Identifying future challenges for climate change adaptation through insights from participatory scenario-downscaling in Mumbai

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Populations in many coastal urban areas are increasingly exposed to climate-related hazards. At the same time, the number of people residing in coastal cities is growing, and, especially in the Global South, these cities are characterised by rapid urbanisation and social inequality. However, the progress of adaptation is lagging, and there is a limited understanding of how future socioeconomic urban developments will affect cities' social vulnerability and challenges to adaptation. We use the case study of Mumbai to apply a participatory scenario approach, in which we downscale the global Shared Socioeconomic Pathway (SSP) narratives to the local level. Our results stress the relevance of addressing social inequality in urban change processes across different sectors, including labour, housing, transport, and health and streamlining urban planning across different governance scales. Our study lays the ground for integrated modelling of future vulnerability and exposure scenarios and the development of local adaptation pathways.

Populations in many coastal urban areas are increasingly exposed to climate-related hazards, such as rising sea levels, increased intensity and frequency of tropical cyclones, and other extreme weather events[1]. Simultaneously, the number of people residing in coastal areas is growing. Approximately 1 billion people globally are living in low-elevation coastal zones, up to 10 m above sea level, with approximately half of that number in urban areas[2,3]. The urbanisation of coastal cities leads to growing population numbers, increasing densification, and an increasing accumulation of critical infrastructure and high-value assets being exposed to climate-related hazards. Moreover, especially in the Global South, these cities are characterised by a high degree of inequality, being home to the rich and elite as well as the extremely poor. Hence, coastal cities are also hotspots of social vulnerability[4].

In addition to the growing exposure of coastal urban populations to climate hazards, these cities are also highly dynamic in various ways that affect urban exposure and vulnerabilities. They are simultaneously home to indigenous population groups that have lived there for generations as well as tourists, work and seasonal migrants, and they can be melting pots of diverse cultural groups. Changing political regimes and management approaches can drive urban infrastructure and housing developments in different directions. Fluctuations in global, national, and regional economies impact urban businesses and markets. Therefore, the dynamic character of cities can constitute not only risks but also opportunities for shaping future adaptation and resilience[5].

Research has widely acknowledged that coastal cities are climate risk hotspots, and adaptations are occurring, especially in terms of planning and reactive responses[4]. However, the current climate change adaptation measures have not been widely implemented and lack evidence of effective risk reduction and long-term pathway perspectives[6]. While considerable research has been conducted on projecting future exposure to climate hazards in coastal cities (i.e., whether and to what extent cities will in the future be exposed to hazards such as sea level rise, fluvial floods or heat), there is a limited understanding of future vulnerability (i.e., how socioeconomic characteristics such as poverty change in the future), and its effect in predisposing people and infrastructure to suffer harm when being exposed to hazards[7–9]. To understand future vulnerability and the associated

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barriers and opportunities for adaptation, scenarios have to address both the physical and social aspects of risk[10] and adopt a long-term and holistic resilient development approach, including social, economic, and ecosystem developments[11].

The Shared Socioeconomic Pathway (SSP) framework was developed to be used alongside the Representative Concentration Pathways (RCPs) to represent the socioeconomic factors of climate change. It is a global approach for a better understanding of the socioeconomic developments that affect future trends in vulnerability and challenges to adaptation and mitigation[12]. That is, while the SSPs provide scenario narratives on how difficult or easy it will be to implement adaptation efforts, they do not automatically translate into adaptation per se. Whether or not, for instance, actors in a world with comparatively small challenges to adaptation (e.g., SSP1) also use this situation to conceive and implement meaningful adaptation is not a given. While there have been recent improvements in explicitly including adaptive capacity assessments within the SSP framework[13], explicit adaptation scenarios which can be superimposed on SSPs have not yet been developed in a coherent manner[14].

Further, while most of the SSP scenario work presents global scale narratives and large-scale modelling, downscaled or localised SSPs nested within global narratives are rare. This lack is critical since most adaptation happens locally or regionally and therefore needs to be guided by socio-economic development scenarios at these scales[14–16]. That is, a city government has a scope of action that needs to plan its adaptation based on regional and local scenario assumptions. National and global level considerations are thus important as a backdrop but cannot be translated one-to-one to the city scale. Instead, globally nested, local narratives are needed. Such narratives can be developed through top-down and bottom-up approaches[17] that implement projections beyond classic socioeconomic indicators to describe broader societal conditions related to social protection, inclusion, governance, and diverse aspects of wellbeing[16]. Such locally adapted SSP narratives can reflect vulnerability trends and diverse conditions for adaptation and establish the basis for the development of local adaptation pathways[18,19].

Our research uses the case study of Mumbai, one of the world's most vulnerable cities, to apply a participatory scenario approach and downscale the SSP narratives with bottom-up input from diverse local stakeholder groups. We draw specifically on SSPs 1 through 3, which are of highest relevance regarding their different implications for challenges to adaptation[20] (in contrast to mitigation, see Methods). Our specific research question is as follows: How will future socioeconomic urban developments affect social vulnerability and challenges to adaptation? The results of our study are relevant to a holistic understanding of future climate risks and challenges and opportunities for adaptation at the local scale. Coastal megacities, such as Mumbai, are among the fastest growing urban agglomerations and hotspots of climate change. They are hence suitable case studies to highlight the importance of a better understanding of social vulnerability trends within a global scenario framework for urban areas in general. Moreover, we contribute to methodological advancement in research by linking the global-scale SSP scenario framework to locally adapted narratives.

Results

The final scenario narratives for Mumbai include the following three downscaled SSPs: 'wider sustainability transitions' (building on the global SSP1), 'partial exploitation of existing potential and current trends' (SSP2), and 'increasing barriers through inequality and fragmentation' (SSP3). Each scenario narrative includes specific characteristics related to eight themes, including demographics, economic growth and transitions, migration and labour, land use transitions, infrastructure, social wellbeing, security and protection, poverty and inclusion, and health. We further translated the themes regarding their effects on vulnerability and challenges to adaptation (see Fig. 1). The following sections summarise the key trends in Mumbai's current socioeconomic development, followed by the three scenario narratives (see Supplementary Material 1 for the full scenario narratives across

the eight themes) and a synthesis of different vulnerability effects and challenges to adaptation across the scenarios.

Current status of and trends in Mumbai's socioeconomic development

Table 1 provides a synthesised overview of Mumbai's status and current trends in terms of the eight themes and highlights their relevance regarding vulnerability and adaptation challenges.

The following sections present each of the local socioeconomic pathways in a summarised form (see Supplementary Material 1 for the full narratives). Finally, we present the outcomes of the synthesis regarding the effects of the SSPs on vulnerability and challenges to adaptation.

SSP1: Wider sustainability transitions

On this pathway, wider sustainability transitions beyond current trends and across various sectors shape Mumbai's socioeconomic development, resulting in fewer challenges to adaptation.

Summary: The Mumbai Metropolitan Region (MMR) experiences strong population growth and urbanisation, expanding the boundaries of the MMR, but the population is also ageing. Mumbai is experiencing strong economic growth, with a reduced informal sector, more female workers, and increased employment of young adults. There is an increase in urban blue and green area (i.e., water bodies and vegetated land). Infrastructure development receives state funding and investments, improving multi-modal public transport, waste management, and drainage infrastructure. Significant investments and expanded social support systems contribute to increased social security and societal equity. Poverty is decreasing, and affordable housing and sustainable improvements to slum areas are being implemented. Migrant communities are recognised and gain access to municipal services. Universal health care needs are met.

SSP2: Partial exploitation of existing potential and current trends

The second scenario follows existing trends, and the existing potential for vulnerability reduction is partially exploited. Still, various challenges remain, resulting in moderate challenges to adaptation.

Summary: The MMR is experiencing strong population growth and continuing urbanisation trends, moderately expanding the MMR's boundaries. The population is experiencing a strong ageing trend. Mumbai is undergoing continuing economic growth with an expanding informal sector. Migrant arrivals, particularly in urban slums, continue to increase informal and precarious work. Cooperation between local and regional authorities is increasing, but real estate trends densify land use. Investments in urban green and blue areas are limited. Public infrastructure development is hindered by a lack of funding, and private vehicles still dominate mobility. Solid waste management is insufficient, and drainage infrastructure capacity is not fully utilised. Access to social services for marginalised communities remains limited. The pace of poverty reduction is increasing, and the relative number of people living in poverty is declining. Affordable housing initiatives and slum resettlement are slowly being implemented. Universal health care is implemented but lacks resources and cannot fully meet targets.

SSP3: Increasing barriers due to inequality and fragmentation

The third scenario is characterised by increasing inequality and regional fragmentation, leading to growing barriers to reducing vulnerability and greater challenges to adaptation.

Summary: The MMR is experiencing moderate population growth and urbanisation rates and increasing segregation within the MMR boundaries. The population is experiencing a strong ageing trend. Mumbai is undergoing moderate economic growth, with an increase in unemployment and people working in informal conditions. Urban green and blue areas are decreasing and degrading. The reduction in infrastructure investments is hindering urban development and a decrease in the dominance of private vehicles. Waste management is only efficient in high-income areas, and drainage infrastructure is not adapted to urbanisation rates. Social security levels are increasingly unequal across social groups. Poverty rates are increasing in
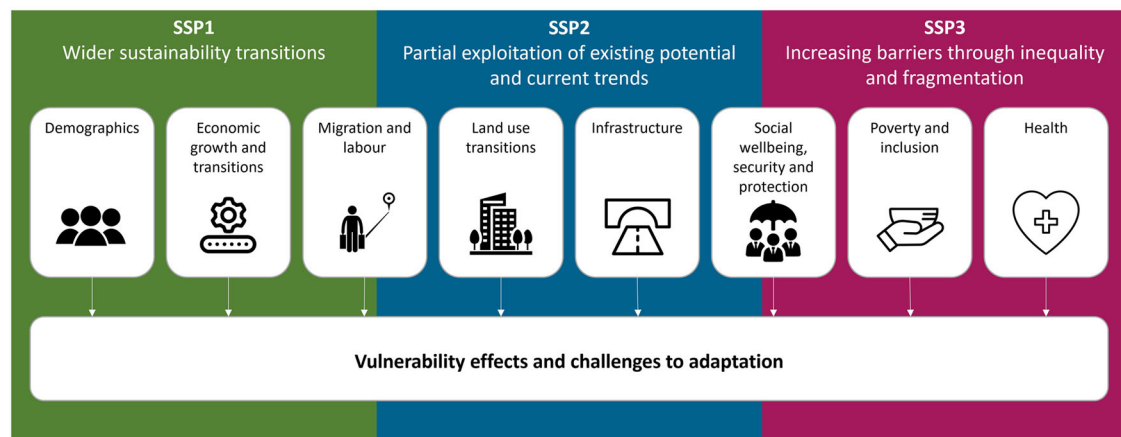
Fig. 1 | Scenario architecture. The downscaled Shared Socioeconomic Pathway (SSP) architecture including case study-specific themes of socioeconomic development resulting in vulnerability effects and challenges to adaptation under the three scenarios.

Table 1 | Examples of the status and trends in Mumbai's socioeconomic development related to vulnerability and challenges for adaptation

Themes	Socioeconomic status and trends	Effects on vulnerability and challenges to adaptation
Demographics and urbanisation	The current population of Mumbai is estimated at approximately 21 million, having more than doubled since 1991[33]. Mumbai is one of the most densely populated cities in the world[50]. There are currently plans for extending urbanisation with the construction of a 'Third Mumbai' in the Navi Mumbai International Airport area[51].	A rapidly growing urban population and high population density are increasing the pressure on infrastructure, civic services, health systems, and the environment.
Economic growth and transitions	Mumbai is the financial and commercial capital of India, a trading hub, and host to many industries, multinational companies, and financial institutions. The city is the leading contributor to India's gross domestic product (GDP)[52]. The city has experienced an economic transition from textile industries to currently being dominated by the service and tertiary sectors (e.g., finance, commerce, trade, IT, real estate)[53].	The plans to increase the GDP of Mumbai and make it a 'growth hub' raise concerns regarding the issue of affordable housing[51]. The decline of the manufacturing sector has led to an increase in unemployment, gaps between the upper- and lower-income classes, and a large informal sector.
Migration and labour	While historically, migration to Mumbai was the key driver of population growth, migration has declined over the past decades. However, there is still a large number of migrants, with different patterns across the Mumbai Metropolitan Region (MMR), from inside and outside Maharashtra state[53]. The lack of large-scale formal employment is argued to be linked to the persistence of slums and informal settlements[54].	Migrants to Mumbai are more likely to live in informal and precarious conditions, which increases their vulnerability, e.g., due to a lack of access to social security, education, and affordable housing and linguistic barriers[37]. Informal labourers are vulnerable due to low wages, low standards of living, work precarity, little access to social security, and increased urban inequality.
Land use transitions	Mumbai has undergone significant land use transitions from being a set of vegetated islands and with hilly outcrops. Extensive land reclamation has resulted in a loss of natural ecosystems, and liberal economic policies have given rise to rapid real estate development[55].	Planning regulations, such as the Floor Space Index, along with modifications and further dilution of the Coastal Regulation Zone laws, have led to an increase in built-up areas and increasing exposure to sea level rise.
Infrastructure	Urban transportation has been one of the major priorities of infrastructure development in the transformation of Mumbai. Public infrastructure, such as waste management, is insufficient or lacking in many parts of Mumbai, especially in slum communities[56].	If not planned well, urban transport and other infrastructure projects may have negative effects related to vulnerability and exposure (e.g., displacements and forced relocation of hutment dwellers, increased sealing and erosion).
Social wellbeing, security, and protection	Mumbai's population's literacy rate of approximately 90% is higher than average in Maharashtra and India[57]. However, Mumbai is characterised by an extremely high degree of socioeconomic inequality as well as socio-spatial segregation along lines of religion, class, and caste[58]. In particular, slum populations rely on informal social networks and support schemes[59].	Higher education and literacy provide opportunities for increased awareness regarding risk and risk reduction. Welfare and social protection are extremely heterogenous, and reliance on informal systems, especially in low-income communities, increases many households' vulnerability to climate-related hazards.
Poverty and inclusion	A large share of the population lives in poverty and informal housing conditions – the slum population is estimated at 41% of Mumbai's population according to the last census[50], yet they occupy only 6% of the total land area in Mumbai[60].	The lack of affordable housing[61], as well as the lack of adequate access to social (e.g., health, education) and physical (e.g., transport, housing, sanitation) infrastructure, increase the vulnerability of the urban poor.
Health	Despite an increasing healthcare budget, there are infrastructure gaps in Mumbai's health facilities[62]. Child mortality rates have decreased in recent years, but the Sustainable Development Goal targets have not yet been achieved. There are decreasing rates of malaria, dengue, diarrhoea and hepatitis A, but increasing cases of diabetes and hepatitis B/C[62].	Combined with highly unequal access to social protection, the inadequate health infrastructure is increasing the vulnerability of especially marginalised populations and those most exposed to climate-related hazards.

absolute and relative terms. There is a growing demand–supply gap for affordable housing and increasing densification and expansion of slum areas. Healthcare in informal settlements largely depends on individual capacities and privatised schemes, with no progress towards universally accessible facilities.

Overall vulnerability effects and challenges and opportunities for adaptation

The three scenarios inform the future trends for the eight themes and present specific challenges and opportunities for adaptation in Mumbai. Table 2 groups these into six domains that synthesise these challenges and opportunities across their most significant influences on vulnerability.

Discussion

The downscaling of the global SSP narratives to regional scenarios for the MMR shows how diverse socioeconomic development trends result in context-specific challenges and opportunities for adaptation to climate change. We co-developed with local stakeholders the three regional scenarios 'wider sustainability transitions', 'partial exploitation of existing potential and current trends', and 'increasing barriers due to inequality and fragmentation'. Specifically, we identified six cross-cutting domains of challenges and opportunities, namely, overall vulnerability, wellbeing of marginalised communities, availability and effectiveness of investments, streamlined governance, infrastructure and land use, and the role and capacity of civil society.

The transdisciplinary nested SSP approach allows for a robust understanding of challenges to adaptation related to different scales. On the one hand, this approach draws on the global SSP narratives and database and builds on global and national socioeconomic development assumptions. On the other hand, bottom-up input from local stakeholders facilitates the identification of local political, technological, and social barriers and opportunities[21]. For example, investment and public resources rely on global and regional economic conditions, funding for public health services depends on national policies, and local infrastructure development depends on local and regional governmental planning. Civil society organisations are important across scales, where global and regional dynamics can severely affect local support for vulnerable communities. Therefore, it is crucial to understand how socioeconomic development across different scales, including intraurban scales, has implications for opportunities for and challenges to adaptation. This is especially true in megacities such as Mumbai where local dynamics are intricately linked to national and global megatrends, for instance, in relation to migration, trade, economic performance and collaboration. Hence, nested scenarios in which city- or metropolitan-scale scenarios are anchored within the global SSP scenarios are particularly important for such large megacities like Mumbai[22,23].

The scenario narratives address the central concern of social inequality trends under different socioeconomic pathways, which is especially significant in megacities in the Global South. The scenarios show how different economic transitions, patterns in public spending, decision-making modes, and priorities in spatial planning and infrastructure development have diverse impacts on vulnerable local populations, such as people living in poverty, migrants, women, the elderly, and people with disabilities. Especially for those populations in Mumbai, limited adaptive capacities are a more important factor in defining their climate risk than hazard exposure[24]. Simultaneously, community resilience is undermined by urban transformation shaped by urban elites, which leads to increased exclusion of

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Table 2 | Synthesis of challenges and opportunities for adaptation under the downscaled SSPs for Mumbai

Domains of challenges and opportunities	SSP1 Wider sustainability transitions	SSP2 Partial exploitation of existing potential and current trends	SSP3 Increasing barriers through inequality and fragmentation
Overall vulnerability	The absolute and relative number of highly vulnerable populations declines due to extended social security services, improved public infrastructure, a strong civil society, and reduced socioeconomic disparities.	A large share of marginalised populations remains highly vulnerable. The relative number of vulnerable people remains high, despite small advances in social security coverage and ongoing support by civil society groups, due to increasing socioeconomic disparities.	Highly vulnerable populations increase in absolute and relative terms due to insufficient access to social security services and public infrastructure.
Wellbeing of marginalised communities	Health conditions improve overall and public services expand, reducing the stress on the most vulnerable populations, such as children, the elderly, or people with disabilities.	Improvements in public health services and health challenges are limited due to pollution and insufficient decentralised and accessible health facilities. The most vulnerable populations, such as children, the elderly, or people with disabilities, continue to experience stress.	There is a lack of funding for the expansion of public health services and accessible decentralised health facilities. This results in increasing health challenges due to more environmental degradation and pollution, adding high stress for the most vulnerable populations, such as children, the elderly, or people with disabilities.
Availability and effectiveness of investments	Local, regional, and national public, community, and private actors coordinate and increase their investment, which is effective, efficacious, and on par with demand.	Public and private actors across the different levels have partially aligned funding agendas, resulting in a focus on well-known initiatives and persistent gaps in vulnerable communities.	Resources and funding from private, governmental, and civil society organisations decrease. Lack of coordination leads to severe gaps and little to no synergy.
Streamlining governance	Cooperation between local and regional authorities facilitates the streamlining of development and adaptation plans. A higher level of involvement from the private sector and local communities facilitates the implementation, monitoring, and evaluation of progress.	The partially improved streamlining across government departments in urban planning facilitates the implementation of adaptation measures to a limited extent. However, it is challenged by the lack of involvement of local communities.	Lack of streamlining across government departments and jurisdictions, lack of involvement of local communities, and strongly competing development agendas favouring the priorities of the private sector hinder the effective implementation of adaptation plans.
Infrastructure and land use	Expansion of blue and green areas provides opportunities for nature-based solutions, and improved public infrastructure and services reduce the vulnerability of marginalised populations.	Infrastructure improvements increase the general capacity to address increasing climate hazards; however, they focus mainly on economically valuable assets.	Infrastructural developments increase resilience only in high-income areas or are implemented through private efforts. Reductions in green and public areas increase the vulnerability of marginalised communities.
Role and capacity of civil society	Local authorities and civil society streamline support for marginalised communities.	Marginalised communities rely strongly on support from civil society groups.	Marginalised communities rely on civil society organisations, which are experiencing a decrease in international funding.

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marginalised populations from urban spaces and conflict between local communities[25]. Coastal transformations, such as infrastructure developments, also affect the indigenous fisher populations in Mumbai's Koli villages, who face increased pressures on their livelihoods[26].

Regarding transferability, the general scenario themes could be transferred to cities with similar socioeconomic development contexts. However, the concrete outcomes within distinct scenarios in Mumbai result from the participatory approach and will be different for each case study. For example, the high ratio of slum dwellers in Mumbai makes this a particularity across the scenarios elements, while other case studies may have a stronger focus on other urban phenomena that are less represented in the scenarios here, such as the industrial production.

Streamlining urban development across different governance scales (i.e., local and regional) and sectors (e.g., transportation and spatial planning) is a prominent cross-cutting aspect that appeared during the co-development of the scenario narratives with local stakeholders. Many of the challenges under SSP3 in Mumbai result from a lack of coordination between different stakeholders, while under SSP1, synergies develop, for example, regarding the benefits of urban green spaces for risk reduction, health, and wellbeing or multi-modal infrastructure development and the reduction of social marginalisation. For the specific issue of flood risks in Mumbai, the most urgent streamlining needs to occur between disaster risk reduction and climate change adaptation planning[27]. The recently published Mumbai Climate Action Plan[28] represents an opportunity to move towards such integration, but gaps remain[29].

In addition to the value of locally adapted and co-developed scenario narratives, this SSP downscaling approach also sheds light on several conceptual and methodological challenges. First, the availability of data to guide the drafting of plausible scenario assumptions varies significantly across the different scenario themes and the three scenario storylines. For example, quantitative data is available for demographics and economics, but it is relatively scarce for health care, inclusion, or wellbeing. Similarly, although the nesting of the narratives in global SSPs is a strength of the method, data and literature on how local developments are shaped by national and international dynamics vary significantly. This aspect may be even more challenging in cases that have been less researched than a megacity such as Mumbai. It remains challenging to communicate future scenarios in general and it was therefore especially difficult for local stakeholders to provide input on scenarios they perceive are less likely to unfold (especially for SSPs 1 and 3). This may be partially explained as their work often deals more with projections based on current trends than with scenario building. Moreover, a concern regarding the SSP approach was that the three scenario narratives seemed to follow either ideal, ongoing, or deteriorating trends too distinctly. This internal consistency may contrast with future reality, where certain aspects may worsen, others may remain the same or improve. Local development pathways may switch from one scenario track to another, potentially due to unforeseen transformations or shocks.

Overall, the input by local stakeholders proved to be particularly important for filling many data gaps and checking consistency across and within the scenario storylines. It also made possible the critical reflection on modelled data built on global and national projections (e.g., population projections for different SSPs) that lacks input in the form of more qualitative and context-specific insights see also [30]. Moreover, the participatory approach proved to be useful not only for the valuable stakeholder input for this research. The discussions in the workshops and interviews also provided platforms for mutual learning exercises between stakeholders and between stakeholders and researchers. In this way, the participatory approach increased the local stakeholders' awareness of the SSP scenarios and value of local narratives as well as the usefulness of the final output for their own work.

Our study demonstrates the value of developing regional scenarios nested within the global SSPs to understand challenges to adaptation that are consistent with narratives on global socioeconomic development. The diverse scenario narratives are potentially valuable tools for local and regional planning and decision-making in the context of rapid urban change

and increasing climate risk[31]. These local baselines should also strengthen regional and comparative studies by providing more diverse evidence that considers inequality and highlights challenges to specific vulnerable groups. Future research can build on the downscaled narratives for more refined vulnerability scenarios and to develop adaptation pathways. Additional studies can also combine pathways through different SSPs over time, address aspects of political instability and external shocks, and capture the interactions of national and local SSPs.

Integrated models often lack socioeconomic assumptions, and the scenario narratives may provide these, thus reducing uncertainty. Integrated modelling can also combine mitigation and adaptation studies based on these narratives. Quantitative studies may be able to use the scenarios to estimate tangible indicators that, in turn, support monitoring and modelling studies. The latter is critical for urban and spatial regulations and could provide mediating evidence that strengthens adaptation mainstreaming. Finally, when debating these narratives, most of the stakeholders expressed the need for further policy integration. The underlying assumptions become clearer through debating future developments, and, conceivably, a more democratic dialogue can ensue in decision-making.

Methods
Study area
The city of Mumbai, India, is shaped by a multi-dimensional interplay of geographic and socioeconomic characteristics that results in high levels of risk from climate change[32]. The city formerly known as Bombay was built with extensive land reclamation and development efforts on a series of islands along the Arabian Sea. The Mumbai Metropolitan Region (MMR) has a population of approximately 21 million that is projected to increase to 25 million by 2030[33]. The continuous process of land reclamation has significantly shaped the city's geographical characteristics and caused higher exposure to the risks associated with urban coastal areas, such as regional sea level rise, storm surges, cyclones, heatwaves, and different types of coastal and inland flooding[34–36].

The city is a national finance focal point and is of critical significance for the socioeconomic fabric of India. Furthermore, an exceptionally high population influx has led to the growth of informal settlements in hazard-prone locations and low-lying coastal landforms[24,37]. The urban area expands continuously beyond the metropolitan boundaries to vent geophysical and socioeconomic pressures resulting from urban development and real estate dynamics. Mumbai has the most intense real estate market in India, and it is divided between two poles. On the one hand, Mumbai is pursuing global city status betting on liberalisation and globalisation. This means strongly advancing technological industries (e.g., data analytics and software development) and increasing its global financial system connectivity (with a significant focus in the real estate market). On the other hand, there is the 'exclusionary subplot' driven by intense accumulation of capital that excludes the poor (notably the migrant ones) from participating in the formal economy. This situation results in social segregation and broader core–periphery dynamics marked by exceedingly high land and property prices. This heated real estate market challenges not only family decisions on housing, but also robs planning policy of its effectiveness by skewing it towards the interests of the main market players[38]. The bulk of this development extends beyond Mumbai to the MMR, often through clustered high-rise formal developments that contrast with tightly packed low-rise slums. The MMR includes nine municipal corporations, covering a total area of 6328 sq. km[39], and equates to ~10 times the area of Mumbai. Recently, national and global attention has been drawn to observing the linked interaction between exponential growth, infrastructure development, economic inequality, and impending climate risks. To respond to these challenges, researchers have acknowledged the need for robust urban planning and adaptation measures[40,41], which must overcome significant barriers[29].

The densely populated urban landscape and inadequate infrastructure in many areas exacerbate the city's vulnerability to climate extremes. Moreover, the potential disruption of essential services such as

transportation and water supply during calamities poses significant challenges to urban resilience. The state government has recognised the urgency of addressing climate risks by formulating a comprehensive Mumbai Climate Action Plan, which outlines high-priority strategies and measures to improve urban resilience. Notably, the plan establishes a blueprint to achieve carbon neutrality[28]. However, Mumbai's development has historically been selective, favouring capital accumulation over universal access to services and infrastructure[38]. Hence, adaptation planning must consider socioeconomic aspects, including income disparities, inequality, lacking resources and services accessibility, and account for the most marginalised. Moreover, future planning should incorporate sustainable urban development practices, improved infrastructure, and land-use policies that prioritise resilience and environmental sustainability[42].

SSP downscaling approach

To develop plausible scenarios regarding Mumbai's future socioeconomic development, we applied a downscaling approach to the SSPs. The five narratives, sustainability (SSP1), middle of the road (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fuelled development (SSP5), include various assumptions concerning global trends regarding demographics, human development, economy and lifestyles, policies and institutions, technology, and environmental and natural resources[12]. Thereby, the SSP narratives provide a basis for integrated assessment modelling and other research informing the development of climate risk and adaptation pathways.

The global scenario narratives provide the basis for sub-national analyses of potential vulnerability and adaptation pathways[43] and can be adapted to develop localised extensions for local adaptation planning. Localised adaptations of the global SSPs should be pertinent to local policy domains and context-specific while remaining consistent with broad global narratives and scenario designs[30]. Moreover, the localised adaptations require translating general global development trends, such as economic transitions, trade networks, population growth, and intergovernmental cooperation, into local implications related to vulnerability and adaptive capacities.

Adopting approaches employed by similar studies[44–47], we used the assumptions of global SSPs as the guiding input, which we then combined with a bottom-up approach to create local scenario narratives compatible with the global SSP narratives. To guarantee general plausibility as a key criterion for scenario narratives, we used the following guiding principles in the scenario development process: vertical and horizontal consistency, salience, legitimacy, richness, and creativity see also [48]. The participatory element including diverse stakeholders is crucial for two reasons. First, Mumbai is a relatively data scarce environment, especially regarding local scale socioeconomic data. Second, plausible and salient narratives (including information ranging from local demographics to land use change) requires a wide range of expertise. Moreover, interactive formats allow the space for identifying and discussing contradicting views on specific aspects of the narratives. Accordingly, our method for developing the downscaled scenarios for the MMR consisted of three different modes of input and an iterative process of three drafting phases (see Fig. 2).

Development of draft narratives

The first scenario development phase consisted of selecting the most meaningful SSP narratives for the downscaling. It also included identifying the key elements of the SSPs for the specific context of Mumbai. After these, we performed a desk-based literature review as a basis for the drafting of a zero-order scenarios draft.

In collaboration with local project partners, we decided to create three alternative scenario narratives that sketch plausible socioeconomic development pathways for Mumbai up to 2050 and are compatible with the global SSPs 1, 2, and 3. We selected these three global scenarios because our primary research focus is on climate risks and the challenges to adaptation. Therefore, we did not include SSPs 4 and 5, as they focus on mitigation. This step was followed by the selection of guiding themes for the downscaling. The discussion with stakeholders balanced three goals: first, selecting those themes most critical; second, maintaining consistency with the global SSP narrative indicators (e.g., trends in poverty, economic productivity, integration into global markets); and finally, considering aspects specific to the Mumbai context (e.g., migration patterns and formal/informal housing and labour).

This structure of three scenario narratives and specific themes formed a scenario matrix. Based on a review of peer-reviewed and grey literature regarding the respective themes, we developed a first draft of scenario narratives (see Supplementary Material 2 for an overview of the literature used for this step).

Evaluation of draft narratives in a scenario workshop

We held a scenario workshop in Mumbai on 25 November 2022 to discuss and evaluate the first draft. The workshop included 25 experts from different stakeholder groups, including regional government, civil society, and academia. All participants received the draft scenario narratives and a concept note explaining the workshop goals. We also shared the SSP scenario downscaling rationale prior to the workshop. In Mumbai, we started with a short introduction to the scenario development approach and its relevance to policy and planning. Thereafter, we explained the full draft narratives in detail to the participants and they were split into three break-out groups according to their core expertise to discuss the vertical and horizontal consistency, plausibility, and comprehensiveness of the respective narratives. Each break-out group was moderated by a member of the project team. The groups submitted their discussion points to the project team in written form and reported to the workshop plenary for further comments and discussion.

Validation of revised scenario draft

The development of the revised scenario narratives was based on a clustering and in-depth review of workshop feedback. We also held follow-up interviews with experts from the stakeholder groups when specific points demanded further clarification, when there were divergent perspectives during the workshop or when more in-depth context-specific input was needed (e.g., regarding plausible assumptions for population dynamics across the three scenario narratives). Overall, we conducted five follow-up interviews (either online or in person) with experts from academia, civil
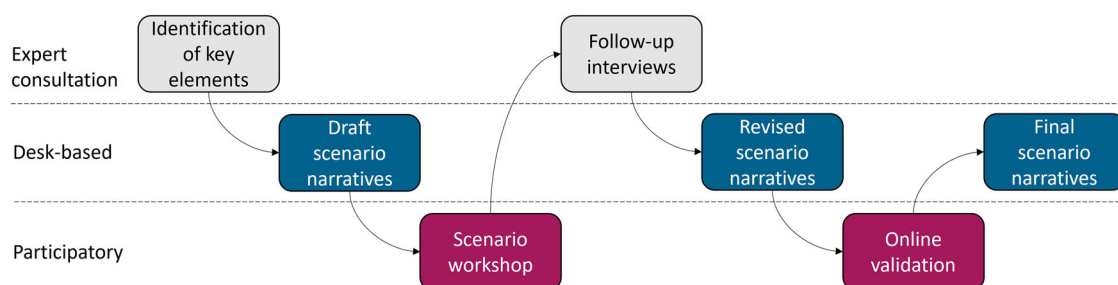

Fig. 2 | Scenario downscaling. The scenario downscaling process in Mumbai, differentiating the different steps and stakeholders involved.

society and urban planning on the topics of land use change, infrastructure, demographics, informal settlements, and health.

Finally, the workshop participants reviewed the revised scenario narratives through an online validation questionnaire using the SoSci tool[49]. In the online validation, we presented the revised narratives and a summary of changes to the first draft and asked the participants to rate the overall plausibility of the narratives and provide specific feedback or suggestions. An evaluation and further comments from 10 experts provided the basis for the finalisation of the scenario narratives.

Ethics statement

This research involves the participation of human subjects, but does not require ethical approval as no personal data was collected during the process. We transparently provided information on the goals and purpose of the research to the participants and all participants provided informed consent verbally concerning the use of the anonymised information provided for publication purposes. Participants had the possibility to drop out of the research at any time. All recorded data was anonymised and stored on secure servers of the Ludwig-Maximilians-Universität München (LMU), Germany.

Data availability

All data generated or analysed during this study are included in this published article (and its supplementary information files).

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Author contributions

M.G. and D.P. conceived the presented research. M.G., A.K. and J.P. developed the methodology. J.P. led the data collection, analysis and writing of the manuscript. S.D. facilitated data collection. R.D., D.D. and A.P.S. contributed to data collection, analysis, and writing of the manuscript. All authors read and approved the final manuscript.

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