be executed directly by the community organizations of the wards under the general control and supervision of urban local bodies.

Source: PTI 2023.

Accessibility analysis for services, amenities, and infrastructure

Accessibility analysis is used to identify areas and settlements that are "underserved" by services, amenities, and infrastructure networks in a city. The aim is to assess the level of service on regular days and compare it with that on extreme event days, both during the event and after it has passed. Disruptions in critical services, amenities, and infrastructure make underserved communities more sensitive to climate and environmental hazards. Two methods are used to assess these indicators: service area delineation (based on pedestrian and vehicular speed-based proximity analysis) and plausible service area reductions due to infrastructure at risk of failure or service disruption.

Methods

- **Service area delineation:** GIS data for the location of critical infrastructure (stations and networks) and stationary assets are used to define service area polygons using network analysis tools. Data layers such as existing road networks, pedestrian walkability standards,[16] and standard response time and average vehicular speeds in the city are used to delineate service areas. Areas outside service area polygons are identified as underserved due to lack of physical access. Further, overlaying real-time traffic and road conditions data may reveal variability in service area delineations through the day, which may be particularly important for emergency response services such as ambulances, fire brigades, and police response. Finally, overlaying sociodemographic data layers, such as sensitive populations and slum settlements (shapefiles or locations), helps emphasize the need for continuous access to essential services and infrastructure in vulnerable communities. Limitations of physical access vary temporally through the day, week, and during festivals, and is further exacerbated during extreme events, as assessed below.
- **Mapping plausible service area reductions due to infrastructure failure or service disruptions:** The service area delineation maps are overlayed with hazard maps to identify infrastructure networks, services, and amenities that may be at risk due to failure or disruption during extreme weather events and other hazards. Further, overlaying sociodemographic data layers, such as sensitive populations and slum settlements (shapefiles or locations), will help identify populations that are most vulnerable to these hazards. Improving access in these areas can ensure timely emergency response and reduce vulnerability in a city.

Potential indicators that can be evaluated using any of the accessibility analysis methods are listed as part of the residential and physical domains in Table 8, Chapter 4. Appendix C gives an exhaustive list of infrastructure assets. Reduction in service area, during and immediately after hazard events, due to potential disruption or limitations of physical access can also be estimated for the same list of assets and infrastructure elements.

Data sources

The latest administrative boundaries including ward and zones with census statistics (Primary Census Abstract and House listing and housing tables), population density can be computed preferably using building footprints or settlements based on ward-wise population statistics from the latest Census.

Slum boundaries, preferably with slum population including notified and non-notified slums, can be obtained from slum boards, municipal corporations, and other line agencies.

Infrastructure networks, including amenities and utilities, comprise road networks; rail, metro, and monorail stations and networks; public transport, including bus stops and terminals; government and private hospitals; emergency and fire stations; disaster relief shelters and schools, both government and private; public green open spaces; and public toilets. Average vehicular speeds for peak hours can be obtained from city mobility plans and traffic or transport surveys.

Case examples

- **Service area delineation:** The areas and population that lie outside the immediate service area of fire stations in Kochi were identified based on the plausible distance covered by a fire engine. The plausible distance was derived using the standard response time for fire and rescue services and the prevalent average vehicular speeds in the city. It was found that nearly 55 percent of the population lived outside areas that fire stations can access within the standard response time (Narayanan et al. 2022) (Figure 22).
- **Service area delineation using estimated and/or real-time prevalent vehicular speeds:** The level of access varies temporally based on traffic and road conditions and activities in the area. Using the Google API, vehicular speed estimates were derived for the Marol fire station in Mumbai. Speed information was used to delineate plausible service areas for the fire station through different time intervals of the day (Ramesh et al. 2022) (Figure 23).
- **Plausible reduction in service area during hazards:** In the event of a flood, the percentage of Mumbai's population with access to a flood shelter within 1 km walking distance can potentially be reduced from 76 percent to 46 percent (Ramesh et al. 2022) (Figure 24).

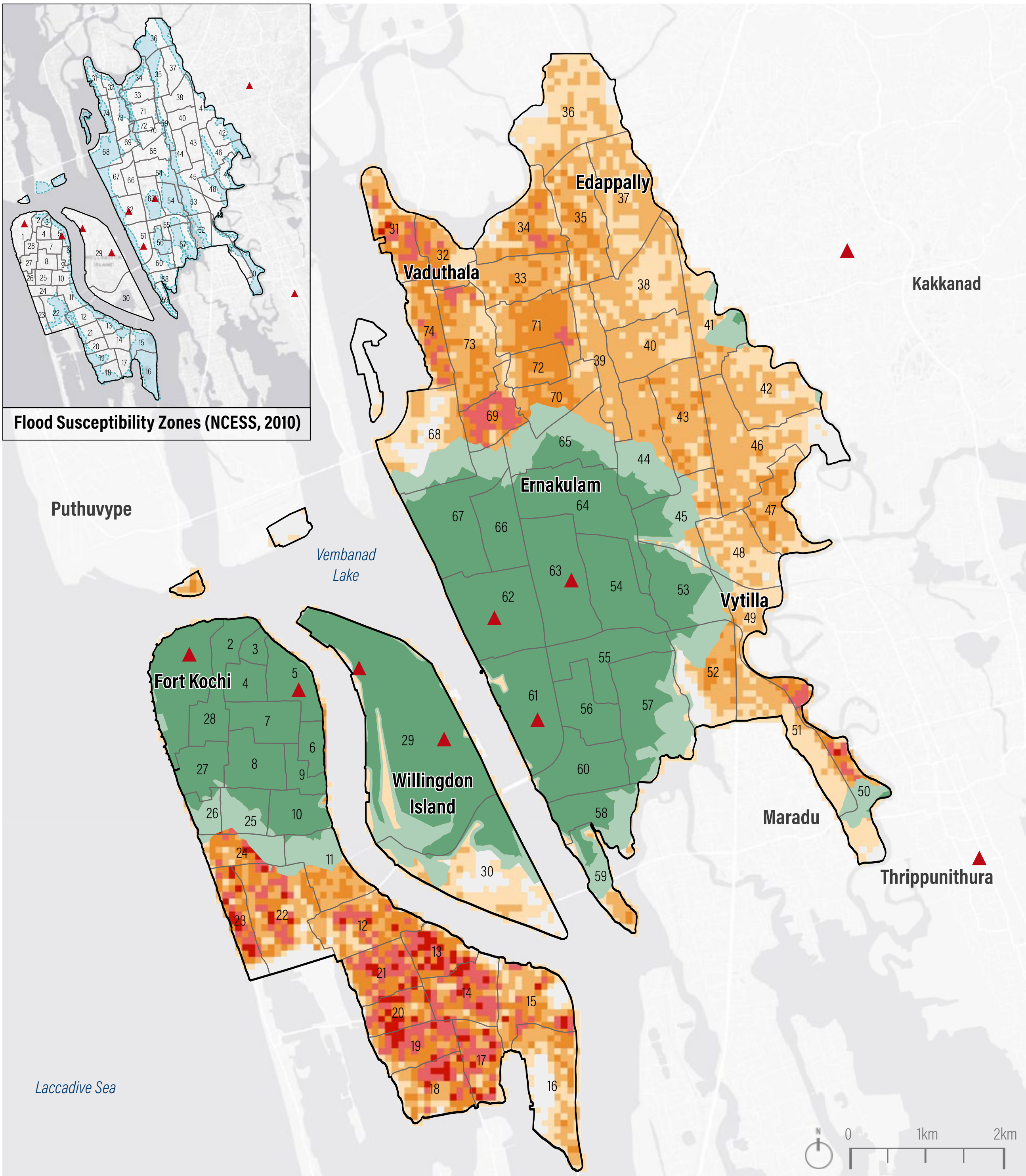
Evaluating loss of life, productivity, and revenue, and additional expenditures incurred due to climate and environmental hazards

Climate and environmental hazards lead to loss of life, loss of productivity, and loss of revenue due to disrupted services. Additionally, expenses are incurred on repair and maintenance of essential public infrastructure due to physical damage. Infrastructure losses are incurred as economic and social costs, and data for these are not readily available. Hence, data may need to be sourced through department reports, detailed project reports (DPRs) of current and future infrastructure projects, news articles reporting loss and damage figures, and informational interviews (see the interview schedule in Appendix D).

Methods and potential parameters to be evaluated

Tables 8 and 9, Chapter 4, can be used to assess the sensitivity of people and infrastructure that could lead to loss of life or economic losses. Within Table 8, two vulnerability domains (sensitivity lens)—socioeconomic

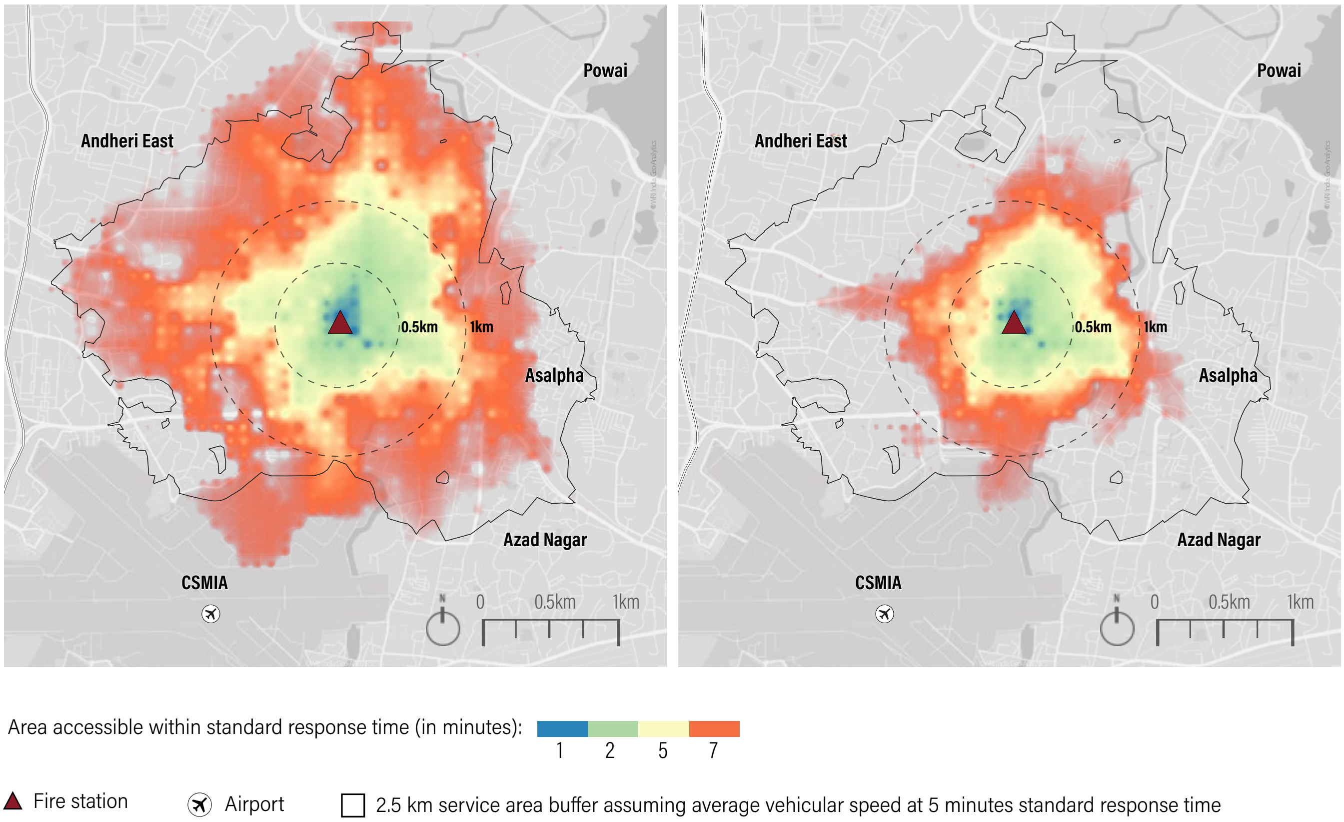
FIGURE 22 | Access mapping using service area delineation for fire and rescue services available in Kochi



Notes: 1. As per the Standing Fire Advisory Committee (SFAC) under the Ministry of Home Affairs, 3 to 5 minutes response time is considered ideal for fire stations in urban areas (ARDC 2012). 2. As per Kochi City Mobility Plan 2007, average vehicular speed during peak hours (Morning 9 AM to 10 AM and evening 6 PM to 8 PM) is 30kmph, and for the lean hours is 35kmph. Based on this, service areas of 2.5 km and 3 km for both peak and lean hours are computed.

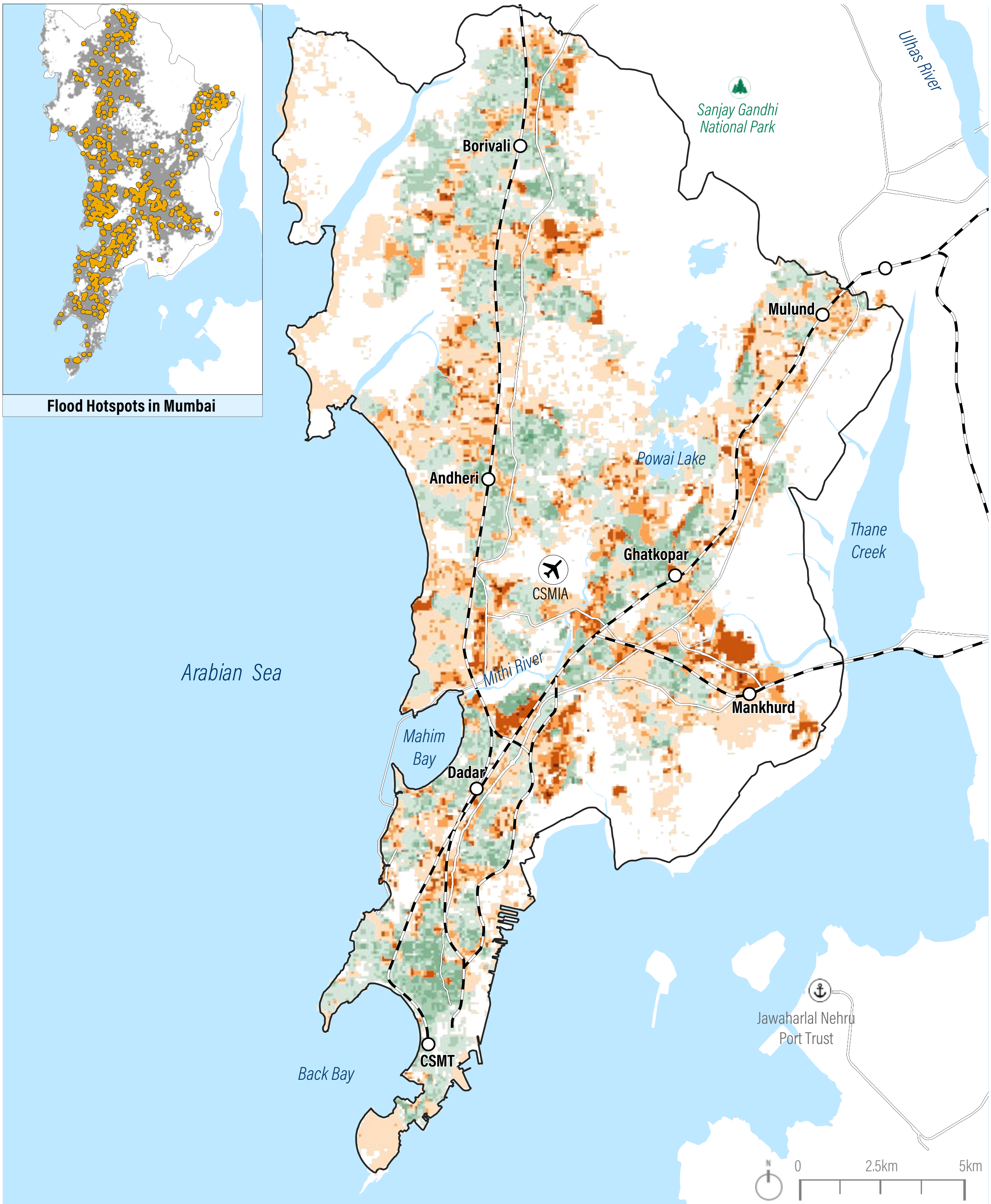
Source: Shaping a Climate Resilient Kochi – Guidance document to develop a comprehensive disaster management plan in Kochi with long term focus; Cities 4 Forests and Centre for Heritage, Environment and Development (c-hed) – Kochi Municipal Corporation.

FIGURE 23 | Temporal analysis of service area changes using near-real-time modeled traffic conditions in Mumbai



Note: In this case of Marol Fire Station, located in Andheri East, the area covered under the Standard Response Time of 5 minutes is highest at 4 AM. During morning peak hour traffic, at around 9 AM and evening peak hour traffic at around 6 PM, this serviced area is drastically reduced due to increased traffic congestion.
Source: Mumbai Climate Action Plan, 2022; Municipal Corporation of Greater Mumbai (MCGM), C40 Cities.

FIGURE 24 | Plausible reduced access to flood shelters during a flood event in Mumbai



Population's access to flood shelter during a flood event

Population density having access (per hectare): 5–500 | 501–1000 | 1001–5000 | 5001–14000

Population density not having access (per hectare): 5–500 | 501–1000 | 1001–5000 | 5001–14000

250 m buffer from the flood locations | Settlements

City boundary | Airport | Sea port | Railway | Railway station

Note: Analysis includes 1km pedestrian shed and 250m buffer around the flooding spots.
Source: Re-created using Mumbai Climate Action Plan 2022; Municipal Corporation of Greater Mumbai (MCGM), C40 Cities.

and sociodemographic—and within Table 9, two vulnerability domains (sensitivity lens)—economic and social—can be used for this assessment. Given the available data and the gaps in them, the following two methods can be used:

- Assess the indicators listed in Table 8 based on secondary data sources from government agencies, NGOs, and other non-state actors.
- Use the questionnaire in Appendix D to assess each infrastructure system and analyze the findings by using the above indicators.

Data sources

Varied, as listed in Appendices B, C, and D.

This assessment has not yet been conducted by WRI India as part of past vulnerability assessments; hence, case examples are not cited here.

City preparedness analysis through a gap analysis of the policy landscape

Along with the mapping of hazard risk at a micro level, cities should also address the underlying risk factors and identify pertinent disaster risk management interventions. City preparedness activities include measures around prevention (relocating people and assets away from a hazard-prone area), mitigation (reducing the adverse impacts of hazards and related disasters), and preparedness (capacity building of governments and communities and establishing evacuation protocols) (UNDRR 2017).

Methods and potential parameters to be evaluated

To assess the adaptive capacity of people and infrastructure, see Tables 9 and 10, Chapter 4, and Appendix D. Examples of using the consultative approach to enhance the quality of information available for these parameters are detailed in Chapters 6 and 7. Given the available data and the gaps in them, the following methods and approaches can be used:

- Mapping primary, secondary, and open-source government data using RSA.
- City preparedness analysis using policy and performance assessment tools. This can also include reviewing documents related to emergency funds at the city level, sectoral or infrastructure-specific funds, and funds available from different institutions for specific preparedness activities. In the project context, the team needs to judge whether the policy factors have positive effects on sustainable development or are at least neutral in terms of unintended side effects.
- Community Resilience Assessment using the UCRA: The UCRA is a community-level bottom-up assessment to understand local and place-based issues (Rangwala et al. 2018). With climate change impacting the most vulnerable areas of the city, disaster risk management should be integrated across sectors and designed to increase the resilience of people and communities. Activities can include identification of hazard risk, capacity building, informing people of risk, incorporating protocols into city planning and investments, strengthening legislation, and providing financial protection (UNDRR 2015). This can also include mapping government programs on social protection with a focus on low-income women, subsidies and loan waivers, jobs, and livelihood security such as through loans, skill development, upgrades, and reskilling opportunities that are available to the urban poor, especially women, during disasters.

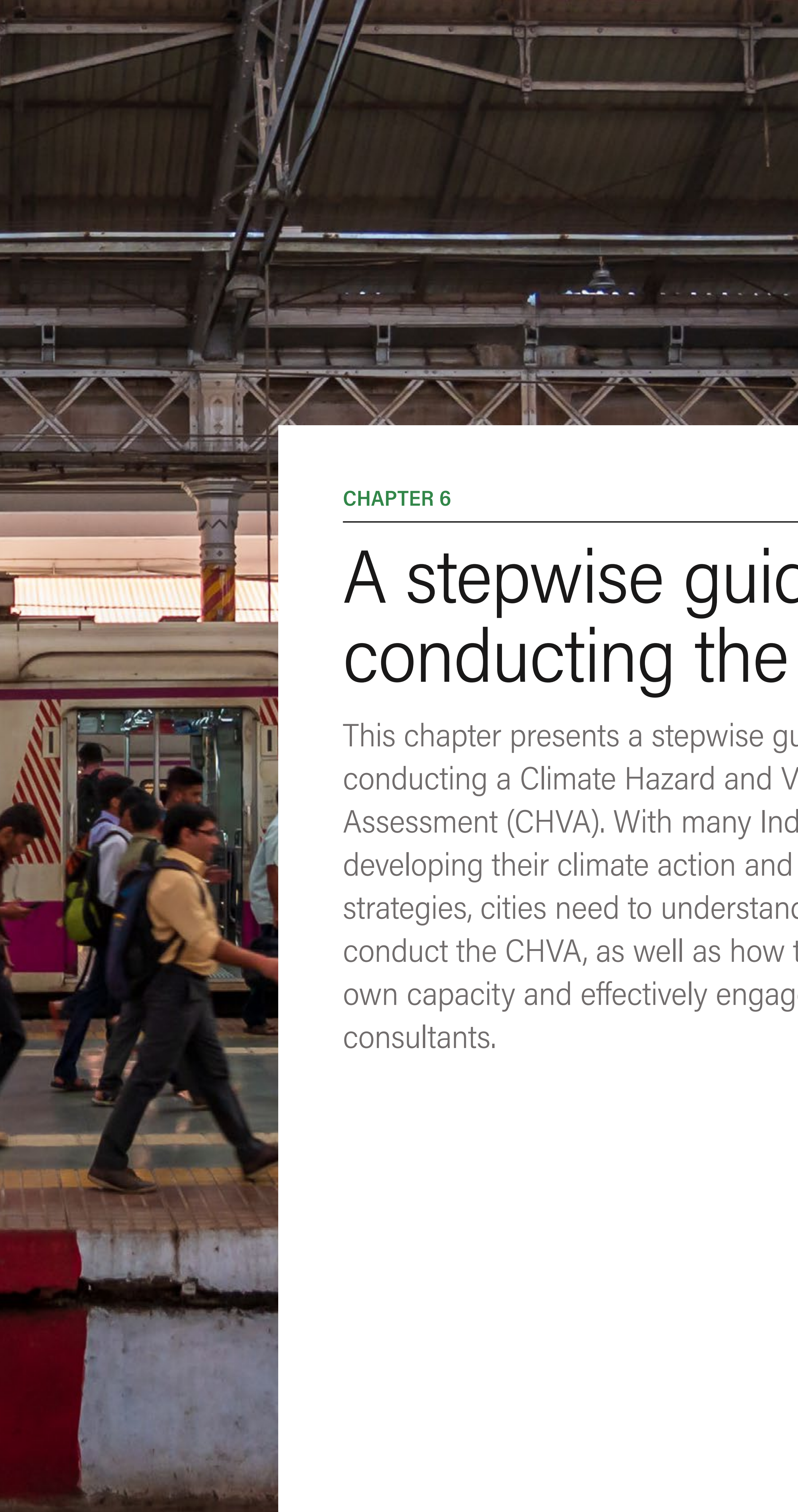
Data sources

Varied, as listed in Appendices B, C, and D.

This assessment has not yet been conducted by WRI India as part of past vulnerability assessments; hence, case examples are not cited here.

This chapter provided a brief overview of recommended techniques and methods of assessing vulnerability of a city, by performing hazard risk assessments and determining the vulnerability of impacted people and infrastructure. Additional information pertaining to measuring hazard risks at an indicator level is given in Appendix B, which also provides details of available data sources classified by geographical scale and applicable thresholds. A technical note series is planned as a follow-up to this report that will describe the methods listed in this chapter in detail along with formulas, tools, platforms, and data sources for analyzing different hazards and the vulnerability associated with them.

Chapter 6 provides guidelines for conducting the CHVA, providing learnings and examples from vulnerability assessments across Indian cities.



CHAPTER 6

A stepwise guide to conducting the CHVA

This chapter presents a stepwise guide to conducting a Climate Hazard and Vulnerability Assessment (CHVA). With many Indian cities developing their climate action and city resilience strategies, cities need to understand how to conduct the CHVA, as well as how to build their own capacity and effectively engage technical consultants.

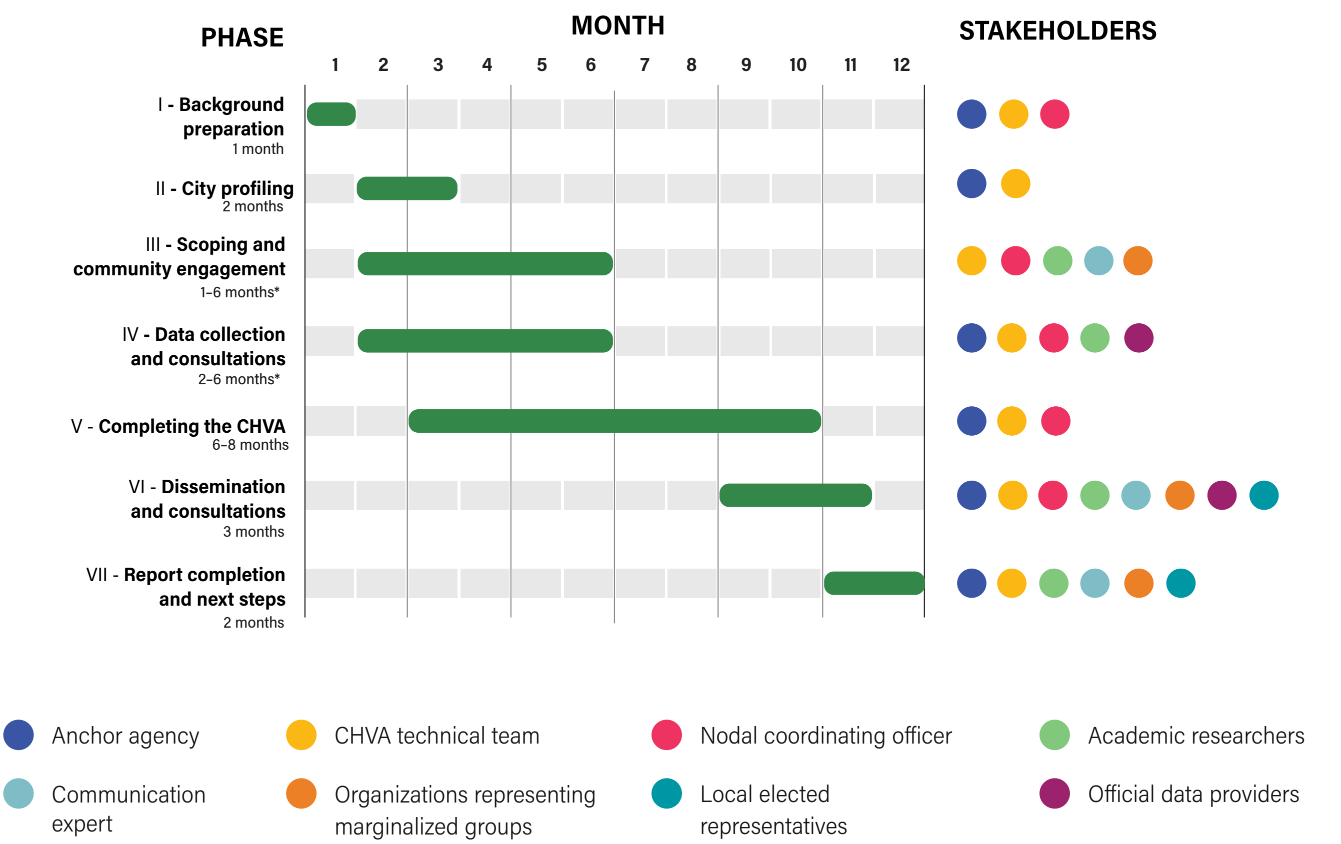
The CHVA is conducted in seven phases. Some steps may overlap across phases (see Figure 25), depending on the local context as determined by the team conducting the CHVA.

Figure 25 presents a timeline and a list of stakeholders for each of the seven phases. However, these can be modified in accordance with the city's context, needs, and resources. Several key stakeholders drive the CHVA process: the anchor agency or department within the municipal corporation, the Smart City Office, the environment department; the coordinating nodal officer appointed by the anchor agency; the CHVA technical team, such as data and GIS analysts, applied researchers, sectoral experts, climate experts, and urban planners; academic researchers and institutions, social scientists, and equity officers; communication experts for social media and news media outreach, website development, data visualization, graphic design, and copyediting; individuals and organizations representing marginalized communities through working groups, civil society organizations, community-based organizations, rights-based groups, and affected communities; official data providers such as municipal departments, service-providing agencies, government, and semi-government agencies; and locally elected representatives.

PHASE 1: BACKGROUND PREPARATION

- Conducting a detailed CHVA relies on initial background and preparatory work. In this initial phase, a team has to be built comprising practitioners such as geospatial scientists, data analysts, climate professionals, social scientists, and urban planners to lay the groundwork for the rest of the CHVA process, and it is critical to ensure that these steps have been completed before moving to the subsequent phases. Key steps during the preparation phase include building a team with experts such as geospatial scientists, data analysts, climate professionals, social scientists, and urban planners.

FIGURE 25 | Seven-phase process for conducting the Climate Hazard and Vulnerability Assessment



Source: Authors.

- Establishing the overarching need for conducting and determining the geographic and technical scope[17] and scale of the CHVA (this could be related to a city's climate action plan or development plan).
- Identifying nodal agencies that will anchor the CHVA (could be within a corporation, municipality, or smart city).
- Identifying and mapping out the governance ecosystem, including all relevant agencies, actors, and organizations that will provide data, information, engagement, inputs (relevant state-level and central agencies, NGOs, private sector, donors and funders, international organizations, etc.)
- Reviewing existing analyses and reports relevant to the CHVA.
- Reaching out to stakeholders for preliminary consultations and engagement informing them of the CHVA exercise and its tentative timeline.

The following case examples illustrate two of the above steps.

- **Setting up a team and collaborating with experts to help create Mumbai's first climate action plan:** The nodal agency that anchored Mumbai's CHVA was the Brihanmumbai Municipal Corporation's Environment Department, which is headed by a Deputy Municipal Commissioner and falls under one of Mumbai's four Additional Municipal Commissioners. The Environment Department is an extension of, and works in conjunction with, the Solid Waste Management (SWM) Department and primarily focuses on issues of pollution control in Mumbai. The department is also responsible for enforcing the environmental protection and pollution control norms established by the state and central pollution control boards. Mumbai became a member of the C40 Cities network in December 2020, which requires member cities to prepare net-zero climate action plans. With BMC leading this effort, WRI India and C40 Cities collaborated as knowledge partners of BMC to help develop the plan, and Climate Voices supported the initiative as a communications partner to disseminate the plan. The CHVA was conducted as part of Mumbai's climate action planning process and published as a separate report along with the plan. Insights from Mumbai's CHVA formed the basis for developing climate actions and strategies for the city (BMC 2022).
- **Identifying the right nodal agency to anchor the CHVA in Nashik, Solapur, and Chhatrapati Sambhajinagar:**[18] It is important to identify appropriate authorities to anchor and support the CHVA process. The Maharashtra government encouraged 43 of the state's cities having a population of at least one million to sign up for the Race to Zero initiative. They also launched the Majhi Vasundhara Abhiyan (MVA, i.e., My Earth Campaign) to encourage local bodies in the state to address issues of climate change and the environment. Eight of the 43 cities were also part of MoHUA's Smart Cities Mission and participated in the CSCAF. Of these eight cities, Solapur, Chhatrapati Sambhajinagar, and Nashik kick-started their climate action planning processes in March 2022 to improve their CSCAF and MVA rankings. Like Mumbai, CHVAs for the three cities were conducted as part of the CAP process. However, each of these three cities have specific governance contexts. Thus, the CHVA was anchored by different agencies in each city. In Chhatrapati Sambhajinagar, the Smart City CEO's post and the Municipal Commissioner's post is held by the same person, and the Smart City Office has a Climate Change Division; thus, the Smart City Office became the anchor agency with buy-in from the municipal corporation. Although Smart City Offices are often better resourced to hire consultants and experts to take on issues such as climate change, important city-level decision-making authority often lies with the municipal corporation. Data collection, engagement, and implementation can be challenging if the appropriate authority does not anchor this exercise. In Solapur, the city's Environment Department, an extension of the SWM Department, is responsible for MVA and managing air pollution through the National Clean Air Program (NCAP), and thus became the anchor agency in that city. Nashik does not have a separate environment department, and the Public Works Department (PWD) is responsible for environment-related initiatives and for managing air pollution in Nashik by leveraging the National Clean Air Programme (NCAP). Thus, the PWD became the anchor agency for the CAP and CHVA process as well, led by the city engineer leading the PWD department. Anchoring the CHVA within a department that has the authority to coordinate with other agencies can allow for continuity in implementation, monitoring, and integrating governance systems.

PHASE 2: CITY PROFILING

The CHVA requires a full understanding of the climatic, environmental, ecological, spatial, social, economic, political, and governance context of the city being assessed. This information helps create a detailed city profile and provide a baseline for the CHVA process. Creating a detailed city profile helps assess the differential vulnerabilities to climate hazards from a systems perspective by identifying citywide socioeconomic needs and the potential impact on marginalized groups. This focus is necessary because climate change does not impact everyone in a city equally; people who are socially, economically, culturally, politically, institutionally, or otherwise marginalized are especially vulnerable to climate change. Key steps include the following:

- Constructing the city profile (demographic, socioeconomic, political, and governance) and the city hazard profile based on Tables 5 and 6, Chapter 3.

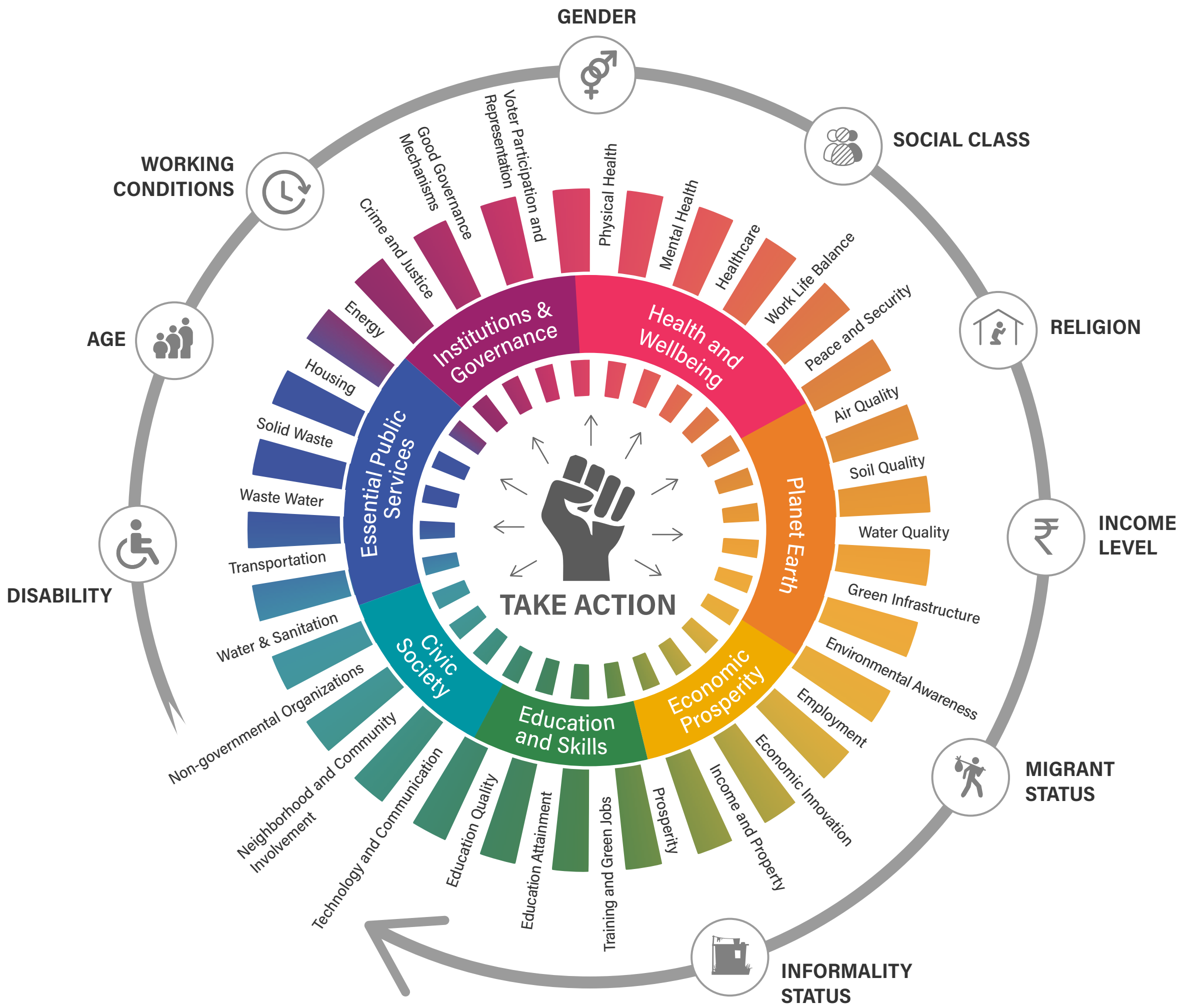
- Understanding which groups, communities, or frontline workers in the city are most vulnerable and could benefit from inclusive climate action. This can be achieved using Table 8, Chapter 4, from this report and the needs assessment framework described in the Inclusive Climate Action Plan (ICAP) process, as shown in Figure Box 4, B4-1. Further, the consultative process described in Step 3 will build on this initial understanding to arrive at a stronger basis for identifying vulnerable groups and communities and establish what perpetuates and exacerbates the vulnerabilities they have in the face of mounting climate hazards.
- Establishing the climate vulnerability context by assessing secondary reports and climate action plans at the national and state levels, district disaster management plans, and so on, to include information about predominant seasons, weather patterns, environmental trends, and climate hazards identified at the macroscale to identify known climate stresses in the region.
- Referring to global, national, and state climate reports and commonly cited climate projection models to determine potential future climate variations for the region under various Representative Concentration Pathway (RCP) scenarios.
- Detailing the geographic context so that citizens can understand the city's topography and location with respect to the watershed; proximity to ecologically sensitive locations such as forests, water bodies, and mountains; and general agroecological factors.
- Analyzing the ecological system, including plants, animals, marine life, wetlands, grasslands, and other ecosystems present in the city and how they are linked to biodiversity, ecosystem services, livelihoods, and local economies.
- Understanding the urban context not just within the city but also in the peripheries, where most urban expansion is occurring, especially in environmentally sensitive areas, by reviewing changes in land use, built infrastructure, and built form density over time that are threatening the natural ecological systems of the city (see the following case example of Bengaluru).
- Aspects that require data collection to complete the city profile may follow the process detailed in Phase 3.

BOX 4 | Inclusive Climate Action Plan framework: Needs assessment tool

The Inclusive Climate Action Plan (ICAP) tool elaborates on the domains that cities should consider based on the relevance of conducting a needs assessment from the perspective of impacted groups. For example, there are often data gaps on slum communities, informal workers, migrants, and homeless people, among others. Although there may not be enough official data on certain groups and places, these are impacted groups in the city and need to be considered and accounted for when conducting the CHVA. The ICAP guidelines prepared by WRI and C40 can help identify, review, and include details on, and the experiences of, differentially impacted groups and their needs, and ensure the assessment is inclusive (Mahendra et al. 2019). For example, establishing that 42 percent of Mumbai's population lives in informal settlements and are highly vulnerable to the impacts of climate change helped emphasize their need for basic services, thermal comfort, and flood resilience, and prioritize climate action in these areas (BMC 2022).

Figure B4-1 is a version of the ICAP model. The second ring represents key sustainability domains that are essential for a city to thrive. The third ring represents various impacted groups. A needs assessment done at the city level will give a snapshot of how different systems interact with impacted groups identified in the city, and the results of such interactions.

FIGURE B4-1 | Inclusive Climate Action Plan diagnosis wheel



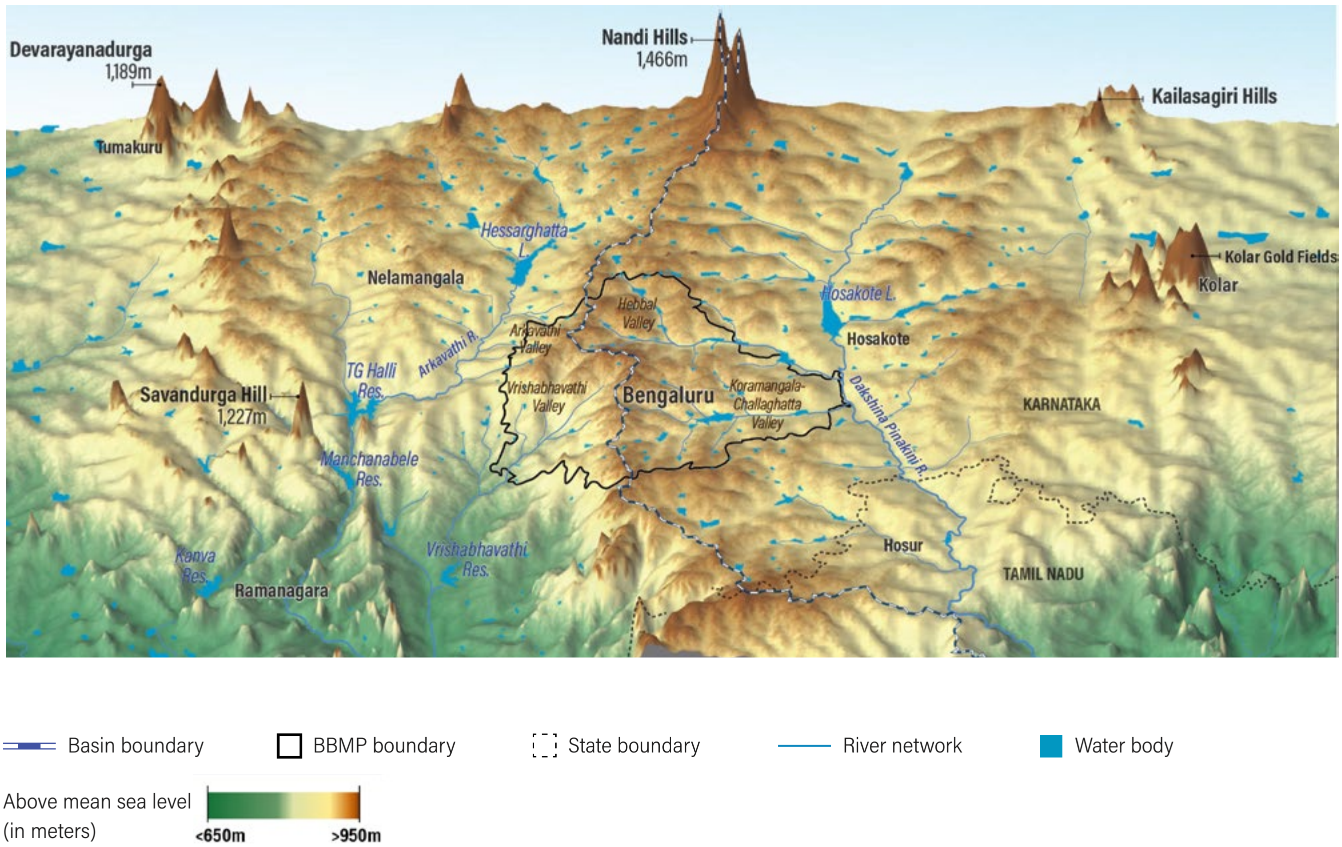
Source: WRI and C40 Cities 2019; Mahendra et al. 2019.

Case example

How a broad assessment of Bengaluru's topography and hydrology helped anchor the drought and flood hazard analysis of the city

Bengaluru's ecological context is a complex landscape of valleys, ridges, rivers, and lakes that work as an interconnected system. The city of Bengaluru is located on a ridge that runs north and south. Its highest point, Doddabettahalli, is nearly 900 m above mean sea level, and valleys on either side of the ridge form the water divide for the city. This forms three watershed areas or valley systems that help excess runoff flow across these valleys, eventually culminating in the Cauvery River or the Ponnaiyar River (Dakshina Pinakini River). The three-valley system of Bengaluru includes the Vrishabhavathi Valley, Hebbal Valley, and Koramangala-Challaghatta Valley, which are also repositories of lakes. The valley system with its lakes generates a cascading effect, ensuring that all the excess runoff eventually flows into the river network and hence does not cause water stagnation (Pavitra 2021). Changes in this network of natural flows due to indiscriminate, unplanned construction that disregarded the city's hydrology has led to Bengaluru's chronic flood problem. Hence, it is important to understand the natural topography to effectively assess the hazards and vulnerabilities in the city. The broad assessment of the city's topography and hydrology helped set the base for both drought and flood hazard analysis as part of the CHVA in the city's climate action plan (see Figure 26).

FIGURE 26 | Bengaluru's topography map used for city profiling, shows critical natural features in the region and urban settlements



Source: Prepared for the Bengaluru Climate Action Plan. Exaggerated relief derived using Shuttle Radar Topography Mission (SRTM).

PHASE 3: SCOPING AND COMMUNITY ENGAGEMENT

In addition to the official data needed to conduct the CHVA, it is important for the coordinating team to have a fuller qualitative understanding of the forms of vulnerability that communities face. This additional data can be layered with official data to help contextualize the dataset and ground it in community experiences. In this phase, we suggest that the team conducting the CHVA, led by the city government, undertake exercises to gain a more complete understanding of community needs, by engaging and partnering with community organizations working with underserved communities and marginalized groups. It is recommended that the lead government agency factor in the resources needed to support such consultations or commission community-level surveys with support from community groups, civil society organizations (CSOs) and community-based organizations (CBOs), nongovernmental organizations (NGOs), academic institutions, and others.

Compared with other phases of the CHVA, this phase is flexible and can be conducted in as much depth as time and available resources allow. The following steps are suggestions that can be tailored based on the city's context:

- Establish a list of relevant stakeholders in the city, including CSOs, CBOs, NGOs, unions, rights-based organizations, other community and nongovernmental groups, and academic institutions that work with or know about social needs and concerns in the city and prioritize marginalized communities, migrants, and homeless people. This is especially important because official data on these groups and communities are often not accurate or up to date.
- Include organizations, initiatives, and groups that work on larger ecological systems and species other than humans to broaden the scope of Vulnerability Assessment from a multispecies, socio-natural perspective.
- Conduct a kickoff meeting with the anchor agency or department, inviting external stakeholders to participate. Through this meeting, initial feedback can be obtained, and preliminary connections can be established between the CHVA team and community organizations.
- The lead government agency or department, as part of the CHVA team, must factor in adequate time and resources for focused discussions with academics and practitioners familiar with the social and environmental context of the city to establish a collective understanding of the priority areas, communities, and topics the CHVA can include, collectively accepting its limitations.
- The CHVA team can carry out town halls, listening sessions, stakeholder meetings, and focus group discussions with vulnerable groups, where community members and leaders can voice their needs and provide initial input on the CHVA process and possible next steps.
- These engagements could be structured as dialogues to encourage meaningful participation and constructive input and feedback, or a longer-term working group can be established for ongoing input in the CHVA process.
- Additional city- and ward-level data can be collected, if available, from sources such as government-run *anganwadis* (part of the flagship Integrated Child Development Scheme funded and operated by the GoI for early childhood health and learning and maternal and adolescent health), taxi and autorickshaw unions, associations of waste pickers, society federation offices in slum rehabilitation buildings, and housing authorities in the city.
- In these meetings, the CHVA team can present data needs to understand whether community data can be incorporated into the VA.

This scoping exercise can begin only after the first two steps are completed and if the team conducting the Vulnerability Assessment has the necessary resources. The data collected from this step will iteratively help revise and strengthen the city profile, particularly regarding excluded and vulnerable groups and communities. The Phase 3 process can continue in parallel with other data collection, allowing for longer-term engagement with the community and a more reflexive approach to data from the people's perspective (see the following case example of the *Main Bhi Dilli* campaign that provided input to Delhi's 2041 Master Plan). Such processes are typically bottom-up and complement the more quantitative parts of city-level analysis. Because of the time-intensive nature of establishing robust relationships with vulnerable communities, the VA team should prioritize working with CSOs and CBOs to expedite this process and build on the expertise of such groups.

The CHVA should be a dynamic process where inputs from the ground are considered on an ongoing basis to update future versions. The CHVA team should ideally work to establish enduring connections with community groups—especially those working with marginalized populations—even if such work is not completed in time to be incorporated into the first edition of the CHVA. In this way, over time, the CHVA process could create a pathway through which the needs of vulnerable and marginalized populations are translated into policies.

Case example

The ***Main Bhi Dilli*** (I, too, am Delhi) campaign that sought to include citizen voices in the Delhi Master Plan 2041

Several researchers, activists, community organizers, planners, architects, and academicians as well as a group of organizations came together to form a city-based campaign in 2018 (Main Bhi Dilli n.d.) with the vision of making Delhi's planning process more democratic and participatory. People were engaged through public meetings. Factsheets in English, Hindi, Urdu, and Punjabi on key issues and themes that prioritize marginalized livelihoods, housing, gender, public spaces, child care, and so on, were distributed, together with technical reports on waste pickers, street vendors, migrant workers' hostels, and so on. This citizen-led campaign contributed key inputs to the draft Master Plan of Delhi 2041—created by the Delhi Development Authority and the NIUA—to ensure that the needs of the most vulnerable and marginalized in the city are well represented. However, because the draft plan has not yet been published, it is difficult to gauge exactly how successful the process has been (Chauhan 2021). Online meetings and consultations often reflect the digital divide, reaching only the select few that have digital and Internet access. Thus, as part of the campaign, along with several online engagements, community meetings and door-to-door campaigns were organized to disseminate the draft plan, highlighting the potential threats to marginalized communities in the draft plan and the campaign's list of recommendations for the plan. Although not all the suggestions were incorporated in the draft plan, the campaign and its contributions to Delhi's masterplan led to a people's movement that went far beyond the ambit of traditional planning processes and allowed people to understand, absorb, and express their needs. Such movements, campaigns, and methods to engage with the community can help prioritize marginalized groups and implement interventions incrementally.

PHASE 4: DATA COLLECTION AND STAKEHOLDER CONSULTATIONS

Building on the city profile, practitioners, in this central phase of the CHVA, will collect and analyze key data on hazards and vulnerability. Collecting data at the urban level can be challenging, and much of this phase will involve soliciting various departments and agencies at the urban and state levels for data and information. Practitioners will check the data for accuracy and robustness and ensure that hazards relevant to the city or vulnerability indicators have not been overlooked. Often, data are received from government agencies in formats that are not conducive for immediate analysis; for example, as manually captured data maintained in a physical format. Before such data can be analyzed, they may need to be scanned, digitized, cleaned, and standardized. The collected data will be stored in a master database. Further, practitioners may conduct preliminary consultations to close data gaps and share their initial findings with the appropriate stakeholders. The following steps can help practitioners conduct this part of the CHVA:

- Depending on the city context and the scale of the CHVA, shortlist relevant indicators for analysis using the framework and methodology detailed in Chapters 3, 4, and 5. In addition:
  - Ensure that no relevant hazards are overlooked while creating this list.
  - Create an exhaustive list of indicators to begin with. This will ensure that no relevant indicators are overlooked and that the city receives the request for data at the outset. This step is crucial for an efficient data collection process in terms of both time and effort.
- Create a checklist of indicators by priority. Organize the data needs, expected format of data to be received (digital, vector, numerical, etc.), and potential sources (government departments, NGOs, private consultants,

satellite imagery, etc.). The priority list must include the most essential data points needed to complete the CHVA. Further, if cities have more data, more exhaustive analysis can be done.

- Assign people to coordinate data collection and "persons of contact" (PoCs) for relevant agencies and organizations.
- Understand the formats in which data are available and can easily be shared. From this, create data collection templates for each data point mentioned in Appendices B, C, and D, acknowledging the availability of spatial and nonspatial datasets.
- Engage with relevant agencies and stakeholder groups for information on data not available with city authorities, and get permission for obtaining and using data wherever necessary. Identify individuals within government who can become data champions for this process (see the following case example of Bengaluru).
- Check the quality of data by testing for the following details:
  - Comprehensiveness: All data points must be filled in, and the scale, unit, and spatial and temporal specificities must be specified.
  - Consistency and continuity: To analyze long-term trends, especially for climate, a minimum of 30 years of consistent data is advisable. To decipher intermittent patterns, the same data should be available in hourly, daily, weekly, monthly, and seasonal scales. Use secondary reports and assessments to plug gaps and corroborate findings.
  - Coherence: Use basic statistical operations to check coherence and comparability. This should also include verifying data sources, data collection, and the purpose of data creation.
- A robust quality check is important for accurate assessments of CHVA indicators.
- Create a master database of all data points relevant to the CHVA in order to effectively monitor progress and corelate relevant indicators.
  - For Excel-based data points, add data to a master Excel workbook; include all information available at the ward level for both the city and administrative ward levels.
  - For geospatial (GIS) data points, create a GIS dashboard that allows different datasets to be overlayed, enabling dynamic analysis and easy correlations for the assessment.
  - For any other forms of information, such as secondary reports, social media feeds (such as reports by citizens on Twitter/X accounts of hazards like flooding), news articles, and photographs, catalog the information in folders and link it to the master Excel database.
- Use proxy indicators/data sources and aggregates to plug the critical gaps:
  - Identify indicators where data are unavailable or do not match the quality standards. Bridge the data gap using proxy indicators, coarser-scale or lower-resolution data, and data interpolation and extrapolation methods. For instance, if building footprint data are unavailable, land use land cover estimates and settlement layers derived from satellite imagery can be used (see Appendices B and C for more details).
  - All proxies, caveats, and assumptions must be properly documented and stated as part of the process and included in the data preparation section of the assessment.
- Attempt to scale all nonspatial data to the appropriate spatial boundaries for robust spatiotemporal analysis that visualizes spatially varying vulnerabilities with the city.
- Reach out to external stakeholders (experts, academics, NGOs, the private sector, etc.) to plug data gaps and help validate data.

Case example

The Bengaluru CAP process highlights that the multiplicity of agencies necessitates data champions from within government

Available but inaccessible geospatial information and multiple stakeholders impede data collection in Bengaluru. The data collection phase for the Bengaluru CAP was complex and took longer than expected because multiple state, city, and parastatal agencies and departments hold data relevant for the CHVA and the city's CAP. With such a diverse range of stakeholders, coordination across departments was a challenge, especially because data were collected from 13 agencies outside the Bruhat Bengaluru Mahanagara Palike (BBMP) and five departments within the BBMP. However, based on the initial assessments, data were sought from 23 agencies outside the BBMP, but only 13 responded. Stakeholder consultations within the BBMP, as shown in Figure 27, helped fill out these data. Unlike secondary cities, Bengaluru's challenges were different: Bengaluru is a data-rich city with sufficient geospatial data. However, obtaining these datasets was an arduous process and delayed the assessments and the CAP.

The Karnataka State Remote Sensing Applications Centre (KSRSAC) is the designated nodal agency for implementing remote sensing and GIS programs in the state. It is headquartered in Bengaluru and has robust geospatial datasets that are relevant for the city's CHVA process. The officer leading this agency became a champion and played a crucial role in making relevant geospatial datasets available to the team through Bengaluru's CAP process.

Although it is prudent to identify and sometimes rely on such leading bureaucrats within Indian cities, it is also crucial to address systemic governance challenges in the long run in order to make climate-related information more accessible to practitioners and policymakers. Chapter 7 expands on some actions that can fill similar data gaps while completing the CHVA.

PHASE 5: COMPLETING THE CHVA

This is the most important phase of the CHVA—the assessment phase. It involves producing an assessment of the main climate-related hazards and vulnerabilities in a city. Using the assessment tables listed in Chapter 4 and the analytical methods, data sources, and case examples presented in Chapter 5, practitioners can complete the CHVA for a given city. First, the Hazard Identification and Assessment is completed, which identifies the dominant hazards and potential impact groups. Next, the

FIGURE 27 | Stakeholder consultations held with departments of the BBMP in Bengaluru

Note: BBMP = Bruhat Bengaluru Mahanagara Palike.
Source: Bengaluru Climate Action Plan team, WRI India 2023.

Exposure Analysis is conducted to identify populations and infrastructure systems potentially at risk of climate hazards, and finally, the Vulnerability Assessment is completed to assess people, communities, and infrastructure networks that are most vulnerable to impending climate risks. Hazards, exposure, and vulnerability indicators are assessed together, to map differential vulnerabilities based on socioeconomic factors. The complete CHVA is submitted to the nodal department as a draft to take it forward to the next phase of internal and external consultations (see the following example of Nashik). To complete the CHVA, the following steps are recommended to cross-check whether all the steps have been effectively completed:

- Create a workbook to document the details of the assessment for shortlisted indicators (both hazard and vulnerability indicators).
- The CHVA is conducted in three steps as described in Chapters 3 and 4:
  - First, complete the Hazard Identification and Assessment:
    - Refer to Table 5, Chapter 3, to assess climate and environmental hazards prevalent in the city region and the potential impact groups.
    - Fill out the checklist in Table 6, Chapter 3, to identify potential *impact elements* that may be vulnerable to the climate and environmental hazards identified in Table 5. A detailed Vulnerability Assessment can be done on the basis of this assessment.
    - Refer to the analytical methodologies listed in Chapter 5 for the methods related to the Hazard Identification and Assessment.
  - Second, complete an Exposure Analysis to identify the most exposed elements:
    - Refer to Table 7, Chapter 3, to assess the extent of exposure from the hazard assessments, to determine the people, communities, and infrastructure elements that are most exposed.
    - Refer to the analytical methodologies described in Chapter 5 for methods related to the Exposure Analysis.
  - Third, complete the Vulnerability Assessment focusing on people and infrastructure:
    - Refer to Tables 8 and 9, Chapter 4, to assess the differential vulnerability of people living and working in a city through the lenses of sensitivity and adaptive capacity.
    - Refer to Table 10, Chapter 4, to assess the differential vulnerability of critical infrastructure in a city.
    - Refer to the analytical methodologies listed in Chapter 5 for methods related to the Vulnerability Assessment.
  - Finally, gauge the city's preparedness for future exposure, extreme events, and so on.
  - Produce a complete draft of the CHVA, listing the methods used and other relevant information in appendices so that interested stakeholders can refer to them after the study is published.
- For all the above-mentioned steps, as part of Phase 4, establish scientific thresholds for all indicators based on the secondary literature review, service delivery benchmarks,[19] and guidance from Appendix B. For certain indicators, thresholds need to be contextualized to the local setting; these can be established through participatory consultations with relevant department officials, NGOs, and other non-state actors.
- Note: For the Vulnerability Assessment of critical infrastructure, follow these additional steps as appropriate:
  - Create a list of critical infrastructure in the city (current and planned)
  - List the agencies and organizations that own, operate, and maintain the infrastructure networks or services identified for the Vulnerability Assessment.
    - Review their roles, responsibilities, and mandates.
    - Based on this, shortlist questions (from the questionnaire; see Appendix D) and request the appropriate agencies and departments for an interview or request the required data.
    - Schedule consultations to fill any data and information gaps to complete Table 10, Chapter 4.

Case example

Multi-hazard analysis to identify high-priority areas in Nashik[20]

To present useful insights from the climate hazard assessment, the team in Nashik developed a multi-hazard map by overlaying flood and heat risk maps, identifying high-priority areas where the two risks overlap. The multi-hazard analysis for urban heat and waterlogging in Nashik shows that about 9 percent of the city's population is exposed to both greater heat and flood risks. These include the city's central core area, Koknipura, Dudhsagar, Shivneri Chowk, Nashik main bus stop, and so on. The core area is also a pollution hotspot with a high concentration of particulate matter (PM) caused by construction, road dust, and so on. The analysis also shows that 42 schools and 18 hospitals; 42.5 percent of the slum area, a disproportionately high percentage; and nearly 2 percent of the industrial area lie in the multi-hazard risk-prone zone. These findings were used to create maps that clearly communicated these findings to local government officials and key stakeholders, as shown in Figure 28. This piqued the corporation's interest and helped initiate a discussion on prioritizing measures in multi-risk zones.

PHASE 6: DISSEMINATION AND CONSULTATIONS

It is essential to disseminate information and insights from the CHVA to multiple city-level stakeholder groups and at different scales of the city such as the ward and the zone (see the following case example of Mumbai). Stakeholders could include the local bureaucracy and departments; implementing agencies; local NGOs, CBOs, CSOs, residential welfare associations (RWAs), and citizen groups; commercial establishments; and people at large. For example, in the following case example of Bengaluru, insights from the CHVA were translated into local languages for developing a prioritization framework to disseminate focused insights to people and decision-makers. Such strategies can help users of the proposed framework in ground truthing, exploring entry points for action, creating an ecosystem of climate actors and collaborators, and building consensus to move from assessment to action. During this phase, practitioners and users must disaggregate information and contextualize and simplify dissemination material for different stakeholder groups. Consultations can be prioritized and planned considering the needs of the city and the chosen stakeholder groups. This phase can potentially facilitate dialogue on issues of climate change and vulnerability among impacted groups, policymakers, and changemakers, and can build on previous phases to map out a wider range of stakeholders in the city. This phase involves the following steps:

- Make a list of relevant stakeholder groups to reach out to for the consultations, prioritizing vulnerable groups that might often be excluded from such consultations.
- Identify the best way to disseminate insights and information from the CHVA based on the city's governance system and bureaucratic and political context (in-person, virtual meetings, website, news outlets, etc.).

FIGURE 28 | Presenting the multi-hazard map of the city to the Nashik Municipal Corporation officials

Source: Nashik Climate Action Plan team, WRI India 2023.

- Prepare dissemination and sensitization material in the form of presentations, blogs, articles, flyers and pamphlets, booklets, videos, social media campaigns, and so on, and consider translating it into the city's local language.
- Conduct workshops, meetings, group discussions, panel discussions, and so on, as may be appropriate for the city and the various stakeholder groups.
- Document insights from this phase, and consider adding to and changing the CHVA document as necessary.

Case examples

Translating insights from the CHVA into local languages and developing a prioritization framework to disseminate focused insights to people and decision-makers in Bengaluru[21]

To collect feedback and information and discuss the climate action plan at the grassroots level, which in Bengaluru's case was among ward committees, the CAP team prepared a toolkit in Kannada that could be disseminated easily by ward-level officials of the civic body to spearhead discussions. CHVA maps, graphs, and geospatial analysis were especially useful in these discussions. For example, the land surface temperature map of Bengaluru shows a correlation between the ward-level vegetation index and surface temperature, thereby making a very compelling case for greening interventions to reduce the urban heat island effect in the city. This especially stood out considering the city has been historically known to be naturally air-conditioned but now experiences soaring temperatures from February onward. To nudge decision-makers and policymakers to use insights from the CHVA, the CAP team prepared a summary of all the quantitative and geospatial insights and results. The intent was to use the key findings of the CHVA to inform decision-makers and help them set priorities and explore solutions to address the city's problems. The summary allows the city authorities to understand where they stand compared to other cities in the state and country, and what wards and indicators need to be prioritized.

More than 50 indicators were analyzed in Bengaluru's CAP as part of the overall CHVA process. The team prepared a concluding summary chapter that indicated the way forward from the CHVA and consolidated the findings of each indicator. This was done to inform policymakers, implementors, and citizen platforms about their respective local priorities based on each indicator at a spatially disaggregated level. Indicators for which information was not available or was not comparable at the ward level were highlighted as the indicators that required detailed future assessments.

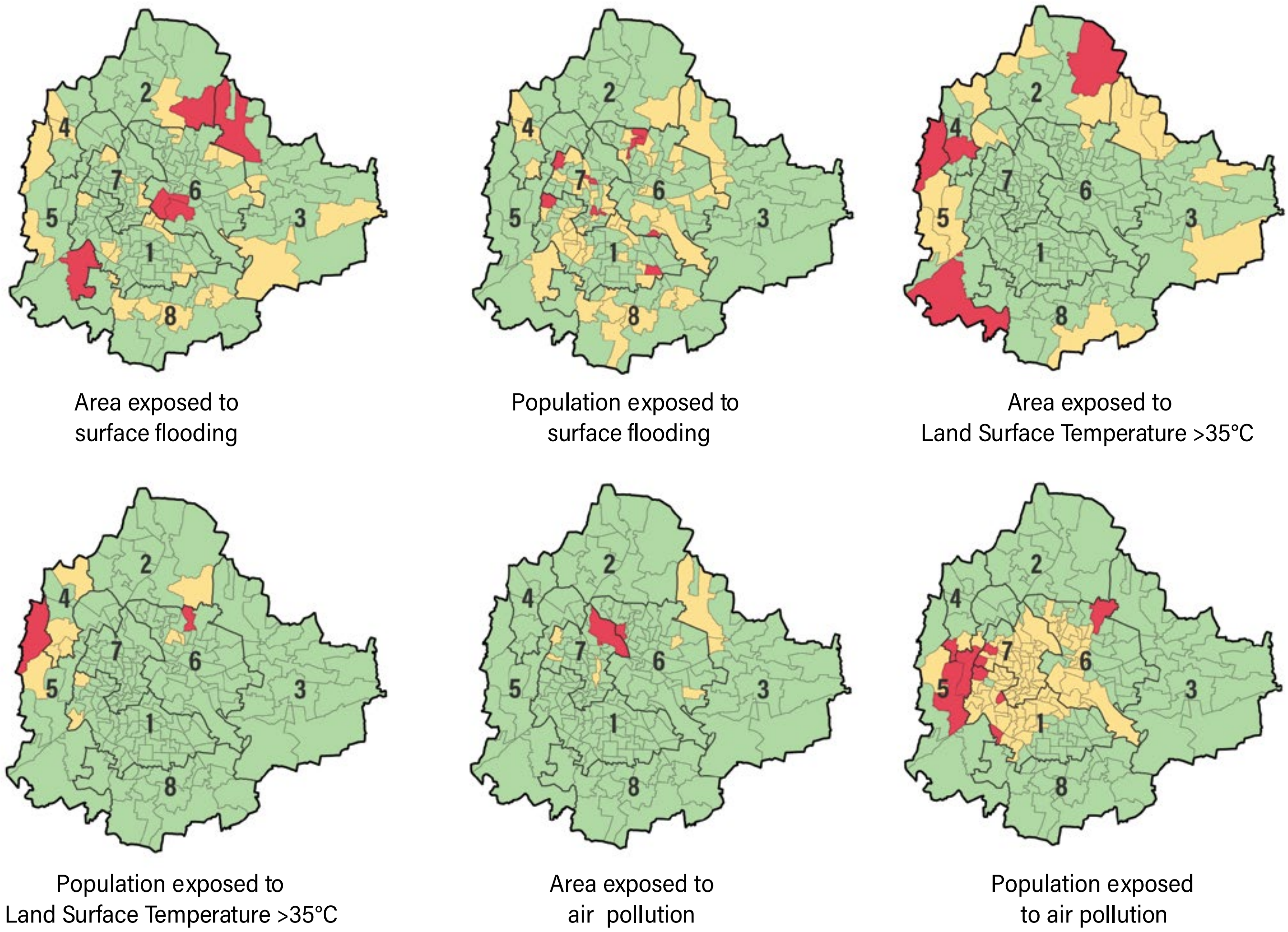
The team listed a final set of indicators that use the hazard and vulnerability assessment to illustrate "risk" in a quantifiable and comparable manner that is representative at the ward level. Risks were estimated and prioritized. An order of priority was assigned at the ward level to help prioritize areas facing the highest levels of vulnerability. Figure 29 indicates the order of priority assessment for six indicators in Bengaluru. For certain other indicators where prioritization was difficult, the order of performance was assessed to better understand whether basic benchmarks specific to an indicator were met.

Disseminating CHVA analysis through zone- and ward-level consultations in Mumbai

Three rounds of stakeholder consultations were conducted to prepare Mumbai's CAP and to share the findings of the CHVA. Disaggregated analysis of key hazard maps was presented, which included the LST map to understand heat risk; waterlogging hotspots and population density exposed around each spot map to understand flood risk; landslide-prone locations and informal settlements map to understand landslide risk; analysis of satellite and monitored air quality data to understand air pollution risk; and coastline change and mangrove area assessment to understand coastal risk. Additionally, a detailed vulnerability analysis was presented to share insights on wards and specific areas, thereby making a case to address existing urban vulnerabilities that amplify the impacts of climate change. The vulnerability indicators presented included those on literacy, access to education, household services, information, public services; ownership patterns, and so on. For each indicator, wards with the lowest scores and highest scores were highlighted to push for prioritization of the most vulnerable wards, thereby making their problems more visible to decision-makers (BMC 2022).

The first round of consultations was public, held with experts and divided into six sectoral consultations to develop an approach and overarching goals for each sector. The second round of consultations, which was hosted with implementing agencies to check the feasibility of the suggested strategies, was also divided into six sectoral

FIGURE 29 | Illustrated summary of "risk" based on hazard exposure in Bengaluru



Order of priority

Priority 1 | Priority 2 | Priority 3 | BBMP | Zone boundary | Ward boundary

Zone 1: South
Zone 2: Yelahanka
Zone 3: Mahadevpura
Zone 4: Dasarahalli
Zone 5: RR Nagar
Zone 6: East
Zone 7: West
Zone 8: Bommanahalli

Source: Prepared for Bengaluru Climate Action Plan. Derived using Shuttle Radar Topography Mission (SRTM); Landsat 8, Surface PM2.5—Atmospheric Composition Analysis Group, Washington University; Bruhat Bengaluru Mahanagara Palike (BBMP), Karnataka State Remote Sensing Applications Centre (KSRSAC), Karnataka State Natural Disaster Monitoring Centre (KSNDMC).

consultations. The third round of consultations was held at the ward level for seven administrative zones across three divisions: City, Western Suburbs, and Eastern Suburbs. Insights and information from the hazard and vulnerability assessment were presented at the ward level to the Assistant Commissioners and zonal Deputy Municipal Commissioners on climate and air pollution risks within their jurisdictions.

PHASE 7: REPORT COMPLETION AND NEXT STEPS

The last phase focuses on putting together and assembling information, the process, maps, insights, and so on, and developing a comprehensive report for the relevant stakeholder groups and policymakers. The report will provide an overview of the city and its features, describe the key hazards it faces, and establish the vulnerability landscape of the city. In this phase, quantitative and geospatial analysis will have to be explained, providing explicit insights to readers. Vulnerable groups, locations, wards, and neighborhoods will have to be highlighted so that public and private changemakers can prioritize action in the city. The practical utility of this exercise could range from climate action, development, and resilience to disaster reduction plans and initiatives. This could potentially provide an evidence base that cities can use to identify projects and obtain climate or development finance. It could also be used to explore governance interventions in order to reduce vulnerability and demonstrate the need for coordination and communication across departments and agencies. This phase involves the following steps:

- Prepare an outline of the final report, based on the overarching need established in the first step of the first phase, for undertaking this exercise.
- The final report should ideally have the following sections:
    - A city profile as described under Phase 2
    - Hazard Identification and Assessment
    - Vulnerability Assessment of people and infrastructure
    - Conclusion and Recommendations
- Identify important insights, maps, and information that need to be highlighted and explained in greater detail, and present these insights to policymakers, community members, activists, and other relevant stakeholders.
- Use insights from the CHVA to make recommendations and suggest strategies for relevant plans, projects, and initiatives, and link evidence wherever possible to prioritize action in vulnerable communities and high-risk neighborhoods.
- Based on the city's context and needs, funding and resource availability, and local priorities, explore opportunities to implement and co-develop projects by collaborating with other stakeholders.
- Create a short compendium, summary, or communication product that can be understood by a wider audience.

Case example

Implementing the Mumbai Climate Action Plan (MCAP) through sectoral convenings and using key insights to prioritize action in high-risk neighborhoods

After the MCAP was launched, four multi-stakeholder workshops were organized in the city on flood risk, nurturing vegetation and community-based adaptation in vulnerable neighborhoods, air quality improvement, and the road to net-zero energy transition in Mumbai. Insights from the climate risk and vulnerability assessment were presented at each of these convenings to initiate a dialogue and create an ecosystem of changemakers to take the implementation forward. A key insight into the occurrence of landslides from the vulnerability assessment was presented at the flood risk workshop (see Figure 30): out of 287 landslide-prone locations in the city, 200 overlap with slums or informal settlements. Slum community members impacted by such landslide occurrences were brought in as key stakeholders and participants at the workshop alongside relevant BMC departments and local organizations. This led to difficult but important conversations on this issue among impacted groups, policymakers and bureaucrats, and CSOs. Among other key insights, takeaways, and outputs, this conversation led to the city corporation facilitating and undertaking landslide preparedness training sessions for high-risk communities in the city (see Figure 31). These training sessions are, of course, not a permanent solution to the problem, but they were deemed necessary as an urgent step toward addressing the intensity of this hazard among slums and informal settlements. Improving urban service delivery would be an essential component of exploring a long-term solution to the risk of landslides in vulnerable communities (Kanekar and Naik 2022).

FIGURE 30 | Multi-stakeholder workshop on flood resilience in Mumbai

Note: At the workshop, residents from informal communities responded to the landslides map of Mumbai, sharing their need for better information, training, and maintenance services to improve the resilience of people living in landslide-prone areas.

Source: Mumbai Climate Action Plan team, WRI India, 2022.

FIGURE 31 | Participants learning how to use a stretcher in a landslide preparedness and training workshop held in Bhim Nagar, Mumbai

Source: Youth for Unity and Voluntary Action (YUVA) (Virani 2022).


CHAPTER 7

Recommendations to address differential vulnerability

This chapter concludes the report by giving concrete recommendations that urban planners and officials as well as other practitioners can follow when using the CHVA. The recommendations focus on making the CHVA more equitable, capturing diverse forms of vulnerability to better inform subsequent resilience and adaptation plans.

As practitioners, scholars, and experts have demonstrated, vulnerability assessments need to take into account not only climate hazards but also social, economic, and political factors that determine how communities cope with and respond to the threats posed by climate change. Existing vulnerability assessments largely focus on hazards, leaving the sensitivity and adaptive capacity of communities insufficiently analyzed. The CHVA fills this gap by using the concept of differential vulnerability to orient focus toward these important aspects of vulnerability, providing a robust tool for assessing vulnerability to climate change in Indian cities.

In this final chapter, we demonstrate how the CHVA addresses many of the limitations of existing vulnerability assessments that we identified in Chapters 2 and 3. We also provide a range of concrete recommendations for practitioners and policymakers to connect the CHVA with both short- and long-term climate actions and interventions. Further, given the relationship between state and urban governments in India, including the role of development authorities in local planning and of state governments in setting local rules and regulations, some of the recommendations in this section are applicable across levels of government, depending on the local context. In addition, because many cities in India are rapidly expanding, the recommendations can be applied beyond urban cores to include peri-urban areas.

Although the CHVA is a diagnostic tool and not a resilience plan, it can serve as a powerful foundation for resilience- and adaptation-focused plans, as well as heat action plans, development plans, and disaster risk reduction efforts. Beyond this, the CHVA can play a key role in promoting urban climate justice and addressing forms of urban marginalization and inequality. In this way, the CHVA contributes to ongoing calls for moving away from incremental solutions to more transformational forms of resilience and adaptation (Chu et al. 2019).

SCOPE, PURPOSE, AND IDEALLY ITERATIVE NATURE OF THE CHVA

As the climate crisis worsens and cities continue to expand, the need for robust and equitable urban resilience and adaptation plans grows. This is especially true in Indian cities (Khosla and Bhardwaj 2019). Creating these plans requires accurate assessments of climate vulnerability, and although assessment frameworks exist, many fail to fully capture the complex multilayered factors that constitute vulnerability. Many frame vulnerability in largely technical terms, focusing on climate hazards rather than on the social, economic, and political factors that determine how communities cope with and respond to those hazards (Eriksen et al. 2021; Pelling 2011). Vulnerability assessments need to take all of these factors into account, addressing the exposure of communities to climate hazards, their sensitivity to those hazards, and their capacity to adapt (IPCC 2022).

The CHVA helps fill this gap. To orient the focus toward the social determinants of sensitivity and adaptive capacity, the CHVA is framed around the concept of differential vulnerability. This framing is important (see Cutter et al. 2001; Cutter 2016; IPCC 2022, 928–30, 1180–81; Thomas et al. 2019). By defining vulnerability as a largely social phenomenon, subsequent solutions, such as resilience or adaptation plans, can be more easily oriented toward highlighting these features of vulnerability. Further, this framework, designed specifically for practitioners and policymakers in Indian cities, outlines methods for determining exposure to hazards as well as threats to critical infrastructure, using a spatial approach that enables practitioners to understand the interactions between hazards and social factors. The CHVA is designed to be an iterative tool that allows practitioners and policymakers to track vulnerability over time, see the progress of interventions in their city, identify and perform more fine-grained assessments in the most vulnerable parts of their city, and compare vulnerability with other cities.

The CVHA, which is centered on the concept of differential vulnerability, enables practitioners and policymakers to understand the social aspects of vulnerability to climate change, including inequality, marginalization, and lack of representation. Although the CHVA is only a diagnostic tool, this approach enables practitioners and policymakers to demonstrate the need for interventions that address these social concerns. In this way, the CHVA responds to calls from practitioners and academics to go beyond incremental changes and to instead propose transformational solutions (see Pelling 2011). Such solutions are less likely to result in maladaptation, are more holistic in the long run, and are a key component of promoting urban climate justice (Bulkeley et al. 2013; Fraser et al. 2016; Thomas et al. 2019).

SUGGESTIONS FOR PRACTITIONERS AND POLICYMAKERS

In this section, we provide recommendations that practitioners and policymakers can use to create enabling conditions and prepare urban governance ecosystems to undertake this assessment. We also provide recommendations that will help practitioners and policymakers to move beyond the assessment to enable implementation and translate the insights, information, and evidence from this assessment into meaningful action. Suggestions and recommendations highlighted in this section link with and seek to address the limitations identified in Chapter 3.

Creating enabling conditions and an ecosystem for CHVAs to be conducted in Indian cities

- **Improve data quality and accessibility through well-maintained data repositories, collaborate with national and state-level GIS agencies, conduct robust city-level baseline assessments, make non-sensitive GIS layers openly available, and tap into local resources and knowledge pools.**

    - Create and maintain data repositories and dashboards and build requisite software and hardware infrastructure.
      Tier 1 cities that have funds available should create and maintain data repositories and dashboards and allocate funding for building data infrastructure to systematize geospatial and data analysis at the city level. Tier 2 and other small cities that often do not have enough funds can align with and tap into the resources of state-level GIS agencies and take their help to build data repositories and use their software and hardware infrastructure to conduct hazard and vulnerability assessments more regularly.

    - Make datasets, maps, and analysis accessible.
      To create an enabling ecosystem of periodic assessments, cities should begin to make datasets and information more openly available. Ward-level administrative boundaries and other non-sensitive datasets that are basic prerequisites for any analysis should be publicly available. City authorities should develop a culture of public sharing of data and maps, and although this can be a cost-intensive exercise for smaller cities to undertake themselves, they can rely on state-level agencies to make their city-level datasets openly and easily available. Making datasets publicly accessible and crowdsourcing data can help cities make their database and dashboards a living repository of information.

    - Collaborate with local institutions and students.
      Consistent training and capacity building are required for efficient data management, quality assurance, and robust data analysis to aid decision-making. Tapping into the local resource and knowledge pool by collaborating with students and local institutions will not just help cities in undertaking resource-intensive processes required for geospatial analysis but will also help students get practical exposure and experience and help build future capacity for the city. Academic institutions can also help disseminate datasets and host dashboards, examples being the NASA, Uppsala, and USGS datasets, which are anchored by universities and have been made publicly available. Cities can also consider partnerships with organizations such as the IMD, NRSC, and other agencies that provide important datasets, so that data can be easily obtained or purchased whenever required.

- **Institutionalize the assessment through capacity building, coordination mechanisms, governance interventions, and collaborations with local and global organizations to move beyond ad hoc efforts to address vulnerability in the context of climate change.**

- Enhance institutional capacity and improve coordination among city authorities.
  In the early stages, practitioners primarily rely on leaders or champions to anchor and enable such work at the city level, but over time, cities need to reduce their dependence on individuals to enable such assessments by building in mechanisms and processes. To mainstream the use of the CHVA for routine decision-making, prioritization, implementation, and urban service provisioning in the context of the climate crisis, it is important to build the capacity of urban local bodies, hire relevant expertise, and promote efforts led by climate champions. This can be done by setting up a dedicated institutional mechanism or body in the form of a cell, department, or working group within the local government, which can also help coordinate across departments, agencies, and sectors. Identifying the nodal agency is essential for institutionalizing the CHVA approach, and nodal agencies would differ across cities based on their capacity and authority and on the agency or department responsible for environmental matters. Additionally, workshops and knowledge sessions with civil society organizations, community members, and academic institutions can help create an ecosystem of actors and build the overall capacity of the city to tackle issues of climate change and vulnerability (Mogelgaard et al. 2018).

- Build on work done by local organizations, especially in marginalized communities and informal settlements, and capitalize on international networks and resources.
  In cities with existing civil society networks, building on and tapping into existing knowledge and expertise would help to build on existing work and relevant good practices without duplicating efforts. This is particularly relevant for work done by organizations in marginalized communities and informal settlements, which typically slip below the radar of formal processes. Along with local knowledge, capitalizing on international networks and resources through formal engagements and partnerships will help cities secure financial and technical support for undertaking such assessments.

- Identify CHVA-specific needs and requirements and allocate a budget for them.
  Activities involved in undertaking and mainstreaming the CHVA can sometimes be financially challenging. Listing relevant activities and including them in annual budgetary requests will help create a governance mechanism to ensure operationalization. Allocations can include budgeting for data collection or purchase, capacity building and training, hiring relevant experts and consultants, obtaining the software and hardware required for geospatial assessment, and so on.

Translating insights from the assessment into meaningful action

- **Prioritize and accelerate climate action in high-risk areas and within marginalized communities in the city, using more detailed assessments through deeper forms of engagement, and ongoing assessments of the qualitative aspects of vulnerability.**

  - Prioritize actions to focus on specific communities by conducting fine-grained assessments of differential vulnerability.
    The CHVA provides a relatively high-level understanding of differential vulnerability in cities. This is helpful for identifying the most vulnerable areas of cities, though often finer-grained analysis is required in particularly vulnerable areas. The UCRA tool developed by WRI (Rangwala et al. 2018) is designed for this purpose, allowing for in-depth assessment within wards. The Needs Assessment module of the ICAP toolkit is also designed for setting context and co-developing an understanding of equity-related urban issues (Mahendra et al. 2019). This prioritization of implementation is important for effective climate action and resilience plans.

  - Create platforms and opportunities for the exchange of knowledge between vulnerable communities and policymakers to fill the gaps left by standardized assessments.
    Although the CHVA is a powerful tool for understanding differential vulnerability, effectively addressing vulnerability requires long-term community engagement to ensure that local knowledge is incorporated into vulnerability-focused interventions.

  - For a robust understanding of vulnerability, focus on its qualitative aspects.
    Vulnerability is in many ways contextual, with

many qualitative aspects across the vulnerability domains comprising physical, social, economic, environmental, and governance-related vulnerabilities. This disaggregation of climate-hazard-related vulnerability is typically not included in standardized vulnerability assessments. The CHVA allows practitioners to identify diverse forms of vulnerabilities and their spatial manifestations, which could help shape and prioritize action. However, ongoing assessments of the qualitative aspects of vulnerability are needed to fully understand the problems causing vulnerability and craft solutions to address them. Tools such as the UCRA (Rangwala et al. 2018) and ICAP (Mahendra et al. 2019) can help understand such aspects at the community level.

- **Avoid maladaptation by working to incorporate social aspects of vulnerability into ongoing analysis and implementation as well as by working with marginalized and highly vulnerable groups toward just outcomes.**
  - Understand how social aspects of sensitivity and adaptivity capacity interact with hazards to avoid maladaptation.
    To help avoid maladaptation, practitioners can use the CHVA to consider the social aspects of differential vulnerability as well as the structural differences between marginalized and non-marginalized communities in their city. Resilience- and adaptation-focused interventions that are overly technocratic or that fail to take social, economic, political, cultural, and other contextual elements into account risk insufficiently addressing vulnerability, sometimes even redistributing or amplifying vulnerability (Atteridge and Remling 2018; Eriksen et al. 2021). Integrating a Monitoring, Evaluation, Reporting & Learning (MERL) framework into resilience-based projects could help ensure that vulnerability is not inadvertently redistributed or is only incrementally addressed.
  - Co-develop solutions with marginalized groups.
    The CHVA allows for and encourages the involvement of a range of community actors in the vulnerability assessment process. This is particularly important for members of marginalized communities; their engagement with practitioners and policymakers can ensure that vulnerability is accurately measured and that interventions work for their communities. Evidence shows that integrating local knowledge into vulnerability assessments and adaptation and resilience interventions is often necessary for such work to be successful (Eriksen et al. 2021; Gallardo et al. 2022; IPCC 2022). Care should be taken to ensure that the needs of one vulnerable group do not conflict with the needs of another and that solutions take into consideration and negotiate the power differentials within and between different communities in cities.
  - Create equitable conditions.
    By helping to uncover and highlight the social aspects of vulnerability in particular cities, the CHVA can be a part of broader development efforts to promote urban climate justice. This focus on urban climate justice may necessitate the procedural involvement of marginalized groups, the acknowledgment of forms of inequality that impact vulnerability, and longer-term interventions that redistribute resources to marginalized groups (Bulkeley et al. 2013; Shi et al. 2016). Such efforts have benefits that extend beyond climate-specific concerns.

A vulnerability assessment helps define the "problem" of vulnerability and spotlight the many ways in which people and infrastructure are vulnerable. Such insights set the tone and direction for appropriate interventions. The CHVA is not a planning framework that leads to resilience or climate action plans; many additional elements and processes are needed before cities can create climate action plans after an assessment. It is designed to function as a key first step in creating subsequent climate action plans, including long-term resilience plans and other disaster preparedness plans. The CHVA requires multilevel engagement across the vertical and horizontal structures of governance: city authorities, state departments, parastatal agencies, and central government agencies such as the National Disaster Management Agency (NDMA) or the Ministry of Housing and Urban Affairs (MoHUA), and so on. The CHVA framework is designed to be adaptable enough to fit cities of different sizes, geographic locations, topographic conditions, and climate hazards. Although the framework has been designed based on the experience of Indian cities and urban areas, it can be contextualized and adapted for conducting vulnerability assessments in cities around the world.

Appendices

APPENDIX A: RATIONALE FOR INDICATORS

Hazard Identification and Assessment

TABLE A-1 | Rationale for hazard categories and sub-categories

HAZARD CATEGORY/ SUB-CATEGORY	RATIONALE
Meteorological	
Thermal Stress Air Temperature Land Surface Temperature (LST) Thermal Comfort Sea Surface Temperature	Annual temperature trends establish overall heat exposure, which is experienced differentially based on the heat island effect and socioeconomic and demographic differences within neighborhoods. In terms of exposure, heat stress is further exacerbated depending on housing type by factors such as indoor light and ventilation, building material, and humidity, which create pockets of heat traps. Additionally, poor communities living in poorly ventilated, dense housing, with compromised access to essential services such as affordable cooling options, are most sensitive to thermal stress.
Precipitation Change Rainfall Snowfall	In the last few years, a significant proportion of precipitation has come in the form of single-day events. Heavy precipitation has many environmental and socioeconomic impacts, from flooding and soil erosion to injuries and drownings (U.S. EPA n.d.). In terms of exposure, the effects of heavy precipitation are heightened in urban areas, where non-permeable infrastructure forces water to quickly run off, which can also lead to water quality degradation, harmful health impacts, etc. Residents in informal settlements, migrant workers, homeless people, and other underserved areas in the city with poor stormwater drainage networks and sewage infrastructure are extremely sensitive to precipitation change (C2ES n.d.).
Windspeed Cyclones Thunderstorms	Weather events such as cyclones and thunderstorms bring violent winds, torrential rain, high waves, lightning, and tornadoes and hailstorms, which cause mortality, injuries, displacement, and infrastructure damage. Coastal settlements and high-density areas are extremely exposed and vulnerable to such events. Additionally, communities living in informal settlements, outdoor workers, homeless people, and other underserved communities are much more sensitive to such events (WMO n.d.).

TABLE A-1 | Rationale for hazard categories and sub-categories (cont'd.)

HAZARD CATEGORY/ SUB-CATEGORY	RATIONALE
Sea Level Change Sea Level Rise and Fall Storm Surge	Higher sea surface temperature increases the intensity of cyclones and storms, which compounds coastal erosion and sedimentation and damages the entire coastal ecosystem. *Exposure:* Limited knowledge of the extent of damage caused by extreme waves and winds can aggravate loss of life and property, primarily for those situated in the immediate vicinity of the city's coastline. *Sensitivity:* The natural variability of the coast makes it challenging to determine the impact of any external stimuli. Therefore, the risk for communities dependent on the sea and mangroves for their livelihood makes them more sensitive to any changes in the coastline.
Hydrological	
Flood Waterlogging Riverine Floods Coastal Floods and Storm Surge Glacial Lake Outburst	Waterlogging and flooding in cities affect infrastructure, property, and personal assets and can also affect lives, livelihoods, and public health. In terms of *exposure*, flood risk is experienced differentially across the city. Low-lying areas are more exposed to frequent waterlogging and flooding. Additionally, low-income communities and people living in informal housing are more sensitive to flooding because it affects their lives, livelihoods, assets, and health.
Drought Hydrological Drought Meteorological Drought Groundwater Exploitation	Drought events in urban areas affect freshwater resources and can pose a great threat to urban water supply systems. They can seriously impact health, food security, and socioeconomic well-being. Households and communities that do not have access to tapped water are especially sensitive to drought events. Additionally, disrupted water supply can also impact sanitation systems in the city. The need and demand for water generally goes up during warmer months and in hotter areas. Reduced water availability during drought events can exacerbate the experience of heat and lead to serious health impacts.
Geological	
Land Deformation Land Subsidence Coastline Changes and Sea Level Rise	Land deformation can seriously damage civil and public infrastructure, road networks, tunnels, pipelines, and so on. Areas in highly seismic zones are more susceptible to land deformation. Households and communities in high-subsidence zones are exposed to the impacts of land deformation. Additionally, informal settlements and low-income communities residing in high-subsidence zones are extremely sensitive and vulnerable to the effects of land deformation.
Ground Movement Landslide Avalanche	Prolonged rainfall, unstable soil structure, geological conditions, and slope failure increase the frequency of landslides. Communities living in or near landslide-prone areas are more exposed. Several informal settlements are located in landslide-prone areas, making them more sensitive than those living in formal housing.

TABLE A-1 | Rationale for hazard categories and sub-categories (cont'd.)

HAZARD CATEGORY/ SUB-CATEGORY	RATIONALE
Environmental	
Air quality degradation Indoor air quality Outdoor air quality	Areas with a high concentration of air pollutants are more vulnerable; the spatial variability of pollutants means that different interventions will be needed to improve air quality. Those living or working in close proximity to polluting sources are more exposed. Adverse socioeconomic factors such as housing conditions (e.g., poor ventilation and use of non-LPG cooking fuel) and occupation (e.g., transport operators, traffic police, construction labor) imply greater sensitivity.
Water quality degradation Surface water quality Ground water quality	Water quality degradation can contaminate important sources of drinking water, harm human health and aquatic ecosystems, affect the livelihoods of fisherfolk, and so on. Climate hazards and other anthropogenic factors can pollute lakes, rivers, bays, groundwater, and other water ecosystems that are essential for a city's ecological health. In areas with heavy rainfall, stormwater runoff often contains pollutants such as heavy metals, pesticides, nitrogen, and phosphorus that can end up contaminating natural water reservoirs and ecosystems in the city. Low-income households and informal settlement communities that rely on groundwater, open wells, and other water bodies for daily needs are extremely sensitive to water pollution. Underserved communities in urban areas often reside close to water bodies and are extremely sensitive to water pollution and at risk of contracting diseases from unhygienic and polluted water systems.
Soil quality degradation	Soil degradation can involve water erosion, wind erosion, salinity, loss of organic matter, fertility decline, soil acidity or alkalinity, structural decline, mass movement, and soil contamination due to pollutants or excessive flooding (NSW n.d.). In terms of exposure, converted land (from forests and natural landscape to crop fields, pasture, and gray infrastructure) is less able to soak up water, reducing its soil-water-holding capacity and making it flood more easily. Sedimentation and pollution due to clogged and polluted waterways due to soil erosion along with chemicals can damage freshwater and marine habitats and harm the local communities that depend on them. Livelihoods of smallholder farmers in urban and peri-urban areas are at risk because the destruction of soil characteristics and loss of topsoil make land less productive (WWF n.d.). Informal settlements and households with no access to tap water that rely on freshwater sources and communities living in temporary roof and wall homes in areas with mass movement and structural decline are highly sensitive to the effects of soil degradation in the urban context.
Vegetation change	Vegetation alters climate and weather patterns, especially in terms of variability in precipitation and surface radiation. Loss of vegetation can exacerbate food insecurity, water risk, droughts, and heat waves (Evarts 2017).
Fire Forest fires Other fires	Increased heat, extended drought, and a dry atmosphere have been key drivers in increasing the risk and extent of wildfires. Forest and other fires can significantly impact mortality and morbidity. Infants, young children, pregnant women, and the elderly are more susceptible to the health impacts of smoke and ash. Those with preexisting respiratory or heart diseases are highly vulnerable to particulate matter, smoke, and ash. Firefighters and emergency response workers are also at risk and can be impacted by injuries, burns, and smoke inhalation. Wildfires release significant amounts of mercury into the air, which can lead to speech, hearing, and walking impairments; muscle weakness; and vision problems (WHO n.d.).

Source: Authors.

Exposure Analysis

TABLE A-2 | Rationale for exposure indicators

VULNERABILITY INDEX	RATIONALE
Vulnerability Domain: Physical	
Variation in density of population residing in hazard-prone areas	Populations living within or in close proximity to hazard-prone or hazard-impacted areas can be directly exposed to and significantly impacted by hazards. It is essential to assess hazard-prone or hazard-impacted areas in the city so that practitioners and policymakers can prioritize efforts and plan interventions to manage exposure to thermal stress, flooding, landslides, etc.
Population residing in slums and informal settlements	Slum populations living within or in close proximity to hazard-prone or hazard-impacted areas are the most vulnerable and sensitive groups, characterized by temporary housing materials and structures, lack of financial and social protection, and limited access to household and civic services. Assessing and identifying low-income communities and informal settlements in close proximity to hazard-prone areas will help make a case for improving service provisioning, help understand high-priority intervention areas, explore resilience measures, and enable deeper engagements and analysis in those areas.
Job density Formal Informal Outdoor	People working within or in close proximity to hazard-prone or hazard-impacted areas can be directly exposed to and significantly impacted by hazards. It is essential to assess jobs and livelihoods in hazard-prone or hazard-impacted areas in the city so that practitioners and policymakers can prioritize efforts and plan interventions to manage exposure to thermal stress, flooding, landslides, etc. Although formal workers may be less sensitive to hazard events, informal workers such as domestic help would be extremely sensitive to them; however, outdoor workers such as construction workers, traffic police, and hawkers would be most exposed.

Source: Authors.

People's vulnerability: Lens of sensitivity

TABLE A-3 | Rationale for sensitivity indicators

VULNERABILITY INDEX	RATIONALE
Vulnerability Domain: Sociodemographic **Vulnerability Index: Disproportionately impacted population groups**	
Women and trans communities Illiterate women[a] SC/ST Age-based vulnerable groups: <6 years of age and >60 years of age Non-workers Illiterates[b] Age-based vulnerable groups: <6 years of age	▪ Gender equality and women's empowerment (SDG 5) is another significant factor that enhances resilience (UN n.d.-b). In addition, limited participation in decision-making along with other social responsibilities makes women more vulnerable (UNFCCC n.d.). This disproportionate impact on women and girls is due to reduced access to resources and services and caregiver responsibilities after a disaster. ▪ Basic literacy levels and quality education empower people to manage adverse situations better. This has also been deliberated at the global level and has hence been included in the Sustainable Development Goals (SDG) (UNESCO n.d.), SDG 4 to be specific. The United Nations (UN) mentions literacy as a crucial factor in addressing climate change and its impacts (UN n.d.-a). Awareness creation on climate-induced hazards, their probable impacts, and better preparedness can reduce risk intensity. Higher literacy levels would also enhance an understanding of the implications of these hazards. Other co-benefits such as better jobs, which would ensure socioeconomic stability, can further enhance resilience. ▪ Caste-based exclusions can result in systemic social marginalization and have a cascading impact on a population's resilience and vulnerabilities. Certain castes may not have equitable access to services and resources; neighborhoods having a higher density of SC/ST communities may thus be underserved, making them more sensitive to climate risk. A recent working paper by IIED reported that the odds of climate-induced migration of SC and ST populations is higher by 338% (Bharadwaj et al. 2022). ▪ Children and the elderly are more susceptible to climate change, and this parameter has been included to represent this aspect. To give an example, a research study conducted in São Paulo, Brazil, reported a 2.6% increase in mortality rates for children under 15 and the elderly above 65 for every degree rise in temperature above 20°C.

TABLE A-3 | Rationale for sensitivity indicators (cont'd.)

VULNERABILITY INDEX	RATIONALE
People with disabilities Religious and ethnic minorities Low-income communities and poor people Migrants	▪ The differently abled population is more vulnerable to climate impacts. Their ability to cope with hazards is also varied. For example, a differently abled person would find it more difficult to cope with floods and landslides than an able-bodied person. ▪ Traditionally, migrants are those who move from their place of origin to a new place, usually for better opportunities (UNHCR n.d.). This move to a new location makes them vulnerable, either due to lack of access to local markets or more often due to lack of an adequate residence (Tanner et al. 2009). To add to these woes, more people are now migrating for climatic reasons, making this parameter an important component of vulnerability and its analysis.
Vulnerability Domain: Socioeconomic **Vulnerability Index: Populations in adverse working conditions**	
Outdoor workers, temporary or informal workers	People who work outdoors are often more exposed to climate hazards. Such groups might include construction laborers; domestic workers such as maids, security guards, and drivers; street vendors; courier delivery workers; door-to-door salespersons; traffic police; firefighters; transportation workers; utility workers; emergency responders; informal daily wage laborers, etc.
Vulnerability Domain: Socioeconomic **Vulnerability Index: Populations involved in high-risk livelihood activity**	
People and communities involved in livelihoods that are climate-sensitive with no social safety net	An individual can work in the formal or informal sector, and this difference would affect his or her economic stability. For instance, street vendors may not be able to operate their stalls during floods, which would affect their daily earnings; however, formal workers may not be directly impacted. Thus, livelihood risks coupled with the absence of a social safety net include loss of productivity due to heat, loss of livelihood itself, or loss of workdays and associated income loss due to health impacts or other physical or infrastructural damage.
Vulnerability Domain: Sociopolitical **Vulnerability Index: Lack of home ownership, limited tenure, and houselessness**	
Households not owning the property they reside in	Home ownership or legal secure tenure can mitigate various disaster-related losses because it incentivizes individuals to adopt construction practices that enhance disaster adaptability (UNEP and SEfficiency 2021). Property losses are also usually attended to promptly if one owns the property. Further, other losses such as income loss due to loss of productive days and health concerns are more easily borne when one has a home to return to. This enhanced socioeconomic security translates to better resilience.
Population living in notified slums with settlement boundaries	In addition to home ownership and housing, whether individuals live in slums—as defined by government institutions—impacts their vulnerability. Slum dwellers typically lack durable housing, access to safe water and sanitation, sufficient living area, and secure tenure. Slums also lack protective infrastructure that can help residents cope with the impacts of environmental degradation and climate change (Wekesa et al. 2011).
Population living with insecure tenure other than notified slums with settlement boundaries	Households with no ownership documents, rental agreements, and rent receipts are often unable to avail themselves of insurance services, financial relief, and other government support programs in extreme climate events and are therefore extremely sensitive to hazards such as landslides, cyclones, flooding, and subsidence. They cannot afford to buy and access better housing and amenities, and could be injured or fatally impacted in extreme climate events.
Houseless population	Although official data on houseless people are negligible, identifying and planning for this group is essential for reducing hazard-related risks, fatalities, and injuries. They are not just extremely sensitive to larger climate hazards such as flooding, cyclones, and landslides but are also more exposed and sensitive to weather fluctuations, temperature, and wind and humidity anomalies and variability.
Vulnerability Domain: Residential **Vulnerability Index: Inadequate housing condition** (Temporary building materials as a proxy for built/structural conditions of the house and socioeconomic condition of the residents)	
Material of roof ▪ Temporary roofing[c] Material of walls ▪ Temporary walls[d]	Housing conditions are studied primarily as a function of the roofing material because it is the roof of the house that protects residents from the vagaries of nature. Houses with temporary roofing thus are more vulnerable to hazard occurrences or extreme weather conditions. In addition, temporary roofing could also represent the economic stability of a household, the probability of Economically Weaker Section (EWS) households having temporary roofing being higher than that of other economic groups.

TABLE A-3 | Rationale for sensitivity indicators (cont'd.)

VULNERABILITY INDEX	RATIONALE
Vulnerability Domain: Residential Vulnerability Index: Inadequate household-level essential services	
Not having access to treated drinking water facility within the house premises: • Location of drinking water source • Source of drinking water	Access to clean water (SDG 6) is crucial for overall public health and the well-being of individuals. Access to formal piped water supply ensures regular availability of treated drinking water to a certain extent. Any service disruption is restored within a reasonable time; otherwise, alternative arrangements are made by the authorities. Households dependent on non-piped sources of water, such as tankers, community handouts, and groundwater, are more vulnerable. They may not have sustainable access to water because of limited physical connectivity during exposure to certain hazards, because of issues with maintenance or water quality, and overall ease of access, especially during hot days.
Not having access to sanitation services	SDG 6 includes access to water, sanitation, and hygiene (WASH) for all because it is one of the basic amenities needed for health and well-being (UN n.d.-c). The vulnerability and resilience of an individual to climate change decreases if there is limited access to these basic facilities. Factors considered include the following: Using latrines within the house premises is more hygienic than using common facilities because diseases will spread faster in common facilities. Also, maintaining hygiene is easier within the house than outside it. Further, disposal of sewage and wastewater ensures clean premises and neighborhoods. Unscientific methods of disposal pose serious public health risks because people residing in the vicinity will be exposed to polluted water. Such risks will only be further aggravated during hazard incidents such as flooding.
Main source of lighting **not connected** to the grid or renewable energy	Grid-supplied electricity as the main source of lighting implies better access to safe and stable electricity. If disruptions occur, power is usually restored quickly, enhancing households' adaptive capacity.
Use of polluting cooking fuels	The use of cooking fuels such as firewood adversely impacts the indoor air quality. Long-term exposure to such pollutants can be compounded by regular exposure to outdoor air pollution. Of special concern are houses that are not well ventilated or do not have a separate kitchen, because all members of the household are impacted by indoor air quality. Children and the elderly in such households are more vulnerable.
Lack of access to information dissemination assets	Immediate access to assets—such as a radio or transistor; landline, cell phone, or both; personal computer with Internet; and television—enables people to become aware of and respond more quickly to emergencies. Ownership of such assets is also an indicator of socioeconomic status. Clustering of such households is a proxy for settlement groups where there is a high possibility of service alerts, warnings, and communication lapses.
Vulnerability Domain: Locational/Physical Vulnerability Index: Lack of access to public infrastructure and amenities	
Access to healthcare	Climate change is one of the biggest health threats and affects the social and environmental determinants of health, such as clean air, safe drinking water, food security, and secure shelter. Deaths due to malnutrition, heat stress, and other climate-related ailments are expected to rise significantly. Areas with weak health infrastructure and poor access to healthcare will be the least able to cope during extreme climate events. SDG 3 aspires to ensure the health and well-being of all, achieve universal health coverage, and provide access to safe and effective medicines and vaccines for all.
Access to education	Access to education empowers people with better knowledge, which translates to better management of adverse situations such as hazards. In addition, often, especially during sudden hazard occurrences, government-aided and government-funded schools serve as relief shelters for affected communities during and after a disaster.
Access to mass transit or public transport	General travel along with travel to work or schools becomes convenient with easy access to mass and public transit. Mass and public transit networks are often interdependent and serve as lifelines for the day-to-day life of city residents. Many city functions and utilities, such as livelihood and transport of essential goods to the public, rely on and benefit from urban transportation services. During any extreme climate or hazard event, easy access to such amenities ensures convenience at affordable rates and is important for evacuation during disasters.
Access to public green open spaces	Public parks and playgrounds serve the residents of a city in multiple ways, as recreational areas, by safeguarding and enhancing the nature component of the city with results such as better air quality and enhanced biodiversity. The open spaces and blue-green networks of the city also act as sponge spaces during hazard events and even otherwise. WHO mentions that vulnerable communities, in particular, benefit more from these spaces as it helps them destress and rejuvenate themselves (WHO 2016). Urban and Regional Development Plans Formulation and Implementation (URDPFI) guidelines, 2015, recommend 10–12 square meters of open green (recreational) space per person.

TABLE A-3 | Rationale for sensitivity indicators (cont'd.)

VULNERABILITY INDEX	RATIONALE
Access to emergency or disaster relief shelters	Easy access to emergency services such as hospitals and fire services facilitates prompt and faster response when such services are needed. Good and affordable medical infrastructure is important for overall public health. The importance of such infrastructure increases manifold when disasters occur, because timely action can save lives. Fire services in India not only fight fires but also mount rescue operations during any kind of hazard, because they serve as the primary emergency service (NDMA n.d.-b). Settlements and infrastructure at higher exposure to a disaster may often be located in areas that are not efficiently and effectively serviceable by fire stations. In certain Indian cities, especially during the winter months, the city temperature drops considerably. In such cases, night shelters serve as temporary shelters for homeless people.

Notes: a. This term and others used as indicators come directly from the Census. We use these terms to stay close to and accurately represent the data. However, when conducting the CHVA and especially when working with vulnerable groups, practitioners can consider using more sensitive terms such as "women who cannot read and write" rather than "illiterate women."
b. This term and others used as indicators come directly from the Census. We use these terms to stay close to and accurately represent the data. However, when conducting the CHVA and especially when working with vulnerable groups, practitioners can consider using more sensitive terms such as "persons who cannot read and write" rather than "illiterates."
c. Unstable roof materials: Grass, thatch, bamboo, wood, mud, etc.; plastic, polythene; galvanized iron, metal, asbestos sheets, tiles, etc.
d. Unstable wall materials: Grass, thatch, bamboo, wood, mud, unburnt bricks, etc.; plastic, polythene, stone not packed with mortar; galvanized iron, metal, asbestos sheets, tiles, etc.

Source: Authors.

The vulnerability lens of adaptive capacity

TABLE A-4 | Rationale for indicators related to the adaptive capacity lens of vulnerability of people

VULNERABILITY INDICATOR	RATIONALE
Vulnerability Domain: Economic Vulnerability Index: Employment and livelihood	
Job security of formal and informal jobs during the onset of a hazard and immediately after it	Secure livelihoods and jobs play an important role in determining the adaptive capacity of individuals and households. Climate hazards can lead to job and financial losses for workers, employees, and businesses. This can be understood and assessed based on workdays or working hours lost, income loss, and level of employment security during the occurrence of a hazard and after it.
Level of dependence on high-risk livelihood activity and adverse working conditions	Economic sectors such as tourism, agroforestry, and fisheries are extremely climate-sensitive and have lower adaptive capacity than other sectors. Additionally, certain livelihoods and jobs demand that people work in adverse conditions; e.g., garbage collectors, waste pickers, street vendors, and daily wage workers. These individuals and economic groups have low adaptive capacity. It is essential to highlight both climate-sensitive livelihoods and other urban livelihoods that are not in the climate-sensitive category but whose adverse preexisting working conditions can lead to prolonged exposure and increased sensitivity.
Livelihood diversification	The ability and flexibility to change occupations and diversify livelihoods is especially relevant and useful in the context of climate events and hazards. It is an important indicator for understanding the adaptive capacity of individuals, communities, and social groups in economic terms. Disruption in livelihoods and jobs can be addressed through opportunities for reskilling and skill upgradation and by making loans available to start small businesses.
Vulnerability Domain: Governance Vulnerability Index: Social security	
Access to secure and adequate housing	Access to secure housing can ensure safety, especially through an extreme climate event or hazard. One of the goals of SDG 11 is also to "ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums." Secure housing is linked with good health and well-being and plays an essential role in building adaptive capacity to climate and environmental hazards (Frediani et al. 2023).

TABLE A-4 | Rationale for indicators related to the adaptive capacity lens of vulnerability of people (cont'd.)

VULNERABILITY INDICATOR	RATIONALE
Access to social welfare schemes	Access to social welfare schemes such as the public distribution system (PDS), programs for the elderly and old age support, health schemes, worker and employment schemes, and rehabilitation programs can play an important role in improving the adaptive capacity of different social groups. However, access to such schemes is linked to official identity documents, which informal settlements, workers, and residents may not possess. Thus, understanding and mapping access to social welfare schemes can help identify vulnerable groups and areas, and plans can be formulated accordingly.
Vulnerability Domain: Governance **Vulnerability Index: Disaster preparedness and response**	
Access to early warning systems and disaster training and capacity building	Early warning systems, an essential adaptive measure in the context of climate change that helps people prepare for hazardous climate-related events, often use integrated communication systems. They are linked to lives, jobs, land, and infrastructure and support long-term resilience. They are essential in helping public officials and administrators plan for climate change; saving resources, assets, and people in the long run; and protecting urban economies (UN n.d.-d).
Access to open spaces to support emergency response	Parks and open spaces can play an important role in increasing communities' resilience to potential extreme climate events and hazards. Open spaces usually serve as playgrounds, parks, recreation and educational spaces, etc. (FEMA 2014). However, open spaces can also be used to capture stormwater in flood-prone cities during a catastrophe, prevent the spread of infectious diseases, build public health, and facilitate other disaster reduction and relief measures (Wei et al. 2020).
Prevalence of community-based disaster resilience and management practices	Disaster resilience measures are most successful when they directly involve the people most likely to be exposed to hazards. Community-based disaster preparedness is a process that mobilizes a group of people in a systematic way toward achieving safe and resilient communities. This approach attempts to help communities become engaged in risk reduction efforts and more empowered to cope with disasters and particular hazards. This would include training, coordination, collaboration, dissemination of best practices, improvement of safety levels of core community facilities, and so on (Bhagat 2012).
Vulnerability Domain: Governance **Vulnerability Index: Disaster mitigation and risk reduction**	
• Protocols for managing different categories of hazards • Plans and policies for directing future population growth while protecting the environment	Disaster management plans aim to safeguard lives and livelihoods; protect the environment, infrastructure, and assets; conduct salvage operations; and provide essential services. The National Disaster Management Authority (NDMA) is the apex body for disaster management in India. At the state and district levels, the NDMA is mandated to create institutional mechanisms by following the policies, plans, and guidelines highlighted in the National Disaster Management Act (NDMA), 2005, through prevention, mitigation, preparedness, and response. A city- or district-level disaster management plan that strives to mitigate the damage and destruction caused by disasters and extreme events, through collaboration and the collective efforts of government agencies, NGOs, and people's participation, is essential for ensuring city-level adaptive capacity to climate and environmental hazards and disasters.
Vulnerability Domain: Governance **Vulnerability Index: Citizen engagement**	
Frequency of neighborhood-, ward-, and zone- level meetings to inform, involve, and engage people	Community-led resilience activities, health awareness programs, and robust civic systems can facilitate inclusive climate action and responses to hazards and disasters. Facilitating community participation can contribute to building trust and enabling collaboration with different stakeholders, which can lead to improved outcomes and more desirable solutions that benefit people. Citizen engagement can also empower people, especially those who are often excluded, to exercise their agency in mobilizing the resources and skills required to address differential vulnerability meaningfully (GFDRR and The World Bank n.d.; Rangwala et al. 2018).

Source: Authors.

Vulnerability of infrastructure

TABLE A-5 | Rationale for indicators to assess vulnerability of infrastructure through the three lenses

VULNERABILITY INDICATOR	RATIONALE
Vulnerability Lens: Exposure Vulnerability Domain: Physical	
Location of infrastructure in high-risk hazard hotspots	Mapping the location of physical infrastructure assets and networks within hazard-prone areas and hotspots or areas likely to be impacted will allow practitioners and policymakers to understand the level of exposure. This is especially important to understand for critical road networks, schools, hospitals, public transit stations, etc.
Physical damage to infrastructure assets	Understanding the nature and extent of damage to specific assets and the location of these assets is the first step toward climate proofing the city. A historical assessment of instances of damage due to different hazards will help the city plan and prepare for future events and catastrophes.
Vulnerability Lens: Sensitivity Vulnerability Domain: Physical	
Reduction in service area due to "lack of" physical access to infrastructure and amenities during and immediately after hazard events	In an extreme climate event, access to essential infrastructure such as healthcare, education, mass transit or public transport, public green open spaces, and emergency or disaster relief shelters is significantly impacted. Understanding how access to these physical infrastructure assets and networks changes during and after hazard events in terms of time, routes, mode, etc., will help gauge how sensitive these assets are to different hazard events and thus improve planning.
Vulnerability Lens: Sensitivity Vulnerability Domain: Economic	
Revenue losses due to disrupted services	Hazard events often disrupt infrastructure services in the city. So, it becomes necessary to understand the extent and duration of the disruption, the time taken to resume services, and the revenue losses due to disruption.
Revenue losses due to damage to physical assets	Hazard events can cause serious damage to physical assets and public infrastructure. Thus, it becomes prudent to track the resulting economic losses, understand their breakup, attribute them to specific assets and hazards, and estimate the duration and cost of repair and rebuilding.
Vulnerability Lens: Sensitivity Vulnerability Domain: Social	
Death and injury	Infrastructural damage from hazard events can impact lives and cause serious injury and death. The impacts of hazards such as heat waves and high humidity often go unattributed, including the number of lives lost and people injured due to physical damage of assets.
Disease outbreaks due to damage to infrastructure	Climate and environmental hazards such as heat stress, water, soil and air pollution, and excessive flooding can lead to disease outbreaks and the spread of communicable diseases. It is necessary to understand the impact of hazards on health due to infrastructure damage.
Vulnerability Lens: Adaptive Capacity Vulnerability Domain: Economic	
Emergency funds, disaster relief funds	In a hazard event, immediate relief and emergency funding are required for relief, rescue, and recovery. Cities must have dedicated emergency funds for specific sectors or infrastructure within different institutions for specific activities. It is also necessary to ascertain who holds and controls the funds and the modalities for disbursement, the scope of utilization, and whether the allocation needs to be adjusted based on need or if there is a standard template.
Insurance	Damage to infrastructure projects and assets can lead to financial losses, which can be a disaster for those affected and the city government. However, this can be prevented by insuring infrastructure. Thus, this indicator represents whether assets in the city are insured and the type and conditions of asset insurance.

TABLE A-5 | Rationale for indicators to assess vulnerability of infrastructure through the three lenses (cont'd.)

VULNERABILITY INDICATOR	RATIONALE
Climate proofing funds	Climate proofing funds ensures that climate change mitigation and adaptation are integrated into the funding and development of projects and infrastructure. This indicator represents whether cities are climate proofing their funds or considering it in the future, the methodology and rationale of climate proofing, and whether they undertake any additional climate proofing measures.
Vulnerability Lens: Adaptive Capacity Vulnerability Domain: Environmental	
Early warning systems	Early warning systems are essential to protect infrastructure and assets from hazard events. This indicator represents whether any early warning systems are in place and describes the communication technology used, whether these systems are maintained and serviced regularly, and whether a feedback system is in place to understand their effectiveness and reach, especially among low-income and informal communities.
Disaster management plans for infrastructure and essential services at the city level	City disaster management plans are essential to build resilience and preparedness and implement measures to achieve a resilient urban environment. They can play an important role in safeguarding life, protecting the environment and installed infrastructure, restoring production, and even conducting salvage operations related to infrastructure and essential services.
Climate proofing assets	Climate proofing integrates mitigation and adaptation measures into the development of infrastructure projects by identifying, classifying, and managing physical climate risks when planning, developing, executing, and monitoring infrastructure projects and programs (European Commission 2021).
Vulnerability Lens: Adaptive Capacity Vulnerability Domain: Governance and Management	
Organization structure	Understanding and being aware of the organization structure of the urban government helps in efficiently responding to climate hazards and disasters and ensuring that the authority responsible for undertaking action has a clear first response plan and mandate.
Coordination and communication mechanisms	In a climate hazard and disaster event, the chain of communication for on-the-ground action and support needs to be clear and well defined for swift, effective action. Communication and coordination are essential for a timely response. The jurisdictional split must be clearly defined for better reach and decentralized action.
Response protocols	In a climate hazard or disaster event, response protocols need to be outlined, ranging from the immediate response action, which involves warning people through print, radio, and electronic media, to secondary modes, which involve reaching people who may have no access to mass media but are in the affected areas. Evacuation drills and protocols and search, rescue, and relief protocols are all essential to strengthen the governance system. An infrastructure recovery and critical infrastructure incident response plan could help restore systems and minimize damage after a major climate event.
Staff capacity and training	Training and capacity building are an essential and ongoing process to ensure that officials, stakeholders, and staff are equipped to manage climate hazard and disaster events (NDMA n.d.-a).
Citizen engagement	Community response, participatory action, and citizen engagement through a bottom-up approach can better identify and address people's needs and vulnerabilities in a climate hazard or disaster event. It can help restore infrastructure through community ownership and response and allow people to benefit from restored operations and infrastructure (GFDRR and The World Bank n.d.; Rangwala et al. 2018).

Source: Authors.

APPENDIX B: METHODS, DATA SOURCES, AND THRESHOLDS BY HAZARD INDICATORS

The tables below list the definitions, methods, categories, and classification of climate hazards and their associated factors as considered by national and international agencies. The datasets and data sources listed are the most recently available in the public domain (at the time of publication) for each authorized agency. Cities may choose to use any other recent and updated or upgraded dataset that their CHVA team deems fit for the analysis.

TABLE B-1 | Meteorological hazards

<table>
<tr><th></th><th></th></tr>
<tr><td rowspan="3">Thermal stress</td><td>Definition: Cities are vulnerable to both heat and cold stress, but heat stress is a particular concern due to increasing temperatures caused by global warming, further exacerbated by heat islands. Urban heat islands are built-up areas with temperatures higher than those of the rural areas surrounding them. This phenomenon causes increased heat stress in cities. Cold and heat exposure is experienced differentially within a city based on microclimates determined by urban form and socioeconomic and demographic differences between neighborhoods.

The stress induced by cold and heat is measured through four lenses—temporal trends in air temperature, extreme temperature events, projected changes to the air temperature in the medium and long term, and spatial "heat" exposure—by using land surface temperature (LST) analysis to identify areas in the city that are more vulnerable to heat stress.</td></tr>
<tr><td>Air Temperature

Air temperature, which is generally measured at altitudes of 1.2 and 2 m above mean sea level, represents the surface air temperature in the city.

Data sources: The Indian Meteorological Department (IMD); automatic, telemetric, and weather station data from state- and city-level agencies; National Centers for Environmental Information (NCEI), ECMWF Reanalysis v5 (ERA5).

▪ <u>Annual air temperature trend analysis and deviations</u>—Air temperature anomalies indicate the degree of deviation of the average annual air temperature with respect to the baseline temperature or long-period average. Linear regression and other algorithms can help identify historical temperature changes.
▪ <u>Long-term temperature trends across seasons and timescales</u>—Trend detection algorithms allow us to determine the magnitude and direction of the annual air temperature trend across different timescales: inter-annual, intra-annual, inter-seasonal, and intra-day.
▪ <u>Frequency of extreme temperature days and nights</u>—High heat index days, heat waves, and cold waves (including warm/cold nights) are defined based on temperature thresholds over a region in terms of the actual temperature or its departure from long-period averages.
▪ <u>Long-term trend of the frequency of extreme temperature days and nights</u>—Temporal trends of the frequency of extreme temperature trends can be analyzed using the statistical procedures mentioned in Chapter 5.
▪ <u>Projected changes in temperature</u>—Data sources: NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) for RCP 4.5, Coupled Model Intercomparison Project Phase 6 (CMIP6) daily data for Representative Concentration Pathway (RCP) 6. Understanding future projected temperature changes is critical. Climate models are used to understand these changes; however, a single model cannot be used at a city level. To reduce the possibility of erroneous results, multiple models are typically analyzed. The scenarios typically used for understanding the changes are Representative Concentration Pathway (RCP) 4.5 and RCP 6 (van Vuuren 2011).</td></tr>
<tr><td>Land Surface Temperature (LST)

LST is estimated from satellite observations (Sobrino et al. 2004) and is the skin temperature of the surface of Earth. Surface temperatures are significantly affected by land use and hence vary from air temperature. Satellites capable of observing radiances in thermal infrared wavelengths can be used to calculate land surface temperature.

Within city boundaries, certain areas experience heat more intensely than others due to factors such as land use, land cover, the material covering the surface or built density, and the presence or absence of nearby vegetation and water bodies. LST is measured during both the day and night, and day and night measurements have different implications. Night-time land surface temperatures are very useful in identifying urban heat islands.

Data sources: Moderate Resolution Imaging Spectroradiometer (MODIS) (NASA LPDAAC), Landsat 5, 7, 8 (USGS).</td></tr>
</table>

Thermal stress	▪ Short-term LST trends—The trends of hotspots and actual land surface temperature of the city over recent time periods will help understanding of local variations due to human interference. Although satellite image availability for LST calculation has become consistent lately, there are coverage gaps for previous years. Because LST can be significantly affected by short-term meteorological events and some satellites have longer revisit durations, temporal LST trends should be studied with the utmost care. ▪ LST hotspots within the city—Spatial analysis of heat risk uses Moderate Resolution Imaging Spectroradiometer (MODIS) night-time LST data to study LST differences between urban areas and rural peripheries, and daytime LST data from Landsat (USGS) help identify local areas that are more exposed to heat stress due to the heat island effect. These data can provide temperature variations from regional averages for specific neighborhoods.
	Thermal Comfort The Universal Thermal Climate Index (UTCI) (CDS 2020) is a human biometeorology parameter that is used to assess the linkages between the outdoor environment and human well-being. Thermal comfort indices describe how the human body experiences atmospheric conditions, specifically air temperature, humidity, wind, and radiation. UTCI is expressed as the equivalent ambient temperature (°C). The number of hours or days above 26°C or below 0°C are calculated, and trends in the duration and frequency of these over-long periods are studied. *Data sources: UTCI derived from ERA5.*
	Sea Surface Temperature Sea surface temperature (SST) is an important physical property that impacts biological processes, flora, and fauna in coastal regions. SST is one of the key factors in the formation of tropical cyclones (TCs), which require an SST of at least 26°C to develop (Dare and McBride 2011). *Data source: MODIS AQUA Sea Surface Temperature Data.* ▪ Temporal trends in SST close to the coastline—Analysis of the annual average SST demonstrates the varying range (the difference between the observed minimum and maximum) of SST across the ocean surface near the coastline and the macro sea region that has direct and indirect impacts on the city. The temporal SST trends can be measured using satellite information.
	Thresholds
	Extreme Temperature Days And Nights ▪ *Heat Index*—The National Weather Service under the National Oceanic and Atmospheric Administration (NOAA) has categorized the Heat Index (HI) (NOAA n.d.) values into four classes: Caution days (26°C–32°C), Extreme Caution (32°C–41°C), Danger days (41°C–54°C), and Extreme Danger days (above 54°C) to identify its differential adverse impact on the human body. Daily minimum, maximum, and mean heat index values are assessed using humidity and air temperature datasets at the monitoring station or grid level. ▪ *Heat and Cold Waves*—The Indian Meteorological Department (IMD), based on daily maximum/minimum temperature station data, prepares the climatology of maximum/minimum temperature for the period 1981–2010 to find out normal maximum/minimum temperature of the day for a particular station. Extreme events such as heat or cold waves are declared based on the actual air temperature or departure from the normal. Heat wave: This occurs when the maximum temperature of a station reaches at least 40°C for the plains and at least 30°C for hilly regions (IMD n.d.-a, 2021a). Heat wave conditions are categorized based on the maximum air temperature as follows: *Based on a positive departure from the normal:* • Heat wave: Departure from the normal is 4.5°C to 6.4°C • Severe heat wave: Departure from the normal >6.4°C *Based on the actual maximum temperature:* • Heat Wave: An actual maximum temperature ≥45°C • Severe heat wave: Actual maximum temperature ≥47°C In coastal areas, the IMD has specified that heat wave conditions may occur when the positive departure of the maximum temperature from the normal is ≥4.5°C provided the actual maximum temperature is ≥37°C. If the above criteria are met in at least two stations in a meteorological subdivision for at least two consecutive days, a declaration is made on the second day. A *cold wave* is declared based on the actual minimum air temperature of a station (IMD 2021-a). It is considered when minimum temperature of a station is 0°C or less for hilly regions, and 10°C or less for the plains.

Thermal stress	*Cold wave conditions are categorized as follows:* Based on the actual minimum temperature (for stations located in the plains) • Cold wave: When the minimum temperature is ≤4°C • Severe cold wave: When the minimum temperature is ≤2°C Based on departure from the normal: • Cold wave: A negative departure from the normal is 4.5°C–6.4°C • Severe cold wave: A negative departure from the normal is >6.4°C Additionally, for coastal areas, a cold wave may be considered if the minimum temperature is ≤15°C and the negative departure from the normal is ≥4.5°C. ▪ *Thermal Comfort*—The categories relate to UTCI (Climate-Adapt n.d.) values are as follows: above +46°C, extreme heat stress; +38°C to +46°C, very strong heat stress; +32°C to +38°C, strong heat stress; +26°C to +32°C, moderate heat stress; +9°C to +26°C, no thermal stress; +9°C to 0°C, slight cold stress; 0°C to –13°C, moderate cold stress; –13°C to –27°C, strong cold stress; –27°C to –40°C, very strong cold stress; below –40°C, extreme cold stress.
Precipitation change	**Definition:** Water being a primary resource, temporal and spatial variation in precipitation has serious implications for urban areas. Extreme rainfall events and their patterns are critical for designing urban areas. **Rainfall** Spatial and temporal variability of rainfall can be analyzed by assessing ground station data recorded by meteorological agencies such as the IMD or from satellite estimate products such as GPM or weather reanalysis products such as ECMWF Reanalysis v5 (ERA5). ▪ Temporal trends in rainfall patterns—The climatological and temporal trends of different cities vary. The inter-annual and intra-annual trends of rainfall give a picture of the city's meteorological situation (IMD n.d.-c). ▪ Spatial trends in rainfall—Large cities have a significant number of micro-climate zones, and spatial variations in rainfall are observed across these zones. Regional analysis is also critical because cities are dependent on these areas for water availability. ▪ Frequency of extreme rainfall days—The number of days of extreme rainfall in a year is a critical parameter and indicates the projected rainfall that the city's infrastructure has to be equipped for. ▪ Temporal trends in frequency of extreme rainfall days—Many studies have projected changes in extreme rainfall events due to climate change. Temporal trends in the frequency of extreme rainfall days (inter- and intra-annual) are critical for understanding their impacts on the city, by analyzing meteorological data from ground stations. ▪ Projected changes in rainfall—Understanding future projected changes in precipitation is critical. Similar to projected changes in temperature, an ensemble of climate models for two RCPs are to be used to project the changes. **Snowfall** Temporal trends in snowfall can be assessed with ground station meteorological data, and spatial trends in snow extent can be assessed with available satellite data. **Thresholds** The IMD's classification scheme (IMD n.d.-a, 2021-a) for 24-hour (daily) accumulated rainfall intensity is used to study extreme rainfall events (EREs) in three categories: heavy, very heavy, and extremely heavy rainfall events. The criterion used for classifying an ERE is based on the intensity of daily accumulated rainfall. Intensity is used to determine the probability of a single rainfall event that can overwhelm the drainage capability of hydraulic structures in a particular locality.
Windspeed	**Definition:** Extreme windspeed that may be associated with weather systems such as thunderstorms and cyclones is one of the major hazards impacting cities, because extreme winds can damage buildings, electrical infrastructure, and telecom networks and affect agriculture, forest, transport, and other sectors. *Data source: The IMD.* **Temporal Windspeed Trends** Characterizing the temporal trends of windspeed at different timescales to analyze the extreme windspeed distribution, variability, and frequency, particularly during extreme weather events, to identify the probable impact or risk.

TABLE B-1 | Meteorological hazards (cont'd.)

Weather events	**Definition** Typically, cities close to the sea are more vulnerable to cyclones. The IMD is the nodal agency in the region for monitoring cyclones in the north Indian Ocean, and data on past cyclones, their intensities, paths, and dates can be obtained from it and analyzed. *Data source: The IMD.*
	Cyclones Cyclones are caused by atmospheric disturbances around a low-pressure area distinguished by swift and often destructive air circulation. Cyclones are usually accompanied by violent storms and bad weather. ▪ Temporal windspeed trends—High frequency of cyclones in the neighborhood of the city is assessed. Because cyclones can affect areas far away from their eye, a buffer distance can be used to find the cyclones close to the city. ▪ Temporal trends of cyclones' strength and accumulated cyclone energy—The IMD classifies cyclones based on 3-minute mean sustained winds.
	Thunderstorms Studies indicate that thunderstorms increase because of both climate change and the heat island effect (Brooks 2013). However, attributing increased thunderstorms to climate change is challenging due to data limitations. ▪ Frequency of lightning strikes—Satellites can detect cloud-to-cloud, cloud-to-air, and cloud-to-ground strikes to a reasonable extent (Boccippio et al. 2001). Though cloud-to-ground strikes are more critical for human safety, the combined estimate is still a good basis for analyzing the vulnerability of a place to lightning strikes. If ground station data are available, cloud-to-ground strikes can be singled out and their spatial trends and frequency can be studied. ▪ Temporal trends in frequency of lightning strikes—Temporal trends across different timescales can be analyzed provided data are available for a significant period of time.
	Thresholds Cyclones are classified as cyclonic storms (34–47 knots [kt]), severe cyclonic storms (48–63 kt), very severe cyclonic storms (64–90 kt), extremely severe cyclonic storms (91–119 kt), and super cyclonic storms (≥120 kt) (IMD 2021b).
Sea level change	**Definition**: The analysis includes estimation and comparison of the annual trend of sea level variations from radar and float sensors, and examination of sea level variations caused by storm surge events. *Data sources: Survey of India and Indian National Center for Ocean Information Services (INCOIS).*
	Sea Level Rise and Fall ▪ Long-term sea level trends—Sea level data observed from tide gauges and other sensors in the city can be analyzed temporally for long-term trends. Increase in sea level can be caused both by climate change as well as by subsidence of the place where the data are recorded. ▪ Temporal tide level trends—Sea level rise is not spatially and temporally uniform. It is critical to understand the seasonal and diurnal variation in tides and how the local sea level has changed over time.
	Storm Surge ▪ Temporal storm surge trends—Storm surge trends are typically positively correlated with the trends in cyclones (Murty 1992). However, because other parameters affect the formation of storm surges, it becomes necessary to study temporal storm surge trends separately. However, in many places, the study of temporal trends would be limited by the low number of significant storm surges, making it mathematically difficult to derive trends. ▪ Frequency of storm surge events—Storm surges caused by cyclones are some of the deadliest hazard events to hit India. Most of the ~10,000 deaths caused by the 1999 Odisha Cyclone were because of storm surges (Jha 2016). However not all cyclones and not all locations face significant storm surge events because they are dependent on both the cyclone's strength, its path, the angle of incidence on the coastline, and the topography and bathymetry of the neighborhood. Frequency analysis of storm surge events can produce details on the vulnerability of a city to storm surge events.

Source: Authors.

TABLE B-2 | Hydrological hazards

Floods	**Definition:** Floods and stagnant rainwater have different causes. Urban areas in India are vulnerable to pluvial, fluvial, and coastal floods, and they are also affected by waterlogging due to a city's urban form, built-up area, storm network capacities, etc. If critical higher-resolution data such as elevation, stormwater network details, and soil information are available for the city, a flood risk model can also be simulated to delineate risk areas for different rainfall scenarios within and outside the urban area (De et al. 2013).
	Waterlogging Waterlogging is primarily caused by inadequate drain infrastructure, obstruction of natural drains, and over-concretization of the urban area (NDMA n.d.-c). Waterlogging hotspots in cities are usually known to the local administration. Spatial and temporal trends in such hotspots can be studied to better understand the risk faced by the urban area. *Data sources: Fire department, municipal corporation, city or district disaster management agency, etc.*
	Riverine Floods Riverine floods occur when the capacity of the river, stream, or channel is exceeded and riverbanks are breached due to heavy rainfall upstream (MIKE Powered by DHI n.d.). Riverine flood risk can be assessed through 2D and 3D modeling of the streams involved. Pluvial and flash floods associated with terrain could also be analyzed along with the riverine flood risk for urban areas. Coarse flood risk datasets such as Aqueduct (WRI n.d.) provide an overview of flood risk in the region. *Data sources: (Apart from modeling) High and low flood lines for the river and major reservoirs.*
	Coastal Floods and Storm Surges Coastal floods due to a rise in storm surge events can be modeled with high-resolution elevation and bathymetry datasets for the region. If high-resolution datasets are unavailable, low-lying areas can be identified using openly available elevation data; however, these may not be precise. *Data sources: National Institute of Ocean Technology (NIOT) and Indian National Center for Ocean Information Services (INCOIS).*
	Glacial Lake Outburst Though most Indian cities are far away from glaciers, glacial lake outburst flooding (GLOF) is a serious threat in some mountainous regions. With climate change, more glacial lakes are projected to form. These lakes are very unstable (Shugar et al. 2020) and can collapse, leading to floods downstream. GLOF modeling with ground-surveyed data can be done for vulnerable regions.
Drought	The dynamics of water–energy–land can greatly impact the sustainability and economy of cities. There are different types of droughts, such as hydrological drought, meteorological drought, and agricultural drought. The CHVA deals with hydrological and meteorological droughts, which are more relevant to urban setups, because the framework focuses on analyzing vulnerability for the cities. It is critical to understand the interconnectedness of droughts at the regional level, water resource distribution policies, and the river basins dominating water security along with the projected socioeconomic demand and long-term climatic scenarios. However, due to the fundamental nature of droughts, many drought types are not relevant to the analysis of intracity variations. *Data sources: WRI Aqueduct and Water Resource Information System (WRIS).*
	Hydrological Drought Hydrological drought results from prolonged meteorological drought, which depletes surface and sub-surface water resources (NIDM 2010). It is discussed as "water stress" at both the watershed scale and city level. Water stress refers to the ability, or the lack thereof, to meet the human and ecological demand for water. It considers several physical aspects related to water resources, including water scarcity, but also water quality, environmental flows, and the accessibility of water (Schulte 2014). Depending on the availability of historical precipitation and temperature datasets, surface flow datasets, soil moisture, water-demand-related datasets, and hydrological drought indices can be calculated (AgriMetSoft n.d.). These indices, which are the Surface Water Supply Index (SWSI), Reclamation Drought Index (RDI), Streamflow Drought Index (SDI), and Palmer Hydrologic Drought Index (PHDI), can also be useful for assessing the abundance of, and volumetric changes in, water resources. Water stress can also be derived using preprocessed products such as WRI Aqueduct 3.0 (cities should use the latest version of Aqueduct data and the tool).
	Meteorological Drought According to the IMD, a region is deemed to be experiencing drought when the rainfall deficit in that area reaches or exceeds 26% of its long-term normal (Shewale and Kumar 2005). Meteorological drought hazard analysis involves a non-parametric analysis of historical precipitation (AMS n.d.). Meteorological hazard is analyzed for the city as well as for the watersheds that it is dependent on.

TABLE B-2 | Hydrological hazards (cont'd.)

Drought	**Groundwater Exploitation** Many Indian cities are greatly dependent on groundwater resources for both drinking water and other needs. Central Ground Water Board (CGWB) assessments are available for multiple years and can be used to conduct a temporal study on groundwater resources. Open well and tube well data provide water table level information. These datasets can be obtained from urban local bodies or state agencies, or the CGWB assessments can be studied for spatial and temporal patterns. **Thresholds** ▪ Meteorological Drought—Meteorological droughts, according to the IMD, are classified as follows based on rainfall deficiency relative to the long-term normal: moderate drought (26%–50% rainfall deficiency) and severe drought (>50% rainfall deficiency). Analyzing trends in the frequency of droughts can be used to obtain the probability of droughts. The IMD uses drought probability to classify drought-prone areas: areas that are least affected (<10% drought probability), areas that are frequently affected (10%–20% probability), and areas that are chronically affected by drought (>20% probability). ▪ Stage of Groundwater Development—The stage of groundwater development is the ratio of the annual groundwater draft to the net annual groundwater availability, expressed as a percentage. Simply put, it is the ratio of the actual groundwater extraction to the permitted groundwater extraction, expressed as a percentage. The stage of groundwater development is categorized as safe (<70%), semi-critical (70–90%), critical (90–100%), and overexploited (>100%) (CGWB n.d.).

Source: Authors.

TABLE B-3 | Geological hazards

Land deformation	**Definition:** Land deformation is any horizontal or vertical change to the landscape. *Data sources: Synthetic Aperture RADAR (SAR) images through Differential Interferometric Synthetic Aperture Radar techniques and Global Navigational Satellite System (GNSS) station datasets.*
	Land Subsidence Land subsidence is the gradual or sudden sinking of the surface. Though land subsidence can occur due to different reasons, one of the important causes is overextraction of groundwater (Galloway and Burbey 2011). Land subsidence can be measured by processing SAR images through Differential Interferometric Synthetic Aperture Radar techniques. It can also be corroborated with the change in vertical position of the place obtained through GNSS station datasets. GNSS stations can provide temporal trends of the change in position with respect to the vertical axis (ground elevation levels).
	Coastline or Sea Level Changes Historical change in coastlines due to natural changes, climate change, and other anthropogenic factors can be assessed through satellite images (Bishop-Taylor et al. 2021). Coastlines delineated by classifying satellite images corresponding to similar tide phases in two time periods can be compared to obtain the change in coastline. Future projections of the change in coastline, however, would require shoreline modeling and data such as sediment inflow and longshore drifts, which are difficult to obtain.
Ground movement	**Definition:** Micro-seismic activities can be analyzed to identify spatiotemporal trends and patterns in ground movement.
	Landslide Many parts of India with significant slopes are vulnerable to landslides. Landslides due to heavy rainfall or other causes are typically aggravated in urban areas due to slope instability caused by construction (Froude and Petley n.d.). Landslide assessments for urban areas can be done by analyzing landslide susceptibility using multiple geological data, slope, land cover, etc. Historical landslide hotspots can also be analyzed to understand spatial and temporal trends. These trends can be overlayed with infrastructure layers to assess landslide risks in transport networks where a lot of slope cutting is done. *Data sources: GSI and Global Landslide Susceptibility (NASA).*
	Avalanche Avalanche effects are limited to the upper reaches of the Himalayas (Government of Himachal Pradesh n.d.), and for urban areas present in that region, historical avalanche occurrence data can be spatially and temporally analyzed.

Source: Authors.

TABLE B-4 | Environmental hazards

Air quality degradation	**Definition:** Anthropogenic air pollution is a major public health hazard worldwide. The human health challenges and threats posed by air pollution can be aggravated by climate change. Also, emissions from fossil fuel sources within the city are a key contributor to greenhouse gases (Kinney 2018). Air pollutant concentrations are compared with the latest National Ambient Air Quality Standards. *Data sources: Pollutant concentrations from the Central Pollution Control Board (CPCB), the respective state pollution control board monitoring stations, and city monitoring stations.*
	Indoor Air Quality Degradation Indoor air quality is the risk faced by the people of the city through exposure to pollutants created inside a house. There are methods to estimate emissions of air pollution inside the city (Walvekar 2019). One of the key datasets for estimating indoor air quality is cooking fuel usage, which can be obtained from the latest Census.
	Outdoor Air Quality Degradation Outdoor air quality risk is defined by two parameters: air pollutant concentration and air pollutant hotspot analysis to determine the temporality and spatial concentration of air pollutants, such as particulate matter (PM2.5, PM10/SPM, Respiratory Suspended Particulate Matter [RSPM]), nitrogen dioxide (NO_2) or oxides of nitrogen, sulfur dioxide (SO_2), carbon monoxide (CO), and ammonia (NH_3). Areas with high concentration of air pollutants in the city are more vulnerable. Interventions to improve air quality depend on the spatial variability of pollutants.
Water quality degradation	Both surface water and groundwater quality are measured using three types of parameters: physical, chemical, and biological. Physical parameters are turbidity, temperature, total suspended solids (TSS), and total dissolved solids (TDS). Chemical parameters are pertain to the chemical state of the water, such as pH, and the presence of minerals or chemicals such as fluorides, nitrates, dissolved oxygen (DO), biological oxygen demand (BOD), organic content, arsenic, etc. Biological parameters are fecal coliform, chlorophyll-a, etc. (O'Donnell 2021). Water quality standards follow the latest standards prescribed by the Central Pollution Control Board (CPCB) of India. *Data sources: Pollutant levels from CPCB, the respective state pollution control board monitoring stations, and city monitoring stations.*
Soil quality degradation	Soil quality is critical for plant and animal productivity and also for hazards faced by urban areas and neighboring regions. Though soil quality is not directly affected by climate change, indirect effects and compounded effects could increase pressure on urban areas. Similar to water quality, soil quality is also measured in three ways: physical (porosity, texture, penetration resistance, etc.), chemical (pH, nutrient levels, nitrate presence), and biological (diversity of organisms in soil from field surveys) (Bünemann et al. 2018). *Data sources: Pollution control boards and soil health cards (Department of Agriculture and Farmers Welfare).*
Vegetation change	Vegetation plays a critical role in hazard reduction and resilience, and can be measured by processing satellite images. Vegetation indices such as Normalized Differential Vegetation Index (NDVI) (USGS n.d.-a) and Enhanced Vegetation Index (EVI) (USGS n.d.-b) calculated from these satellite images are observed for spatial and temporal variations. *Data sources: Landsat 5, 7, 8 (USGS), Moderate Resolution Imaging Spectroradiometer (MODIS) (NASA Land Processes Distributed Active Archive Center [LPDAAC]), Bhuvan (National Remote Sensing Centre [NRSC]).*
Fire	Thermal anomalies at a coarse resolution have been regularly observed by satellite sensors such as MODIS and Visible Infrared Imaging Radiometer Suite (VIIRS). Spatial and temporal patterns of these fire observations in close proximity to the city are useful to understand the pollution and heat faced by the city (NASA n.d.). *Data sources: Fire Information for Resource Management System (FIRMS) (LANCE NASA).*

Source: Authors.

APPENDIX C: DATASETS NEEDED FOR CREATING A CITY PROFILE

TABLE C-1 | Datasets needed for creating a city profile

S.NO.	CATEGORY	DATASET
1	Key boundaries	▪ District, taluk, village, city (corporation/urban local body [ULB] limits), wards (census and administrative) ▪ Watershed, basin or sub-basin ▪ National parks, sanctuaries, forests, and reserves within the watershed region ▪ Water bodies, lakes, reservoirs, rivers, streams, *nullahs* (watercourses), railway lines, etc. ▪ Coastal zone regulation boundaries ▪ Slum and informal settlement locations, names, and boundaries, preferably with population, household, details of access to household basic services and amenities along with slum typology: Notified Slums, Unauthorized Colonies, Resettlement Colonies and Squatters (*jhuggis*, i.e., houses, usually made from mud and sheets of iron), etc., if any ▪ Mining and quarrying areas (in and around city) ▪ Industrial estates and industrial development boards (in and around city)
2	Economic losses	Infrastructure: Damage, repairs, new construction, etc., due to a major climatic disaster event, preferably segregated by hazard category
3	Key physical infrastructure locations and network	▪ Important transport terminals, hubs, ports, harbors, and shipyards—air and sea ▪ Roads and transport network with road width and footpaths ▪ Bus network including bus stops and terminals (intra- and intercity) ▪ Rail network with stations ▪ Metro and monorail stations and networks ▪ Water resources (dams, reservoirs and tanks, etc.), treatment facility, supply, and distribution ▪ Sanitation and sewage network, public and community toilets, and treatment facility (sewage treatment plant [STP], common effluent treatment plant [CETP], fecal sludge treatment plant [FSTP], tertiary treatment plant [TTP], etc.). ▪ Stormwater network and management system ▪ Solid waste network, management systems, and treatment facilities, dump yards, collection centers, landfill sites, etc. ▪ Power generation, distribution, and supply; power stations and substations ▪ Oil and gas infrastructure and network ▪ Emergency, safety, fire, and disaster relief service stations including sensors and station locations critical for environmental and climate monitoring (seismic sensors, air pollution monitoring stations, automatic weather stations, telemetric stations, rain gauge, environment stations, flowmeters, flow sensors, etc.) ▪ Digital and communications: Fiber, Internet, and telecommunication networks ▪ Social Infrastructure - Hospitals (preferably segregated by government and non-government typology and bed counts) - Schools (preferably segregated by government and non-government typology) - Disaster and flood relief shelters - Public distribution system - Important food storage sites such as markets and warehouses - Public information systems and early warning systems and units - Night shelters - Public green open spaces (preferably segregated by typology and area per the latest Urban and Regional Development Plans Formulation and Implementation [URDPFI] guidelines, including tree census if any) - Heritage buildings and important monuments ▪ Housing and other built infrastructure ▪ To assess the adequacy of infrastructure networks such as stormwater, sewage, water supply, etc., carrying capacity assessment or other allied studies will be helpful. Otherwise, network lengths and diagrams as shapefiles/digital files along with the network inlet/outlet, slopes, cross sections, times of supply and flow pressures along with siltation level, if any, at regular intervals will be needed to compute infrastructure network capacities

TABLE C-1 | Datasets needed for creating a city profile (Cont'd)

S.NO.	CATEGORY	DATASET
4	Land use	Existing land use (latest) as approved by the ULB; master and development plans and associated critical city project documents to supplement sectoral knowledge and infrastructure (capacity) assessments of the city
5	Building footprints	Building footprint data, preferably with heights, floor area ratio (FAR) or floor space index (FSI) used, and plot area details or plot boundaries to estimate FAR consumed Tentative agency: State or city GIS agency, National Remote Sensing Center (NRSC), or satellite-derived products such as Global Human Settlement Layer JRC, Microsoft Global Building Footprint, and World Settlement Footprint ESA
6	Land use land cover (LULC)	Detailed land use land cover classification (approved by nodal agencies) Tentative agency: State or city GIS agencies, NRSC, or satellite-derived products such as ESA WorldCover, Sentinel 2 derived,[22] etc.
7	Topography and river flows	Granular level contour detail, Digital Elevation Model (DEM) and Digital Terrain Model (DTM) (suitably conditioned if available) along with additional studies available on watershed, basins, associated river flows, and dam capacities and discharge Tentative agency: State or city GIS agencies; Central Water Commission (CWC); NRSC; satellite-derived products such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Shuttle Radar Topography Mission (SRTM), Cartosat, and Advanced Land Observing Satellite (ALOS) DEMs; or by using LiDAR and land surveying techniques
8	Jobs	▪ Locations of employment centers, industrial hubs, special investment regions and economic zones, industrial parks, industries, factories, and manufacturing units with employment data ▪ City's central or commercial and business district boundaries
9	Important documents (latest)	▪ City master plan and development plan ▪ City, district, state disaster management plan ▪ City environment plan ▪ Clean air action plan ▪ Comprehensive mobility plan, comprehensive traffic and transportation plan, approved traffic and transport studies ▪ Emission inventory and source apportionment studies ▪ Studies on floods and flood forecasting, if applicable ▪ Statements of purpose for respective departments for all climate or environmental hazards ▪ Previously conducted climate action plans and vulnerability assessments or related studies (if any) ▪ Documents pertaining to all climate, environmental, socioeconomic aspects and surveys in the city or region that can supplement the CHVA ▪ Plans and documents of related central-, state-, and city-level missions and schemes that can supplement the CHVA

Note: All datasets (primarily rows 1 to 5), unless mentioned, can be collected from the respective departments of state, parastatal, district, metropolitan, or city nodal agencies; corporations; and allied departments. Some datasets may also be available with national agencies such as the Forest Survey of India, Survey of India, NRSC, CWC, Central Pollution Control Board, Pradhan Mantri Gati Shakti, National Informatics Center–Open Government Data Platform India, etc. Most of the datasets associated with the physical features of the city can also be derived from satellite data by using the sources mentioned in the table and Appendix B, or through surveys deemed suitable by the CHVA steering agency. It is suggested that all datasets be collected and optimized for the CHVA (see Chapter 6).

Source: Authors.

APPENDIX D: QUESTIONNAIRE TO ASSESS VULNERABILITY OF INFRASTRUCTURE

With reference to Table 10, Chapter 4, the following list of questions is framed to assist and supply exhaustive leads to investigate and collect the information needed to assess infrastructure vulnerability in any study area. Before beginning the questionnaire-based assessment, the agency undertaking the assessment needs to clearly define the scope, scale, and institutional matrix of the city, including identifying the relevant stakeholders for the interviews and discussions corresponding to the questionnaire, such as national, state, and local institutions. Thereafter, the questionnaire can be used, not as a checklist, but as a guiding tool that can be modified to suit the relevance of the subject and stakeholder.

The NDMA has laid down a comprehensive structure for tiered disaster management and risk reduction planning at both the state and district levels through disaster management plans (DMPs). According to the National Disaster Management Plan (NDMP) 2019, the detailed responsibility matrix for all associated agencies and departments is designed for each hazard, and its interlinkage with climate change is identified and defined by the NDMA (2019). Alongside NDMP 2019, the NDMA and the National Institute of Disaster Management (NIDM) provide the framework (NDMA 2014; Singh 2019), explanatory guidance,[23] Standard Operating Procedures (SoPs) (NDMA n.d.-e), and training to all institutions and departments (NDMA n.d.-f) involved in creating and implementing state- and district-level DMPs (NIDM 2018). The mandates and roles of many of the agencies identified for assessing the intangible elements of infrastructure and governance systems as part of the CHVA assessment, therefore, need be thoroughly reviewed on the basis of the latest NDMP protocols laid down for the ministries and departments of the states and of the Government of India (GoI).

The questionnaire (see Table D-1) attempts to simplify the complex interlinkages between the social, technical, and physical aspects of the infrastructure and its operating systems in the city, which can be impacted by hazards in multiple ways. Exposure analysis and a part of sensitivity analysis (mapping plausible service area reductions due to hazards), as listed in Table 10, demarcate which infrastructure assets are physically located in hazard-prone areas. The questionnaire targets information characterizing infrastructure in terms of its effectiveness, functional capacities, efficiencies, and interdependencies with regard to other social, economic, and governance aspects, including hazard response and mitigation. The agencies undertaking the assessment need to review and provide qualitative and quantitative assessments based on the information collected using the questionnaire (in accordance with Table 10). This could take the form of comparative reviews, sectoral gap assessments, performance and risk assessments of infrastructure systems, and so on.

TABLE D-1 | Questionnaire: Identifying intangible elements of infrastructure and governance systems in the city

Q. NO.	LIST OF QUESTIONS AND LEADS
1	Which institutions can help your local government conduct a vulnerability assessment of the critical infrastructure in the city? ** Institutions should include (but not be limited to) the listed sectors: roads and transport; water resource and supply; sanitation and sewage; stormwater management; solid waste management; power generation and distribution; emergency and disaster relief; digital communications; social infrastructure; blue-green infrastructure; urban agriculture and food systems; and housing and other built infrastructure.*
2	Who is responsible for the first response during a specific climate-related or climate-induced disaster? What are the roles and responsibilities of the agency?
3	Are any previous assessments or studies available to support the design of existing infrastructure and its carrying capacity? Can you share the relevant documents to support your answer?
4	Given the current and projected population growth per the development plan, what are the recognized critical demand supply gaps in the listed critical infrastructure categories? Can you share the relevant documents to support your answer?
5	Given the current and projected population growth per the development plan, what are the ongoing or future initiatives to reduce "infrastructure gaps"? Can you share the relevant documents to support your answer?
6	Will any of the initiatives answered for Q. 4–5 internalize hazard risk reduction or vulnerability reduction as targets? How? Can you share the relevant documents to support your answer?

TABLE D-1 | Questionnaire: Identifying intangible elements of infrastructure and governance systems in the city (cont'd.)

Q. NO.	Vulnerability indicator	Information needs	Questions
1	Physical damage to infrastructure assets	Reports regarding the nature and extent of damage to specific assets: location of these assets, historical instances of damage due to different hazards	Is there a system to identify the loss and damage caused to infrastructure assets due to hazards? If so, can the "information needs" (see the adjacent column) for this assessment be shared?
2	Reduction in service area due to "lack of" physical access to infrastructure and amenities during and immediately after hazard events, such as · Healthcare · Education · Mass transit or public transport · Public green open spaces · Emergency or disaster relief shelters	Map of the location of physical infrastructure assets and network within hazard-prone areas or hotspots or area likely to be impacted by each sub-category of hazards and multiple hazards	What are the types of service disruption complaints or emergency service delivery requests most often received during various types of hazards identified in the city?
			Through institutional memory, can the extent of damage (spatial and temporal disruption) to the infrastructure, asset, or amenity be estimated? For example, the extent of inundation around the metro station in terms of the radius around the station in meters and the number of hours or days of disruption?
			If any amenity or public asset becomes dysfunctional due to hazard impact, what are the protocols around improving the situation immediately?
			After the impact, which teams or agencies are responsible for management and recovery of the assets impacted? What is the line of action?
	Vulnerability indicator	**Information needs**	**Questions**
3	Revenue losses due to disrupted livelihoods and services	Reports regarding revenue losses due to disruption in services during a disaster event, the extent and duration of the disruption, time needed to resume services (including previous instances of similar challenges)	On an average, how many days and hours of service disruption occur in the city for each identified hazard?
			Are there any records that estimate the loss in revenue incurred due to service disruption? Can you share the relevant documents to support your answer?
		Reports regarding estimated GDP or working hours/days lost due to a disaster event or due to a serious disruption in services (including previous instances of similar challenges)	Do social safety nets exist for lost livelihoods (loss of working hours or days), especially for identified vulnerable groups. Can you share the relevant documents to support your answer?
4	Revenue losses due to damage to physical assets	Reports regarding economic losses due to physical damage of assets during a disaster event, the breakup of these losses and attribution to specific assets, repair and rebuilding (including previous instances of similar challenges)	Is there a mechanism to distinguish the annual repair and maintenance costs incurred on the infrastructure and systems from the loss and damage incurred due to hazards?
			Can you share the relevant documents to support your answers to the previous questions?
			Which particular assets repeatedly incur major losses due to hazards?
5	Death and injury	Reports regarding the number of lives lost and people injured due to physical damage of assets.	Is your staff appointed to run the day-to-day operations of these critical infrastructure and systems trained and given drills on evacuating people or assisting them during the hazard events?
			What are the protocols around training the concerned staff and equipping them with hazard response and preparedness strategies?
6	Disease breakouts due to damage to infrastructure	Reports regarding health impact of the hazard	Have there been any instances of infrastructure asset damage leading to hazardous situations or leading to chemical leaks or prolonged shortages in supplies?

TABLE D-1 | Questionnaire: Identifying intangible elements of infrastructure and governance systems in the city (cont'd.)

			Have any assessments been conducted on the historical or potential health risks associated with the failure or damage of any infrastructure in the city, such as sewage treatment plants (STPs), landfills, and water treatment plants (WTPs)?
			Can you share relevant documents to support your answers to the previous questions?
7	Emergency funds, disaster relief funds	Amounts the city has previously accessed as emergency or disaster relief funds for the last 10 years, along with disbursement and utilization records	What is the funding or financing mechanism for disaster response and relief? Who are the responsible agencies?
			Are there emergency funds at the city, sector, or infrastructure level within different institutions for specific activities?
			Who holds and controls the funds and what is the modality for disbursement?
			What is the scope of utilization? Is there any participatory budgeting for these emergency or disaster relief funds?
			Can the allocation be adjusted based on need or is there a standard template for fund utilization?
			Are there any mechanisms to direct funding to the most vulnerable communities? Do mechanisms for cash transfers exist? If yes, can you share the relevant documents to support your answers to the previous questions?
	Vulnerability indicator	**Information needs**	**Questions**
8	Insurance	Are the assets insured? If yes, which assets and under what conditions?	
		Can you share the relevant documents to support your answers to the previous questions?	
9	Climate proofing funds	Reports regarding repairing the damage of specific assets: proposals to change, relocate, and expand specific assets	What is the rationale and funding or financing mechanism?
			Is there any additional user fee to fund the climate proofing?
10	Early Warning Systems	Documents to understand the capacities of existing or proposed early warning systems and related schemes applicable in the city	What sort of public information systems exist in the city?
			Are there any early warning systems in place?
			Is the public information system also used to broadcast early warnings and evacuation guides?
			Which agency is responsible for the regular maintenance and upkeep of these systems?
			Is there a feedback system to understand the effectiveness and reach of these early warning systems, especially in low-income vulnerable communities?
			Can you share the relevant documents to support your answers to the previous questions?

TABLE D-1 | Questionnaire: Identifying intangible elements of infrastructure and governance systems in the city (cont'd.)

11	Disaster management plans (DMPs) at the city level and for infrastructure and essential services	State, district, and city disaster management plans, departmental or ministerial DMPs and SoPs, community-based disaster management plans (CBDMs), disaster risk reduction (DRR) and recovery plans, clean air action plans, hazard-specific action plans (such as action, work, and management plans related to heat and floods), disaster mitigation plans and schemes for community volunteers in disaster response (Aapda Mitra) (NDMA n.d.-g), documentation of disaster relief and rescue, recovery, reduction, mitigation, management, early warning, evacuation, first aid, etc., allied ongoing or proposed schemes and plans	Does the city have a disaster management plan? If yes, how is compliance with and implementation of the plan ensured? How often is the plan revised based on new information? What climate-hazard-specific measures are included in these plans taken up by the city to mitigate the negative impacts of hazards? Are there reliable public distribution systems for food, medicines, communication, and other basic supplies? Can details be given of SoPs related to basic essential civic services before and after disaster onset?
12	Climate proofing of assets	Are there any documents to support the current infrastructure to validate its "climate proofing" abilities? Any upcoming proposals for climate proofing assets: passive and modified design techniques, change in technology or material through both construction and maintenance phases? Do these upgrades consider carrying capacity assessments for different climate and environmental hazard scenarios?	
	Vulnerability indicator	**Information needs**	**Questions**
13	Coordination and communication mechanisms	What is the chain of communication and chain of command for initiation of on-ground support? What is the approximate time for a response? What is the jurisdictional split of the response to a particular hazard and on what basis is the split made? What is the coordination protocol for first responders? What is the communication channel used to inform residents about whom to contact during an emergency and how?	
14	Response protocols	What is the response protocol during a disaster event? Who provides remote support and how? Who provides on-ground support and how? Are there any periodic routing protocols for disaster-proof architecture of critical city infrastructure? Are there any documents, such as an "Emergency Preparedness Guide," for making alternative plans during emergencies, both localized and citywide?	
15	Staff capacity and training	Is there regular training for staff on the latest technologies, sectoral challenges, climate change implications, impact on services and business, and first response (if on-ground support is provided)?	
16	Citizen engagement and community participation	Are workers, women, communities, and citizens involved in planning and undertaking response action? Are they involved or consulted in on-ground support and operations? How often are meetings scheduled to consult and inform them and engage with them?	

Exposure Sensitivity Adaptive capacity

Source: Authors.

ABBREVIATIONS

100RC	100 Resilient Cities
ACCCRN	Asian Cities Climate Change Resilience Network
API	application programming interface
AR	Assessment report of the IPCC
ARC3.2	Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network
ASI	Annual Survey of Industries
AWS	automatic weather station
BBMP	Bruhat Bengaluru Mahanagara Palike
BCAP	Bengaluru Climate Action Plan
BMC	Brihanmumbai Municipal Corporation
BUR	Biennial Update Report
CAP	climate action plan
CBO	community-based organization
CCRA	Climate Change Risk Assessment
CEEW	Council on Energy, Environment, and Water
CEO	chief executive officer
CGWB	Central Ground Water Board
CHVA	Climate Hazard and Vulnerability Assessment
CRZ	Coastal Regulation Zone
CSCAF	Climate Smart Cities Assessment Framework
CSO	civil society organization
CVI	climate vulnerability index
DEA	Department of Economic Affairs
DMA	Disaster Management Authority
DoE	Department of Expenditure
DPR	detailed project report
DRR	disaster risk reduction
DST	Department of Science and Technology
EA	Exposure Analysis
ECLAC	Economic Commission for Latin America and the Caribbean
ESRI	Environmental Systems Research Institute
GCoM	Global Covenant of Mayors for Climate and Energy
GFDRR	Global Facility for Disaster Reduction and Recovery
GIS	geographic information systems
GoI	Government of India
HFL	high flood line
HIA	Hazard Identification and Assessment
HIGS	Hazards, Infrastructure, Governance, and Socioeconomic Framework
ICA	Inclusive Climate Action
ICAP	Inclusive Climate Action Planning
IDF	intensity, duration, frequency
IISc	Indian Institute of Science
IIT	Indian Institute of Technology
ILO	International Labour Organization
ILOSTAT	International Labour Statistics
IMD	India Meteorological Department
IMF	International Monetary Fund
INCOIS	Indian National Center for Ocean Information Services
IPCC	Intergovernmental Panel on Climate Change
KSNDMC	Karnataka State Natural Disaster Monitoring Center
KSRSAC	Karnataka State Remote Sensing Applications Centre
LPDAAC	Land Processes Distributed Active Archive Center
LST	land surface temperature
MCAP	Mumbai Climate Action Plan
MODIS	Moderate Resolution Imaging Spectroradiometer
MoEFCC	Ministry of Environment, Forests, and Climate Change
MoHUA	Ministry of Housing and Urban Affairs
MVA	Majhi Vasundhara Abhiyan
NAPCC	National Action Plan on Climate Change

NASA	National Aeronautics and Space Administration
NATCOM	National Communication to the UNFCCC
NCAP	National Clean Air Program
NDMA	National Disaster Management Authority
NDVI	Normalized Difference Vegetation Index
NGO	nongovernmental organization
NIUA	National Institute of Urban Affairs
NRSC	National Remote Sensing Centre
PIB	Press Information Bureau
PM	particulate matter
PMAY	Pradhan Mantri Awas Yojana
PoC	point of contact
PRA	participatory rural appraisal
PWD	Public Works Department
RCP	Representative Concentration Pathways
RSA	rapid social analysis
RWA	residents welfare association
SAPCC	State Action Plan on Climate Change
SC	Scheduled Caste
SDG	Sustainable Development Goals
SSI	small scale industry
ST	Scheduled Tribe
SWM	solid waste management
TERI	The Energy and Resources Institute
UCRA	Urban Community Resilience Assessment
URDPFI	Urban and Regional Development Plans Formulation and Implementation
UHI	urban heat island
ULB	urban local body
UN	United Nations
UNDP	United Nations Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations International Children's Emergency Fund
USGS	United States Geological Survey
VA	Vulnerability Assessment
WB	World Bank
WG	Working Group of the IPCC
WHO	World Health Organization
WRI	World Resources Institute
WRIS	Water Resource Information System
WSF	World Settlement Footprint
YUVA	Youth for Unity and Voluntary Action

GLOSSARY

Adaptation: "In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (IPCC 2022, 2898). For a discussion of adaptation compared to resilience, see Pelling (2011).

Adaptive capacity: "The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or respond to consequences" (IPCC 2022, 2899).

Anthropogenic: "Resulting from or produced by human activities" (IPCC 2022, 2900). Anthropogenic climate change refers to climate change that is directly attributable to human actions and not the result of natural changes.

Climate action plan: In cities, a plan, or a collection of plans, that is intended to provide a comprehensive path forward in the face of climate hazards. Climate action plans often include both elements of mitigation and adaptation, also often focusing on mainstreaming climate-focused interventions into other urban planning initiatives.

Climate change: "A change in the state of the climate that can be identified [. . .] by changes in the mean and/or variability of its properties that persists for an extended period of time [. . .]. Climate change may be due to natural internal processes or external forcings [. . .] and persistent anthropogenic changes in the composition of the atmosphere or in land use" (IPCC 2022, 2902).

Climate justice: "Justice that links development and human rights to achieve a human-centred approach to addressing climate change, safeguarding the rights of the most vulnerable people and sharing the burdens and benefits of climate change and its impacts equitably and fairly" (IPCC 2022, 2913).

Compound risks: These risks "arise from the interaction of hazards, which may be characterised by single extreme events or multiple coincident or sequential events that interact with exposed systems or sectors" (IPCC 2022, 2921).

Critical infrastructure: Urban infrastructure, such as public transport, roads and highways, water distribution, sanitation, solid waste management, healthcare, and other essential aspects of urban infrastructure that are often publicly provided or supported.

Differential vulnerability: A conceptualization of vulnerability that centers the fact that how hazards are experienced differs greatly depending on the social, economic, political, and cultural features of the affected people (Thomas et al. 2019). This concept is cross-scalar and acknowledges that how climate change is experienced is uneven, contextual, and deeply connected with forms of inequality, poverty, and marginalization.

Disaster risk reduction (DRR): "[T]he strategic and instrumental measures employed for anticipating future disaster risk; reducing existing exposure, hazard or vulnerability; and improving resilience" (IPCC 2022, 2906). In practice, it is often an incremental rather than transformational policy or set of policies that focuses on coping with and recovering from disasters. DRR rarely focuses on fundamentally changing social or economic systems, addressing the root social causes of vulnerability to disasters, or considering slower-onset climate hazards.

Exposure: "The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected" (IPCC 2022, 2908).

Hazard: "The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources" (IPCC 2022, 2911).

Incremental adaptation: "Adaptation that maintains the essence and integrity of a system or process at a given scale" (IPCC 2022, 2899). Incremental forms of adaptation focus on maintaining or returning to an existing socio-economic or political status quo, even if that status quo engenders enduring forms of climate vulnerability. It is broadly acknowledged in the literature that incremental forms of adaptation are insufficient for coping with climate change and that transformational adaptation is necessary (see Pelling [2011] for an in-depth description of incremental adaptation and a comparison with the concept of resilience).

Maladaptation: "Actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas (GHG) emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, diminished welfare, now or in the future" (IPCC 2022, 2915).

Mitigation: "Human intervention to reduce emissions or enhance the sinks of greenhouse gases" (IPCC 2022, 2915).

Multi-hazard analysis: A form of climate hazard analysis that takes into account multiple hazards (e.g., heat, sea level rise, flooding) simultaneously, considering the compound effects of those hazards.

Resilience: "The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure" (IPCC 2022, 2921). For a discussion of resilience compared to adaptation, see Pelling (2011).

Risk: "The potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. [. . .] In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards" (IPCC 2022, 2921).

Sensitivity: "The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change" (IPCC 2022, 2922).

Spatial analysis: In the context of vulnerability assessments, a form of analysis where exposure to hazards, sensitivity, and adaptive capacity are considered spatially and mapped for a complete understanding of how hazards interact with social and geographical factors.

Temporal analysis: In the context of vulnerability assessments, a form of analysis where vulnerability is analyzed over time, taking into account past data as well as future projections.

Transformational adaptation: "Adaptation that changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts" (IPCC 2022, 2899). Transformational adaptation is understood to be quite rare in practice but necessary to cope with climate change. Such forms of adaptation are impeded by the inertia of existing social, economic, and political systems (see Pelling [2011] for an in-depth description and comparison of the concepts of incremental adaptation and resilience).

Urban heat island: "Urban heat islands occur when cities replace natural land cover with dense concentrations of pavement, buildings, and other surfaces that absorb and retain heat. This effect increases energy costs (e.g., for air conditioning), air pollution levels, and heat-related illness and mortality" (U.S. EPA n.d.).

Vulnerability: "The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC 2022, 2927).

Vulnerability assessment: A tool or framework intended to assess the vulnerability of a given area in a standardized manner.

Water stress: Water stress refers to the ability, or the lack thereof, to meet the human and ecological demand for water. It considers several physical aspects related to water resources, including water scarcity, but also water quality, environmental flows, and the accessibility of water (Schulte 2014).

Note: As noted, many of these definitions have been taken directly from WGII of the AR6 IPCC Report (IPCC 2022).

ENDNOTES

1. The range of climatic hazards faced in Indian cities is broad, and the climate crisis is set to make such hazards more intense, worsening the vulnerability of urban populations. However, tracing the origins of these hazards can be complicated, and causal connections between hazards and climate change are not always clear. For example, the attribution of particular events to climate change is inherently speculative; individual cyclones, heat waves, or storms are not necessarily attributable to human-caused climate change. However, recent climate science confirms that the aggregate frequency and intensity of such events has already increased and is set to worsen (IPCC 2021). Further, slow-onset concerns, such as sea level rise, changes in precipitation patterns, and increases in average temperatures, are more directly attributable to climate change and are already affecting South Asia (see IPCC 2021,10).

   However, the analysis of climate hazards, vulnerability, and risks is complex, and many hazards faced by particular cities are mediated by non-climatic aspects of urbanization (see IPCC WGI 2021:25). In this report, we analyze how exposure to climate-induced hazards—many of which have been brought on or intensified by climate change and are set to become worse due to climate change—contribute in part to the differential vulnerability of urban populations. Further, as outlined below, exposure to these hazards does not alone explain climate vulnerability, especially the concern of differential vulnerability that we focus on in this report.

2. The Common Reporting Framework (CRF) of The Global Covenant of Mayors for Climate & Energy (GCoM) provides guidance for cities on how to report on risk and vulnerability assessments to better understand the impact of hazards and the adaptive capacity of local governments. Launched in 2018, the CRF highlights the importance of reporting on climate hazards, adaptive capacity, and major climate hazards that occurred in the past years (GCoM 2018).

3. Launched in 2019, C40's Inclusive Climate Action resources have been an important effort to center inclusivity through process, policy and impact towards making climate action plans equitable and people-centric.

4. Tension exists between the concepts of adaptation and resilience. However, differences between the terms are often unclear, and they are frequently used interchangeably. *Adaptation* is broadly favored in some academic spaces as well as within the UNFCCC and by the IPCC. Many academics have claimed that adaptation can take various forms, ranging from incremental change to much more substantial "transformational" change (see Pelling 2011; IPCC 2022).

   This approach generally assumes that resilience is inherently incremental in nature and cannot focus on the system-level change needed for transformation. However, the definitional differences between the terms erode in practice. In India, practitioners largely prefer the term *resilience*, understand adaptation as inherently incremental, and suggest that resilience better addresses the complexity of urban systems. Because of this approach to the term, we broadly favor the use of the term *resilience* in this report. However, it is important to note that vulnerability assessments are critical whether or not the resulting plans are labeled *resilience* or *adaptation* (Chu et al. 2019).

5. Supported by the Swiss Agency for Development and Cooperation's (SDC) Global Programme on Climate Change, the CapaCITIES project will support and accelerate the Government of India's efforts for sustainable urbanization. The project goal was to strengthen the capacities of Indian cities to identify, plan, and implement measures for achieving a lower greenhouse gas emissions growth path and enhancing resilience to climate change in an integrated manner.

6. One of the five CSCAF categories. More on CSCAF can be read here: https://www.niua.org/c-cube/e-reports/cscaf.php.

7. See Chapter 6 for details on how cities and agencies conducting the CHVA can deduce thresholds from scientific reports and methods and use participatory approaches to localize indicators.

8. Sociopolitical determinants of vulnerability are inherently challenging to measure with available data. Housing and tenure are imperfect proxies, and when conducting the CHVA, it is important to consider the broader context of how tenancy and home ownership relate to potential precarity and climate vulnerability. Other proxies to assess sociopolitical vulnerability in localities could include voting rates, estimates of migrants living in an area, and the proportion of the population with legal documents. However, these proxies are also challenging to measure and difficult to interpret.

9. See Glen (n.d.). Sen's slope test is a non-parametric test suitable for highly varying 2-dimensional datasets whose values may not pertain to certain distribution characteristics. This test is used to identify the magnitude of the trend line slope, that is, by how much is the trend increasing or decreasing.

10. Anomalies indicate the extent of deviation of annual averages with respect to the baseline or long-period average. According to the India Meteorological Department (IMD), the 30-year period between 1981 and 2010 is used to estimate the baseline average air temperature. The direction and range of deviation from the baseline marks positive or negative variance as an indicator of change.

11. Change points divide each time series into segments, where the values within each segment have a similar mean, standard deviation, or linear trend (slope and intercept). Change points are defined as the first time step in each new segment starting with the second segment, so the number of change points is always one fewer than the number of segments. How does change point detection work? See Esri (n.d.-a).

12. An example of spatiotemporal analysis: A long-term (over 18 years) seasonal average trend was recorded using groundwater-level data from observation wells (point data), overlaid with *taluk*-level "stage of ground water extraction" data (polygons) to determine groundwater fluctuations in water-stressed areas, over time. The linear trend is plotted on a year-on-year basis. Consistently increasing or decreasing slope and changes to the trend line indicate the rate of change observed in the groundwater levels. The spatial distribution of the wells and temporal changes with respect to the observed decline in groundwater levels indicate the areas with higher tendencies of groundwater dependence. (A *taluk* is an administrative district for taxation purposes, typically comprising a number of villages.)

13. The annual average LST from 2019 to 2021 was analyzed using the methodology described in Appendix B. Built settlements with an annual average LST higher than the overall city's annual average were identified as hotspots. These areas were termed hotspots because their annual average LST is higher than that of their neighborhoods. Overlaying the slum boundaries with the hotspots enabled us to determine which slum communities might be at higher risk of thermal stress than others.

14. In the Bengaluru Climate Action Plan, the city's floodplains were determined by using the flood modeling methods discussed in Appendix B. Dynamic rapid simulations were performed to determine composites of various flood extents and depths estimated on the basis of several exceedance probabilities or return periods and other hydrological and topographical parameters. Return periods were analyzed using IMD-gridded rainfall data for the period 1985–2020. The flood risk categories "high," "medium," and "low" are subjective and correspond to the selection of return periods and depth of inundation; hence, risk categories vary with the selection.

15. The Disaster Management Department, Nashik Municipal Corporation, has compiled a list of places that experienced recurrent flooding between 2007 and 2020. A flood impact area of 100 m radius (buffer) from the flood and waterlogging complaint locations was delineated based on the ground information of flood and waterlogging spread and extent shared by the city authorities. Population density was estimated using the methods detailed in the section titled "A spatial assessment of population impacted due to climate and environmental hazards." Built settlement with Census-based ward-level population density was overlaid with the flood impact area to estimate the population potentially at risk due to flood and waterlogging hotspots.

16. Access is computed based on serviceable catchment of 10-minute walking distance; that is, 800–1000 m based on a "comfortable 10 min walkshed for adults in Indian weather" (Bernard van Leer Foundation 2019, 15).

17. Geographic scope refers to the spread of the area considered for assessment. For technical scoping, cities need to identify the indicators listed in Chapters 3 and 4 that are relevant to their city.

18. Based on interviews with WRI teams working on climate action plans of Nashik, Chhatrapati Sambhajinagar, and Solapur.

19. Refer to the definition of "Thresholds" in Table 4, Chapter 2, for more details.

20. Based on analysis and consultation with the WRI team working on Nashik's CAP.

21. Based on consultation with the Bengaluru CAP's team lead.

22. Sentinel2GlobalLULC: A Sentinel-2 RGB image tile dataset for global land use/cover mapping with deep learning. The main characteristics of the 15 global land use and land cover (LULC) products available in Google Earth Engine (GEE) that were combined to arrive at a consensus in the global distribution of the 29 main LULC classes (see table 2 in Benhammou et al. [2022]): https://www.nature.com/articles/s41597-022-01775-8/tables/3.

23. As a supplement to the District Disaster Management Plan (DDMP) framework issued by the NDMA, the explanatory notes by NDMA (see NDMA n.d.-d) on the preparation of the DDMP provide a guide to risk-informed planning and decision-making.

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ABOUT WRI INDIA

WRI India, an independent charity legally registered as the India Resources Trust, provides objective information and practical proposals to foster environmentally sound and socially equitable development. Our work focuses on building sustainable and liveable cities and working towards a low carbon economy. Through research, analysis, and recommendations, WRI India puts ideas into action to build transformative solutions to protect the earth, promote livelihoods, and enhance human well-being. We are inspired by and associated with World Resources Institute (WRI), a global research organization.

Our challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to inform government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

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