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Cities, Settlements and Key Infrastructure

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Executive Summary

In all cities and urban areas, the risk faced by people and assets from hazards associated with climate change has increased (*high confidence*[1]). Urban areas are now home to 4.2 billion people, the majority of the world's population. Urbanisation processes generate vulnerability and exposure which combine with climate change hazards to drive urban risk and impacts (*high confidence*). Globally, the most rapid growth in urban vulnerability and exposure has been in cities and settlements where adaptive capacity is limited, especially in unplanned and informal settlements in low- and middle-income nations and in smaller and medium-sized urban centres (*high confidence*). Between 2015 and 2020, urban populations globally grew by more than 397 million people, with more than 90% of this growth taking place in less developed regions. {Box 6.1; 6.1.4; 6.2.1; 6.3.2; 6.3.3.4; 6.2.2.2; 6.4.4}

The documentation of climate-related events and observed human and economic losses have increased since AR5 for urban areas and human settlements. Observed losses arise from single, compound, cascading and systemic events (*medium evidence, high agreement*). Losses from single events include the direct impact of heat stress on human health. Compound event losses arise from the interaction of single climate hazards with at least one other hazard driver such as heat with poor air quality (e.g., from traffic fumes or wildfire), flooding with poor water quality (e.g., from contaminated runoff and flood water) or land subsidence. Cascading impacts are observed when damages in one place or system reduce resilience and generate impacts elsewhere (e.g., when flood waters damage energy infrastructure causing blackouts and knock on financial and human impacts). Losses become systemic when affecting entire systems and can even jump from one system to another (e.g., drought impacting on rural food production contributing to urban food insecurity) (*medium confidence*). In some cases, maladaptive responses to hazards have exacerbated inequality in the distribution of impacts, for example shifting risk from one community to another. {Figure 6.2; 6.2.6; 6.3.4.1; 6.4.5; Cross-Chapter Paper 2; Cross-Working Group Box URBAN in Chapter 6}

Evidence from urban and rural settlements is unequivocal; climate impacts are felt disproportionately in urban communities, with the most economically and socially marginalised being most affected (*high confidence*). Vulnerabilities are shaped by drivers of inequality, including gender, class, race, ethnic origin, age, level of ability, sexuality and non-conforming gender orientation, framed by cultural norms, diverse values and practices (*high confidence*). Intersections between these drivers shape unique experiences of vulnerability and risk and the adaptive capacities of groups and individuals. Robust adaptation plans are those developed in inclusive ways. However, few adaptation plans for urban areas and infrastructure are being developed through consultation and co-production with diverse and marginalised urban communities. The concerns and capacities of marginalised communities are rarely considered in planning (*medium confidence*). {Box 6.3, Box 6.4; 6.4.3.1; 6.4.5.2, Case Study 6.7; Cross-Working Group Box URBAN in Chapter 6}

The COVID-19 pandemic has had a substantial impact on urban communities and climate adaptation (*medium evidence*, *high agreement*). The pandemic has revealed both systemic under-investment resulting in multiple, persistent health-related vulnerabilities (many of which also exacerbate climate change risk) and co-benefits for urban interventions to reduce future pandemic and climate change risk. The COVID-19 pandemic is estimated to have pushed an additional 119 to 124 million people into poverty in 2020, with South Asia and Sub-Saharan Africa each contributing roughly two-fifths of this total (*medium confidence*). At city level, community groups, non-governmental organisations (NGOs) and local governments face challenges to bring agencies already working on social and economic development into coordinated action to reduce urban vulnerabilities and manage risks. COVID-19 and climate change impacts are exacerbated by widening social inequality. Addressing the causes of social vulnerability creates opportunity for transformative adaptation. {Box 6.4; 6.1.4; 6.2.2.4; 6.2.5; 6.4.1.3; Case Study 6.4; Cross-Chapter Box COVID in Chapter 7}

The number of people expected to live in urban areas highly exposed to climate change impacts has increased substantially (*high confidence*). An additional 2.5 billion people are projected to be living in urban areas by 2050, with up to 90% of this increase concentrated in the regions of Asia and Africa. Projections of the number of people expected to live in urban areas highly exposed to climate change impacts have increased. Sea level increase and increases in tropical cyclone storm surge and rainfall intensity will increase the probability of coastal city flooding, with more than a billion people located in low-lying cities and settlements expected to be at risk from coastal-specific climate hazards by 2050 (*high confidence*). Sea level rise, increases in tropical cyclone storm surges and more frequent and intense extreme precipitation will increase the number of people, area of urban land, and damages from flood hazard (*high confidence*). The main driver for increased heat exposure is the combination of global warming and population growth in already-warm centres, and the majority of the population exposed to heatwaves will live in urban centres. An additional 350 million people living in urban areas are estimated be exposed to water scarcity from severe droughts at 1.5°C warming, and 410.7 million at 2°C warming. {6.1; 6.2.2; Cross-Chapter Paper 2}

Many more cities have developed adaptation plans since AR5, but only a limited number of these have been implemented (*medium confidence*). Many of these plans focus narrowly on climate risk reduction, missing opportunities to advance co-benefits of climate mitigation and sustainable development, compounding inequality and reducing well-being (*medium confidence*). However, an increasing array of adaptation options are available. Nature-based solutions are now mainstream urban adaptation options and there remains considerable scope for their wider application. Social-policy-based adaptation, including education and the adaptation of health systems offers

1 In this Report, the following summary terms are used to describe the available evidence: limited, medium or robust; and for the degree of agreement: low, medium or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

considerable future scope. Options of adapting physical infrastructure are similarly advancing, though at times constrained by existing infrastructure design and location. The greatest gaps between policy and action are in failures to manage adaptation of social infrastructure (community facilities, services and networks) and failure to address complex interconnected risks for example in the food–energy–water–health nexus or the inter-relationships of air quality and climate risk (*medium confidence*). Barriers to implementing plans include lack of political will and management capacity, limited financial means and mechanisms (especially for smaller urban settlements) and competing priorities (*limited evidence*, *high agreement*). {6.3.1, 6.4.3; 6.4.5; 6.4.5.1; 6.4.5.2; Figure 6.5}

The shift from urban planning to action in ways that identify and advance synergies and co-benefits of mitigation, adaptation and Sustainable Development Goals (SDGs) has occurred slowly and unevenly (*high confidence*). While there is ambition for joined-up policy, action and research, this is still the exception. One area of sustained effort is community-based adaptation planning and resilience actions which have potential to be better integrated to enhance well-being and create synergies with the Sustainable Development Goal ambitions of leaving no one behind. Complex trade-offs and gaps in alignment between mitigation and adaptation over scale and across policy areas where sustainable development is hindered or reversed also remain. {6.1.1, Table 6.2; 6.1.5; 6.4.1.4; 6.4.3; 6.4.4}

Urban adaptation gaps exist in all world regions and for all hazard types, although exposure to the limits to adaptation is unevenly distributed. Governance capacity, financial support and the legacy of past urban infrastructure investment constrain how all cities and settlements are able to adapt (*high confidence*). Critical capacity gaps exist at city and community levels that hinder adaptation. These include the limited ability to identify social vulnerability and community strengths; the absence of integrated planning to protect communities; and the lack of access to innovative funding arrangements and limited capability to manage finance and commercial insurance (*medium confidence*). These can be addressed through enhanced locally accountable decision making with sufficient access to science, technology and local knowledge to support widespread application of adaptation solutions. {6.3.1, 6.4.3; 6.4.5; 6.4.5.1; 6.4.5.2; Figure 6.4; Figure 6.5}

Slow uptake of monitoring and evaluation frameworks constrains potential for developing climate resilient urban development pathways (*medium confidence*). A lack of agreement on metrics and indices to measure urban adaptation investment, impacts and outcomes, reduces the scope for sharing lessons and joined-up action across interconnected sectors and places in the face of compound and systemic risks. These constraints affect the potential for climate resilient development pathways. Limits to adaptation are often most pronounced in rapidly growing towns and cities and smaller settlements including those without dedicated local government. At the same time, legacy infrastructure in large and mega-cities, designed without taking climate change risk into account, constrains innovation leading to stranded assets and increasing numbers of people unable to avoid harm, including heat stress and flooding, without transformative adaptation. {6.2.5; 6.3.3.3; 6.3.7; Figure 6.4; 6.4.4; 6.4.6 FAQ6.5}

City and local governments are key among multiple actors facilitating climate change adaptation in cities and settlements (*medium confidence*). City and local governments can invest directly and work in partnership with community, private sector and national agencies to address climate risk. Private and business investment in key infrastructure, housing construction and through insurance requirements can also drive widespread adaptive action, though at times excluding the priorities of the poor (*medium confidence*). Networked community actions can also go beyond neighbourhood-scale improvements to address widespread vulnerability. Such actions include fostering roles of intermediaries and multiple spaces for networked governance across scales of decision-making, improving development processes through an understanding of social and economic systems, foresight, experimentation and embedded solutions, and social learning. Transnational networks of local government can also enhance city level capacity, share lessons and advocacy (*medium confidence*). {Table 6.2; 6.3.3.4; 6.3.3.5; 6.4.1; 6.4.1.1; Case Study 6.2; FAQ 6.5}

Globally, decisions about key infrastructure systems and urban expansion drive risk creation and potential action on climate change (*high confidence*). Urban infrastructure concentrates and connects populations, physical assets and energy use. Urban expansion and the compromising of green infrastructure and ecosystem services reduce adaptive capacity and can increase risk: the urban heat island, a product of expansion, can add 2°C to local warming. How settlements and key infrastructure are planned, designed and maintained determines patterns of exposure, social and physical vulnerability and capacity for resilience. Unplanned rapid urbanisation, including peri-urban development, is a major driver of risk, particularly where cities and settlements are expanding into land that is prone to coastal flooding or landslides, or where there is inadequate water to meet the needs of growing populations. Urban decision making processes equally shape how far low- and zero-carbon development can meet social needs; enhancing well-being while enabling climate change mitigation and advancing the SDGs. {6.1.3; 6.2.3; 6.2.4; 6.3.3; 6.3.4; 6.3.5; 6.4.6; Cross-Working Group Box URBAN in Chapter 6}

Investment in urban adaptation has not kept pace with innovations in policy and practice (*medium confidence*). Knowledge transfer and innovation in adaptation has broadened advances in social and ecological infrastructures including disaster risk management, social policy and green/blue infrastructure, especially where these are integrated with grey/physical infrastructure (*medium evidence*, *high agreement*). Innovation has also taken place at the interface of difference systems, for example information and communications technology (ICT) and water or energy, although financial investment has been slow to recognise and support these activities. Adaption finance continues to be directed at large-scale grey/physical engineering projects, neglecting maintenance and reproducing risk of stranded assets if climate change risk accelerates beyond planned-for levels. Finance deployed at the interface of multiple, integrated adaptation measures can support climate resilient development (*high confidence*). Access to finance is most difficult for city, local and non-state actors, and in conditions where governance is fragile. {6.3.3; 6.3.4; 6.3.6; 6.4.5; 6.4.5.2; Table 6.10; Table 6.11; Box 6.8; Case Study 6.2; Case Study 6.3; Case Study 6.5}

Global urbanisation offers a time-limited opportunity to work toward widespread and transformational adaptation and climate resilient development (*high confidence*). Current dominant models of energy intensive and market-led urbanisation build high carbon dependency and high vulnerability into cities, but this need not be the case. Integrated development planning that connects innovation and investment in social, ecological and grey/physical infrastructures can significantly increase the adaptive capacity of urban settlements and cities. Transitioning cities to low carbon development and equitable resilience may lead to trade-offs with dominant models of economic growth based on housing and infrastructure investment. Integrated planning approaches are important for climate resilient development to enable planning and monitoring of interactions between development, mitigation and adaptation. Urban adaptation measures can offer a considerable contribution to climate resilient development. This potential is realised by adaptations that extend predominant physical infrastructure approaches to also deploy nature-based solutions and social interventions. The most consistent limit for all infrastructure types is in risk transfer. Current adaptation approaches in cities, settlements and key infrastructure tend to move risk from one sector or place to others. Multi-level leadership and institutional capacity, together with financial resources (including climate finance) to support inclusive and sustainable adaptation in the context of multiple pressures and interconnected risks, can help to ensure that global urbanisation of an additional 2.5 billion people by 2050 reduces rather than generates climate risk (*medium confidence*). {Table 6.7; Table 6.5; 6.1.3; 6.3.6; 6.3.5.2; 6.4.7; Box 6.5; Cross-Working Group Box URBAN in Chapter 6; Cross-Chapter Paper 2}

Intersectional, gender-responsive and inclusive action can accelerate transformative climate change adaptation. The greatest gains in well-being in urban areas can be achieved by prioritising investment to reduce climate risk for low-income and marginalised residents and targeting informal settlements (*high confidence*). These approaches can advance equity and environmental justice over the long term in ways more likely to lead to outcomes that reduce vulnerability for all urban residents. Participatory planning for infrastructure provision and risk management to address climate change and underlying drivers of risk in informal and underserviced neighbourhoods, the inclusion of Indigenous knowledge and local knowledge, communication and efforts to build local leadership, especially among women and youth, are examples of inclusive approaches with co-benefits for equity. Providing opportunities for marginalised people, including women, to take on leadership and participation in local projects can enhance climate governance and its outcomes (*high confidence*). Since AR5 (IPCC, 2014), social movements in many cities, including movements led by youth, Indigenous and ethnic communities have also heightened public awareness about the need for urgent, inclusive action to achieve adaptation that can also enhance well-being. {6.1.5; 6.3.5; 6.4.1.2; 6.4.7; Box 6.6, Case study 6.2; Case study 6.4, FAQ6.3}

City and infrastructure planning approaches that integrate adaptation into everyday decision making are supported by the 2030 Agenda (the Paris Agreement, the SDGs, the New Urban Agenda and the Sendai Framework for Disaster Risk Reduction) (*high confidence*). The 2030 Agenda provides a global framework for city and community level action to be points of alignment between Nationally Determined Contributions, National Adaptation Plans and the SDGs. City and local action can complement, and at times go further than national and international interventions. Similarly, the Convention on Biological Diversity offers a global agreement through which nature-based solutions can be viewed as benefits for biodiversity, social justice and climate resilience. However, there is no specific global agreement that addresses informality and city-level climate adaptation. More comprehensive and clearly articulated global ambitions for city and community adaptation will contribute to inclusive urbanisation, by addressing the root causes of social and economic inequalities that drive social exclusion and marginalisation, so that adaptation can directly support the 2030 Sustainable Development Agenda (high confidence). {6.1.1; Table 6.2; 6.2.3.2; 6.4.1.4; Case Study 6.4}

6.1 Introduction and Points of Departure

6.1.1 Background and Chapter Outline

Cities and urbanising areas are currently home to over half the world's population. What happens in cities is crucial to successful adaptation (Grafakos et al., 2019). By 2050, over two thirds of the world's population is expected to be urban, many living in unplanned and informal settlements and in smaller urban centres in Africa and Asia (*high confidence*) (UNDESA, 2018). Between 2015 and 2020, urban populations globally have grown by about 397 million people, with more than 90% of this growth taking place in less developed countries (UNDESA, 2018). Projections of the number of people expected to live in urban areas highly exposed to climate change impacts have also increased, exacerbating future risks under a range of climate scenarios. Rates of population growth are most pronounced in smaller and medium-sized settlements of up to 1 million people (UNDESA, 2018).

Since AR5, there has been increasing understanding of the interdependence of meta-regions, large, small and rural settlements which may be connected through key infrastructure (Lichter and Ziliak, 2017), including national and trans-national infrastructure investments (Hanakata and Gasco, 2018). Almost all the world's non-urban population and its provisioning ecosystems are impacted by urban systems through connecting infrastructure and family and kinship ties, remittances and trade arrangements that influence flows of water, food, fibre, energy, waste and people (Trundle, 2020; McIntyre-Mills and Wirawan, 2018; Zhang et al., 2019; Nerini et al., 2019; Friend and Thinphanga, 2018). Many rural places are so deeply connected to urban systems that risks are observed to cascade from one to the other, for example, when drought in arable zones leads to food insecurity in cities, or where flood damage to urban transport infrastructure leads to prolonged isolation of small towns and rural settlements (Friend and Thinphanga, 2018; McIntyre-Mills and Wirawan, 2018). A focus of this chapter is the experience of a range of urban settlements, from small to large, and the connecting infrastructure and formal and informal networks and systems that join them to each other. There are close synergies with Chapters 7 (Health, Well-being and the Changing Structure of Communities) and 8 (Poverty, Livelihoods and Sustainable Development). There are further important synergies with Working Group III Chapter 8 (Urban Systems and Other Settlements) and the Cross-Chapter Paper 2: Cities and Settlements by the Sea.

Well-planned climate adaptation can have far reaching co-benefits for sustainable development and community well-being (Nerini et al., 2019; Tonmoy et al., 2020). However, the varied success of cities' responses to the global COVID-19 pandemic underscores how social and economic conditions, built environments and local planning can exacerbate or reduce vulnerability and long-term sustainable, community well-being (Megahed and Ghoneim, 2020; Plastrik et al., 2020; Hepburn et al., 2020; Sarkis et al., 2020).

Many of the significant sustainable development initiatives that have been proposed and implemented in the last five years recognise the critical importance of cities, settlements and key infrastructure in responding to the crisis of climate change (Zhang et al., 2019; Nerini et al., 2019). There is widespread acceptance of the need for far-reaching responses by actors from the local to the global scales to make human settlements and infrastructure more resilient (UNDP, 2021). There is recognition also of the considerable capacity in settlements to meet climate change challenges, if the governance, financial and social conditions are in place (Carter et al., 2015; MINURVI, 2016). And yet the implementation of climate adaptation planning lags behind climate mitigation efforts in urban communities (Sharifi, 2020; Grafakos et al., 2019; Nagendra et al., 2018).

Since the publication of AR5, there has been rapid expansion in policy, practice and research related to climate change and human settlements. The 2030 Agenda for Sustainable Development (the SDGs) agreed in September 2015, was preceded by the Sendai Framework for Disaster Risk Reduction 2015-30 and followed shortly afterwards by the Paris Agreement (December 2015) (United Nations, 2015b). These make explicit mention of 'mainstreaming of disaster risk assessments into land use policy development and implementation, including urban planning' (Sendai Framework) (UNISDR, 2015). The agreements identify 'sustainable cities and communities' (SDG11) and 'cities and subnational authorities' (Paris Agreement) as important actors in integrating climate and development goals (Sanchez Rodriguez, Ürge-Vorsatz and Barau, 2018). However not all urban SDGs have measurable targets yet, or data, particularly in regard to children and youth, the elderly and disabled (Klopp and Petretta, 2017; Reckien et al., 2017; Nissen et al., 2020). Clear procedures for linking climate adaptation in communities at all scales to the SDGs is lacking (Major, Lehmann and Fitton, 2018; Sanchez Rodriguez, Ürge-Vorsatz and Barau, 2018).

The New Urban Agenda (NUA) (October 2016), with its focus on housing and sustainable urban development, commits its signatories to building resilient and responsive cities that foster climate change mitigation and adaptation (United Nations, 2016b). This agreement followed the Geneva UN Charter on Sustainable Housing, endorsed by 56 member states of the United Nations Economic Commission for Europe (United Nations, 2015d). The NUA aims to ensure access to decent, adequate, affordable and healthy housing for all, while reducing the impact of the housing sector on the environment and increasing resilience to extreme weather events (United Nations, 2016b). Voluntary, networked action led by cities was also illustrated by a November 2019 call to Mayors and youth climate activists to sign a voluntary pledge in a 'Race to Zero' ahead of the Conference of the Parties 26, which included endorsing principles of a New Green Deal (C40, 2019). Other voluntary, global, urban efforts have been led by the scientific community including the Research and Action Agenda on Cities and Climate Change Science which aims to promote research and reports (Prieur-Richard, Walsh and Craig, 2019).

These collaborative global changes are reflected in the bodies of literature assessed for this report. In AR5, the section on 'human settlements, industry, and infrastructure' contained three chapters: urban areas; rural areas; and key economic sectors and services. This chapter covers the full range of human settlements: from small settlements in predominantly rural areas, to large metropolises in both high-income and low-income countries. It also assesses evidence of climate change impacts, vulnerability and adaptation on a range of urban infrastructures, including infrastructure that incorporates socio-economic and ecosystem dimensions (see Section 6.1.3).

This assessment also considers new literature about how enabling environments can support adaptation in ways that are also sensitive to Indigenous knowledge and Local knowledge (see below Section 6.1), social justice (6.4.3.4)) and climate mitigation (Section 6.3.5.2). It builds on the findings of AR5 which highlighted the concentration of global climate risks in urban areas, the complex causal chains that mediate climate impacts for smaller settlements and rural areas, and the multiple issues shaping and influencing economic sectors and infrastructure. This integrated chapter enables a more detailed analysis of the inter-connected drivers of risk that affect urban people and settlements of different sizes. This discussion also highlights the inter-connections within and between urban areas, and between different types of infrastructure and how these complex relationships accentuate or limit the effects of climate change and the institutional structures that play a critical role in mediating and govern these relationships.

This chapter has five main sections. The first elaborates on changes in the international policy context since 2014, highlighting the implications that this has for responses to climate change in cities, settlements and key infrastructure. Section 6.2 is focused on observed and projected climate risks, paying particular attention to the ways in which these are created through processes of urbanisation and infrastructural investment. Section 6.3 takes an integrated and holistic approach to an assessment of adaptive actions relevant to key infrastructures (those that form the material basis for resilience in cities and settlements, drive economies and are essential for human well-being). Section 6.4 assesses the enabling conditions and leadership qualities associated with adaptation processes that can also meet the equity agenda of the SDGs, to leave no-one behind, including the role of governance, finance, institutions and emerging literature around the limits of urban adaptation.

Case studies highlight how climate and other issues interrelate to create (or reduce) urban risk within and between scales of decision making. They illustrate how multiple levels of governance and formal and informal decision making sectors influence how risk production/reduction plays out across a range of urban contexts and networks.

6.1.2 Points of Departure

The AR5 conceptualised cities and settlements as complex interdependent systems that could be engaged in supporting climate change adaptation (Revi et al., 2014 8.8.2). Effective municipal governance systems and cooperative multi-level governance supported adaptation action. The AR5 report expressed *medium confidence* that governance interventions can help develop synergies across geographical and institutional scales. Urban areas face challenges of infrastructure investment and maintenance, land use management, livelihood creation and ecosystem services protection. AR5 also considered how urban localities can encourage incremental and transformative adaptation, build resilience and support sustainable development. The assessment identified the need for multi-level and multi-partner action in rapidly growing cities where institutions and infrastructure are still not established to meet the growing demands of the cities. However, there was only *medium confidence* that adaptation action was happening in the AR5 review period.

The framing of 'key economic sectors and services' in AR5 focused primarily on three infrastructural areas (energy, water services, transport) and on primary and secondary economic activities (including recreation and tourism, insurance and financial services). Cities, settlements and key infrastructure are also referred to in the IPCC special reports released since AR5. The Special Report on Global Warming of 1.5°C (IPCC, 2018) examines impacts of global warming on urban systems and infrastructure in the context of advancing sustainable development and eradicating poverty. It highlights the risks facing residents of unplanned and informal urban settlements, many of which are exposed to a range of climate-related hazards (Sections 3.4.8 and 4.4.1.3). The Special Report on Global Warming of 1.5°C also identifies green infrastructure, sustainable land use and planning, and sustainable water management as key adaptation options that can reduce risks in urban areas (SPM C2.4; C2.5), and highlights 'urban and infrastructure' as one of four system transitions required to limit warming to 1.5°C to create an enabling environment for adaptation (Section 4.3.3). Innovative governance arrangements that go beyond formal 'government' and political arrangements and that include non-state actors, networks and informal institutions were identified as important in addressing climate change and implementing responses to 1.5°C-consistent pathways (Special Report on Global Warming of 1.5°C [Sections 4.4.1 and 5.6.2]). In addition, the Special Report on Global Warming of 1.5°C mentions, with *high confidence*, the climate-related health effects of urban heat islands, urban heatwaves and increasing risks from some vector-borne diseases (illnesses caused by pathogens and parasites in human populations) (SPM B5.2). The report also notes both trade-offs and important co-benefits of sustainable development in pursuit of climate resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities (SPM D6).

The Special Report on Oceans and Cryosphere (SROCC) similarly emphasizes the role governance plays in reducing disaster risk, through planning, and zoning (IPCC, 2019b). It identifies vulnerability factors such as poverty, which can undermine resilience and sustainable development in urban communities (IPCC, 2019b SPM C3.1,and Section 2.3.2) The SROCC report shows that the emerging climate-related challenges are impacting the accessibility and availability of vital resources and blurring the public and private boundaries of risk and responsibility (Cross-Chapter Box 3). According to the SROCC report, new governance arrangements are emerging to address these challenges, including participatory and networked structures, and institutions linking formal and informal networks involving state, private sector, Indigenous and civil society actors (Cross-Chapter Box 3). The SROCC report calls for place-specific action because there is no single climate governance panacea for the ocean, coasts and cryosphere (Cross-Chapter Box 3). The SROCC report highlights evidence of the importance of inclusivity, fairness, deliberation, reflexivity, responsiveness, social learning, the co-production of knowledge, and respect for ethical and cultural diversity in climate-related urban decision making (Cross-Chapter Box 3). In addition, the Special Report on Climate Change and Land notes that urbanisation can intensify extreme rainfall events over the city or downwind of urban areas and have can significant consequences for heat island effects on loss of food production, posing additional risks to the food system (IPCC, 2019b SPM A5.3 and Cross-Chapter Box 4 in Chapter 2).

An additional research bridge between AR5 and AR6 was the IPCC Cities and Climate Change Science conference held in Edmonton, Canada, in March 2018 (Prieur-Richard, Walsh and Craig, 2019). This generated a 'Global Research and Action Agenda on Cities and Climate Change Science' (Prieur-Richard, Walsh and Craig, 2019), which highlights six topical research areas where more evidence is needed to inform action: finance; informality; uncertainty; urban planning and design; built and green/blue infrastructure; and sustainable consumption and production. These areas are addressed in specific sections of this chapter or as cross-cutting themes. The Cross-Working Group Box URBAN in this chapter provides a linkage with perspectives from Working Group III.

6.1.3 Terminology and Definitions

This chapter covers both 'cities and settlements' and 'key infrastructure'.

Definitions of 'urban' have become more nuanced since the AR5 review with the publication of the OECD report 'A new perspective on urbanisation' (OECD and European Commission, 2020). This report presents two new global definitions of urbanisation reflecting the degree of urbanisation on a continuum of cities, towns and semi-dense areas, and rural areas. The OECD estimates almost half the world's population (48%) live in cities, while just 24% live in rural areas and 28% live in towns and semi-dense areas (28%). In addition, the OECD report defines metropolitan areas as functional urban areas together with their surrounding commuting zones 'to capture the full extent' of a city's working population. Metropolitan areas account for 54% of total world population, with the OECD estimating that commuting zones representing 17% of the overall metropolitan population, rising to 31% in high-income countries. In the context of these global definitions, this chapter identifies 'cities and settlements' as concentrated human habitation centres (along a dynamic continuum from rural to urban) (Murali et al., 2019; Ward and Shackleton, 2016) (Figure 6.1) that are fundamentally inter-connected to other urban centres and rural areas as nodes within broader networks.

Key infrastructure is used here to refer to 'critical nodes and arteries' that comprise urban energy, food, water, sewerage, health, transport and communication systems (Steele and Legacy, 2017; Maxwell et al., 2018; Bassolas et al., 2019). Key or critical infrastructure provides much of the material basis of cities and settlements, as well as the mechanisms for enabling flows of people, goods, data, waste, energy (through urban metabolism processes of consumption and production) and capital, between urban regions and rural areas (Blay-Palmer et al., 2018; Dijst et al., 2018). An overview of this process of 'planetary' urbanisation is provided in Box 6.1. The balance of accumulated scientific knowledge on climate risks, impact and adaptation has been generated from studies in large and medium-sized cities of 1 million or more. While these larger cities continue to grow rapidly (UNDESA 2018), settlements of more than 5 million people contain less than a quarter of the world's urban population, and more than half of the world's urban residents live in settlements of 1 million or less (Table 6.1). There is a key gap in knowledge, especially concerning urban enabling environments and how smaller settlements can be supported to accelerate equitable and sustainable adaptation in the face of financial and governance constraints (Birkmann et al., 2016; Shi et al., 2016; Dulal, 2019; Rosenzweig et al., 2018b).

This chapter takes a comprehensive approach to understanding 'key infrastructure' as expressed in social, nature-based and physical infrastructure. Social infrastructure includes the social, cultural, and financial activities and institutions, as well as associated property, buildings and artefacts and policy domains such as social protection, health and education that support well-being and public life (Frolova et al., 2016; Latham and Layton, 2019). Nature-based infrastructure focuses on solutions to risk, applying natural assets such as trees or open water, physical infrastructure describes engineering approaches and grey/physical infrastructure refers to engineered assets that provide one or multiple services required by society, such as transportation or wastewater treatment ([IISD, N.D.]; see also Annex II: Glossary).

This approach is based on a framing of cities and settlements as complex systems where social, ecological and physical processes interact in planned and unplanned ways. This chapter therefore builds on the AR5 Chapter 10 (Arent et al., 2014) conception of key economic sectors and services (e.g., energy, water, transport, waste, sanitation and drainage) by positioning these within three major categories of infrastructure: social, nature based and physical (see Section 6.3). Where adaptation challenges can be responded to by more than one approach, sometimes working together, this is noted (see also Sections 17.2 and 17.4). This approach allows an understanding of adaptation that is not constrained to the administrative boundaries of cities and settlements, but that includes the networks and flows

Table 6.1 | Proportion of the urban population in different size class urban areas (UN-DESA 2018). Each column indicates the percentage of urban residents in that region living in cities of that size class.

Proportion (by region) of urban population living in cities with population size	Africa	Asia	Latin America and the Caribbean	Europe	Northern America	Oceania	World
10 million +	8	15	17	4	10	0	13
5–10 million	6	9	3	5	17	0	8
1–5 million	22	22	25	16	30	60	22
500,000–1 million	9	10	8	11	13	2	10
300,000–500,000	6	6	6	8	7	11	6
Under 300,000	48	38	40	57	24	27	41

Defining 'urban' and 'rural' in relation to cities and settlements

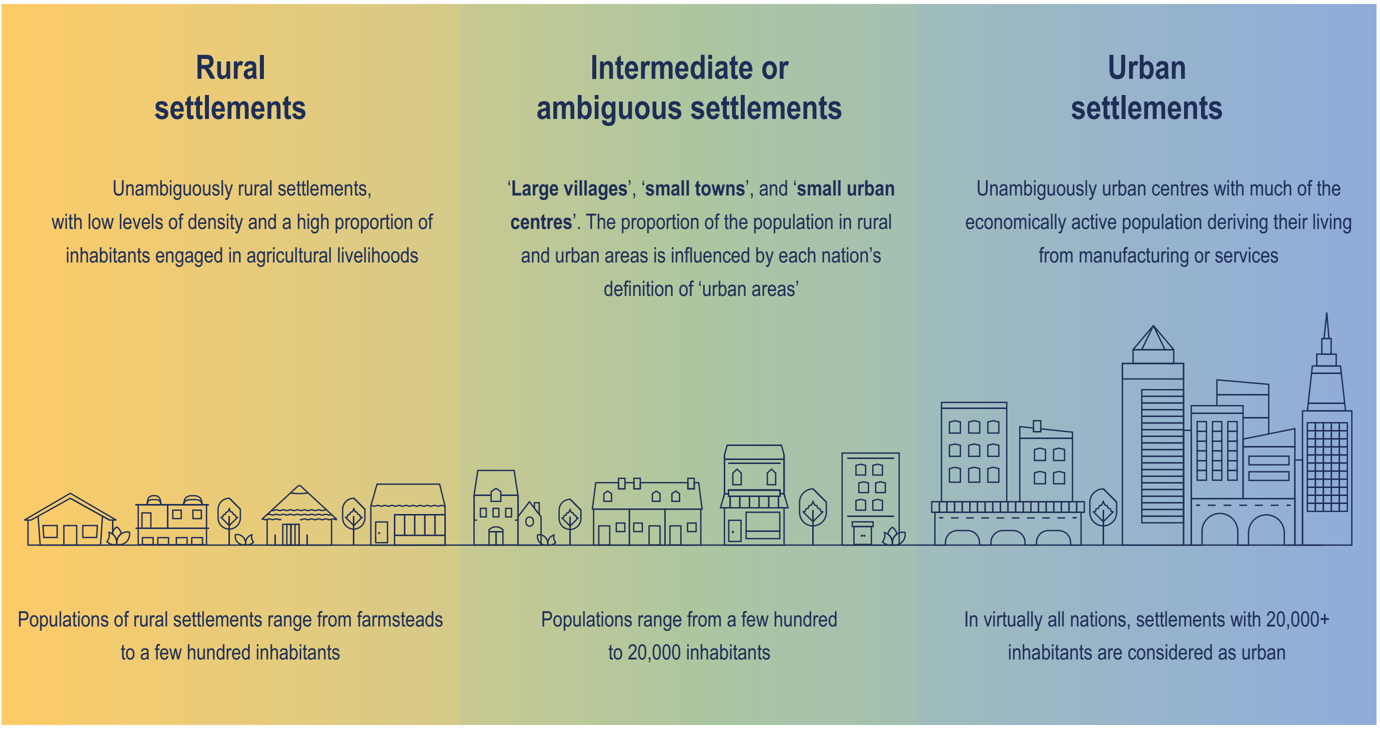

Figure 6.1 | Defining 'urban' and 'rural' in relation to cities and settlements

that connect peri-urban communities, metropolitan regions, suburban settlements and more rural places (see Box 6.1). Both formal provision of infrastructure services by government and informal provision by communities and individuals are considered at risk from climate change, as are existing adaptation pathways and actions.

Cities are complex entities where social, ecological and physical systems interact in planned and unplanned ways (Markolf et al., 2018). The complexity of cities, settlements and key infrastructure (Figure 6.2) where multiple functional systems continuously interact makes it difficult to distinguish risks (Box 6.1). The literature often resolves this by offering discrete assessments for specific sectors (see Section 6.3). This fragmented approach to understanding climate change associated impacts and risks is then reflected also in siloed approaches to risk management and adaptation financing (see Section 6.4). Recent literature notes that resilience planning has begun to overcome this tendency by presenting climate change impacts, losses and damages, and urban processes, as unfolding together in interacting and cascading pathways (Fraser et al., 2020; Eriksen et al., 2020) (Figure 6.2). The chapter reflects this change in the literature by presenting climate change impacts through a series of risk assessments, including by hazard type, through indirect impacts on health or food security, key infrastructure systems, land use and human mobility, water flows and on structural conditions, such as poverty and justice in the city (see Sections 6.3 and 6.4). In a departure from AR5 we also consider the consequential interactions of climate risks, impacts, adaptation and climate mitigation (see also Cross-Working Group Box URBAN in Chapter 6).

The IPCC 1.5°C Special Report commented that 'The extent of risk depends on human vulnerability and the effectiveness of adaptation for regions (coastal and non-coastal), informal settlements, and infrastructure sectors (energy, water, and transport) (*high confidence*)' (IPCC, 2018). We take this statement as a starting point for assessing the risks to cities, settlements and key infrastructure, with infrastructure extended as noted above. Risks from climate change are understood as the product of climate change associated hazards impacting on exposed and vulnerable people and assets (including biodiversity). Adaptation can, in some cases, reduce exposure and susceptibility and enable recovery and scope for transformation toward long-term equitable and sustainable development. Risks describe both present conditions and future prospects. Direct attribution of hazards to climate change remains limited to temperature extremes and sea level rise, though we consider all hydrometeorological hazards as systems associated with climate change processes.

This chapter also assesses conditions supporting incremental and transformative adaptation (Section 6.4). Incremental and transformative adaptation are both important but serve distinct roles in the interaction of urban systems, climate risk and risk management, and in advancing social justice, just transitions and climate resilient development (see Section 6.4). Climate resilient development pathways are an emerging concept in the literature since the AR5 (Schipper et al., 2020). Climate resilient development is an iterative process of systemic change that integrates both mitigation and adaptation efforts (see Annex II: Glossary). Initial studies highlight the way rapid urbanisation and precarious urban housing and land tenure can undermine climate resilient development, while human settlements that are managed to protect housing tenancy and land tenure rights can advance land use planning and social learning while reducing inequalities and vulnerability and enhancing resilient development (Mitchell, Enemark and Van der Molen, 2015; Bellinson

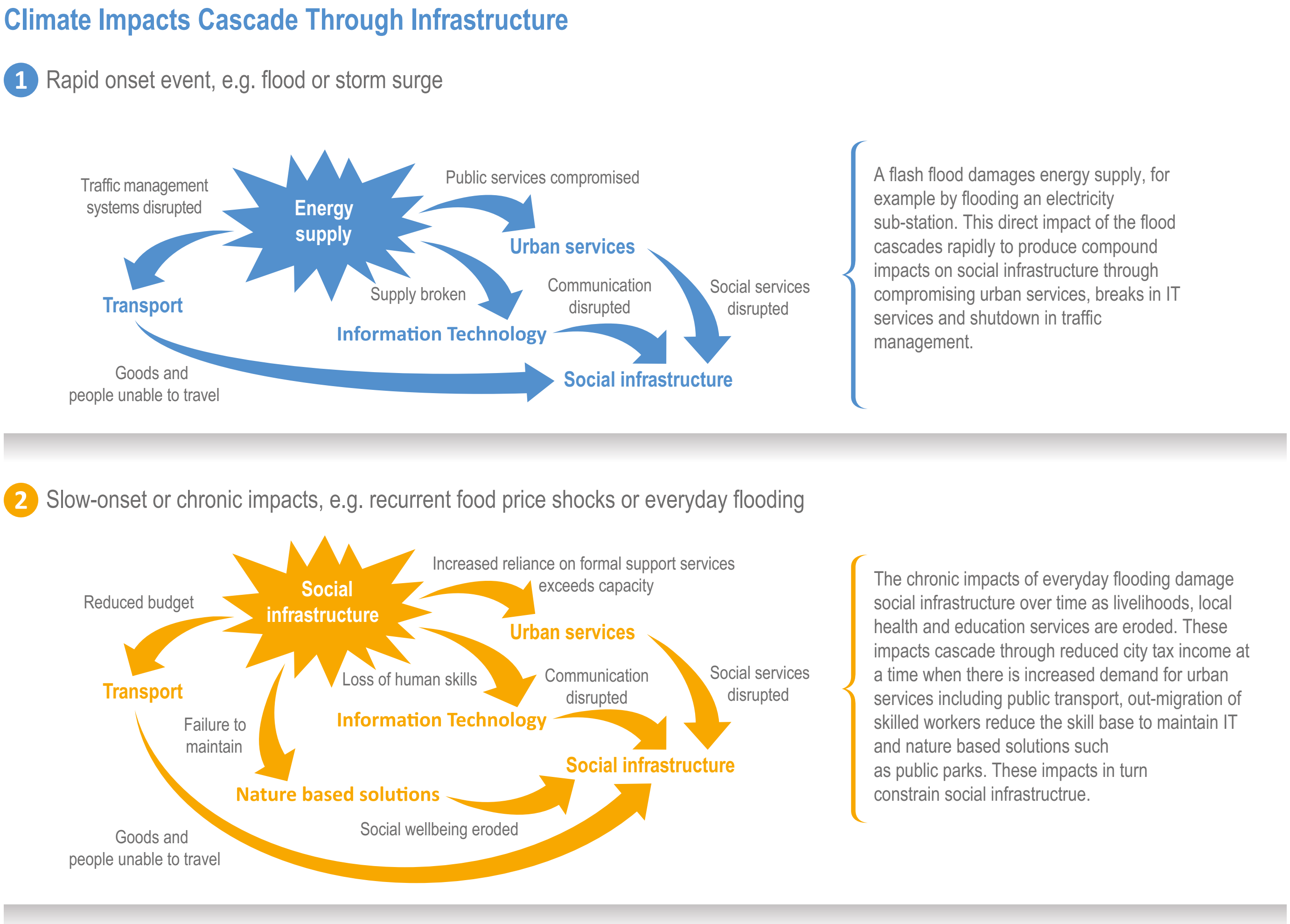

Figure 6.2 | The interconnected nature of cities, settlements and infrastructure

and Chu, 2019; Ürge-Vorsatz et al., 2018). The benefits of integrating decision making across scales for climate resilient development is also highlighted in Section 6.4. How households engage with communities and neighbourhoods and larger units within cities, and how cities (both formal and informal) interact with sub-national and national actors is also discussed, as is the role of finance and community-based organisations (CBOs)/NGOs in the governance process.

6.1.4 Global Urban Trends

Since AR5, many cities and other settlements, particularly unplanned and/or informal in Asia and Africa, have continued to grow at rapid rates (van den Berg , Otto and Fikresilassie 2021). Elsewhere, in Latin America in particular, while growth is less rapid, inequality persists. As a result, cities and settlements are crucial both as sites of potential action on climate change, and sites of increased exposure to risk (*medium evidence, high agreement*).

Patterns and trends for urban population growth were described in detail in AR5. Between 2015 and 2020, urban populations globally have grown by more than 397 million people, with more than 90% of this growth taking place in less developed regions (UNDESA, 2018).

The latest population projections from UNDESA (2018) reinforce the trends identified previously, with even higher estimates for global urban populations. The 2012 data used in AR5 projected a global urban population of 4984 million in 2030 and 6252 million in 2050; the 2018 revisions project 5167 million and 6680 million respectively. Particularly noteworthy is the higher projection provided for sub-Saharan Africa's urban population: increasing from 596 million to 666 million in 2030, and from 1069 million to 1258 million in 2050. These figures highlight the continued trend toward larger urban populations, and the particular significance of this in areas which currently have relatively small proportions of their populations living in towns and cities; this is also true in some Small Island States (e.g., the Solomon Islands) (McEvoy et al., 2020). The proportion of the global urban population living in megacities (with populations of more than 10 million people) is expected to continue growing slowly (to 16% of the urban total, or 862 million people, living in 48 agglomerations) by 2035 (UNDESA, 2018). The size and form of these megacities presents particular challenges with climate change impacts, in areas including air quality (Baklanov, Luisa and Molina, 2016), flooding (Januriyadi et al., 2018), and temperature increase (Darmanto et al., 2019) (see Section 6.2.3).

While there are few analyses of urban trends at the global scale, an additional 2.5 billion people are projected to be living in urban areas by 2050, with up to 90% of this increase concentrated in the regions of Asia and Africa, particularly in India, China and Nigeria, where 35% of this urban growth is projected to occur (UNDESA, 2018). Growth rates are slowing down in North America, South America and Europe (UNDESA, 2018). Much global growth continues to outstrip the ability of governments or the private sector to plan, fund and provide for sustainable urban infrastructure and this is most marked in low-income and informal settlements (Angel et al., 2016). Rural migration as a driver of urbanisation is discussed in 6.2.4.3, and literature has documented the way urban expansion and the conversion of agricultural land is also driven by investment incentives and weak planning policies (Colsaet, Laurans and Levrel, 2018; Woodworth and Wallace, 2017). At the same time, early evidence suggests that, at least in some locations, out-migration from cities occurred as a result of the COVID-19 pandemic (Rajan, Sivakumar and Srinivasan, 2020), but the evidence is not clear and in some cases may have increased migration to other megacities (Chow et al., 2021). There is also growing recognition that poor planning has exacerbated the concentrated of deprivation in specific locations, deepening a cycle of exclusion and marginalisation (UNDESA, 2020).

One critical element of global urban trends which has received growing attention is informality (see also Prieur-Richard, Walsh and Craig, 2019). Informality is one of the key defining features of cities and settlements in the Global South (see Annex II: Glossary; Banks, Lombard and Mitlin, 2020; Myers, 2021; UN-Habitat, 2016c). In almost all nations in the Global South, more than half the urban workforce work in informal employment; the proportions are particularly high in South Asia (82% in informal employment) and sub-Saharan Africa (66%) (Chen, Roever and Skinner, 2016; Chen, 2014). The term 'informal settlement' refers to urban settlements or neighbourhoods that developed outside the formal system that is meant to record land ownership and tenure and without meeting a range of regulations relating to planning and land use, built structures and health and safety. Informality is a broader concept than 'slums', which are usually defined using measures of housing quality, provision of services and overcrowding. While most countries do not generate formal statistics on the number of people living in informal settlements, UN Habitat provides regional and global estimates of the number of urban households that are 'slum' households and therefore likely to include most residents of informal settlements. These estimates suggest that there were 1034 million slum dwellers in 2018, including some 56% of the urban population in sub-Saharan Africa and more than 30% of the urban population of South Asia (UN-Habitat, 2020). Informality is particularly important in understanding climate risks and responses in cities and settlements, and also in relation to key infrastructure (Trundle, 2020; Taylor et al., 2021).

Evidence since AR5 confirms that occupants of informal settlements are particularly exposed to climate events given low-quality housing, limited capacity to adapt, and limited or no risk-reducing infrastructure (*high confidence*) (Melore and Nel, 2020; Twinomuhangi et al., 2021; Satterthwaite et al., 2020; Patel et al., 2020a)(see Section 6.2 and case study). The impacts of COVID-19 are also increasingly impacting high-density informal and slum settlements where social distancing and access to water for handwashing are limited (Bhide, 2020; Pinchoff et al., 2021; Tagliacozzo, Pisacane and Kilkey, 2021; Wilkinson, 2020). This compounds pre-existing vulnerability to climate change associated hazards. Box 6.1 expands on trends in informality as part of global urbanism, peri-urbanisation and suburbanisation, with implications for the global distribution of climate risks and adaptive capacity.

Box 6.1 | Planetary Urbanisation and Climate Risk

The scale, reach and complexity of contemporary urbanisation compounds climate risks and conditions adaptation (*high confidence*) (Miller and Hutchins, 2017; Rosenzweig et al., 2018b). Urbanisation manifests as a heterogeneous and plural process with varied spatial manifestations (Oswin, 2018) that extends beyond cities and settlements, defining actions elsewhere in what has been called 'planetary urbanization' (Brenner, 2014b). While the concept of planetary urbanisation is contested, for example for a predominantly Eurocentric focus (Vegliò, 2021), the concept has reflected human urbanisation as a mega-trend of urban expansion and landuse intensification (Capon, 2017; Lauermann, 2018). Three dimensions of planetary urbanisation are currently shaping adaptation actions: the new forms and scales of urbanisation, the blurring of boundaries around clearly demarcated territories, and the fragmentation of the urban hinterland into units that serve productive functions for the reproduction of urban space under capitalism (Brenner and Schmid, 2017).

Planetary scale urbanisation challenges current understandings of spatial settlements and how risk affects urban communities (*limited evidence, medium agreement*) (Ruddick et al., 2018). Massive urbanisation manifests in large agglomerations such as metropolitan areas and urban regions, conurbations with unique risk challenges, particularly when interacting with other drivers of vulnerability (Adetokunbo and Emeka, 2015; Maragno, Pozzer and Musco, 2021). Experiences of regional collaboration to scale adaptation to metropolitan areas have shown to be effective, particularly facilitating information and technology exchanges and institutional cooperation (Shi, 2019; Lundqvist, 2016), but may face challenges such as addressing administrative and fiscal requirements and enrolling local populations in a meaningful participation process (Shi, 2019). For example, the coordination of planning policies in the Vienna–Bratislava metropolitan region, further divided by an international border, demonstrates that institutional coordination alone is not sufficient to deliver effective spatial governance: instead, meaningful spatial policies required the involvement of multiple actors (Patti, 2017). In addition to institutional coordination, adaptation in rapidly urbanising areas requires understanding how these processes magnify risk and condition urban responses (see also Section 6.3).

Urban expansion processes affect human settlements everywhere, regardless of their size. Figure 6.1 represents a continuum of settlements from high- to low-density areas (Ward and Shackleton, 2016). Urban and rural areas are not always clearly differentiated (Brenner, 2014a;

6

Box 6.1 (continued)

Brenner and Schmid, 2017). For example, in 2010/2011, drought-exacerbated wildfires across Russia's agricultural hinterland not only led to increased air pollution in Moscow and other large cities in the region, it also disrupted global supply chains of wheat and caused skyrocketing global food prices (Zscheischler et al., 2018). Floods in Bangkok, Thailand in 2011 destroyed many foreign-owned factories, leading to a global shortfall in different types of IT equipment (Levermann, 2014).

Rural areas provide ecosystem services that benefit cities directly, including through reducing hazards (runoff, and temperature) and through carbon storage, and can be maintained through urban markets and other inputs (Gebre and Gebremedhin, 2019). Most urban areas extend into dispersive peri-urban areas where urban and rural land uses co-exist (Simon, 2016) and/or suburban areas which are lower density and primarily residential in function. Moreover, the urban and rural differentiation creates normative expectations at the heart of planning conflicts and constraints of urban governance (Taylor, Butt and Amati, 2017). Expanding peri-urban areas pose specific structural constraints to addressing risks. In Bogotá, Colombia, a study found marked inequalities as more impoverished families had restricted access to peri-urban forests, trees and tree services (Escobedo et al., 2015). Factors such as limited land ownership and tenure insecurity in peri-urban areas hinder people's ability to invest in permanent infrastructure to buffer themselves from flood events, as witnessed in the slums in Nairobi (Thorn, Thornton and Helfgott, 2015). Building resilience and adaptation via community mobilisation may not be effective in peri-urban areas shaped by migration, agricultural intensification and industrialisation (Wandl and Magoni, 2017).

At the same time, actions to improve access to peri-urban services almost always improve resilience (Simon, 2016) Evidence from Kampala, Addis Ababa, Dar es Salaam, Douala, Ibadan, Nairobi, Dakar and Accra shows that urban and peri-urban agriculture and forestry can support adaptation (Lwasa et al., 2014). In the metropolitan area of Milan, multi-functional agriculture supports a local, more sustainable food chain (Magoni and Colucci, 2017). Since communities in peri-urban areas are often transitory, efforts toward creating social capital by promoting civic engagement are crucial to facilitate collective action (Narain et al., 2017). For example, adaptation actions can help to build the capacity of the community to engage with service providers (Harris, Chu and Ziervogel, 2018; Ziervogel et al., 2017), as demonstrated in parts of peri-urban Kolkata, India and Khulna, and Bangladesh (Gomes and Hermans, 2018; Gomes, Hermans and Thissen, 2018).

Urbanisation on an immense scale blurs the boundaries that previously defined cities and settlements (Arboleda, 2016a; Shaw, 2015; Brenner, 2014a; OECD and European Commission, 2020; Schmid, 2018; Davidson et al., 2019; Wu and Keil, 2020). For example, peri-urban areas typically extend over multiple government jurisdictions (Wandl and Magoni, 2017). Adaptation actions can be difficult to plan, coordinate, implement and evaluate in these transboundary contexts (Solecki et al., 2018; Srivastava, 2020; Fünfgeld, 2015; Rukmana, 2020; Carter et al., 2018). In Medellín, Colombia, a 46-mile-long green belt is being built to stop urban expansion while also protecting urban forests, providing access to green spaces, and reducing urban heat island effects (Anguelovski et al., 2016). However, large-scale infrastructure projects such as this one require coordination between regional transport authorities and the different municipalities in charge of housing and public services, in addition to consulting communities on their social impact (Chu, Anguelovski and Roberts, 2017). Local and regional authorities have competing mandates, such as a competition for taxpaying residents in peri-urban, commuting zones, and different infrastructure investment logics, political drivers and constituent needs. Smaller discrete infrastructure projects that actively engage local populations may provide better opportunities to build resilience across fragmented spaces (Santos, 2017; Kamalipour and Dovey, 2020).

Suburbanisation follows a gradual movement of citizens from high-density urban centres to the suburbs (Pieretti, 2014). The development of enclaves for higher-income people that appropriate resources and constrain access to those resources for disadvantaged populations has been recorded in places as distant as Santiago de Chile, People's Republic of China, India, Indonesia and the Philippines (Calvet and Castán Broto, 2016; Phelps, Miao and Zhang, 2020; Bulkeley, Castán Broto and Edwards, 2014; Buchori et al., 2021; Kleibert, 2018). The appropriation of land and resources in enclaves defends exclusive, privileged communities at the expense of everyone else. Enclaves exacerbate inequalities because those who cannot afford to live in the enclave suffer the fragmentation of public services, restrictions in access to resources, and greater exposure to climate risks (Hodson, 2010; Haase et al., 2017). Moreover, suburbanisation is linked to the privatisation of public spaces and the decline of public infrastructures, collective spaces and green projects (Long and Rice, 2019; North, Nurse and Barker, 2017). Climate gentrification, whereby vulnerable communities are displaced from urban areas with lower climate risks (UN-Habitat, 2020), reconfigures urban areas, for example, as higher-income populations move away from the city centres, as shown in North American cities that have already suffered climate-related impacts such as Miami, Philadelphia and New Orleans (Keenan, Hill and Gumber, 2018; Shokry, Connolly and Anguelovski, 2020; De Koning and Filatova, 2020; Aune, Gesch and Smith, 2020).

Urbanisation leads to the spatial fragmentation of the hinterland, divided alongside functional units to serve the demands of the capitalist urban economy (Brenner and Schmid, 2017). Urbanisation is thus linked to new intensities of resource exploitation that threaten vulnerable land and ecosystems, as shown in the Amazon, and that extend across scales (Arboleda, 2016b; Wilson, 2018). The fragmentation of the hinterland for extractivist purposes depletes ecosystem services and further exacerbates cascading risks (*high confidence*) (Section 6.2.6).

Adaptation and related concepts of urban climate resilience are also concerns for the broader agenda of sustainable development (Wachsmuth, Cohen and Angelo, 2016). Urban areas can play a positive role in advancing sustainability, but the pace and scale of urban development can also undermine progress in SDGs (Barnett and Parnell, 2016; Maes et al., 2019; Anarfi, Hill and Shiel, 2020) (*high confidence*). With careful planning, urbanisation can be a transformative force, enhancing equity and well-being through co-benefits and synergies between climate change adaptation, equitable urban development and mitigation (*medium evidence, medium agreement*) (Parnell, 2016a; Solecki et al., 2015; Sharifi, 2020). Cities can be effective change agents when supported by networked local and national institutions, including professional bodies (*high confidence*) (Andonova, Hale and Roger, 2017; Brandtner and Suárez, 2021; Heidrich et al., 2016; Kern, 2019; Farzaneh and Wang, 2020). Low Emission Development Strategies (LEDS) have developed effective science–policy interactions to support energy-system, environmental and economic development planning strategies in the city of Shanghai, China (Farzaneh and Wang, 2020). New literature is emerging about how adaptive changes at the urban level could integrate both far reaching rapid emission reduction and community protection in transformative ways (Wamsler and Raggers, 2018; Rosenzweig and Solecki, 2018; UN-Habitat, 2020; Ziervogel, 2019a). There is an increasing consensus about the need for integrated governance of urban areas within and across regions, so that urban risk management and adaptation happen hand in hand with more general processes of transition toward more sustainable urban regions (Simon, 2016; UN-Habitat, 2020).

Since AR5, there has also been increasing recognition of the contribution of diverse knowledges including local and Indigenous knowledge in contributing to the development and interpretation of urban relevant climate change data and policy for effective action (Klenk et al., 2017; Hosen, Nakamura and Hamzah, 2020; Makondo and Thomas, 2018). Indigenous and local knowledge inform coping strategies in urban adaptation planning and new directions for action (Nakashima, Krupnik and Rubis, 2018; Abudu Kasei, Dalitso Kalanda-Joshua and Tutu Benefor, 2019). Indigenous and local knowledge is also found to shape perceptions about urban climate risk awareness, its acceptable limits, causation and preferences for adaptation (see also Pyhälä et al., 2016 for a review; see Jaakkola, Juntunen and Näkkäläjärvi, 2018 for impacts on Indigenous peoples in the EU; Saboohi et al., 2019). Local perceptions about climate change in turn influence adaptation behaviours in settlements and urban communities (Lee et al., 2015; Larcom, She and van Gevelt, 2019). Engagement with Indigenous and local knowledge is an enabling condition for planning community-appropriate climate adaptation responses (Fernández-Llamazares et al., 2015). Urban decision making that includes Indigenous and local knowledge has co-benefits for addressing indigenous dispossession, historical inequities and marginalisation of indigenous values that occurred (Parsons et al., 2019; Carter, 2019; Maldonado et al., 2016; Orlove et al., 2014; Pearce et al., 2015). Indigenous and local knowledge can help deliver culturally appropriate strategies and local choices for urban risk management through, for example community-based observation networks (Alessa et al., 2016), integrating ecosystem-based adaptation strategies in institutional structures (Nalau et al., 2018), using multiple evidence-based approaches (Tengö et al., 2014), and adopting forms of governance that centre Indigenous peoples in urban adaptation and decision making (Horn, 2018; Parsons, Fisher and Nalau, 2016).

6.1.5 Changes in the Global Enabling Environment

This section reports on changes in global enabling environment; the architecture of international agreements available to inform policy for national governments and others on urbanisation and climate adaptation, since the AR5.

Six new international agreements and initiatives have been achieved, each of which has far-reaching implications for the management of rapid urbanisation and climate change: the Paris Climate Agreement (United Nations, 2015b); the 2030 Agenda for Sustainable Development, including the SDGs (United Nations, 2015c); the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015); the New Urban Agenda (United Nations, 2016a); Addis Ababa Action Agenda (July 2015); and the World Humanitarian Summit (May 2016). Table 6.2 summarises these.

Alongside new international agreements are a series of new landmark global stocktake reports: three IPCC special reports including the IPCC 1.5 report (IPCC, 2019a; IPCC, 2019b Hoegh-Guldberg et al., 2018), the UN Environment GEO6 (UN Environment, 2019) and IPBES 2019 (Brondizio et al., 2019), and UNDRR 2019 (UNDRR, 2019), each have argued for urgent action on climate mitigation and to invest in inclusive strategies for adaptation if the SDGs are to be met. These findings are comprehensively evidenced and do not need to be revisited here. Our starting point then is to assess the science on how inclusive, sustainable development can be delivered through enhanced adaptation to climate change risks.

As a blueprint for advancing human dignity, the SDGs emphasize the need to consider how to achieve a better and more sustainable future while 'leaving no one behind.' In doing so, they highlight an agenda focused on well-being, equality and justice. The objective for SDG11 is defined as: 'Make cities and human settlements inclusive, safe, resilient and sustainable' with 10 associated targets including ensuring access for all to adequate, safe and affordable housing and basic services; participatory planning; safeguarding heritage features; reducing disasters, particularly water related disasters and economic impacts on the poor; and promoting resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement plans, in line with the Sendai Framework for Disaster Risk Reduction. Similarly, SDG9 aims to build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation, with associated targets. The IPCC 1.5 special report emphasized that there are often co-benefits in pursuit of SDGs and adaptation strategies where 'well-designed mitigation and adaptation responses can support poverty alleviation, food security, healthy ecosystems, equality and other dimensions of sustainable development' (IPCC, 2018 FAQ5.1). However there may also be negative trade-offs, for example between pursuit of growth and reducing climate change risk (International Council for Science, 2017; IPCC, 2018 Executive Summary; Roy et al., 2018a).

The Paris Agreement also envisioned a significantly more active role for cities and other non-state actors in facilitating policy change (Hale, 2016), including through participation in Nationally Determined Contributions (NDCs), although there is little systematic review of the

Table 6.2 | International policy agreements with implications for urbanisation and climate adaptation

Agreement (date of agreement)	Scope of agreement	Relevance for cities, settlements and infrastructure	Relevance for addressing climate change risk
Sendai Framework for Disaster Risk Reduction (March 2015)	Global agreement for reducing disaster risks in all countries and at all levels. Highlights urbanisation as a key driver of risk and resilience.	Identifies rapid urbanisation as a key underlying risk factor for disasters and driver of resilience. Promotes shift from disaster response to disaster risk management and reduction through cooperation between national and local governments. Limited focus on the role of civil society.	Highlights the need to respond to systemic risk, including compound and cascading risks and impacts from natural, technological and biological hazards. Includes focus on chronic stressors and sudden shocks through governance, planning, disaster response, post-event recovery.
Addis Ababa Action Agenda (July 2015)	Global agreement arising from the International Conference on Financing for Development (United Nations, 2015a) emphasized the need for adequate financing at all levels of government, especially sub-national and local, to support sustainable development, infrastructure and climate mitigation (UN-Habitat, 2016b).	Includes general comments on the importance of local actors and recognises the need for strengthening capacities of municipal and local governments. Commits to 'support' local governments to 'mobilise revenues as appropriate'. Offers little on how to get finance to support local governments addressing these commitments.	Financing a critical element of risk reduction in cities and settlements (see Section 6.4). Underlying variability of institutional arrangements inhibits development of universal framework.
Transforming our world: the 2030 Agenda for Sustainable Development (September 2015)	Global agreement adopted by 193 governments that includes the 17 Sustainable Development Goals (SDGs).	SDG11 speaks explicitly to making cities 'inclusive, safe, resilient and sustainable'. Extensive reference to universal provision of basic services in other SDGs which will require substantial efforts in cities; equality and governance are also stressed. Focuses on national goals and national monitoring with insufficient recognition of key roles of local and regional governments and urban civil society in addressing most of the SDGs.	SDG13 on climate action requires action in cities and settlements. Integrated approach can address underlying drivers of risk.
The Paris Agreement (December 2015)	Global agreement under UN Framework Convention on Climate Change: signed by 194 and ratified by 189 member states (05/01/21).	References the role of the local or sub-national levels of government and cities as non-state actors.	Encourages cities to develop specific agendas for climate action (mitigation and adaptation).
The World Humanitarian Summit (May 2016)	Not an agreement, but a summit of 180 member states generating over 3500 commitments to action and addressing the role of non-state actors in reducing risk of climate change related forced displacement of people.	Includes five agreed 'core responsibilities' with relevance for urban areas, and commitments were made by professional associations, non-governmental organisations and networks of local authorities to address these in towns and cities.	Climate change likely to shape flows of refugees and migrants who are likely to live in highly exposed areas, particularly in low-income cities. However 'meagre funding for collaboration, poor data collection and sharing' (Acuto, 2016) limits commitment effectiveness (Speckhard, 2016).
The New Urban Agenda (October 2016)	Global agenda adopted at UN Conference on Housing and Sustainable Urban Development (Habitat III) envisioned national urban policies and adaptation plans as a central device to inform sub-national governments addressing sustainable development.	Intended as the global guideline for sustainable urban development for 20 years, seeking to provide coherence with other agreements. Focus on national policy and action. Limited recognition of urban governments or civil society as initiators and drivers of change.	Clearly frames roles for cities within national and international systems in contributing to sustainability (including low-carbon development) and resilience (including adaptation). Frames the role for cities within national and international systems, including an ongoing assessment of their contribution to sustainability and resilience (Kaika, 2017; Valencia et al., 2019).

contributions made by cities to NDCs (Hsu et al., 2020; Bäckstrand and Kuyper, 2017). Over two-thirds, 113 out of 164, of initial Intended Nationally Determined Contributions (INDCs), prior to ratification, had referenced urban responses in the context of sustainable development, climate mitigation and adaptation (UN-Habitat, 2016a). Analysis of those INDCs revealed 58 focused on urban climate adaptation, 17 focused on both adaptation and mitigation, and 4 focused on mitigation (UN-Habitat, 2017). Simultaneously, multiple efforts have emerged to align the actions of nation states with those of other actors, including the UNFCC 2014 Global Climate Action Portal (Hsu, Weinfurter and Xu, 2017). While significant optimism has been gathered around the possibility to intervene at sub-national level, the most difficult challenge has been to establish a coherent view of the overall contribution that cities and settlements are making (Hale, 2016; Chan et al., 2015b). Although meeting the Paris goals will require staying within a 'carbon budget', supporting rapidly developing urban areas in the Global South to the same infrastructure level as developed cities may consume significant proportions of that budget (Bai et al., 2018).

There is increasing international effort among non-Party stakeholders to the Paris Climate Agreement to collaborate to meet the Paris Climate goals (Data Driven Yale New Climate Institute PBL, 2018; Chan et al., 2015a). A review of contributions by non-state actors in 2019 by the EU Covenant of Mayors identified 10427 cities with climate commitments, while the Global Covenant of Mayors included 10543 cities representing a population of 969 million citizens (Palermo et al., 2020; Peduzzi et al., 2020). International efforts also include the United Nations Framework Convention on Climate Change (UNFCCC) Non-State Actor Zone for Climate Action (Data Driven Yale New Climate Institute PBL, 2018). There is also a proliferation of new non-governmental and public-private actors that address both adaptation and mitigation in cities and settlements, including: the C40 Cities Climate Leadership Group, 100 Resilient Cities; the Global Resilient Cities Network, We Mean Business, and We Are Still In (Ireland and Clausen, 2019) and the Global Alliance for Buildings and Construction (Dean et al., 2016). However, there is as yet limited research into the effectiveness of these initiatives in enhancing medium and small city adaptation and limited documentation of climate adaptation actions by non-traditional agents, particularly in the Global South (Lamb et al., 2019).

New urban activists and stakeholders, including youth, and Indigenous and minority communities and NGOs alongside business groups have also been visible in the global urban climate debate, pressing for faster, more far-reaching change (Frantzeskaki et al., 2016; O'Brien, Selboe and Hayward, 2018; Alves, Campos and Penha-Lopes, 2019; Smith and Patterson, 2018; Crnogorcevic, 2019; Campos et al., 2016; Hayward, 2021). Emergent urban social movements for climate justice often build on established international networks including local activists such as Shack and Slum Dwellers International, while others are inspired by Indigenous movements and are focused on human rights, indigenous sovereignty and land claims, access to water, intergenerational justice, and gender and youth movements coordinated on social media (Agyeman et al., 2016; Cohen, 2018; Ulloa, 2017; Hayward, 2021; Prendergast et al., 2021). The emergence of climate justice movements in urban communities has the potential to reframe policy discussion in cities in ways that also bring inequality and climate justice to the fore (Sheller and Urry, 2016), underscoring growing public calls for more far-reaching, transformative changes toward socially just urban transformations (Akbulut et al., 2019; Foran, 2019; Vandepitte, Vandermoere and Hustinx, 2019; Smith and Patterson, 2018).

This section demonstrates the consistency with which urban processes and places have been rising to the top of international agreements and agendas in the last 10 years (Bulkeley, 2015; van der Heijden et al., 2018; Knieling, 2016). However, many cities, particularly smaller cities and informal settlements in the Global South where development is rapid, need greater support for local governance, more information, and more diverse sources of finance to meet the vision of global climate agreements (Greenwalt, Raasakka and Alverson, 2018; Cohen, 2019). Moreover, the response of many cities to climate change is often constrained by wider political, social and economic structures, development path dependences and high carbon lock in (Princeti, 2016; Johnson, 2018; Jordan et al., 2015).

6.2 Impacts and Risks

This section assesses the impacts of hazards associated with climate change that will affect cities, settlements and key infrastructure, particularly how climate systems and urban systems interact to produce patterns of risk and loss. The conclusions of the IPCC Special Report on Global Warming of 1.5°C noted that 'Global warming of 2°C is expected to pose greater risks to urban areas than global warming of 1.5°C (*medium confidence*)'.

This section commences with a review of scenarios and pathways linking urban and infrastructural development with climate change; then assesses the key risks (with a focus on those for which there is a greater degree of evidence or confidence since AR5) and how these risks are created in urban settings. It then assesses evidence on the differentiated nature of human vulnerability and the risks affecting key infrastructure. Finally, this discussion reviews compound and cascading risks, and risks created by adaptation actions.

6.2.1 Risk Creation in Cities, Settlements and Infrastructure

In addition to direct climate impacts, interactions among changing urban form, exposure and vulnerability can create climate change-induced risks and losses for cities and settlements. Climate change already interacts with ongoing global trends in urbanisation to create regionally specific impacts and risk profiles. Through demographic change and encroachment into natural and agricultural lands and coastal zones, rapidly expanding urban settlements can place new physical assets and people in locations with high exposure (Tessler et al., 2015; Arnell and Gosling, 2016; Kundzewicz et al., 2014). Increasing rates of global urbanisation will pose additional challenges to areas that have high levels of poverty, unemployment, informality, and housing and service backlogs (Jiang and O'Neill, 2017; Williams et al., 2019). There is some evidence to suggest that climate change impacts themselves are increasing urbanisation rates, generating a challenging feedback loop. In sub-Saharan Africa, for example, manufacturing towns have experienced growth because of population movement following droughts in agricultural hinterlands (Henderson, Storeygard and Deichmann, 2017). The rapid rate of urbanisation therefore presents a time-limited opportunity to work toward risk reduction and transformational adaptation in towns and cities. The following sections explore these dynamic interactions between urban systems and climate change, and how these shape risk for people and for key infrastructures.

Examining projected climate change impacts and resulting risks in cities, settlements and key infrastructures requires the prerequisite development of scenarios which are plausible descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces, (e.g., rate of technological change, prices and relationships) and pathways or the temporal evolution of natural and/or human systems, such as demographic and urban land cover change, toward a future state or states (Gao and O'Neill, 2020; Gao and O'Neill, 2019; see also Section 6.1.5).

Climate change research creates scenarios integrating emissions and development pathways dimensions (Ebi et al., 2014; van Vuuren et al., 2017b; van Vuuren et al., 2017a) and Representative Concentration Pathways (RCPs) (Riahi et al., 2017). For risk reduction at regional scales, scenarios require urban-relevant climate projections, for example, downscaling from global and regional climate models of variables such as temperature, precipitation, air pollutants and sea level rise that are analysed usually for mid- or end-21st Century timeframes (e.g., Mika et al., 2018; Kusaka et al., 2016; Masson et al., 2014b). These data are needed to ascertain likely ranges of climate change impacts within city and settlement boundaries, and to quantify physical exposure when developing pathways for risk reduction. Consideration of current and projected future growth pathways of multiple urban sectors and key infrastructure, for example, transport, energy and buildings, are also needed to estimate probabilities of risk outcomes and damages within and across urban systems (O'Neill et al., 2015)(WGIII AR6 Section 8).

The challenges of managing these risks are amplified by the complex interactions between climate and urban scenarios, owing to the smaller spatial–temporal scales of urban areas in climate change modelling relative to global climate models (GCM) and shared socioeconomic pathways (SSP); geographical or geomorphological variations in city location; uncertainties arising from incomplete assumptions about socio-economic pathways at urban scales affecting urban demographics, for example, fertility rates and life expectancies or increased rural–urban migration; and challenges in modelling the urban climate and in developing urban climate observational networks in cities (WGI Box 10.3; Kamei, Hanaki and Kurisu, 2016; Yu, Jiang and Zhai, 2016; Jiang and O'Neill, 2017; Baklanov et al., 2018). Additionally, carbon-intensive economic growth, increasing inequalities, global pandemics, and uncontrolled or unmanaged urbanisation will exacerbate the exposure and vulnerability of urban systems modelled in existing climate scenarios and pathways (*high confidence*) (Phillips et al., 2020; Jackson, 2021; Raworth, 2017; Moraci et al., 2020). Mitigating these outcomes requires new forms of urban governance for climate adaptation, disaster risk reduction and building resilience (see Section 6.4).

Strong connections exist between climate change scenarios and urban climate-related risks. In some cases, the linkage is direct as climate change is associated with more frequent and more intense extreme weather and climate events, as assessed in Section 6.2.3. In other contexts, the connection is mediated by urban developmental pathways arising from local-scale environmental stresses and degradation, and access to adaptation options, as reviewed in Section 6.2.4.

6.2.2 Dynamic Interaction of Urban Systems with Climate

Urban systems interact with climate systems in multiple, dynamic and complex ways (Section 6.1.1, Doblas-Reyes et al., 2021 Box 10.3). Climate change can have direct impacts on the functioning of urban systems, while the nature of those systems plays a substantial role in modifying the effects of climate change (*high confidence*) (Frank, Delano and Caniglia, 2017; Smid and Costa, 2018). An example of this urban system climate nexus is the urban heat island effect (discussed in Section 6.2.3.1) (Susca and Pomponi, 2020). Assessing the inter-relationships between multiple systems and a range of hazards is particularly important as many cities are presently exposed to multiple climate-related hazards: more than 100 cities analysed as part of a 571 city study in Europe were deemed vulnerable to two or more climate impacts (Guerreiro et al., 2018). Rapid expansion of urban areas increases the exposure of urban populations to various hazards independent of global climate change. Huang et al. (2019) project that urban land areas will expand by 0.6–1.3 million km^2 between 2015 and 2050, an increase of 78–171% over the urban footprint in 2015. Specifically in relation to floods and droughts, Güneralp et al. (2015) calculate that even without accounting for climate change, the extent of urban areas exposed to flood hazards will increase 2.7 times between 2000 and 2030, the extent exposed to drought hazards will approximately double during this period, and urban land exposed to both floods and droughts will increase more than 2.5 times.

This section assesses observed and expected impacts from the main hazards identified for cities, settlements and infrastructure; temperature extremes (and the urban heat island), flooding (including sea level rise), water scarcity and security, as well as other hazards that are either less well-studied and/or likely to affect only a limited number of locations. The data assessed in this section are limited by uneven coverage. Despite improvements since AR5, data continue to be more complete for extreme events than for chronic hazards and everyday risks, which may have high aggregate impacts and disproportionately erode the well-being of urban poor households, especially for the most vulnerable, including women, children, the aged, disabled and homeless (van Wesenbeeck, Sonneveld and Voortman, 2016; Kinay et al., 2019; Connelly et al., 2018). Data coverage is also less comprehensive for smaller settlements in poorer countries, the locations where urban growth is often high and adaptive capacities are often low (e.g., Rufat et al., 2015). Thus, data gaps frequently coincide with highly vulnerable populations (Rufat et al., 2015; Satterthwaite and Bartlett, 2017). Here, even small changes in livelihoods, health, or representation and voice can rapidly bring households into positions of risk, even when hazard conditions are relatively stable (Ziervogel et al., 2017). These structural limits in available data are discussed also in Section 7 (Health, Well-being and the Changing Structure of Communities) and Section 8 (Poverty, Livelihoods and Sustainable Development), and in Doblas-Reyes et al. (2021) Box 10.3. There are implications also for adaptation (Section 6.3), where the greater availability of evidence on exposure-driven risk can limit resilience-building interventions that focus on the reduction of vulnerability.

6.2.2.1 Temperatures and the Urban Heat Island

Higher temperatures associated with climate change, through warmer global average temperatures and regional heatwave episodes, will interact with urban systems in a variety of ways (Doblas-Reyes et al., 2021 Box 10.3). Future urbanisation will amplify projected local air temperature increase, particularly by strong influence on minimum temperatures, which is approximately comparable in magnitude to global warming (*high confidence*) (Arias et al. In Press Box TS14). Within cities, exposure to heat island effects is uneven, with some populations disproportionately exposed to risk including low income communities, children, the elderly, disabled, and ethnic minorities (Quintana-Talvac et al., 2021; Sabrin et al., 2020; Chambers, 2020; and see later in this section).

The risks to cities, settlements and infrastructure from heatwaves will worsen (*high confidence*) (Leal Filho et al., 2021; see also Sections 6.2.5; 6.3.3.1, Arias et al. In Press Box TS14). Depending on the RCP, between half (RCP2.6) to three-quarters (RCP8.5) of the human population could be exposed to periods of life-threatening climatic conditions arising from coupled impacts of extreme heat and humidity by 2100 (Figure 6.3; Mora et al., 2017; Zhao et al., 2021). Cities in mid-latitudes are potentially subject to twice the levels of heat stress compared with their rural surroundings under all RCP scenarios by 2050, for example Belgian cities (Wouters et al., 2017). A disproportionate level of exposure exists in subtropical cities subject to year-round warm temperatures and higher humidity, requiring less warming to exceed 'dangerous' thresholds, for example Nairobi (Scott et al., 2017) and São Paulo (Diniz, Gonçalves and Sheridan, 2020). It is expected that more than 90% of the 300 million people who will be exposed to super- and ultra-extreme heatwaves in the Middle East and North Africa will live in urban centres (Zittis et al., 2021), while the major driver for increased heat exposure is the combination of global warming and population growth in already-warm cities in regions including Africa, India and the Middle East (Klein and Anderegg, 2021).

Locally, the urban heat island also elevates temperatures within cities relative to their surroundings. It is caused by physical changes to the surface energy balance of the pre-urban site from urbanisation, resulting from the thermal characteristics and spatial arrangement of the built environment, and anthropogenic heat release (Oke et al., 2017; Chow et al., 2014; Susca and Pomponi, 2020; Doblas-Reyes et al., 2021 FAQ10.1). A considerable body of evidence exists on how the multi-scale impacts and consequent risks arise when local elevated temperatures within settlements are enhanced by climate change, with

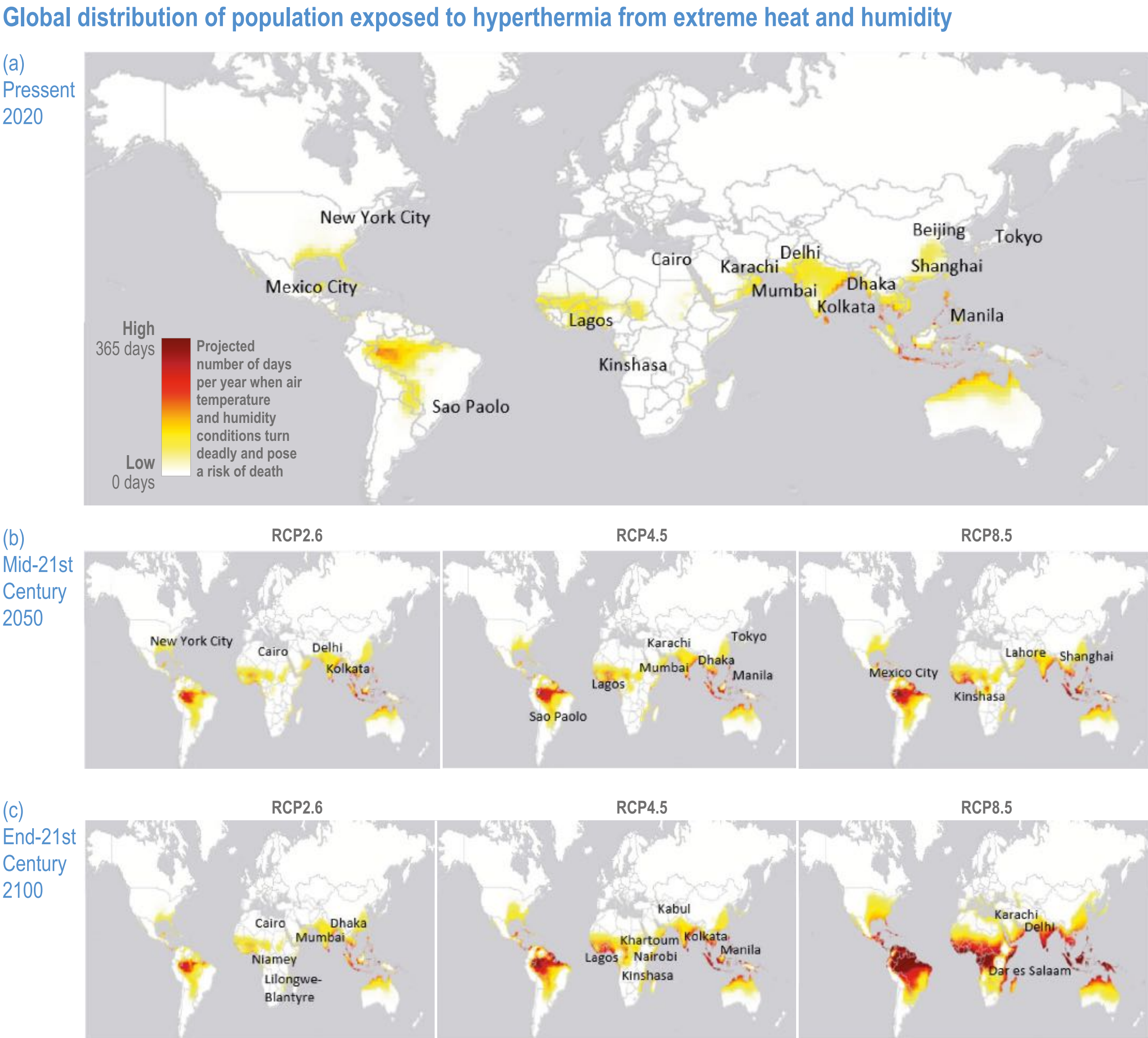

Figure 6.3 | Global distribution of population exposed to hyperthermia from extreme heat for (a) the present, and projections from selected Representative Concentration Pathways in (b) the mid-21st century and (c) the end of the 21st century. Shading indicates projected number of days in a year in which conditions of air temperature and humidity surpass a common threshold beyond which climate conditions turned deadly and pose a risk of death (Mora et al., 2017). Named cities are the top 15 urban areas by population size during 2020, 2050 and 2100, respectively, as projected by Hoornweg and Pope (2017)

specific elements of this affecting megacities (Darmanto et al., 2019). The urban heat island itself is amplified during heatwaves (Founda and Santamouris, 2017), but the extent to which varies regionally and by time of day (Ward et al., 2016a; Zhao et al., 2018b; Eunice Lo et al., 2020). When combined with warming induced by urban growth, extreme heat risks are expected to affect half of the future urban population, with a particular impact in the tropical Global South and in coastal cities and settlements (Huang et al., 2019; Section CCP2.2.2; Table CCP2.A.1).

Heat risk is associated with a range of health issues for urban residents, with the consequences of higher urban temperatures being unevenly distributed across urban populations (*high confidence*). Clear evidence exists of increased health risks to elderly populations in settlements, especially higher levels of mortality in elderly populations from urban heat islands during heatwave events (Fernandez Milan and Creutzig, 2015; Taylor et al., 2015; Ward et al., 2016a; Heaviside, Macintyre and Vardoulakis, 2017; Gough et al., 2019; Xu et al., 2020a), while health and fitness variables are also major determinants of the effects of heat stress (Schuster et al., 2017) (see also Table 7.2). Heat stress and dehydration are also related to behavioural and learning concerns, with dehydration impairing concentration and cognition for both adults and children (Merhej, 2019). Literature on paediatric heat exposure is associated with increases in emergency department visits for heat-related illnesses, electrolyte imbalances, fever, renal disease and respiratory disease in young children (Winquist et al., 2016), with less severe outcomes such as lethargy, headaches, rashes, cramps and exhaustion negatively affecting children in school and play environments (Vanos, 2015; Hyndman, 2017). Young children in cities are particularly sensitive to heatwaves, and may have little experience or capacity to cope with heat extremes (Norwegian Red Cross, 2019). Such vulnerability of young children to heat is compounded with projected urbanisation rates and poor infrastructure, particularly in South Asian and in African cities (Smith, 2019). There is evidence that socioeconomically disadvantaged populations are more *likely* to live in hotter parts of cities associated with higher-density residential land use in dwellings with less effective insulation built with poorer or older construction materials (Inostroza, Palme and de la Barrera, 2016; Tomlinson et al., 2011). Specific emerging risks for occupational and related heat illnesses are found in urban tropical or subtropical low- and middle-income countries (Andrews et al., 2018; Green et al., 2019).

There is an emerging risk of diminished indoor thermal comfort due to climate change, evidenced by research into negatively affected thermal comfort indices and/or increased number of overheating hours under future emissions scenarios (*medium confidence*) (e.g., Liu and Coley, 2015; van Hooff et al., 2014; Vardoulakis et al., 2015; Dodoo and Gustavsson, 2016; Invidiata and Ghisi, 2016; Makantasi and Mavrogianni, 2016; Mulville and Stravoravdis, 2016; Taylor et al., 2016; Hamdy et al., 2017; Pérez-Andreu et al., 2018; Salthammer et al., 2018; Dino and Meral Akgül, 2019; Osman and Sevinc, 2019; Roshan, Oji and Attia, 2019). Decreases in thermal comfort and increases in overheating risks depend on building characteristics, such as thermal resistance, presence of solar shading, thermal mass, ventilation, orientation and geographical location (e.g., Liu and Coley, 2015; van Hooff et al., 2014; Vardoulakis et al., 2015; Dodoo and Gustavsson, 2016; Invidiata and Ghisi, 2016; Makantasi and Mavrogianni, 2016; Mulville and Stravoravdis, 2016; Taylor et al., 2016; Hamdy et al., 2017; Pérez-Andreu et al., 2018; Salthammer et al., 2018; Dino and Meral Akgül, 2019; Osman and Sevinc, 2019; Roshan, Oji and Attia, 2019; Alves, Gonçalves and Duarte, 2021). Most of these studies employed numerical simulations in which different climate scenarios were used to construct future climate data. In hot climates, energy-efficient buildings with high insulation values and high airtightness, which have insufficient protection from solar heat gains and/or limited ventilation capabilities, are generally more vulnerable to overheating than older buildings with lower insulation levels (e.g., van Hooff et al., 2014; Vardoulakis et al., 2015; Makantasi and Mavrogianni, 2016; Mulville and Stravoravdis, 2016; Salthammer et al., 2018; Fisk, 2015; Hamdy et al., 2017; Fosas et al., 2018; Ozarisoy and Elsharkawy, 2019; see also Fox-Kemper et al., 2021 9.7 for building heat mitigation/adaptation links).

Higher urban temperatures result in lower labour productivity levels and economic outputs (*medium confidence*) (Graff Zivin and Neidell, 2014; Yi and Chan, 2017; Houser et al., 2015; Stevens, 2017; see Section 8.2.1). Globally, urban heat stress is projected to reduce labour capacity by 20% in hot months by 2050 compared with a current 10% reduction (Dunne, Stouffer and John, 2013). Burke et al. (2015) demonstrate a nonlinear relationship between temperature and global economic productivity, with potential global losses of 23% by 2100 due to climate change alone. In specific cases, Zander et al. (2015) estimate heat-related reductions in urban labour productivity in Australia to cost USD 3.6–5.1 billion yr^{-1}, based on self-reported performance reduction and absenteeism among 1726 workers in 2013–14[2]; while the high-temperature subsidies given in China at outdoor air temperatures above 35°C are projected to increase to USD 35.7 billion yr^{-1} after 2030 (compared with USD 5.5 billion yr^{-1} for 1979–2005) (Zhao et al., 2016)[3].

Higher urban temperatures place unequal economic stresses on residents and households through higher utilities demand during warm periods, for example, electricity in regions where air conditioning is predicted to become more prevalent, and due to medical costs associated with care for heat illnesses and related health effects, missed work and other related impacts (*medium confidence*) (Jovanović et al., 2015; Liu et al., 2019; Schmeltz, Petkova and Gamble, 2016; Soebarto and Bennetts, 2014; Zander and Mathew, 2019; Zander et al., 2015). Such stresses are projected to increase in many regions associated with continuing global-scale climate change and urbanisation (e.g., Véliz et al., 2017; Ang, Wang and Ma, 2017; Bezerra et al., 2021), although some of these effects in cold-climate cities are offset by reduced stresses in winter associated with urban heat island or rising temperatures more generally (see Section 6.2.2.4).

Thermal inequity can also be seen as a distributive justice risk (Mitchell and Chakraborty, 2018). There are often disproportionate increases of

2 Paper provides figures in Australian dollars: AUD 5.2–7.3 billion. Exchange rate correct July 2020.

3 Paper provides figures in yuan: 250 billion yuan yr^{-1} after 2030 (compared to 38.6 billion yuan yr^{-1} for 1979–2005). Exchange rate correct July 2020.

risk for individuals of lower socioeconomic status, especially migrants, from exposure to urban heat. These arise from inadequate housing, less access to air-conditioning, and occupations, such as manual labour and waste picking, that exacerbate heat exposure (Chu and Michael, 2018; Santha et al., 2016). Research from South Africa has shown that housing occupied by poor communities regularly experience indoor temperature fluctuations that are between 4°C and 5°C warmer compared with outdoor temperatures (Naicker et al., 2017); while evidence from the USA indicates that historical housing policies, particularly the 'redlining' of neighbourhoods based on racially motivated perceptions, are associated with areas that are exposed to elevated land surface temperatures (Hoffman, Shandas and Pendleton, 2020).

Social surveys from temperate and tropical cities highlight the risk of reduced quality of life during heat events, including increased incidence of personal discomfort in indoor and outdoor settings, elevated anxiety, depression and other indicators of adverse psychological health, and reductions in physical activity, social interactions, work attendance, tourism and recreation (*high confidence*) (Chow et al., 2016; Elnabawi, Hamza and Dudek, 2016; Obradovich and Fowler, 2017; Wang et al., 2017; Wong et al., 2017; Lam, Loughnan and Tapper, 2018; Alves, Duarte and Gonçalves, 2016). Extreme heat may also have a cultural impact, for example affecting major sporting events, with negative impacts on the athletic performance (Brocherie, Girard and Millet, 2015; Casa et al., 2015) and the experience and health of spectators (Hosokawa, Grundstein and Casa, 2018; Kosaka et al., 2018; Matzarakis et al., 2018; Vanos et al., 2019).

6.2.2.2 Urban Flooding

Flood risks in settlements arise from hydrometeorological events interacting with the urban system which exposes settlements to river (fluvial) floods, flash floods, pluvial (precipitation-driven) floods, sewer floods, coastal floods and glacial lake outburst floods (IPCC, 2012). Sea level increase and increases in tropical cyclone storm surge and rainfall intensity will increase the probability of coastal city flooding (*high confidence*) (WGI Box TS14). Globally, the increase in frequencies and intensities of extreme precipitation from global warming will *likely*[4] expand the global land area affected by flood hazards (*medium confidence*) ((Alfieri et al., 2018; Alfieri et al., 2017; Hoegh-Guldberg et al., 2018); Section 4.2.4.2). Mishra et al. (2015) noted that out of 241 urban areas, only 17% of cities experienced statistically significant increases in frequencies of extreme precipitation events from 1973 to 2012. In the future, there is some evidence that changes in high-intensity short duration (sub-daily) rainfall in urban areas will increase (*limited evidence*, *medium agreement*) (Kendon et al., 2014; Ban, Schmidli and Schär, 2015; Abiodun et al., 2017).

Flooding associated with sea level rise is addressed in more detail in Cross-Chapter Paper 2, with detailed regional examples from Africa discussed in Section 9.3. Coastal flooding associated with sea level rise is exacerbated due to the significant number of people living in subsiding areas. As a result of this, the average coastal resident is experiencing (over the last two decades) rates of relative sea level rise three to four times higher than typical estimates due to climate-induced changes (Nicholls et al., 2021). This process can also result in release of coastal waste into urban areas (Beaven et al., 2020).

Urban flooding risks are also increased by urban expansion and land use and land cover change which enlarges impermeable surface areas through soil sealing, impacting drainage of floodwaters with consequent sewer overflows (*high confidence*) (Arnbjerg-Nielsen et al., 2013; Ziervogel et al., 2016; Aroua, 2016; Kundzewicz et al., 2014). These risks are also driven by increasing societal complexity, urban developmental policy on flood control and long-term economic growth (Berndtsson et al., 2019), including in mega-cities (Januriyadi et al., 2018). The increase in flood risk from urban development can be considerable; based on modelling of two RCP (4.5 and 8.5) scenarios, Kaspersen et al. (2017) noted flooding in four European cities could increase by up to 10% for every 1% increase in impervious surface area. Risks are also compounded by the location of settlements, with greater risks within cities located in low elevation coastal zones subject to sea level rise, potential land subsidence and exposure to tropical cyclones ((Koop and van Leeuwen, 2017; Hoegh-Guldberg et al., 2018; see also Section CCP2.2) and within informal settlements, where generally little investment in drainage solutions exists and flooding regularly disrupts livelihoods and disproportionately undermines local food safety and security for the urban poor (Dodman, Colenbrander and Archer, 2017; Dodman et al., 2017; Kundzewicz et al., 2014; Sections 5.4 and 5.8).

Future risks of urban flooding is increasing in conjunction with continued increases in global surface temperature (*high confidence*) (IPCC, 2019b; Winsemius et al., 2015; Kulp and Strauss, 2019; Hoegh-Guldberg et al., 2018). In particular, Asian cities are highly exposed to future flood risks arising from urbanisation processes. Between 2000 and 2030, rapid urbanisation in Indonesia will elevate flood risks by 76–120% for river and coastal floods, while sea level rise will further increase the exposure by 19–37% (Muis et al., 2015). In Can Tho, Vietnam, current urban development patterns put new assets and infrastructure at risk due to sea level rise and river flooding in the Mekong Delta (Chinh et al., 2017; Chinh et al., 2016). Flooding in urban areas is exacerbated both by the encroachment of urban areas into areas that retain water and by the lack of infrastructure such as embankments and flood walls, as is the case for large areas of Dhaka East (Haque, Bithell and Richards, 2020). Zhou et al. (2019) have also shown that for the city of Hohhot, China, the increase in impervious surfaces contributes between 2–4 times more to modelled annual flood risk compared with risk induced by climate change.

Global trends in surface water flooding are increasing, which poses risks to vulnerable urban systems depending on current adaptation measures to manage flooding impacts, for example, stormwater management, green infrastructure and sustainable urban drainage systems (Molenaar et al., 2015). The economic risks associated with future surface water flooding in towns and cities are considerable. For example in the UK, expected annual damages from surface water

4 In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10% and exceptionally unlikely 0–1%. Additional terms (extremely likely: 95–100%, more likely than not >50–100% and extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17–83% probability range.

flooding may increase by £60–200 million for projected 2–4°C warming scenarios; enhanced adaptation actions could manage flooding up to a 2°C scenario but will be insufficient beyond that (Sayers et al., 2015). Analyses conducted in South Korea suggests that future flood levels could exceed current flood protection design standards by as much as 70% by 2100, considerably increasing urban flood risk (Kang et al., 2016). Modelling of urban flood damage in the Kelani River Basin in Sri Lanka showed increased frequency of flooding by 2030 could increase potential urban property damage by up to 10.2% (Komolafe Akinola, Herath and Avtar, 2018). Urban flood impacts may also exacerbate health burdens (including disease outbreaks of malaria, typhoid and cholera), which are compounded by damage to medical facilities (e.g., damage to hospitals and disruption of medicinal supply chains), as observed in urban areas of Ghana (Gough et al., 2019). In addition, emerging research shows the cascading consequences of hazard events, in this case urban flooding, on other risks to well-being in ways that are particularly severe for the urban poor, including mental ill-health, incidents of domestic violence impacting children and women, chronic diseases and salinity of drinking water ((Matsuyama, Khan and Khalequzzaman, 2020); Section 4.2.4.5; Section 6.2.4.2; Box 7.2; Section 8.4.5.2).

6.2.2.3 Urban Water Scarcity and Security

Urban water scarcity occurs when gaps exist between supply and demand of available freshwater resources (Zhang et al., 2019). Urban water security requires a sustainable quantity and quality of water to meet community and ecosystem needs in a changing climate (Romero-Lankao and Gnatz, 2019; Allan, Kenway and Head, 2018; Huang, Xu and Yin, 2015; Chen and Shi, 2016). Risks arising from urban water scarcity worldwide are *very likely* increasing due to climate drivers (e.g., warmer temperatures and droughts) and urbanisation processes (e.g., land use changes, migration to cities and changing patterns of water use including over extraction of surface and groundwater resources) affecting supply and demand (*high confidence*) (Allan, Kenway and Head, 2018; Crausbay et al., 2020; Haddeland et al., 2014; Pickard et al., 2017; De Stefano et al., 2015; Sun et al., 2019; Van Loon et al., 2016; Zhang et al., 2019; Section 4.2.4.4; See Box 8.6 for case study on 2018 Cape Town drought). Flörke et al. (2018) estimates that nearly a third of all major cities worldwide may exhaust their current water resources by 2050. Globally, projections suggest that 350 million (± 158.8 million) more people living in urban areas will be exposed to water scarcity from severe droughts at 1.5°C warming and 410.7 million (± 213.5 million) at 2°C warming (Liu et al., 2018).

Decreased regional precipitation and associated changes in runoff and storage from droughts is exacerbating urban scarcity by impairing the quality of water available for its resource management in cities (*high confidence*). For example, less runoff to freshwater rivers can increase salinity and concentrate pathogens and pollutants that increases risks of urban water scarcity (Hellwig, Stahl and Lange, 2017; Jones and van Vliet, 2018; Leddin and Macrae, 2020; Lorenzo and Kinzig, 2020; Ma et al., 2020; Mosley, 2015; Zhang et al., 2019; van Vliet, Flörke and Wada, 2017; see also Box 6.2). Drought also changes the dynamics of groundwater pollution, leading to increased environmental health risks when those sources are used for urban water supplies (Kubicz et al., 2021; Moreira et al., 2020; Pincetl et al., 2019). Changes in the nature of droughts, for example, hotter droughts (Herrera and Ault, 2017), snow droughts (Cooper, Nolin and Safeeq, 2016; Mote et al., 2016) or 'flash' droughts (Otkin et al., 2016; Otkin et al., 2018; Pendergrass et al., 2020) can exacerbate urban water scarcity, exposing the limitations of engineered water infrastructure designed to accommodate historical patterns of supply and demand (Gober et al., 2016; Ulibarri and Scott, 2019; Zhao et al., 2018a).

Risks of urban water scarcity and security are compounded by vulnerabilities such as service availability and quality of infrastructure to supply water for increased urban demand from in-migration to cities (*medium confidence*) (Ahmadalipour et al., 2019; Dong et al., 2020; Reynolds et al., 2019; Thomas et al., 2017; Mullin, 2020). Risks to local water security in cities are also exacerbated by drivers such as dependence on imported water resources from distant locales that may be exposed to additional drought risks (*high confidence*) (Ahams et al., 2017; Li et al., 2019b; Marston et al., 2015; Zhao et al., 2020; Zhang et al., 2020); from considerable projected urban expansion in drought-stressed areas, for example, across drylands of Western Asia and North Africa (Güneralp et al., (2015); and by export of virtual water (i.e., export of water embedded in food and energy) from local sources to distant trading partners (Djehdian et al., 2019; D'Odorico et al., 2018; Fulton and Cooley, 2015; Rushforth and Ruddell, 2016; Verdon-Kidd et al., 2017; Vora et al., 2017).

Droughts interact and manifest in complex ways in interconnected urban areas that *likely* increase risks of urban water scarcity (Tapia et al., 2017; Rushforth and Ruddell, 2015). Urban interdependencies mean droughts in one region can limit water resources availability in another (e.g., Macao and Zhuhai, Hong Kong, Shenzhen in China, Singapore and Johor, in cities in Pakistan and India, and in the west and southwest USA) (Chuah, Ho and Chow, 2018; Gober et al., 2016; Srinivasan, Konar and Sivapalan, 2017; Zhang et al., 2019; Zhao et al., 2020). Likewise, physical and social teleconnections mean decisions made about water resources in one region or location may impact another in unexpected ways (Moser and Hart, 2015; Liu et al., 2015).

Urban water security risks are confounded by inequities in economic opportunity, risk exposure and human well-being (*medium evidence*) (Sena et al., 2017; Stanke et al., 2013; Section 4.2.4.5). Water scarcity is felt more acutely among low-income compared with high-income populations (Nerkar et al., 2016), and scarcity on top of inequities and political instability can lead to security issues, for example, conflict between different water users (Cosic et al., 2019; von Uexkull et al., 2016; Ahmadalipour et al., 2019; Döring, 2020; Ide et al., 2021), particularly when road infrastructures and access to water are limited (Detges, 2016; Sena et al., 2017). Scarcity risks may also be exacerbated by human and ecosystem needs in water-short years (Srinivasan, Konar and Sivapalan, 2017). Finally, growing populations along with migration into water scarce regions can exacerbate water security issues (Akhtar and Shah, 2020; Singh and Sharma, 2019).

6.2.2.4 Other Dynamic Interactions

A range of other dynamic climate interactions are relevant for cities, settlements and infrastructure: cold spells, landslides, wind, fire and air pollution.

Cold spells. Although frequencies and intensities of cold spells/cold waves are *virtually certain* to have decreased globally, and are projected to consistently decrease for most warming levels (*high confidence*; WGI Table 11.2), cold weather events can periodically occur and impact urban areas and their connected infrastructures. For cities in eastern Canada, the intra-annual distribution of freezing rain events may become more frequent from December to February, and less frequent in other months by 2100 (Cheng, Li and Auld, 2011). Freezing rain is also a risk to urban populations and infrastructure. In general, higher population mortality rates *likely* occur during the winter season, while more temperature-attributable deaths are caused by cold than by heat in cities located in temperate climates (Gasparrini et al., 2015; Chen et al., 2017; Ryti, Guo and Jaakkola, 2016). Winter mortality is *unlikely* to significantly decrease due to warming trends, partly because a range of other medical factors (e.g., influenza seasons and elevations in cardiac risk factors) also drive this winter-excess mortality (Kinney et al., 2015). However, the evidence is unclear whether mortality related to cold waves will decrease in coming decades in European (Smid et al., 2019) or US cities (Wang et al., 2016). While projected global cold extremes are expected to decrease in frequency and intensity, the higher regional variability of future climates means that cold waves may remain locally important threats, including in milder regions where there are larger temperature differences between 'normal' winter days and extreme cold events, and where there is less capacity to adapt (Ma, Chen and Kan, 2014; Ho et al., 2019). This will be accentuated in many cities, particularly in Europe, by anticipated demographic changes that result in a more elderly population susceptible to cold wave health risks (Smid et al., 2019).

The effects of cold waves on the energy sector include breakdowns in power plants and reduced oil and gas production (Jendritzky, 1999), as well as failures in overhead power lines and towers leading to outages in Moscow and Bucharest (Panteli and Mancarella, 2015; Andrei et al., 2019). Six major power outages associated with cold shocks and ice storms have been recorded since 2010, the majority recorded from large cities in the USA (Añel et al., 2017). Cold waves can also significantly increase energy demand. A cold wave that affected the Iberian Peninsula in January 2017 caused electricity prices to peak at a mean price of 112.8 €/MWh, the highest ever recorded in Spain (AEMET, 2017).

Landslides. While geomorphological events (e.g., land subsidence from permafrost thaw at high latitudes or from groundwater extraction) and factors associated with the built environment (e.g., settlement location adjacent to steep slopes and zonation laws for building construction) are major factors determining urban landslide risk, these can also be influenced by a range of climatic variables, namely precipitation (frequency, intensity and duration), snow melt and temperature change. Some 48 million people are exposed to landslide risk in Europe alone, with the majority in smaller urban centres (Mateos et al., 2020). Travassos et al. (2020) also documented all landslide deaths in the São Paulo Macro Metropolis Region from 2016 to 2019 that occurred from extreme rainfall events in vulnerable areas prone to landslides. An increase in the number of people exposed to urban landslide risks is projected for landslide-prone settlements lying within regions projected to experience a corresponding increase in extreme rainfall (Gariano and Guzzetti, 2016). In addition, human factors such as expansion of towns onto unstable land and land use changes within settlements (e.g., road building, deforestation) are increasing human exposure to landslides and the likelihood of landslides occurring (Kirschbaum, Stanley and Zhou, 2015). Rainfall triggered landslides kill at least 5000 people per year, and at least 11.7% of these landslides occurred on road networks (Froude and Petley, 2018). Although the spatial footprint of an individual landslide might be small (i.e., < 1 km^2), the 'vulnerability shadow' cast over an area in terms of regional transport network disruptions can be a significant proportion of a region, and cascade to other infrastructures (Winter et al., 2016).

Landslides tend to occur on moderate to steep slopes, and are thus particularly prevalent in mountainous regions which are also characterised by low infrastructure redundancy (i.e., few alternative routes) and increased impacts from climate change (Schlögl et al., 2019). More robust forecasts of landslides driven by climate risk requires (a) more complete long-term records of previous landslides and (b) baseline studies of the Global South which are currently missing from the literature (Gariano et al., 2017).

Wind. Urban morphology alters wind conditions at multiple spatial scales; generally, increased surface roughness in settlements have resulted in declining trends in both measured wind speed and frequency of extremely windy days (Mishra et al., 2015; Peng et al., 2018; Ahmed and Bharat, 2014; WGI Box 10.3).

Urban wind risks can also be affected by location adjacent to mountains, lakes or coasts with localised wind systems (WGI 10.3.3.4.2; WGI 10.3.3.4.3). In large cities with significant urban heat island, an urban-driven thermal circulation can enhance pollution dispersion under calm conditions (Fan, Li and Yin, 2018) or advect heat to areas downwind of the city (Bassett et al., 2016). Microscale wind conditions within urban canyons also strongly affect ventilation of air pollution dispersion and thermal comfort at pedestrian level, especially in cities located in warm climates (Rajagopalan, Lim and Jamei, 2014; Middel et al., 2014; Lin and Ho, 2016).

In cities, wind risks from climate change hazards can arise from increased exposure from the expanding built environment. Very high wind speeds associated with severe weather systems, for example, tropical cyclones or derechos can cause significant structural damage to buildings and key infrastructure with insufficient wind load, as well as causing human injury through flying debris (Burgess et al., 2014). In particular, there is evidence from North American cities that tornado damage are *likely* fundamentally driven by growing built-environment exposure (*medium confidence*) (Ashley et al., 2014; Rosencrants and Ashley, 2015; Ashley and Strader, 2016).

Extreme winds in urban areas can have particularly damaging effects on poorly constructed buildings, including low-income houses in African cities (Okunola, 2019), and on urban trees that may be uprooted by strong wind gusts from downbursts (Ordóñez and Duinker, 2015; Pita and de Schwarzkopf, 2016; Brandt et al., 2016), as well as on disrupting transportation along urban road and railway networks (Koks et al., 2019; Pregnolato et al., 2016).

Fire. Hotter and drier climates in several regions, for example Australia, the Western USA, the Mediterranean and Russia (IPCC, 2018), *likely* enable weather conditions driving fire events impacting cities within these regions (Section 2.4.4.2, 2.5.5.2). These include wildfires along the margins where cities are adjacent to wildlands, that is, the wildland-urban interface (WUI) (Bento-Gonçalves and Vieira, 2020; Radeloff et al., 2018), or fires in cities with a high degree of informal settlements having greater vulnerability to fire hazards (Kahanji, Walls and Cicione, 2019; Walls and Zweig, 2017; Sections 8.3.3.2). This vulnerability is considerable; over 95% of urban fire related deaths and injuries occur within informal settlements in low- and middle-income countries (Rush et al., 2020).

For wildfires at the WUI, anthropogenic climate change, natural weather variability, expansion of human settlement and a legacy of fire suppression are key factors in determining fire risk (Abatzoglou and Williams, 2016; Knorr, Arneth and Jiang, 2016; van Oldenborgh et al., 2020). Recent wildfires in Australia and California both occurred under hot and dry weather conditions exacerbated by climate change, and resulted in substantial property damage along the WUI, ecosystem destruction and lives lost (Brown et al., 2020; Lewis et al., 2020; Yu et al., 2020). Future climate risk of fires at the WUI are *likely* (*medium confidence*), and are compounded by projected urban development along the WUI within several regions, such as in the Western USA (Syphard et al., 2019), Australia (Dowdy et al., 2019) and the Bolivian Chiquitania (Devisscher et al., 2016).

Air Pollution. Despite recent observed improvements in air quality arising from COVID-19 restrictions (Krecl et al., 2020; Naik et al., 2021 Cross-Chapter Box 6.1), significant risks to human health in cities leading to premature mortality *very likely* arise from exposure to decreased outdoor air quality from a combination of biogenic (e.g., wildfires at the WUI that advect into the urban atmosphere [Reddington et al., 2014; Naik et al., 2021 Chapter 12 Box 12.1]) and anthropogenic sources that are influenced by climate change (e.g., fine particulate matter such as $PM_{2.5}$, tropospheric ozone, oxides of nitrogen and volatile organic compounds [Burnett et al., 2018; Knight et al., 2016; Turner et al., 2016; West et al., 2016; Chang et al., 2019b; Li et al., 2019a; Alexader, Luisa and Molina, 2016; Naik et al., 2021 Sections 6.5.1, 6.7.1.1, 6.7.1.2]). Risks of premature mortality from indoor air pollution in cities, arising from biomass burning for heating in winter or cooking, indoor pesticide use or exposure to volatile organic compounds from poor thermal insulation in buildings, are also *likely* to occur (Leung, 2015; Peduzzi et al., 2020; Cross-Chapter Box HEALTH in Chapter 7).

The mortality risk for several pollutants, for example $PM_{2.5}$, is considerable (*high confidence*). Current estimates indicate that 95% of global population live in areas where ambient $PM_{2.5}$ exceeds the WHO guideline of annual average exposure of 10 µg m^{-3} (Shaddick et al., 2018a; Shaddick et al., 2018b; Chang et al., 2019b). Among the 250 most populous urban areas, estimated $PM_{2.5}$ concentrations are generally highest in cities in Africa, South Asia, the Middle East and East Asia; $PM_{2.5}$ in many cities in North Africa and the Middle East is *likely* due mainly to wind-blown dust, whereas that in South Asia and East Asia are mainly anthropogenic in origin (Anenberg et al., 2019). However, data on $PM_{2.5}$ concentrations are unavailable in many cities in low- and middle-income countries owing to a lack of measurements (Martin et al., 2019).

For some air pollutants, for example concentrations of $PM_{2.5}$ in several US, Western European and Chinese cities have recently decreased as a result of clean air regulations that have controlled emissions from sources such as motor vehicles, fossil fuel power plants and major industries (Zheng et al., 2018a; Fleming et al., 2018). These decreases have brought substantial improvements in public health in settlements within these regions (Ciarelli et al., 2019; Zhang et al., 2018). In South Asia, Southeast Asia and Africa, however, concentrations of other air pollutants, for example tropospheric ozone, oxides of nitrogen and volatile organic compounds are *likely* to continue to grow and peak by mid-century before they subside due to global urbanisation assumptions embedded in the SSPs (Naik et al., 2021 Sections 6.2.1; 6.7.1.2). Broadly, future air pollutant emissions are projected to decline globally by 2050 as societies become wealthier and more willing to invest in air pollution controls, but the trajectories vary among pollutants, world regions and scenarios (Silva et al., 2016b; Rao et al., 2017; Silva et al., 2016c). Whereas cities in East Asia and South Asia currently have large exposure to anthropogenic air pollution, African cities may emerge by 2050 as the most polluted because of growing populations and demand for energy, increased urbanisation and relatively weak regulations to control emissions (Liousse et al., 2014).

Studies modelling climate change impacts on air quality find that the spatiotemporal patterns of concentration changes vary strongly at urban scales, and that often those patterns differ among the different years modelled due to internal variability (Saari et al., 2019) and different models used (Weaver et al., 2009). Changes in $PM_{2.5}$ due to climate change are less clear than for ozone and may be relatively smaller (Westervelt et al., 2019) as climate change can affect $PM_{2.5}$ species differently (Fiore, Naik and Leibensperger, 2015). For Beijing, climate change is expected to cause a 50% increase in the frequency of meteorological conditions conducive to high $PM_{2.5}$ concentrations (Cai et al., 2017). The impacts of future climate change on air quality and consequent risks on human health have been studied at urban (Knowlton et al., 2004; Physick, Cope and Lee, 2014) and national scales (Fann et al., 2015; Orru et al., 2013; Doherty, Heal and O'Connor, 2017); globally, these studies have found a *likely* net increased risk of climate change on air pollution-related health (*low confidence*). They have focused mainly on the USA and Europe, with few studies elsewhere (Orru, Ebi and Forsberg, 2017), although the relationship between climate and air quality in megacities is particularly complex (Baklanov, Luisa and Molina, 2016). Silva et al. (2017) found that global premature mortality attributable to climate change (and not from urbanisation) from ozone and $PM_{2.5}$ will increase by about 260,000 deaths per year in 2100 under RCP8.5, but substantial variance in results exists between individual models.

6.2.3 Differentiated Human Vulnerability

Evidence from urban and rural settlements is unambiguous; climate impacts are felt unevenly, with differentiated human vulnerability leading to uneven social, spatial and temporal loss, risk and experiences of resilience, including capacity for transformation (*high confidence*) (Woroniecki et al., 2019; Tan, Xuchun and Graeme, 2015; Simon and Leck, 2015; Long and Rice, 2019; Chu, Anguelovski and Roberts, 2017; Borie et al., 2019). The evidence is also clear that for those with fewest resources and already constrained life chances, losses from climate change associated events reduce well-being and exacerbate vulnerability (*high confidence*) (van den Berg and Keenan, 2019; Kashem, Wilson and Van Zandt, 2016; Michael, Deshpande and Ziervogel, 2018). Human vulnerability is influenced by the adaptive capacity of physical (built) structures, social processes (economic, well-being and health) and institutional structures (organisations, laws, cultural and political systems/norms) (see Section 6.4). This section should be read in conjunction with Chapter 8 (Poverty, Livelihoods and Sustainable Development) and will emphasise urban processes that lead to the creation of differential vulnerability, risks and impacts.

6.2.3.1 Urban Poverty and Vulnerability

In both developed and less-developed regions, poverty in urban areas is frequently associated with higher levels of vulnerability (Huq et al., 2020b). This is evident in both rural and urban settlements in a wide range of contexts, including the Philippines (Porio et al., 2019; Valenzuela, Esteban and Onuki, 2020); Bangladesh (Matsuyama, Khan and Khalequzzaman, 2020); Brazil (Lemos et al., 2016), Santiago, Chile (Inostroza, Palme and de la Barrera, 2016); and New York City (Madrigano et al., 2015).

For individuals in urban communities, new literature highlights how differences in vulnerability established by social and economic processes are further differentiated by household and individual variability and intersectionality (Kaijser and Kronsell, 2014; Kuran et al., 2020).This includes differences in wealth and capacity (Romero-Lankao, Gnatz and Sperling, 2016); gender and non-binary gender (Michael and Vakulabharanam, 2016; Sauer and Stieß, 2021; Mersha and van Laerhoven, 2018); education, health, political power and social capital (Lemos et al., 2016); age, including young and elderly, low physical fitness, pre-existing disability, length of residence and social and ethnic marginalisation (Inostroza, Palme and de la Barrera, 2016; Schuster et al., 2017; Malakar and Mishra, 2017). An increasing proportion of refugees and displaced people now live in urban centres, and their characteristics also make them vulnerable to a range of shocks and stresses (Earle, 2016). While some individuals, including children, may be able to exercise agency to reduce their risk (Treichel, 2020), and some indicators are culturally specific, overall, poor, marginalised, socially isolated and informal urban households are particularly at risk (*high confidence*) (Brown and McGranahan, 2016; Kim et al., 2020b; Huq et al., 2020a; Huq et al., 2020b).

6.2.3.2 Informality, Planning and Vulnerability

Particularly in low- and middle-income countries, much urban building occurs outside formal parameters and entails a high degree of urban informality. According to the United Nations statistics, the proportion of urban populations living in slums and informal settlements increased from 23% in 2014 to 23.5% in 2018 (United Nations, 2018). Informality is one pathway through which urbanisation generates differentiated vulnerability, tending to increase exposure and susceptibility of physical structures and their occupants to climate-related risks (Dodman et al., 2017; Dobson, 2017) in contexts including Guadalajara, Mexico (Gran Castro and Ramos De Robles, 2019), Kampala, Uganda (Richmond, Myers and Namuli, 2018), Bengaluru, India (Kumar, Geneletti and Nagendra, 2016), and Dar es Salaam, Tanzania (Yahia et al., 2018). In addition to facing emerging water- and heat-related risks, such areas are also more vulnerable to the health impacts of climate change (Scovronick, Lloyd and Kovats, 2015).

Even where formal planning is the norm, this has often remained oriented toward enabling value by adding construction or the protection of existing high-value physical assets, for example infrastructure and built cultural heritage, private residential) rather than enabling disaster risk reduction for all (Long and Rice, 2019). This tendency has been widely documented, including from cases in Australia, Thailand, Indonesia (King et al., 2016), Canada (Stevens and Senbel, 2017), Amman, Moscow and Delhi (Jabareen, 2015), and South Africa (Arfvidsson et al., 2017). Such inconsistencies between the delivery of land use planning and the aims of the SDGs combine with other social structures, economic pathways and governance systems to shape city risk profiles (Dodman et al., 2017).

6.2.3.3 Migration and Differentiated Vulnerability

Migration, displacement and resettlement each play a foundational role in differentiated vulnerability (see Cross-Chapter Box MIGRATE in Chapter 7). The relationship between migration and vulnerability is complex (*robust evidence*, *high agreement*), and is the first of the three components discussed within this section. Climate change, as a push factor, is only one among multiple drivers (political, economic and social) related to environmental migration (Heslin et al., 2019; Plänitz, 2019; Luetz and Merson, 2019). There is consensus that it is difficult to pin climate change as the sole driver of internal (within national boundaries) rural to urban migration decisions owing to, among other factors, the disconnect between national and international policies (Wilkinson et al., 2016), the lack of unifying theoretical frameworks and the complex interactions between climatic and other drivers (social, demographic, economic and political) at multiple scales (Cattaneo et al., 2019; Borderon et al., 2019). Environmental migration, including rural to urban migration, triggered by climate change may ensue from either slow- or rapid-onset climatic events and could be either temporary, cyclical or permanent movement that occurs within or beyond national boundaries (Heslin et al., 2019; Silja, 2017).

A range of specific studies highlight certain elements of vulnerability and migration, including the ways in which slow-onset events affect precarious, resource-dependent livelihoods (such as farming and fisheries) (Cai et al., 2016). In small town Pakistan and Colombia, heat stress increases long-term migration of men, driven by a negative effect on farm income (Mueller, Gray and Kosec, 2014; Tovar-Restrepo and Irazábal, 2013). A study from Mexico reveals that an increase in drought months led to increased rural to urban migration, while increased heat (temperature) led to a 'nonlinear' pattern of rural to urban migration that occurred only after extended periods of heat (nearly 34 months) (Nawrotzki et al., 2017). This aligns with other findings that a consistent increase in temperature between 2°C and 4°C in some parts of the world renders involuntary, forced migration inevitable (Otto et al., 2017).

The complexity of migration drivers (as push or pull factors) explains why there is little agreement around quantitative estimates on migration (especially international) triggered by climate change (Silja, 2017; Otto et al., 2017), and why estimates of future displacement attributed to climate change and other environmental causes vary between 25 million and 1 billion in 2050 (Heslin et al., 2019). Many authors are critical of existing perspectives on climate-related migration, and argue for more nuanced research on the topic (Boas et al., 2019; Kaczan and Orgill-Meyer, 2020; Silja, 2017; Sakdapolrak et al., 2016; Singh and Basu, 2020; Luetz and Havea, 2018).

Climate-induced migration is not necessarily higher among poorer households whose mobility is more likely to be limited due to the poverty trap (i.e., lack of financial resources) (*high confidence*) (Cattaneo et al., 2019; Kaczan and Orgill-Meyer, 2020; Silja, 2017). For example, in Bangladesh, vulnerability of rural populations is increasing, so many of the poorest employ migration as a strategy of last resort (Paprocki, 2018; Penning-Rowsell, Sultana and Thompson, 2013; Adri and Simon, 2018) that occurs as soil salinity (as opposed to inundation alone) increases and is paralleled by economic diversification (i.e., aquaculture) (Chen and Mueller, 2018). There is *robust evidence* and *high agreement* that rapid-onset climatic events trigger involuntary migration and short-term, short-distance mobilities (Cattaneo et al., 2019). There is also *robust evidence* and *high agreement* that slow-onset climatic events (such as droughts and sea level rise) lead to long-distance internal displacement, more so than local or international migration (Kaczan and Orgill-Meyer, 2020; Silja, 2017), while sea level rise is expected to lead to the displacement of communities along coastal zones, such as in Florida in the USA (Hauer, 2017; Butler, Deyle and Mutnansky, 2016).

Migration, including rural–urban migration, is also recognised as an adaptation strategy in some circumstances, whether this is voluntary or planned (Jamero et al., 2019; Esteban et al., 2020a; Bettini, 2014). Voluntary migration can be an element of household strategies to diversify risk, depending on the nature of the climatic stress, and interacts with household composition, individual characteristics, social networks, and historical, political and economic contexts (Hunter, Luna and Norton, 2015; Carmin et al., 2015; Hayward et al., 2020). For example, in Colombia, rural to urban migration is differentiated across gender depending on the climatic stress whereby men migrate due to droughts, while women migrate due to excessive rain triggers (Tovar-Restrepo and Irazábal, 2013). Especially in Pacific small island developing states, migration can be a strategy for urban settlements or tribal communities to relocate in customary areas, as in the case of Vunidogoloa in Fiji (McMichael, Katonivualiku and Powell, 2019; Hayward et al., 2020); it can be a livelihood strategy as shown in the Cataret Islands in Papua New Guinea (Connell, 2016); or it can be used to enhance education and international networks (i.e., voluntary 'migration with dignity') as is the case in Kiribati (Heslin et al., 2019; Voigt-Graf and Kagan, 2017).

The second component, displacement, also plays a crucial role in differentiated vulnerability. The lack of resources and capacities to support mobility limits the effectiveness of migration as an adaptation strategy, therefore leading to both displacement and trapped populations in the future (Adger et al., 2015; Faist, 2018). For example, studies from Colombia (Tovar-Restrepo and Irazábal, 2013), India (Singh and Basu, 2020), Mekong Delta in Vietnam (Miller, 2019) and Pakistan (Islam and Khan, 2018) showed that migration as an adaptation strategy can be constrained due to resource barriers and low mobility potential, and also, to high levels of place attachment such as in the Peruvian Highlands (Adams, 2016), Vanuatu (Perumal, 2018) and the Tulun and Nissan Atolls of Bougainville, Papua New Guinea (Luetz and Havea, 2018). Migration can also be maladaptive for the receiving contexts, whether due to the pressure on and/or conflict over land and/or the urban resources (*high confidence*) (Faist, 2018; Singh and Basu, 2020; Luetz and Havea, 2018). Other views maintain that migration as adaptation overlooks the agency of people and their resilience, that is the nuances of 'translocal social resilience' (Kelman, 2018; Silja, 2017; Sakdapolrak et al., 2016). For example, the ni-Vanuatu prioritise *in situ* adaptation measures and leave migration as a last resort (Perumal, 2018).

Regardless of the reasons and the initiators for migration, community control over resettlement both at the origin and destination leads to more positive outcomes for both the communities being resettled and the receiving communities (*high confidence*) (Perumal, 2018; Ferris, 2015; Price, 2019; Mortreux and Adams, 2015; Tadgell, Doberstein and Mortsch, 2018; Luetz and Havea, 2018). The protection of livelihoods contributes to ensuring the well-being (physical and mental) and the protection of the rights of communities (*high confidence*) (Ferris, 2015; Price, 2019). There is *limited evidence* but *high agreement* that the outcomes of resettlement initiatives are complex and multi-faceted (Ferris, 2015). For example, in Shangnan County, northwest China, the Massive Southern Shaanxi Migration Program, based on voluntary participation, reduced risk exposure and improved the quality of life in general, but also disproportionately increased the vulnerability of disadvantaged groups (the poor, migrants, and those left behind) (Lei et al., 2017). Similarly, vulnerability increased due to the loss of connection to place and community bonds in Mekong Delta, Vietnam (Miller, 2019), and due to unsafe construction, poor infrastructure, institutional incapacity and general neglect in resettlement initiatives in Malawi, sub-Saharan Africa (Kita, 2017).

6.2.4 Risks to Key Infrastructures

Projected climatic changes, such as changing precipitation patterns, temperatures and sea levels, contribute to pressures on human well-being and the functioning of infrastructure systems (*high confidence*). Furthermore, risks evolve due to macro-scale drivers of change such as urbanisation, economic development, land use changes and other emergent factors (Adger, Brown and Surminski, 2018). Infrastructure networks are rapidly growing around the world (see Table 6.3). Since the quality and accessibility of infrastructure services are varied, it is important to understand how climate change poses different kinds of risk on them. Infrastructure can be broadly understood to include social infrastructure (housing, health, education, livelihoods and social safety nets, security, cultural heritage/institutions, disaster risk management and urban planning), ecological infrastructure (clean air, flood protection, urban agriculture, temperature, green corridors, watercourses and riverways) and physical infrastructure (energy, transport, communications [including digital], built form, water and sanitation and solid waste management) (Thacker et al., 2019). This section focuses especially on physical infrastructure where the literature

Table 6.3 | Selected indicators of global proliferation of infrastructure networks and their annual usage.

Infrastructure	Scale	Usage on annual basis	Coverage/equity of access	References
Electricity networks	> 20 million km of power lines in Europe and USA	25,721 TWh (2017)	Global: 3130 kWh per person Haiti: 39 kWh per person Iceland: 53,832 kWh per person	IEA (2019); World Bank (2019); ETSAP (2014)
Gas and LPG pipelines	Worldwide: > 2.5 million km w^{-1}	40,531 TWh (2017)	Global: 4.96 MWh per person (2015) South Africa: 0.96 MWh per person (2015) Saudi Arabia: 34.65 MWh per person (2015)	CIA (2015); OWID (2020)
Railways	2.69 million km	3835 billion passengers km^{-1} (2019) 9279.81 billion tonnes km^{-1} (2019)	Switzerland: 0.7 m per person; 141 m km^{-2} Canada: 2.2 m per person; 8.6 m km^{-2} India: 0.06 m per person; 23 m km^{-2}	Koks et al. (2019); Statista (2020)
Roads	63.46 million km	12,148 billion passengers km^{-1} private vehicles (2015) 5713 billion passengers km^{-1} public vehicles, e.g., buses (2015) 302.5 billion passenger km^{-1} active modes, e.g., walking and bicycles (2015)	Belgium: 15 m per person; 5 km km^{-2} Malawi: 1 m per person; 164 m km^{-2} Canada: 31 m per person; 115 m km^{-2}	Koks et al. (2019); WorldByMap (2017); ITF (2019)
Information and Communication Technology	Worldwide: 91 million mobile phones in 1995; 8.2 billion in 2018 worldwide	Worldwide: 43,000 PB in 2014 242,000 PB in 2018 (*1PB = 1 million GB)	Europe: 85% of population are unique mobile subscribers; Asia Pacific: 66%; Sub-Saharan Africa: 45%	ITU (2019); Vodafone (2019); GSMA (2019)
Water	3.3 million km^2 land equipped for irrigation The Global Reservoir and Dam Database (conservatively records) at least 7100 dams	This irrigated land accounts for about 70% of total water withdrawals These dams can retain over 7800 km^3 water.	Sub-Saharan Africa: 24% coverage of safely managed drinking water services, 28% safely managed sanitation services, Europe and North America: 94% and 78%, respectively.	Grigg (2019); Lehner et al. (2011); Lehner et al. (2019); UN Water (2018)

provides discrete risk and impact assessments. Physical infrastructure systems are often immobile, indivisible, involve high fixed costs and have longer lifecycles. Social and ecological infrastructure elements are rarely assessed alone and instead tend to be included in wider assessments of event impacts.

Current climate variability is already causing impacts on infrastructure systems around the world (*high confidence*). For global physical infrastructure with a present value of USD 143 trillion, The Economist Intelligence Unit (2015) estimates present value losses of USD 4.2 trillion by 2100 under a 2°C scenario. This estimation rises to USD 13.8 trillion under a 6°C scenario. Extreme events are associated with disruption or complete loss of these infrastructure services, whilst gradual changes in mean conditions are altering physical infrastructure performance. Physical infrastructure is usually costly to repair and also have significant impacts on people's health and well-being.

This section synthesises and assesses the emerging literature on climate change risks to key physical infrastructure domains as listed in Table 6.3: energy/electricity infrastructure, transportation infrastructure and information and communication technology (ICT) (water infrastructure is discussed in Section 6.2.2). It draws on evidence from around the world, but the specific risks to infrastructure in different contexts are explained in more detail in the regional chapters (especially Section 9.8.4.1 for Africa, Section 10.4.6.3.8 for Asia and Section 13.6.1 for Europe). For cities and settlements, such risks are of particular concern owing to a lack of adaptive capacity across many economically important sectors and low levels of resource and capacity support to enhance adaptive capacity. Recent literature also illustrates the interconnected and interdependent nature of infrastructure systems (see Box 6.2), which lead to uncertainties over how risks in one sector lead to cascading, compounding or knock-on effects across other sectors (Zscheischler and Seneviratne, 2017) (see Section 6.2.6 for elaboration). Therefore, adaptation options should address climate risks to infrastructure in an integrated and co-beneficial manner (*medium evidence*, *high confidence*) (see Sections 6.3 and 6.4).

6.2.4.1 Energy Infrastructure

Energy infrastructure underpins modern economies and quality of life. Disruption to power or fuel supplies impacts upon all other infrastructure sectors, and affects businesses, industry, healthcare and other critical services both within and across jurisdictional boundaries (Groundstroem and Juhola, 2019). The economic impacts of climate change risks are significant, for example in the EU, the expected annual damages to energy infrastructure, currently €0.5 billion yr^{-1}, are projected to increase 1612% by the 2080s (Forzieri et al., 2018). In China, 33.9% of the population are vulnerable to electricity supply disruptions from a flood or drought (Hu et al., 2016), whilst in the USA, higher temperatures are projected to increase power system costs by about USD 50 billion by the year 2050 (Jaglom et al., 2014). In a study of 11 Central and Eastern European countries, researchers found that energy poverty is exacerbated by existing infrastructure deficits and energy efficient building stock, as well as income inequality, which can lead to reduced economic productivity (Karpinska and Śmiech, 2020). Climate change is expected to alter energy demand (Viguié et al., 2021), for example heatwaves increase spot market prices (Pechan and Eisenack, 2014), with a disproportionate impact on the poorest and most vulnerable populations. Energy infrastructure are susceptible to a range of climate risks (Cronin, Anandarajah and Dessens, 2018), whilst issues pertaining to energy demand are considered by Working Group III.

6

Box 6.2 | Infrastructure Interdependencies

Infrastructure networks are increasingly dependent on each other—for power, control (via ICT) and access for deliveries or servicing (Figure 6.2). Moreover, a range of other mechanisms can create interdependencies that impact upon climate risks by creating pathways for cascading failure (Undorf et al., 2020; Barabási, 2013). In the UK, for example, all infrastructures utilities identify failure of components in another utility as a risk to their systems (Dawson et al., 2018).

Key interdependencies include:

i. The use of ICT for data transfer, remote control of other systems, and clock synchronisation. Pant et al. (2016) show that ICT is crucial for the successful operation of the UK's rail infrastructure. The study shows that flooding of the ICT assets in the1-in-200 year floodplain would disrupt 46% of passenger journeys across the whole network.
ii. Water to generate hydroelectricity and for cooling thermal power stations. Reductions in usable capacity for 61–74% of the hydropower plants and 81–86% of the thermoelectric power plants worldwide for 2040–2069 (van Vliet et al., 2016), with some power generation technologies, including carbon capture and storage, requiring far higher volumes of water for cooling (Byers et al., 2016).
iii. Energy to power other infrastructure systems. Failure of urban energy supply disrupts other infrastructure services, with disproportionate impacts on the urban poor (Silver, 2015).
iv. Transport systems that ensure access for resources such as fuel, personnel and emergency response. Pregnolato et al. (2017) show disruption across the city from a 1-in-10 year storm event could increase by 43% by the 2080s.
v. Green infrastructure can provide multiple services, creating interdependencies between multiple physical infrastructure systems. For example, green space can support sustainable urban drainage, *in situ* wastewater treatment and urban cooling (Demuzere et al., 2014).
vi. Geographical proximity of assets leads to multiple infrastructures being simultaneously exposed to the same climate hazard. Disruption is disproportionately larger for interconnected networks (Fu et al., 2014).

There is usually limited information on the risks between infrastructure sectors. Without frameworks for collaboration, and coupled with commercial and security sensitivities, this remains a barrier to routine sharing and cooperation between operators. Despite this, methods to tackle interdependence in climate risk analysis are emerging (Dawson, 2015). For example, Thacker et al. (2017) analysed the criticality of the UK's infrastructure networks by integrating data on infrastructure location, connectivity, interdependence and usage. The analysis showed that criticality hotspots are typically located around the periphery of urban areas where there are large facilities upon which many users depend or where several critical infrastructures are concentrated in one location. As infrastructure systems become increasingly interconnected, associated risks from climate change will increase and require a cross-sectoral approach to adaptation (Dawson et al., 2018).

Climate change can, for example, influence energy consumption patterns by changing how household and industrial consumers respond to short-term weather shocks, as well as how they adapt to long-term changes (Auffhammer and Mansur, 2014). Recent studies from Stockholm, Sweden, show that future heating demand will decrease while cooling demand will increase (Nik and Sasic Kalagasidis, 2013). A study from the USA showed that climate change will impact buildings by affecting peak and annual building energy consumption (Fri and Savitz, 2014). From an infrastructure standpoint, the vulnerability of current hydropower and thermoelectric power generation systems may change due to changes in climate and water systems and projected reduction of usable capacities (van Vliet et al., 2016; Byers et al., 2016). These examples show how energy infrastructure planning under climate change must take into account a greater number of scenarios and investigate impacts on particular energy segments (Sharifi and Yamagata, 2016).

6

Electricity generation. Electricity generation infrastructure can be directly damaged by floods, storm and other severe weather events. Furthermore, the performance of renewables (solar, hydro-electric, wind) is affected by changes in climate.

Most thermoelectric plants require water for cooling, many are therefore situated near rivers and coasts and thus vulnerable to flooding. Increases in water temperature or restrictions on cooling water availability affect hydroelectric and thermoelectric plants. A 1°C increase in the temperature of water used as coolant yields a decrease of 0.12–0.7% in power output (Mima and Criqui, 2015; Ibrahim, Ibrahim and Attia, 2014). Excess biological growth, accelerated by warmer water, increases risk of clogging water intakes (Cruz and Krausmann, 2013). While some regions are expected to experience increased capacity under climate change (namely India and Russia), global annual thermal power plant capacity is *likely* to be reduced by between 7% in a mid-century RCP2.6 scenario and 12% in a mid-century RCP8.5 scenario (van Vliet et al., 2016). Worldwide, hydroelectric capacity reductions are projected at 0.4–6.1% (van Vliet et al., 2016). Analysis of the UK's water for energy generation abstractions showed that an energy mix of high nuclear or carbon capture technologies could require as much as six times the current cooling water demands (Byers, Hall and Amezaga, 2014; Byers et al., 2016).

Increasing temperatures improve the efficiency of solar heating but decrease the efficiency of photovoltaic panels, and deposition and abrasive effects of wind-blown sand and dust on solar energy plants can further reduce power output, and the need for cleaning (Patt, Pfenninger and Lilliestam, 2013). Projected changes in wind and solar potential are uncertain; the trends vary by region and season (Burnett, Barbour and Harrison, 2014; Cradden et al., 2015; Fant, Schlosser and Strzepek, 2016). In an RCP8.5 scenario, Wild et al. (2015) conservatively calculate a global reduction of 1% per decade between 2005 and 2049 for future solar power production changes due to changing solar resources as a result of global warming and decreasing all-sky radiation over the coming decades. However, positive trends are projected in large parts of Europe, the south-east of North America and the south-east of China.

Electricity Transmission and Distribution. Electricity transmission and distribution networks span large distances, with overhead power lines often traversing exposed areas. Power lines and other assets, such as substations, are often located near population centres, including those in floodplains. Structural damage to overhead distribution lines will increase in areas projected to see more ice or freezing rain (e.g., most of Canada), snowfall (e.g., Japan) or wildfires (e.g., California, USA) (Bompard et al., 2013; Mitchell, 2013; Sathaye et al., 2013; Jeong et al., 2018; Ohba and Sugimoto, 2020). Electricity outages may last for prolonged periods of time and across vast areas, in addition to potentially disproportionately affecting poorer or more vulnerable communities. Increases in windstorm frequency and intensity increase the risk of direct damage to overhead lines and pylons, in many locations this is limited but Tyusov et al. (2017) calculate an increase as high as 30% in parts of Russia. Where the mode of failure is recorded, transmission pylons are seen to be more susceptible to wind damage, whilst distribution pylons are more *likely* to be affected by treefall and debris (Karagiannis et al., 2019). Increased temperatures can lead to the de-rating (lower performance) of power lines, whose resistance increases with temperature with efficiency reductions of 2–14% being projected by 2100 (Cradden and Harrison, 2013; Bartos et al., 2016).

Fuels Extraction and Distribution. Non-electric energy infrastructure is susceptible to many of the same impacts as electric infrastructure. Extreme weather events impact extraction (onshore and offshore) and refining operations of petroleum, oil, coal, gas and biofuels. Disruption of road, rail and shipping routes (see Section 6.2.5.2) interrupts fuel supply chains. However, there are a number of risks that are specific to these sectors. Heat can lead to expansion in oil and gas pipes, increasing the risk of rupture (Sieber, 2013), whilst heatwaves and droughts can reduce the availability of biofuel (Moiseyev et al., 2011; Schaeffer et al., 2012). Subsidence and shrinkage of soils damages underground assets such as pipes intakes (Cruz and Krausmann, 2013), while additional human activity such as extractive drilling may induce earthquakes, as observed in the northern Dutch province of Groningen (Van der Voort and Vanclay, 2015). In Alaska, USA, the thaw of permafrost and subsequent ground instability is estimated to lead to USD 33 million damages to fuel pipelines in an end-of-century RCP8.5 scenario (Melvin et al., 2017), with low-lying coastal deltas particularly vulnerable (Schmidt, 2015).

6.2.4.2 Transport

Since AR5, research has highlighted the implications for disruption to global supply chains (Becker et al., 2018; Shughrue and Seto, 2018; Pató, 2015), and has made advancements in quantifying costs of climate risks to transportation infrastructure. Climate risks to transport infrastructure (from heat- and cold waves, droughts, wildfires, river and coastal floods, and windstorms) in Europe could rise from €0.5 billion to over €10 billion by the 2080s (Forzieri et al., 2018). Across the Arctic, nearly four million people and 70% of all current infrastructure, including resource extraction and transportation routes, will be at risk by 2050 (Hjort et al., 2018), although the design of specific infrastructure may also affect the degree of infrastructure damage, depending on local geological and ecological conditions. Globally, Koks et al. (2019) calculated that approximately 7.5% of road and railway assets are exposed to a 1-in-100 year flood events, and total global expected annual damages (EAD) of USD 3.1–22 billion (mean USD 14.6 billion) due to direct damage from cyclone winds, surface and river flooding, and coastal flooding. The majority of this is caused by surface water and fluvial flooding (mean USD 10.7 billion). Although twice as much infrastructure is exposed to cyclone winds compared with flooding, a mean EAD of USD 0.5 billion is significantly less than for coastal flooding (USD 2.3 billion), as cyclone damages are largely limited to bridge damage and the cost of removing trees fallen on road carriageways and railway tracks. This is small relative to global gross domestic product (GDP; ~0.02%). However, in some countries EAD equates to 0.5–1% of GDP, which is the same order of magnitude as typical national transport infrastructure budgets, but especially significant for countries such as Fiji that already spend 30% of their government budget on transport (World Bank Group, 2017). Koks et al. (2019) did not assess future climate change impacts, but comparable studies calculating changes in EAD from flooding based upon land use show increases of 170–1370%, depending on global greenhouse gas emissions levels (Alfieri et al., 2017; Winsemius et al., 2015). Moreover, Schweikert et al., (2014) report that climate risks to transport infrastructure could cost as much as 5% of annual road infrastructure budgets by 2100, with disproportionate impacts in some low and lower middle-income countries.

Changes in rainfall and temperature patterns are expected to increase geotechnical failures of embankments and earthworks (Briggs, Loveridge and Glendinning, 2017; Tang et al., 2018; Powrie and Smethurst, 2018) from landslides, subsidence, sinkholes, desiccation and freeze-thaw action. For instance, Pk et al. (2018) show this could lead to a 30% reduction in the engineering factor of safety of earth embankments in Southern Ontario (Canada). Increased river flows in many catchments will also increase failures from bridge scours (Forzieri et al., 2018). HR Wallingford (2014) calculate that the projected 8% increase in scouring from high river flows in the UK will lead to 1 in 20 bridges being at high risk of failure by the 2080s, whilst in the USA the 129,000 bridges currently deficient could increase by 100,000 (Wright et al., 2012). With respect to temperature, analysis by Forzieri et al. (2018) concludes that heatwaves will be the most significant risk to EU transport infrastructure in the 2080s, as a result of buckling of roads and railways due to thermal expansion, melting of road asphalt and softening of pavement material. In the USA, over 50% more roads will require rehabilitation (Mallick et al., 2018), whilst USD 596 million will be required through 2050 to maintain and repair roads in Malawi, Mozambique and Zambia (Chinowsky, Price and Neumann, 2013).

In addition to direct damages from flooding and heatwaves, disruption caused by road blockages will be increased by more frequent flood events. For example, in the city of Newcastle upon Tyne (UK), road travel disruption across the city from a 1-in-50 year surface water flood event could increase by 66% by the 2080s (Pregnolato et al., 2017), whilst heatwaves could treble railway speed restrictions in parts of the UK (Palin et al., 2013). Knott et al. (2017) highlighted risks to coastal infrastructure where ~30 cm sea level rise sea level rise would also push up groundwater and reduce design life by 5–17% in New Hampshire (USA). Heavy rain and flooding can also inundate underground transport systems (Forero-Ortiz, Martínez-Gomariz and Canas Porcuna, 2020).

Many airports, and by their nature ports, are in the low elevation coastal zone, making them especially vulnerable to flooding and sea level rise. Under a 2°C scenario, the number of airports at risk of storm surge flooding increases from 269 to 338 or as many as 572 in an RCP8.5 scenario; these airports are disproportionately busy and account for up to 20% of the world's passenger routes (Yesudian and Dawson, 2021). Airport and port operations could be disrupted by icing of aircraft wings, vessels, decks, riggings and docks (Doll, Klug and Enei, 2014; Chhetri et al., 2015). Warming will increase microbiological corrosion of steel marine structures (Chaves et al., 2016). Fog, high winds and waves can disrupt port and airport activity, but changes are uncertain and with regional variation (Mosvold Larsen, 2015; Izaguirre et al., 2021; Becker, 2020; León-Mateos et al., 2021; Taszarek, Kendzierski and Pilguj, 2020; Danielson, Zhang and Perrie, 2020; Kawai et al., 2016).

Waterways are still important transport routes for goods in many parts of the world, although they are mostly expected to benefit from reduced closure from ice (Jonkeren et al., 2014; Schweighofer, 2014), low flows will *likely* lead to reduced navigability and increased closures; van Slobbe et al. (2016) estimate the Rhine may reach a turning point for waterway transportation between 2070–2095. Obstruction due to debris and fallen vegetation of roads and rails and to inland and marine shipping from high winds are expected to increase (Koks et al., 2019; Kawai et al., 2018; Karagiannis et al., 2019)..

6.2.4.3 Information and Communication Technology

Information and communication technology (ICT) comprises the integrated networks, systems and components enabling the transmission, receipt, capture, storage and manipulation of information by users on and across electronic devices (Fu, Horrocks and Winne, 2016). ICT infrastructure faces a number of climate risks. Increased frequency of coastal, fluvial or pluvial flooding will damage key ICT assets such as cables, masts, pylons, data centres, telephone exchanges, base stations or switching centres (Fu, Horrocks and Winne, 2016). This leads to loss of voice communications, inability to process financial transactions and interruption to control and clock synchronisation signals. Insufficient information about the location and nature of many ICT assets limits detailed quantitative assessment of climate change risks.

Fixed-line ICT networks that sprawl over large areas are especially susceptible to increases in the frequency or intensity of storms that would increase the risk of wind, ice and snow damage to overhead cables and damage from wind-blown debris. More intense or longer droughts and heatwaves can cause ground shrinkage and damage underground ICT infrastructure (Fu, Horrocks and Winne, 2016). In mountain and northern permafrost regions, communications and other infrastructure networks are subject to subsidence because of warming of ice-rich permafrost (Shiklomanov et al., 2017; Li et al., 2016; Melvin et al., 2017).

6.2.4.4 Housing

For the urban housing sector, climate impacts such as flooding, heat, fire and wind assessed in Section 6.2.3 will *likely* have detrimental effects on housing stock (including physical damage and loss of property value) and on residents exposed to climate risks (*robust evidence, high agreement*).

In the USA, for example, 15.4 million housing units fall within a 1-in-100-year floodplain (Wing et al., 2018). Assessment of the Miami-Dade area in Florida noted that coastal inundation caused by tidal flooding (and to a lesser extent sea level rise) resulted in over USD 465 million in lost real-estate market value between 2005 and 2016 (McAlpine and Porter, 2018), although property values have increased from high-end housing construction and climate adaptation measures (Kim, 2020). Emergent risk reflecting novel research include aggravated moisture problems in buildings from wind driven rain (Nik et al., 2015). Future risks from future sea level rise are elaborated in Section CCP2.2.1. Housing infrastructure are also susceptible to extreme heat and wind events (Stewart et al., 2018). These risks are further elaborated on in Section 6.2.3, although it is important to note that heat risks, in particular, tend to be concentrated within communities with a higher proportion of social housing (Mavrogianni et al., 2015; Sameni et al., 2015) or low-cost government-built houses and informal settlements.

6.2.4.5 Water and Sanitation

Apart from land subsidence from urbanisation (e.g., Case Study 6.2), substantial climate risks to urban sanitation arise from droughts, flooding and storm surges. Low flows from drought can lead to sedimentation, increase pollutant concentration and block sewer infrastructure networks (Campos and Darch, 2015). Flooding poses a greater risk for urban sanitation in low- and middle-income settings (Burgin et al., 2019) where onsite systems are more common. Floodwater may wash out pits and tanks, mobilising faecal sludges and other hazardous materials leading to both direct and indirect exposure via food and contaminated objects and surfaces, and pollute streams and waterbodies (Howard et al., 2016; Braks and de Roda Husman, 2013; Bornemann et al., 2019). Floods also damage infrastructure; toilets, pits, tanks and treatment systems are all vulnerable (Sherpa et al., 2014; UNICEF and WHO 2019).

Sanitation systems coupled with floodwater management are at risk of damage and capacity exceedance from high rainfall (Thakali, Kalra and Ahmad, 2016; Kirshen et al., 2015; Dong, Guo and Zeng, 2017). In England, the number of water and wastewater treatment plants at risk of flooding is projected to increase by 33% under a 4ºC scenario (Sayers et al., 2015), but risks are generally increasing for both formal and informal urban sanitation systems (Howard et al., 2016).

6.2.4.6 Natural and Ecological Infrastructure

Urban ecological infrastructure includes green (i.e., vegetated), blue (i.e., water-based) and grey (i.e., non-living) components of urban ecosystems (Li et al., 2017). While land cover change from urbanisation directly reduces the extent of natural and ecological infrastructure (e.g., Lin, Meyers and Barnett, 2015), notable risks arise from climate drivers. Recent research particularly highlights future climate impacts on coastal natural infrastructure, including beaches, wetlands and mangroves, which cause significant economic losses from property damage and decreasing tourism income, as well as loss of natural capital and ecosystem services. Research on climate risks to urban trees and forests is comparatively limited. Instead, urban vegetation and green infrastructure are most often cast as adaptation strategies to reduce urban heat, mitigate drought and provide other ecosystem benefits (see Section 6.3.2).

Coastal natural infrastructure is exposed to sea level rise, wave action and inundation from increasing storm events (See also Section CCP 2.2.1). Beaches, in particular, are highly exposed to climate-induced coastal erosion (Toimil et al., 2018; Section CCP2). Research from settlements across coastal Southern California, USA, show that 67% of all beaches may completely erode by 2100 (Vitousek, Barnard and Limber, 2017). Coastal zones across Cancún, Mexico, are exposed to a combination of sea level rise and tropical hurricanes, further exacerbated by urban development patterns blocking natural sediment replenishment to beaches (Escudero-Castillo et al., 2018). In another case, beach erosion along the heavily urbanised Valparaíso Bay, Chile, is heightened by El Niño Southern Oscillation (ENSO) events, which in the past have caused an additional 15–20 cm in mean sea level rise (Martínez et al., 2018).

Wetlands, mangroves and estuaries, which tend to be heavily urbanised areas, are highly at risk from sea level rise and changing precipitation (Green et al., 2017; Feller et al., 2017; Alongi, 2015; Osland et al., 2017; Chow, 2018; Godoy and Lacerda, 2015). Sea level rise is a concern for wetlands and mangroves across coastal urban Asia, the Mississippi Delta (US) and low lying small island states (Ward et al., 2016b). Research on the highly urbanised Yangtze River estuary in China shows that soil submersion and erosion from sea level rise, compounded by land conversation to agriculture and urban development, will cause all tidal flats to disappear by 2100 (Wu, Zhou and Tian, 2017). In another example, sea level rise and high rates of tidal inundation have increased overall salinity in the San Francisco Bay-Delta estuary, threatening the ecosystem's ability to support biodiversity (Parker and Boyer, 2019).

Research on climate risks to urban trees and forests highlight direct impacts from extreme temperatures, precipitation, wind events and sea level rise, as well as exposure to other hazards such as air pollution, fires, invasive species and disease (Ordóñez and Duinker, 2014). Since the 1960s, climate change has enabled growth of urban trees, supported by longer growing seasons, higher atmospheric CO_2 concentrations and reduced diurnal temperature range (Pretzsch et al., 2017), as well as increased fertilisation through urban-enhanced nitrogen deposition (Decina, Hutyra and Templer, 2020). However, these trends may change in the future as further warming and decreasing water supply may depress tree fitness, thus enabling more pests (Dale and Frank, 2017).

Climate risks to urban natural and ecosystem infrastructure entail significant economic costs. For example, in 2012, Hurricane Sandy led to total losses of up to USD 6.5 million to the New York City region's low-lying salt marshes and beaches (Meixler, 2017). Research from coastal settlements across Catalonia, Spain, shows significant levels of tourism loss (which contribute to 11.1% of the region's GDP), infrastructure damage and natural capital loss attributed to inundation and erosion of beaches, which are projected to retreat by –0.7 m yr^{-1} given current sea level rise projections of 0.53–1.75 m by 2100 (Jiménez et al., 2017).

6.2.4.7 Health Systems Infrastructure

Healthcare facilities (hospitals, clinics, residential homes) will suffer increasing shocks and stresses related to climate variability and change (Corvalan et al., 2020). Some may be sudden shocks from extreme weather events, which both threaten the facility, staff and patients and increase the number of people seeking health care. There are extensive reports of health facilities being damaged after major floods and windstorms (e.g., 2010 floods in Pakistan, Hurricane Sandy in the USA) which can be further exacerbated by power and water supply failures (Powell, Hanfling and Gostin, 2012). Disruption to services may persist for many months because of damage to buildings, loss of drugs and equipment, and damaged transport infrastructure significantly increasing travel time for patients (Hierink et al., 2020). The impacts of climate change on the health of residents of 'slum' settlements will also compound the existing health burdens faced by these individuals, including infectious disease and other environmental public health concerns (Lilford et al., 2016; Mberu et al., 2016).

6.2.5 Compound and Cascading Risks in Urban Areas

Compound events can be initiated via hazards such as single extreme events, or multiple coincident events overlapping and interacting with exposed urban systems or sectors as compound climate risks (Leonard et al., 2014; IPCC, 2019b; Piontek et al., 2014). Hydrometeorological hazards, such as extreme precipitation from tropical cyclones, fronts and thunderstorms, often combine with storm surges and freshwater discharge leading to high compound risks at exposed settlements (Zheng, Westra and Sisson, 2013; Chen and Liu, 2014; Ourbak and Magnan, 2018; Dowdy and Catto, 2017). The compounding effect between these hydrometeorological hazards suggest that the combined impact of these events are greater than each of these variables on its own, and can amplify risks in affected settlements (Kew et al., 2013; Vitousek et al., 2017). These risks are concentrated in coastal cities exposed to sea level rise and severe storms (van den Hurk et al., 2015; Wahl et al., 2015; Paprotny et al., 2018b; Lagmay et al., 2015), or in settlements located in valleys prone to slope failure, such as the 2013 Uttarakhand floods and landslides arising from extreme precipitation and glacial lake outbursts along the Mandakini river in India (Ziegler et al., 2016; Barata et al., 2018).

Cascading climate events occur when an extreme event triggers a sequence of secondary events within natural and human systems that causes additional physical, natural, social or economic disruption. The resulting impact can be significantly larger than the initial hazard (IPCC, 2019b). Each step in a risk cascade can generate direct (immediate impacts) and secondary (consequential impacts) losses. Risks from these cascading impacts are complex and multi-dimensional (Hao, Singh and Hao, 2018; Zscheischler and Seneviratne, 2017). For instance, combined droughts and heatwaves increases risks of urban water scarcity (Miralles et al., 2019; Gillner, Bräuning and Roloff, 2014; Gill et al., 2013), as well as increasing wildfire extent and lowering snowpack conditions that affected peri-urban settlements adjacent to forested areas, as observed in California during the 2014 drought (AghaKouchak et al., 2014). Similarly, heatwaves can increase the risk of mortality associated with air pollution (see Section 7.2.2.5).

Urban areas and their infrastructure are susceptible to both compounding and cascading risks arising from interactions between severe weather from climate change and increasing urbanisation (*medium evidence*, *high agreement*) (Moretti and Loprencipe, 2018; Markolf et al., 2019). Risks are complex and multi-dimensional, and can significantly amplify the impact of single events across space, scale and time. Impacts are determined by the magnitude of urban vulnerability and/or the interdependence of urban critical infrastructure (Pescaroli and Alexander, 2018; Zuccaro, De Gregorio and Leone, 2018). Poorer and wealthier settlements and cities are then both at risk from compound and cascading risks though potentially through contrasting mechanisms. For richer and poorer cities, managing climate risk as part of compound and cascading risks that can also include technological, biological and political risks places renewed emphasis on investment in generic capabilities that reduce vulnerability and on risk monitoring capability to track and respond to impacts across infrastructures and places (*limited evidence*, *high agreement*). Considering climate risk and managing such risk as part of complex, compounding and/or cascading risks is in its infancy but rapidly being accepted as necessary, especially when considering the wider poverty and justice implications of climate change arising from differentiated vulnerability in cities.

Compound risks to key infrastructure in cities have increased from extreme weather (*medium evidence*, *high agreement*), such as from urban flooding from extreme precipitation and storm surges disrupting transport infrastructure and networks, for example Mehrotra et al. (2018), see also San Juan case study in this chapter), ICT networks, for example underground cables or transmission towers (Schwarze et al., 2018), and energy generation from power plants (Marcotullio et al., 2018).

The increased risk arises not just from greater exposure from climate events impacting cities, but is also magnified by low adaptive capacity that can arise from intra-urban variations in infrastructure quality. For instance, infrastructure within expanding informal settlements is associated with deficiency in materials, structural safety and a lack of accessibility. These areas are often located in the most risk-prone urban areas in developing nations that are vulnerable to compound hazards (Dawson et al., 2018). Further, these risks can be exacerbated from complications arising from local versus national governance and/or regulations related to hazard management (Garschagen, 2016; Castán Broto, 2017).

Projected global compound risks will increase in the future, with significant risks across energy, food and water sectors that likely overlap spatially and temporally while affecting increasing numbers of people and regions particularly in Africa and Asia (*high confidence*) (Hoegh-Guldberg et al., 2018). In cities, the prevalence of compounding risks therefore necessitates methodologies accounting for non-stationary risk factors.

Secondary impacts occurring sequentially after an extreme hazard can severely affect disaster management, especially in complex urban systems (*robust evidence*, *high agreement*). Over time, relatively small perturbations can cascade outward from a primary failure, triggering further failures in other dependent parts of the network some distance away from the primary failure (Penny et al., 2018). In some cities, such as those prone to compound flood hazards, these dependent network parts can be dams, levees or other critical flood protection infrastructure that are essential for managing these cascading risks (Serre and Heinzlef, 2018; Fekete, 2019). Failure of these infrastructure systems can result in sequential failures in urban transport (Zaidi, 2018), energy networks (Sharifi and Yamagata, 2016), urban biodiversity (Solecki and Marcotullio, 2013) and so-called na-tech disasters; when natural hazards trigger technological disasters (Girgin, Necci and Krausmann, 2019). This risk cascade can propagate more widely by stopping flows of people, goods and services, with economic consequences beyond urban areas (Wilbanks and Fernandez, 2014).

Compound and cascading climate risks require a different way of accounting for cumulative hazard impacts in urban areas (*medium evidence*, *high agreement*). There is emerging literature calling for analysis on interactions between individual and inter-related climate extremes with complex urban systems, so as to ascertain how urban and key infrastructural vulnerabilities can be identified and managed in a warming world (Butler, Deyle and Mutnansky, 2016; Gallina et al., 2016; Moftakhari et al., 2017; Zscheischler et al., 2018; Baldwin et al., 2019; Pescaroli and Alexander, 2018; Yin et al., 2017; AghaKouchak et al., 2020), as well as in managing adaptation for present and future pandemics, for example COVID-19 (Pelling et al., 2021; Phillips et al., 2020).

In terms of policy, case studies from London's resilience planning process stressed the need for intermodal coordination, hazard risk and infrastructure mapping, clarifying tipping points and acceptable levels of risk, training citizens, strengthening emergency preparedness, identifying relevant data sources, and developing scenarios and contingency plans (Pescaroli, 2018). Others also note the utility of a systems approach to analysing risks and benefits, including considerations of potential cascading ecological effects, full lifecycle environmental impacts, and unintended consequences, as well as possible co-benefits of responses (Ingwersen et al., 2014). Lowering these risks requires urban stakeholders to reduce urban vulnerability by going beyond linear approaches to risk management (*medium evidence*, *high agreement*).

6.2.6 Impacts and Risks of Urban Adaptation Actions

Planning and implementing climate adaptation in cities and settlements can be hampered by incomplete scientific knowledge, a lack of awareness of cascading impacts (and residual risks), mismanagement of actions, human capacity and financing deficits, as well as opportunities for eroding long-term sustainable development priorities (Juhola et al., 2016). These tensions can become acute in fragile and conflict affected states (see Box 6.3). It is important to differentiate between the climatic drivers of risk and social drivers that may compound risk exposures and experiences (Brown, 2014; Nightingale et al., 2020), especially since technically- and scientifically-informed adaptation actions can be redirected depending on socioeconomic, political or cultural conditions on the ground (Eriksen, Nightingale and Eakin, 2015). The implementation of adaptation, whether by government, private sector or civil society actors, can therefore lead to unanticipated and unintended amplification of political, economic and ecological risks (Swatuk et al., 2020). Many cities are still in the phase of piloting or testing out appropriate adaptation actions, although there is emerging consensus that adaptation plans and projects should acknowledge trade-offs, intentionally avoid past development mistakes, not lock-in detrimental impacts or further risks arising from implementation and explicitly anticipate the risks of maladaptation in decision making (Magnan et al., 2016; Gajjar, Singh and Deshpande, 2019). Maladaptation describes actions that lead to increased vulnerability or risk to climate impacts or diminish welfare. Urban examples include green gentrification which offers nature-based solutions to the few, social safety nets that promote risk inducing subsidies. Whether an action is maladapted can depend on context, for example air conditioning can reduce risk for the individual but is maladaptive at a societal level (see Section 6.3.4.2). It is informed by process; corruption can distort processes and generate maladaptation (see Section 6.4.5.2). Climate resilient development raises the ambition for adaptation actions so that it is also possible to describe actions that do not also enhance climate mitigation and sustainable development outcomes as maladaptive (see Section 6.4.3.1). This section assesses three broad categories of risk arising from downstream adaptation actions, including interventions that transfer vulnerability across space and time, plans that yield socioeconomically exclusionary outcomes, and actions that undermine long-term sustainable and resilient development priorities.

Downstream impacts occur because adaptive capacity is often unequally distributed across sectors and communities (Matin, Forrester and Ensor, 2018; Makondo and Thomas, 2018). In cities and settlements, adaptation interventions can displace ecological impacts to more vulnerable areas or directly lead to socioeconomically exclusionary outcomes (Anguelovski et al., 2016), particularly when adaptation plans and actions are primarily assessed through the prism of economic and/or financial viability (Shi et al., 2016; Klein, Juhola and Landauer, 2017). As a result, adaptation actions make only minimal contributions to the reduction of vulnerability, as the increased vulnerability of excluded communities more than offsets the decreased vulnerability of more well-off communities. Numerous examples, ranging from the mega coastal planning in Jakarta, Indonesia (Salim, Bettinger and Fisher, 2019; Goh, 2019), fragmentation of urban infrastructure intended to promote climate resilience in Manila, Philippines (Meerow, 2017), exclusionary modes of flood control in São Paulo, Brazil (Henrique and Tschakert, 2019), strategies to reduce risks in the event of mudslides in Sarno, Italy (D'Alisa and Kallis, 2016), and involuntary community relocations in Vietnam (Lindegaard, 2020) and Mozambique (Arnall, 2019) all point to how an economic logic to adaptation can lead to exclusion of lower income, informal or minority communities in adaptation.

Box 6.3 | Climate Change Adaptation for Cities in Fragile and Conflict Affected States

Larger cities may be the most stable administrative entities in states affected by conflict. Even here, ability to plan and deliver adaptation can be hampered. Extending into urban areas within stable states, alienation and loss of trust between local populations and the state can be exacerbated by top-down adaptation planning and delivery; socially and spatially uneven adaptation investment; and in the economic and administrative limits of government that can lead to some places being excluded from formal planned investment (*high confidence*) (see Sections 6.3 and 6.4). These pathways for exclusion can combine among already marginalised and low-income populations where trust in government agencies may already be low (Rodrigues, 2021).

Climate change can be a threat multiplier in cities and urban regions, exacerbating existing human security tension (*limited evidence*, *medium agreement*) (Froese and Schilling, 2019; Flörke, Schneider and McDonald, 2018; Rajsekhar and Gorelick, 2017). Where conflict or administrative tensions extend beyond cities, adapting regional infrastructure systems that underpin urban life is challenging, for example where elements of networked infrastructure are under the control of conflicting political interests. This has been noted for the water sector (Tänzler, Maas and Carius, 2010). Coordinating political processes is a major challenge even for industrialised countries with adequate administrative capacity. In post-conflict societies, the difficulties of coordination for urban planning are disproportionately greater (Sovacool, Tan-Mullins and Abrahamse, 2018).

In planning adaptation measures in cities, conflict-sensitive approaches to ensure participatory methods (Bobylev et al., 2021) can avoid adaptation being a polarising activity (Tänzler, Maas and Carius, 2010; Tänzler, 2017). Adaptation can provide a common goal reaching across political differences and be a part of building political trust and local cooperation between alienated communities (Tänzler, Maas and Carius, 2010). Peacebuilding programmes led by government or civil society are typically concerned with the short-term and framed by socioeconomic policy, integrating the longer-term view and engineering-technical expertise for adaptation is a challenge (*limited evidence*, *medium agreement*) (Ishiwatari, 2021).

Table 6.4 | Key Risks to cities, settlements and infrastructure

Synthesis of key risks for cities, settlements and key infrastructure								
Key risk	**Geographic region**	**Consequence that would be considered severe, and to whom.**	**Hazard conditions that would contribute to this risk being severe.**	**Exposure conditions that would contribute to this risk being severe.**	**Vulnerability conditions that would contribute to this risk being severe.**	**Adaptation options with highest potential for reducing risk.**	**Confidence in key risk identification.**	**Chapter and section**
Risk to population from increased heat	Global but higher risk in temperate and tropical cities. (6.2.3.1)	Increased heat stress, mortality and morbidity events from urbanisation and climate change. Increased health risks and mortality in elderly population; vulnerability of the young to heat. (6.2.3.1)	Substantial increase in frequency and duration of extreme heat events, exacerbated by urban heat island effects. (6.2.3.1) Concentration of a mixture of extreme heat and humidity. (6.2.3.1)	Large increases in exposure, particularly in urban areas, (6.2.3) driven by population growth, changing demographics, and projected urbanisation patterns. Urbanisation increases annual mean surface air temperature by more than 1°C Correlation between rising temperatures and increased heat capacity of urban structures, anthropogenic heat release and reduced urban evaporation. (6.2.3.1)	Changing demographics from aging populations, potential for persistent poverty, slow penetration and increasing cost of air conditioning, and inadequate improvements in public health systems. (6.2.3.1) Inadequate housing and occupations with exposure to heat. (6.2.3.1)	Nature-based solutions e.g., urban greenery at multiple spatial scales; vegetation; shading; lower energy costs; green roofs; community gardens; (6.3.3.1) enhanced space conditioning in buildings; broader access to public health systems for most vulnerable populations. Less economic stress on residents through utilities, especially electricity. (6.2.3.1) Tree planting in communities that lack urban greening. (6.3.3.1)	*High confidence*, robust *evidence* and high *agreement*.	6.2, 6.3
Urban infrastructure at risk of damage from flooding and severe storms	Global, but higher risk in coastal cities.	Damage to key urban infrastructure (e.g., buildings, transport networks, and power plants) and services from flood events, particularly high risk within coastal cities, especially those located in low elevation coastal zones. (6.2.3.2)	Substantial increase in frequency and intensity of extreme precipitation (6.2.3.2) from severe weather events and tropical cyclones contributing to pluvial and fluvial floods, which are exacerbated by long-term sea level rise and potential land subsidence. (6.2.3.2)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics, and projected urbanisation patterns with a geographical focus in coastal regions. Flooding is exacerbated both by encroachment of urban areas into areas that retain water, and lack of infrastructure such as embankments and flood walls. (6.2.3.2)	Costly maintenance of protective infrastructure, downstream levee effects, and increased concentrations of coastal urban population. Little investment in drainage solutions. (6.2.3.2)	Early warning systems, Adaptive Social Protection (ASP) to reduce vulnerable populations, nature-based solutions e.g., in sponge cities to enhance flood protection and regulate storm- and floodwaters; this can be improved through reduced risk unto vulnerable urban systems such as stormwater management, sustainable urban drainage system, etc. (6.2.3.2) Green infrastructure can be more flexible and cost effective for providing flood risk reduction. (6.3.3)	*High confidence*, *robust evidence* and high agreement	6.2, 6.3, CCP2
Population at risk from exposure to urban droughts	Cities located in regions with high drought exposure (e.g., Europe, South Africa, Australia).	Water shortages in urban areas, and restricted access to water resources to vulnerable populations and low-income settlements. People living in urban areas will be exposed to water scarcity from severe droughts. (6.2.3.3) Increased environmental health risks when using polluted groundwater. (6.2.3.3)	Projections of more frequent and prolonged drought events potentially compounded with heatwave hazards, and land subsidence from coastal cities that extract groundwater. Climate drivers (warmer temperatures and droughts) along with urbanisation processes (land use changes, migration to cities and changing patterns of water use) contribute to additional risks. (6.2.3.3)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics, and projected urbanisation patterns. Limitations of engineered water infrastructure is also exposed by flash droughts. (6.2.3.3) Settlements are increasingly dependent on imported water resources by locales that may also be exposed to drought risk. (6.2.3.3)	Greater water demand from urban populations from in-migration and key economic sectors, and inefficient or ineffective water resource management. (6.2.3.3)	Demand and supply side management strategies that include incorporation of indigenous/local knowledge and practices, equitable access to water. Better water resource management will increase quality of water available. More beneficial physical and social teleconnections to bring mutual benefit of water resources between regions. (6.2.3.3)	*High confidence*, *robust evidence* and high agreement	6.2, 6.3

Synthesis of key risks for cities, settlements and key infrastructure								
Key risk	**Geographic region**	**Consequence that would be considered severe, and to whom.**	**Hazard conditions that would contribute to this risk being severe.**	**Exposure conditions that would contribute to this risk being severe.**	**Vulnerability conditions that would contribute to this risk being severe.**	**Adaptation options with highest potential for reducing risk.**	**Confidence in key risk identification.**	**Chapter and section**
Health risks from air pollution exposure in cities	Global, in cities located in Africa, South Asia, the Middle East and East Asia	Increased mortality and morbidity events from respiratory-related illnesses and co-morbidities toward vulnerable urban populations, arising from PM2.5 and tropospheric ozone exposure.	Increased emissions of pollutants from anthropogenic (e.g., transportation, electric power generation, large industries, indoor burning of fuel, and commercial and residential sources) and biogenic (e.g., forests, windblown dust, and biomass burning) emissions. Potential for severe compound risks arising from droughts and wildfire. Projections for frequency of meteorological conditions are expected to severe PM2.5 concentrations. (6.2.3.4)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics, projected urbanisation patterns and demand for energy combined with weak regulations for emissions control. (6.2.2.4)	High proportion of young or aging populations vulnerable to respiratory illness, potential for persistent poverty, advection of pollutants from upwind, ex-urban areas, and stay in shelter policies from COVID-19. (Box 6.4; 6.2.5)	Enhanced monitoring of air quality in rapidly developing cities, investment in air pollution controls, e.g., stricter emissions. regulations, and increased GHG emissions controls resulting in co-benefits with air quality improvements. Increase in trees or vegetated barriers with low VOC emissions, low allergen emissions, and high pollutant deposition potential to reduce particulate matter and maximise adaptation benefits. (6.3.3.2)	*High confidence*, *medium evidence* and high *agreement*	6.2, 6.3
Health risks from water pollution exposure and sanitation in cities	Cities located in regions with high drought exposure resulting in polluted water.	Increased environmental health risks when using polluted groundwater. (6.2.3.3) Vulnerability of users such as women; children; the elderly; ill or disabled. (6.3.4.6)	Decreased regional precipitation and changes in runoff and storage from droughts impairs the quality of water available. Less runoff to freshwater rivers can increase salinity, concentrate pathogens, and pollutants. (6.2.2.3)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics, and projected urbanisation patterns. Low flows from drought can lead to sedimentation, increase pollutant concentration and blocking of sewer infrastructure networks. (6.2.4.8).	Costly maintenance of protective infrastructure. Sanitation systems coupled with flood water management are at risk of damage and capacity exceedance from high rainfall. (6.2.4.8)	Investment in well-regulated water sections; wastewater treatment plants; pumping stations. Reducing impacts of floods on sanitation infrastructure through active management such as reducing blockage in sewer infrastructure (6.3.4.6) Adaptive planning; integration of measures of climate resilience; improved accounting and management of water resources. (6.3.4.6)	*High confidence*, *medium evidence* and High agreement	6.2, 6.3

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A specific form of maladaptation is so-called green gentrification, this privileges wealthy urban residents in urban greening projects (Rice et al., 2020; Shokry, Connolly and Anguelovski, 2020; Anguelovski, Irazábal-Zurita and Connolly, 2019; Blok, 2020). For example, in Miami-Dade County, Florida, USA, researchers found that adaptation functionality had a positive effect on property values (Keenan, Hill and Gumber, 2018). In New York City and Atlanta, Georgia, USA, research has shown that adaptation investments can increase property values and lead to neighbourhood change (Immergluck and Balan, 2018; Gould and Lewis, 2018). In the Gold Coast and Sunshine Coast, South East Queensland, Australia, where local communities have a strong preference for waterfront living, local governments are pressured by property developers to protect these coastal zones (Torabi, Dedekorkut-Howes and Howes, 2018). In Lagos, Nigeria, efforts to achieve climate resilience and sustainability through future city practices risk perpetuating the enclosure and commodification of land (Ajibade, 2017). The exclusionary outcomes of some adaptation interventions can therefore further heighten the risk to communities that are socioeconomically more vulnerable. See Section 6.3 for further discussion of equity and justice considerations in local climate adaptation.

Human behaviour can exacerbate climate impacts, for example in the emergence of 'last chance tourism', Lemieux et al. (2018) focused on built cultural heritage at risk from climate change associated events, including from decay or even total loss generated by increased flooding and sea level rise (Camuffo, Bertolin and Schenal, 2017) and water infiltration from post-flood standing water (Camuffo, 2019). Last chance tourism can lead to increased touristic interest over a short time horizon and to precarious economic conditions, which can lead to further accelerated degradation cultural heritage sites already at risk from climate change.

Finally, some adaptation policies or actions can erode the preconditions for sustainable and resilient development by indirectly increasing society's vulnerability (Neset et al., 2019; Juhola et al., 2016). Mandates to mainstream adaptation into existing development logics and structures perpetuates development-as-usual, reinforcing technocratic forms of local governance and locking in structural causes of marginalisation and differential vulnerability (Scoville-Simonds, Jamali and Hufty, 2020). Adaptation policy examples include: Australia's adaptation policy focus on financial strategies, preference for business-as-usual scenarios and incremental change will not contribute to transformative change (Granberg and Glover, 2014); Surat, India, where a focus on adapting industries and economically important assets in the city can divert policy attention away from general social equity and urban sustainability priorities (Chu, 2016; Blok, 2020); Cambodia, where conflict between adaptation practitioners and local communities and non-compliance with regulatory safeguards led to conflict and potential for maladaptation (Work et al., 2018). Finally, although insurance has the potential to incentivise practices to reduce risks, including through measures to reduce premiums (see Section 6.4.5 for additional details), researchers of insurance-led adaptation actions have argued that, since insurance regimes privilege normality, they tend to structurally embed risky behaviour and inhibit change (O'Hare, White and Connelly, 2016). All of these examples illustrate how incremental strategies that rely on business-as-usual actions can further entrench unequal and unsustainable development patterns in the long term. There are also significant limits to urban adaptation (see Section 6.4) with consequential impacts on human well-being.

Table 6.4 lists a selection of key risks (broadly defined as have severe outcomes common to a majority of cities) identified in our assessment of urban impacts and risks in this section. It provides a description of the consequences of the risk that would constitute a severe outcome, as well as the hazard, exposure and vulnerability conditions contributing to its severity. It also provides adaptation options identified and elaborated on in Section 6.3 as having the highest potential for reducing the risk, and an assessment of the confidence in the judgement that this risk could become severe. This table is also reflected in Section 16.5.1, and the methodology is described in Table SM16.5.1.

Following Chapter 16, the severity of a risk or impact is a subjective judgment based on a number of criteria. Key risks are 'potentially' severe because, while some could already be severe now, more typically they may become so over time because of changes in the nature of the climate-related hazards and/or of the exposure and/or vulnerability of societies or ecosystems to those hazards. They also may become severe owing to the adverse consequences of adaptation or mitigation responses to the risk.

6.3 Adaptation Pathways

6.3.1 Introduction

Adaptation pathways are composed of sequences of adaptation actions connected through collaborative learning with the possibility of enabling transformations in urban and infrastructure systems (Werners et al., 2021). Individual adaptation actions co-evolve with risks (see Section 6.2) and development processes (Section 6.4) to compose more or less planned adaptation pathways that can include a range of unanticipated outcomes. This section engages with this complexity by approaching adaptation through the notion of infrastructure. The adaptation options for individual infrastructure systems are reviewed, and in Section 6.4 brought together through assessment of cross-cutting enabling conditions. Interpreted broadly, infrastructure includes the social systems, ecological systems and grey/physical systems that underpin safe, satisfying and productive life in the city and beyond (Grimm et al., 2016). Social infrastructure includes housing, health, education, livelihoods and social safety nets, cultural heritage/institutions, disaster risk management and security and urban planning. Ecological infrastructure includes nature-based services: temperature regulation, flood protection and urban agriculture. Grey, or physical infrastructure, includes energy, transport, water and sanitation, communications (digital), built form and solid waste management. Framing infrastructure in this way enables an assessment of adaptation that is not constrained to the administrative boundaries of urban settlements, but also includes the flows of material, people and money between urban, peri-urban and more rural places, and can include adaptation actions deployed by government, individuals and the private sector. Recognising the complexity of adaptation and the research literature that reaches beyond individual infrastructural domains, the section also reviews urban adaptation through the cross-cutting lenses of equity and mitigation. Section 6.4 assesses the enabling environment (political will, governance, knowledge, finance and social context) that shapes specific adaptation contexts and futures.

6.3.2 The Adaptation Gap in Cities and Settlements

The adaptation gap is the difference between the ability to manage risk and loss and experienced risk and loss (Chen et al., 2016; UNEP, 2021). It describes both levels of capacity and residual risk. Figure 6.4 presents an analysis by IPCC World Region for urban populations and

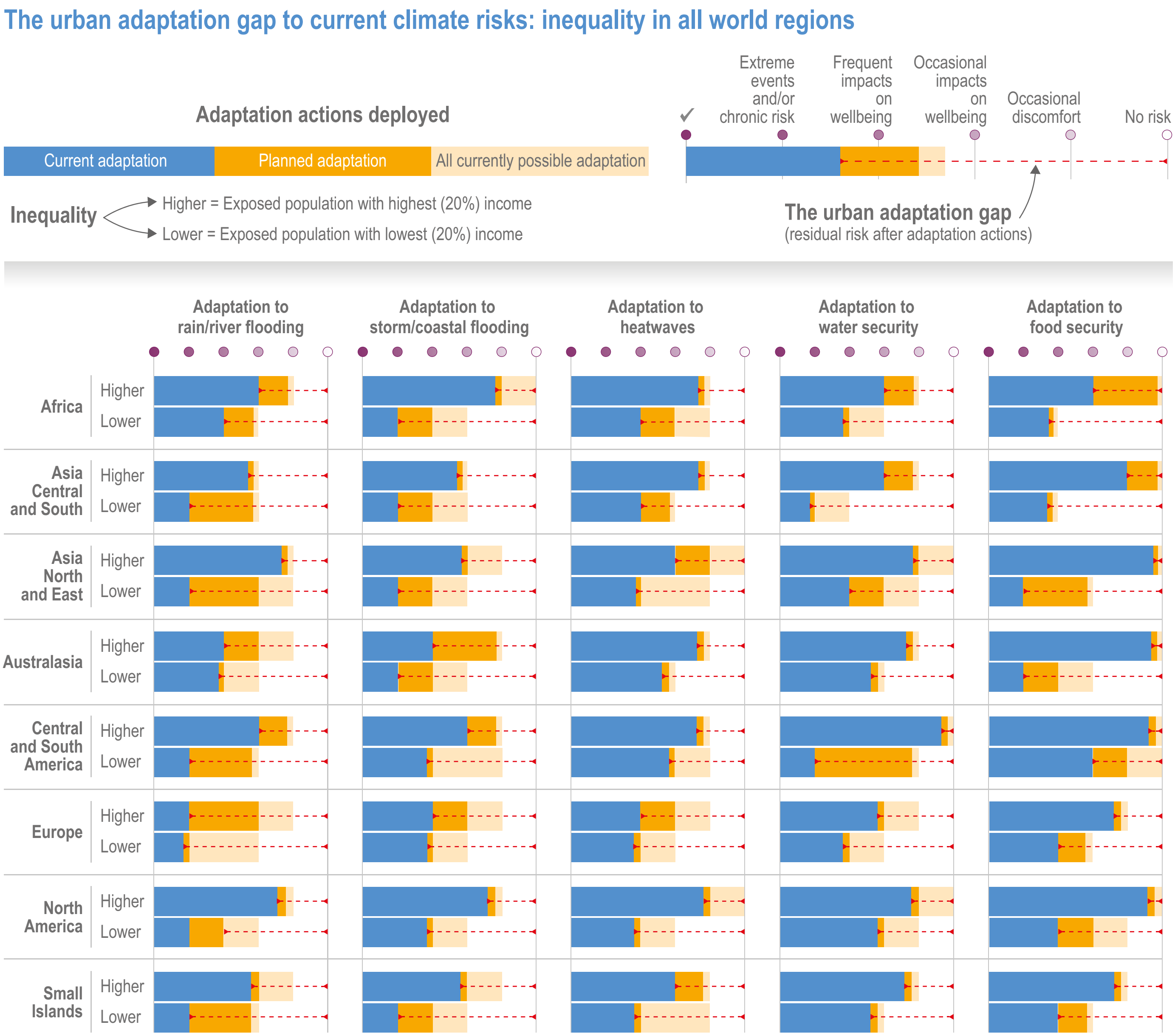

Figure 6.4 | The Urban Adaptation Gap. This is a qualitative assessment presenting individual, non-comparative data for world regions from 25 AR6 Coordinating Lead Authors (CLAs) and Lead Authors (LAs), the majority from regional chapters. Respondents were asked to make expert summary statements based on the data included within their chapters and across the AR6 report augmented by their expert knowledge. Multiple iterations allowed opportunity for individual and group judgement. Urban populations and risks are very diverse within regions making the presented results indicative only. Variability in data coverage leads to the overall analysis having *medium agreement*, *medium evidence*. Major trends identified in 6.3.1 at least meet this level of confidence. Analysis is presented for current observed climate change associated hazards and for three adaptation scenarios: (1) current adaptation (based on current levels of risk management and climate adaptation), (2) planned adaptation (assessing the level of adaptation that could be realised if all national, city and neighbourhood plans and policies were fully enacted), (3) transformative adaptation (if all possible adaptation measures were to be enacted). Assessments were made for the lowest and highest quintile by income. Residual risk levels achieved for each income class under each adaptation scenario are indicated by five adaptation levels: no risk, occasional discomfort, occasional impacts on well-being, frequent impacts on well-being, extreme events and/or chronic risk. The urban adaptation gap is revealed when levels of achieved adaptation fall short of delivering 'no risk'. The graphic uses IPCC Regions, and has split Asia into two regions: North and East Asia, and Central and South Asia. Technical support is acknowledged from Greg Dodds and Sophie Wang

current levels for risk and loss. The analysis seeks to draw out equity considerations by comparing the poorest and wealthiest quintiles for each region and for adaptation to the direct impacts of flooding and heatwave, as well as impacts felt in cities that include climate change impacts on supply chains; water and food security. Figure 6.4 should not be used to compare regions but can be used to contrast adaptation gaps by hazard type within regions.

The key finding from Figure 6.4 is that for all urban populations, both *currently deployed* and *currently planned* adaptations are not able to meet current levels of risk associated with climate change. Even if *all conceivabl*e adaptation was to be deployed, the majority of risks faced by the urban rich and poor today would not be fully resolved. This clearly emphasizes the fundamental importance of climate change mitigation to avoid urban risk and loss.

The urban adaptation gap is also found to be unequal. The poorest quintile has a larger adaptation gap than the richest quintile. Reported inequality in the application of urban adaptation is greatest in North, East and Southeast Asia, reflecting rapid urbanisation in this region. Reported inequality is lowest in Europe and Australasia. Observed inequalities indicate that the markets, government actions and civil society investments available to reduce vulnerability and risk among the poor have not been observed to offset inequalities based on individual and household capacities.

There is some catch-up as analysis moves through *actually deployed* to *planned* and *all conceivable* deployment, particularly for water and food security, but even here, inequality in risk is not fully resolved. Africa and South and Central Asia in particular show considerable disparity in adaptation to urban food security even with *all conceivable adaptation*. This means that even if all available adaptation was to be deployed, inequality in ability to adapt to climate change would remain. This highlights the significance of addressing underlying inequalities in development that shape differential vulnerability (see Section 6.2.3.1, 6.2.3.3, 6.3.5.1 and 6.4) as part of vision and action on reducing risk to climate change so that no one is left behind.

Some hazard types and regions show strong capacity to close the adaptation gap if *all planned* adaptation was to be deployed: for example, Europe for heatwave and Europe and Central and South America for riverine and coastal flooding (particularly for wealthier populations). This reveals capacity within the current approaches to climate risk management, but also highlights the importance of resolving challenges that prevent planned adaptation from being deployed and deployed equitably.

6

6.3.3 Adaptation Through Social Infrastructure

Social infrastructure refers to social, cultural and financial activities and institutions as well as associated property, buildings and artefacts that can be deployed to reduce risk and recover from loss. This section examines land use planning, livelihoods and social protection, emergency and disaster risk management, health systems, education and communication, and cultural heritage.

6.3.3.1 Land Use Planning

Land use planning plays a major role in the siting of settlements and infrastructure. In relation to climate change, it affects whether development takes place in locations that are exposed to hazards; similarly, it shapes the potential effects that the built environment can have on natural systems. Despite this, generally speaking, there is limited implementation of zoning and land use measures for climate adaptation from cities across diverse contexts (*robust evidence*, *high agreement*), see for example Maputo (Castán Broto, 2014), sub-Saharan cities (Dodman et al., 2017) and Amman, Moscow and Delhi (Jabareen, 2015). Certain countries, such as South Korea, have, however, recently begun to address disaster risk reduction within their land use planning systems (Han et al., 2019).

Conventional zoning regulations (in which only one kind of use is permitted in a given area) and land use planning range in scale from the regional to the local and can be deployed to minimise risks through protection, accommodation or retreat. Protection entails, in addition to allocating zones for protective urban infrastructure (such as seawalls, levees and dykes, and slope revetments), avoidance measures that restrict or prevent urban development (e.g., through growth containment and/or no-build zones). Accommodation involves land use modifications and/or conversions while retreat requires either compulsory or voluntary relocations and may entail buyouts (Butler, Deyle and Mutnansky, 2016; León and March, 2016; Lyles, Berke and Overstreet, 2018). Risk eliminating retreat measures are less widely adopted than other risk reducing zoning and land use measures (Anguelovski et al., 2016; Butler, Deyle and Mutnansky, 2016; Lyles, Berke and Overstreet, 2018). This is attributed to the controversies of relocation and to the complexities of buyouts (Butler, Deyle and Mutnansky, 2016; King et al., 2016).

Evidence from both richer countries and the Global South reveals that conventional zoning is more effective when governance systems facilitate the implementation of land use policies for climate adaptation that preclude negative human-nature interactions and that curb spatial inequity, both of which can trigger climate gentrification and increase the vulnerability of economically disadvantaged groups to climate-related risk (*high confidence*) (Marks, 2015; Liotta et al., 2020; Keenan, Hill and Gumber, 2018). Cascading benefits of zoning and land use planning for climate adaptation are associated with the use of soft land cover, green infrastructure and improvement of livability through better conditions for walkability and cycling. This decreases auto-dependency and contributes to health and economic development (by attracting businesses and retail that stimulate economic prosperity and increase property values) (Larsen, 2015; Carter et al., 2015). Such increases in property values have also been observed in zones and areas protected from risks (such as flooding), where it may trigger spatial inequity leading to climate gentrification (Marks, 2015; Votsis, 2017; Votsis and Perrels, 2016; Keenan, Hill and Gumber, 2018).

Adaptation actions through zoning and land use are more effective when combined with other planning measures (*high confidence*), for example with ecosystem-based adaptations (e.g., for flood management and curbing the urban heat island effect) (Larsen, 2015;

Nalau and Becken, 2018; Perera and Emmanuel, 2018; Anguelovski et al., 2016; Carter et al., 2015; Tsuda and Duarte, 2018; Nolon, 2016); with community-based adaptations (trade-offs and valuations, i.e., which land uses are valued more) (Larsen, 2015; Nalau and Becken, 2018; Perera and Emmanuel, 2018; Anguelovski et al., 2016; Carter et al., 2015; McPhearson et al., 2018; Nolon, 2016); and with built form regulations and codes (León and March, 2016; Yiannakou and Salata, 2017; Perera and Emmanuel, 2018; Straka and Sodoudi, 2019; Larsen, 2015; Nolon, 2016). The imposition of planning-based tools such as scenario planning, flexible zoning and development incentivisation (among others) has the capacity to influence and encourage these adaptations (United States Environmental Protection Agency, 2017). Local risk-reduction inputs can inform land use adaptation policies (accommodation and/or avoidance, specifically growth containment and no-build zones) that are better integrated within larger urban plans (Lyles, Berke and Overstreet, 2018; Nalau and Becken, 2018; Tsuda and Duarte, 2018) (*limited evidence*, *high agreement*).

Implementation of zoning and land use measures for climate adaptation from cities across diverse contexts remains limited (*high agreement*, *robust evidence*) owing to a range of challenges. A range of evidence from multiple locations indicates the challenges of mainstreaming land use planning for climate adaptation, including in Bangkok, Thailand (Marks, 2015), Legazpi City and Camalig Municipality in the Philippines (Cuevas et al., 2016; Cuevas, 2016), the USA (Cuevas et al., 2016; Cuevas, 2016), British Columbia, Canada (Stevens and Senbel, 2017), and Australia (Serrao-Neumann et al., 2017). Mainstreaming is hindered by a lack of clarity of implementation strategies for climate adaptation, insufficient funding, competing priorities (especially among professional planners and politicians), institutional challenges (see Jabareen's [2015] study of 20 cities globally) and the need to fill data gaps and continuously update weather statistics (Oberlack and Eisenack, 2018) (*medium evidence*, *high agreement*). At the same time, however, limited evidence from cities around the world such as the urban regions of Stuttgart and Berlin in Germany (Larsen, 2015), Greater Manchester in the UK (Carter et al., 2015), and Colombo in Sri Lanka (Perera and Emmanuel, 2018) reveals that risk reduction through zoning and land use can effectively protect and expand green infrastructure and soft land cover to alleviate pluvial flooding and decrease the urban heat island effect. This evidence points that one of the primary roles of land use planning is to guide the development of the urban form. As such, it underpins and establishes the basis for other infrastructure systems such as physical infrastructure and nature-based solutions (Morrissey, Moloney and Moore, 2018).

6.3.3.2 Livelihoods and Social Protection

Understanding how livelihoods, particularly of the urban poor, are both impacted by climate risk and how they might be strengthened is central to understanding climate adaptation in cities and settlements (Dobson et al. 2015). Rapid urbanisation and expanding physical infrastructure do not have a clear relationship with improved outcomes for urban livelihoods of low-income residents (Soltesova et al., 2014). Municipal and national efforts need to be closely aligned with building adaptive capacity of residents themselves, often through community-based adaptation (Soltesova et al., 2014; Dobson, Nyamweru and Dodman, 2015). Social safety nets protect individuals or households from falling below a defined standard of living by providing cash, in kind and other social transfers to fight vulnerabilities (Islam and Hasan, 2019) including those associated with climate change impacts including food shocks. Strengthening the financial and social infrastructure of poor households is a critical component of adaptive and transformative capacity (Haque, Dodman and Hossain, 2014; Ziervogel, Cowen and Ziniades, 2016). Social safety nets are one mechanism for strengthening this capacity.

Social protection, or social security, is defined as the set of policies and programmes designed to reduce and prevent poverty and vulnerability throughout the lifecycle (ILO, 2017). Safety nets are intended to protect vulnerable households from impacts of economic shocks, natural hazards and disasters, and other crises. The UN policy frameworks for sustainable development, including the Sendai Framework for Disaster Risk Reduction 2015–2030, the new Strategic Framework 2018–2030 of the United Nations Convention to Combat Desertification (UNCCD) and UNFCCC, highlight the essential role of social protection in promoting comprehensive risk management (Aleksandrova, 2019). Since the term Adaptive Aocial Protection was introduced by the World Bank (2015) and the IPCC (2014), it has been an emerging strategic tool to integrate poverty reduction, disaster risk reduction and humanitarian development into adaptation to climate change (Béné, Cornelius and Howland, 2018; Aleksandrova, 2019; Watson et al., 2016).

Adaptive social protection (ASP) is defined as a resilience-building approach by combining elements of social protection, disaster risk reduction and climate change adaptation, so as to break the cycle of poverty and vulnerability of household by investing in their capacity to prepare for, cope with and adapt to all types of shocks, especially under climate change and other global challenges (Bowen et al., 2020; Ivaschenko et al., 2018). ASP has been justified as an effective instrument to build household and community resilience to climate extremes and slow-onset climate events such as sea level rise and environmental degradation (Schwan and Yu, 2018; Aleksandrova, 2019). In contexts of extreme poverty or climatic extremes, international development organisations, national provisions and market charities are complementary where family and kinship networks are weak and inadequate. To deal with short-term vulnerability to climate shocks, ASP can act as a crucial complement to risk management tools provided by communities and markets, tools which tend to be insufficient in the face of large or systemic shocks, by providing predictable transfers, developing human capital and diversifying livelihoods (Hallegatte et al., 2016). ASP can also facilitate long-term change and adaptation by improving education and health levels, as well as providing a proactive approach to managing climate-induced migration in both rural and urban areas (Schwan and Yu, 2018; Adger et al., 2014).

Many national ASP programmes are established to cover both rural and urban areas, however, only a small number of researchers pay attention to urban cases (Aleksandrova, 2019). ASP instruments can be classified into four major types as presented in Table 6.5 (Ivaschenko et al., 2018; ILO, 2017). ASP can contribute to both incremental and transformative interventions both at the system level (short-term and long-term coping strategies from communities) and at the beneficiaries' level (vulnerable populations) (Béné, Cornelius and Howland, 2018; World Bank, 2015; Aleksandrova, 2019; Ivaschenko et al., 2018).

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Table 6.5 | Four categories and examples of adaptive social protection.

Category	Example	Urban cases	Function
Social safety nets (or social assistance)	Conditional and unconditional cash transfers, including non-contributory pensions and disability, birth and death allowances; Food stamps, rations, emergency food distribution, school feeding and subsidies; Cash or food for work programmes; Free or subsidised health services; Housing and utility subsidies; Scholarships and fee waivers, etc.	– A targeted asset transfer project for urban extreme poor in Dhaka city (Hossain and Rahman, 2018) – Emergency food stockpiling in Japan; safety net food stocks in India, Indonesia and Malaysia (Lassa et al., 2019) – Household cash transfer programme in contingency planning in Mexico (Ivaschenko et al., 2018) – Governmental transfer to hurricane affected households in USA (Bowen et al., 2020) – Non-contributory disability cash benefits (ILO, 2017)	Incremental adaptation; protective measures
Social insurance	Old age, survivor and disability contributory pensions; Occupational injury benefit, sick or maternity leave; Health insurance, etc.	Old-age social pensions (Ivaschenko et al., 2018)	Incremental adaptation and *ex ante* prevention
Labour market policies	Unemployment, severance and early retirement compensation; Training, job sharing and labour market services; Wage subsidises and other employment incentives, including for disabled people, etc.	Public works and employment protection in Africa, Asia cases (World Bank, 2015; ILO, 2017; Ivaschenko et al., 2018)	*Ex post* protection and *ex ante* prevention measures, incremental adaptation
Livelihood development measures	Income diversification, employment support, weather-index insurance, housing subsidies, post-disaster construction, relocation planning, livelihood shift strategies, etc.	Multiple programmes for differing household needs in Philippines (Bowen et al., 2020); Weather-index insurance in Chinese coastal cities (Rao and Li, 2019); Early warning forecast system and public meteorological service information in Beijing (Song, Zheng and Lin, 2021)	Promotive and anticipatory measures; transformational adaptation

ASP may be very good at reducing extreme poverty by helping to meet individual or household needs but not collective needs to mitigate long-term climate shocks. For example, few programmes consider risk assessment and climate-proof infrastructures as anticipatory measures to foster early action and preparedness (Aleksandrova, 2019; Costella et al., 2017). They therefore need to enable the adoption of forward-looking strategies for long-lasting adaptation (Tenzing, 2020). Some examples from China show social protection can improve adaptive capacity of urban communities with social medical insurance, housing subsidies, weather-index insurance, post-disaster construction, relocation planning, livelihood shift strategies, and so on. (Pan et al., 2015; Zheng et al., 2018b; Rao and Li, 2019; Song, Zheng and Lin, 2021). However, social protection may lead to maladaptation in urban policy when social security, or similar tools (for example insurance) to compensate for exposure deincentivise risk reduction (Grove, 2021). In many developing countries, high concentrations of poor and vulnerable groups living in disaster-prone zones of urban centres, new urban dwellers and informal residents are often excluded from community-based networks and social services (Aleksandrova, 2019). Risk transfer tools (such as insurance) and risk retention measures (such as social safety nets) can avoid and minimise the burden of loss and damage and limit secondary and indirect effects (Aleksandrova, 2019; Roberts and Pelling, 2018).

Inclusive, targeted, responsive and equitable social protection can support long-term transition toward more sustainable, adaptive and resilient societies (Hallegatte et al., 2016; Shi et al., 2018; Béné, Cornelius and Howland, 2018; Carter and Janzen, 2018; Adger et al., 2014). ASP systems can be cost effective and equitable when targeting accuracy, timely risk sharing (disaster assistance) and improved policy coherence. Carter and Janzen (2018) find that the long-term level and depth of poverty can be improved by incorporating vulnerability targeted social protection into a conventional social protection system.

Countries at all income levels can set up ASP systems that increase resilience to natural hazards, but the systems need to identify cost–benefits and be scalable and flexible to adjust to future, increasing climate risk. Bastagli (2014) suggested a new design for effective social protection including: (i) increasing the amount or value of transfer; (ii) extending the coverage of beneficiaries; and (iii) introducing payments or new programmes of social protections. For social protection programmes to contribute more effectively to adaptation, they need to be better coordinated across a range of agencies; better integrated with climate data to anticipate times of need for vulnerable groups; and better aligned with other risk management instruments such as insurance (Agrawal et al., 2019).

6.3.3.3 Emergency and Disaster Risk Management

There is growing evidence of the benefits of early warning systems for urban preparedness decision making and action for climate and weather-related hazards such as cyclones, hurricanes and floods (*medium evidence*; *high agreement*) (Lumbroso, Brown and Ranger, 2016; Zia and Wagner, 2015; Marchezini et al., 2017). Climate forecasting is constantly evolving and becoming increasingly accurate. Global organisations such as the World Meteorological Organizations are increasingly focusing on new and emerging technologies such as crowdsourced data collection to support integrated city services and early warning systems (Baklanov et al., 2018). However, while climate forecasting is an increasingly central tool for risk management agencies, a focus on urban areas or key infrastructure is still considerably rare (Lourenço et al., 2015; Nissan et al., 2019; Harvey et al., 2019). The significant rise in urban risks poses significant challenges to humanitarian agencies. Humanitarian responses and local emergency management are vital for disaster risk reduction yet are compromised in urban contexts where it is difficult to confirm property ownership and where renters and informal dwellers are often excluded from decision-making and planning (Parker and Maynard, 2015; Maynard et al., 2017). Disaster survivors and growing urban refugee populations are often displaced across the city thereby complicating efforts to track and provide support (Maynard et al., 2017).

Existing early warning systems remain insufficient and the complexity of urban landforms makes accurate and detailed early warning difficult (*medium evidence*; *high agreement*) (Jones et al., 2015). This is particularly the case in low- and middle-income countries (LMICs) where urban centres are often characterised by rapid expansion of interlinked formal and informal human settlements and land use zones. In such contexts, early warning services vary in effectiveness within the same urban centre (Allen et al., 2020c; Rangwala et al., 2018). Often, forecast-based action follows linear structures where forecast information is applied mainly for responding to negative impacts rather than anticipatory decision-making and preparation to avoid such impacts (Marchezini et al., 2017). Early warning systems are effective for warning of threshold breaching events including cyclonic activity and riverine flooding but less able to provide localised warning, though capability is rapidly increasing. Probabilistic risk forecasting and forecast based early action are only beginning to be applied to urban contexts and often those that are most vulnerable do not receive warnings regarding hazardous events (Nissan et al., 2019). There is less capacity for early warning systems in LMICs with key challenges linked to a lack of well-established risk baseline information; accessibility, communication and understanding of forecast information, as well as political and institutional barriers and limited resources and capacities to act on such information (Jones et al., 2015; Mustafa et al., 2015; Zia and Wagner, 2015; Marchezini et al., 2017; Gotgelf, Roggero and Eisenack, 2020). Political and institutional barriers to the incorporation of climate information to decision-making are not limited to LMICs (Harvey et al., 2019). For example, comprehensive studies on sectoral use of climate information in Europe revealed that, despite climate services becoming increasingly accessible and well resourced, there is limited organisational uptake of seasonal climate forecasts across key sectors (e.g., energy, transport, water and infrastructure) in informing their decision making processes (Soares and Dessai, 2016; Soares, Alexander and Dessai, 2018). This is due both to technical and non-technical barriers such as lack of awareness and knowledge of climate information and forecasting (Soares and Dessai, 2016; Soares, Alexander and Dessai, 2018).

Globally, a considerable diversity of tools and frameworks for urban resilience assessments are being developed at multiple scales (Arup and Rockefeller, 2015; Elias-Trostmann et al., 2018). These include hybrids such as ecosystem-based disaster risk reduction (Eco-DRR) (Begum et al., 2014).While important advances have been made in assessing urban resilience, much debate remains around such tools and assessment approaches regarding issues such as validation, dynamics in exposure and vulnerability, and appropriateness of generic methods in high-density urban settlements (Leitner et al., 2018; Cardoso et al., 2020; Rufat et al., 2019). Disaster impact and recovery time are strongly influenced by the behaviour and actions of individuals, communities, businesses, and government organisations (Meriläinen, 2020; Räsänen et al., 2020). For example, the review by Aaerts et al. (2018) shows how the limitations of existing flood risk assessment methods (which tend to account for human behaviour in limited terms) can be addressed through innovative flood-risk assessments that integrate behavioural adaptation dynamics. The study by Moghadas et al. (2019) highlights the importance of hybrid multi-criteria approaches for assessing urban flood resilience in Tehran, Iran. A growing literature shows how multidisciplinary and inclusive approaches that include Local knowledge can achieve greater accuracy in risk characterisation and support lasting impact of investments into more robust climate services (Aerts et al., 2018; Lourenço et al., 2015; Sword-Daniels et al., 2018; Singh et al., 2018; Nissan et al., 2019; Harvey et al., 2019; Simon and Palmer, 2020). This literature highlights the need for innovative approaches in urban contexts that transcend traditional approaches of local knowledge inclusion widely applied in rural contexts, such as participatory rural appraisal.

The inclusion of Local knowledge and Indigenous knowledge in urban vulnerability and risk assessments can strongly enhance local resilience, but its effectiveness is constrained by wider decision making and policy contexts dominated by top-down approaches (*medium evidence*; *high agreement*) (Jones et al., 2015; Sword-Daniels et al., 2018; Nissan et al., 2019). Established non-state actors such as Shack and Slum Dwellers International are particularly effective at implementing inclusive approaches for local knowledge incorporation into urban decision-making. Climate change and disaster risk exacerbate existing problems of economic development, yet macro-economic planning seldom incorporates adaptation. Recent evidence also confirms the role of Indigenous knowledge and local knowledge in management practices to reduce climate risks through early warning preparedness and response (see also Section 6.3.2.3). These practices are particularly important where alternative early warning methods are absent. For instance, Abudu Kasei et al. (2019) show that Indigenous knowledge gathered through observations on changes in natural indicators (such as links between rainfall patterns, certain flora and fauna, and temperature changes) could be applied to develop early warning of climate hazards (floods and droughts) in informal urban settlements in African countries such as Ghana. Similarly, Hiwaski et al. (2015) show that observations of changes in the environment and celestial bodies are used to predict climate-related hazards in Indonesia, the Philippines and Timor-Leste where communities in turn use local materials and methods, and customary practices to respond to the impacts of climate change.

Insurance is a risk transfer mechanism for middle- and high-income countries, yet is less widely available in LMICs (Surminski and Thieken, 2017). Additionally, where insurance options do exist in LMICs, these are not usually available to large populations living or operating in the informal sector. Flood insurance is widely available in many Organisation for Economic Co-operation and Development (OECD) countries but the demand and uptake differ significantly across countries (Hanger et al., 2018). This financial tool is subject to increasing pressure under the changing climate, with growing concerns around affordability and availability. More integrative approaches are required, such as where changes in the insurance industry are closely linked to adaptation strategies, building standards and land use planning and their application (Cremades et al., 2018). This is particularly important in LMICs and of central concern for all insurance schemes is ensuring access, fairness and affordability for the most poor and vulnerable. However, there are some notable examples of low-income communities setting up their own disaster insurance mechanisms. For example, the Community Development Funds for the Baan Mankong upgrading programme in Thailand include disaster funds as insurance against housing damage (Archer, 2012). Such approaches also need to be more closely linked to existing urban risk management planning approaches where urban livelihoods are seldom integrated and informed by more dynamic risk reduction frameworks that consider adaptive cycles and how resilience changes over time (Beringer and Kaewsuk, 2018; Cremades et al., 2018).

Disaster risk management systems face increasing challenges in adapting to evolving risk profiles, shaped by expanding urban areas and changing environmental conditions associated with climate change. In addition to flooding, risk monitoring and management systems have recently shown considerable shortfalls in planning for and responding to increased fire risk such as the devastating Californian wildfires in October 2019 (Morley, 2020) and Australia's unprecedented and catastrophic 2019–2020 wildfire season. Risk management has also been challenged by new risk experiences including wild/bush fires encroaching on expanding urban areas and fire outbreaks in densely populated informal settlements pose increasing threats to livelihoods, human health and habitats globally (see also Sections 2.4.4.2 and 2.5.5.2).

6.3.3.4 Climate Resilient Health Systems

Climate resilient health systems are a vital part of adaptation to protect the most vulnerable from climate change (WHO, 2020). Cardiovascular fitness for example is a root cause of morbidity and mortality form heat stress (Schuster et al., 2017). The World Health Organization has developed a framework of climate-resilient health systems that addresses both mitigation and adaptation goals (WHO, 2015). Universal health coverage (UHC) is an essential component of climate-resilient health systems. In most countries, access to health services is better in urban than in rural areas. However, there remain large urban populations with insufficient coverage of health services (WHO and WB, 2015) and UHC tracking needs to take better account of inequalities in coverage, including differences in access within cities and further disaggregation of urban populations by income. Thus, health sector investment is an important tool in adaptive action and capacity. Analyses of health survey data shows that, globally, access to health care is increasing toward UHC targets (Lozano et al., 2020). Financing for global health has increased steadily in the last two decades and modelling shows this trend is *likely* to continue to 2050, but at a slower pace of growth and the current disparities in per-capita health spending persist between high and low/middle income countries, leading to insufficient health service coverage for the poorest populations (Chang et al., 2019a). Out-of-pocket spending is projected to remain substantial in LMIC and will remain the only means to access health care for many poor urban populations.

The WHO Operational Framework highlights the components that can be strengthened to adapt to extreme weather (e.g., health care workforce, information systems, etc.). The evidence is greatest for impacts on larger health facilities (such as hospitals) and there is less evidence regarding impacts on health service delivery outside these settings (smaller health facilities, pharmacies, first responders, public health inspectors, etc.). Improved building design and spatial urban planning (where facilities are located) are essential to increase resilience for higher temperature and flood risk (*medium evidence*; *high agreement*) (WHO, 2021; Codjoe et al., 2020; Korah and Cobbinah, 2017). Public health systems rely on information systems (including disease and vector surveillance and monitoring) to identify new and emergent public health risks. Improvements to health surveillance will increase resilience, particularly for populations in informal settlements that are absent from health and vital registration systems.

City-level and local government adaptation planning is facilitated by information on health impacts (Reckien et al., 2015), highlighting the need for monitoring and surveillance and the need for local evidence-based risk assessments. Adaptation in the health sector can be limited by lack of collaboration between health and other sectors, although this is often easier to facilitate at the local level (Woodhall, Landeg and Kovats, 2021).

6.3.3.5 Education and Communication

Since AR5, there has been significant growth in research about climate education and activism (Simpson, Napawan and Snyder, 2019; O'Brien, Selboe and Hayward, 2018; Hayward, 2021). Access to knowledge is an important determinant of well-being, inclusivity and livelihood mobility and of driving human behaviour. Knowledge systems include formal educational provision (capital assets, syllabus and human capital), informal learning based in social interaction and customary institutions (including through social media) and public communication (news media, government and other information systems including commercial messaging). There is a growing body of literature addressing the role of information and communication technology in shaping behaviour in disaster response and recovery and climate action, with particular focus on social media use and serious gaming (Houston et al., 2015; Carson et al., 2018) (see Section 6.3.4.3)

Given the amount of time that children spend in school settings, adapting educational infrastructure and programmes to climate change is highly important. This includes not only making physical structures safe, but also providing students with the knowledge and confidence to support individual and family-based adaptation. Several UN agencies (e.g., UNICEF and UNDRR) and international non-governmental agencies (e.g., Plan International) have prioritised safer schools and child-centred risk management that often focus on schools as places that should be prioritised for retrofitting and safe construction, but also as focal points for knowledge dissemination and community organising where impacts can extend beyond the school to reduce risk among students' families. Universities and think tanks, as well as the third and private sector are key support mechanisms, particularly at the local level and when working in collaboration with local government and communities. They can support the development of critical educational resources and innovative communication methods, as well as facilitate the design and implementation of climate policies and related action plans.

Youth, adult communities, social media and the commercial media can have a significant impact on advancing climate awareness and the legitimacy of adaptive action, particularly in large urban areas (*medium evidence*, *high agreement*). Climate change education in urban settlements has increasingly focused on enhancing children and young people's political agency in schools, universities, and in formal and informal media settings (Cutter-Mackenzie and Rousell, 2019). However, an ambiguous framing of climate impacts and adaptation, for example around the science of urban heat islands by the media, can also exacerbate local community confusion and uncertainty (Iping et al., 2019) and further training and capacity building opportunities such as for vocational qualifications is still required across diverse settings (Simmons, 2021). Communication strategies deployed in formal education and social media can be highly influential in exchanging information and establishing narratives and viewpoints that frame what adaptive action is legitimate, especially in large cities (Simpson, Napawan and Snyder, 2019). However, the effectiveness of communication strategies for change, for example from Mayoral offices, can also be influenced by wider political and structural drivers including community literacy or political partisanship (Boussalis, Coan and Holman, 2019). Recent research (e.g., Macintyre et al., 2018) highlights the need for new learning approaches to climate education from school age to adult education. Emphasis is on inclusivity in learning and recognising diverse perspectives across multiple levels and settings, from formal and informal education to wider social learning. Informal learning that takes place outside of school settings, such as in libraries and botanical gardens, in everyday life is increasingly recognised as a key arena for climate education, life-long learning and nurturing environmental citizenship and activism (Paraskeva-Hadjichambi et al., 2020).

6.3.3.6 Cultural heritage/institutions

The integration of culture into urban policy and planning is increasingly recognised as critical to developing sustainable and resilient cities, and features in international agreements such as the SDGs (*limited evidence*; *high agreement*) (Sitas, 2020). However, urban cultural policies are still limited, for example, Cape Town is the only African city to have developed a city-level cultural policy (Sitas, 2020). Cultural heritage refers to both tangible (e.g., historic buildings and sites) and intangible (e.g., oral traditions and social practices) resources inherited from the past (Fatorić and Egberts, 2020; Jackson, Dugmore and Riede, 2018). Learning about past societal and environment changes through heritage offers opportunity for reflection and transfer of knowledge and skills. This takes place in multiple contexts such as museums and cultural landscapes, and in everyday life (Fatorić and Egberts, 2020; Jackson, Dugmore and Riede, 2018). Cultural heritage is primarily associated with identity and is closely intertwined with the complexities of history, politics, economics and memory. Climate change adds another layer of complexity to cultural heritage and resource management (Fatorić and Seekamp, 2017b). Changing climatic conditions are already negatively impacting World Heritage Sites such as the Cordilleras' Rice Terraces of the Philippines and earthen architecture sites, for example the Djenné mosque in Mali, are particularly vulnerable to changes in temperature and water interactions (UNESCO, 2021). Climate change impacts intangible cultural heritage across diverse settings such as in the Caribbean and Pacific Small Island Developing States (SIDS) where traditional ways of life and related aspects such as oral traditions and performing arts are under threat from extreme weather events (UNESCO, 2021).

The climate change adaptation options for built cultural heritage fall into seven categories (Rockman et al., 2016; Fatorić and Seekamp, 2017b). Financial constraints are the primary barriers that underpin the first four adaptation options: no action at all, merely monitoring and/or documenting, or annual maintenance (Xiao et al., 2019; Sesana et al., 2019; Fatorić and Seekamp, 2017a; Fatorić and Seekamp, 2017b; Fatorić and Seekamp, 2018). Core and shell preservation, the fifth and sixth categories, are cost effective when they improve the condition of built cultural heritage (BCH) (Bertolin and Loli, 2018; Loli and Bertolin, 2018a; Loli and Bertolin, 2018b), while elevation and/or relocation, the final adaptation options, are extremely costly and might jeopardise the historic value (Xiao et al., 2019). To date, however, evidence indicates that adaptation actions prioritise archaeological sites (Carmichael et al., 2017; Fatorić and Seekamp, 2018; Pollard et al., 2014; Dawson, 2013). The efficacy of adaptation of historic buildings can be increased through increased and stable funding, incentives, stakeholder engagement, and legal and political frameworks (Dutra et al., 2017; Fatorić and Seekamp, 2018; Fatorić and Seekamp, 2017b; Fatorić and Seekamp, 2017a; Leijonhufvud, 2016; Phillips, 2015; Sesana et al., 2019; Sesana et al., 2018; Sitas, 2020).

Other barriers to implementation include harnessing expert and local knowledge (of individuals and organisations) to identify both quantitative and qualitative methods and indicators that connect cultural significance and local values vis-à-vis climatic change over time and that move beyond the prevalent high-risk or high-vulnerability centred approaches (Carmichael et al., 2017; Fatorić and Seekamp, 2018; Haugen et al., 2018; Leijonhufvud, 2016; Pollard et al., 2014; Puente-Rodríguez et al., 2016; Richards et al., 2018; Dawson, 2013; Filipe, Renedo and Marston, 2017; Kotova et al., 2019). This is particularly important given that the significance of cultural heritage is often intangible, and its value cannot be determined solely through quantitative indicators. Accessing local resources (craftsmanship and materials compatible with the originals) can also improve built cultural heritage's adaptation capacity (Phillips, 2015).

Effective decision-making and practice for adapting built and intangible cultural heritage requires open dialogue and exchange of cultural, historical and technical information between diverse stakeholders and decision makers (Fatorić and Seekamp, 2017b; Benson, Lorenzoni and Cook, 2016). As noted in Section 6.2.6, human behaviour can be a driving force for adaptation impacts on BCH at risk. Despite challenges associated with intangibility, socio-cultural heritage such as Indigenous knowledge (e.g., food security and water management practices) presents important opportunities for climate adaptation and resilience building. More research is needed across diverse contexts to understand feasible climate adaptation measures, and barriers and opportunities for building the resilience of both built and intangible cultural heritage, as well as to increase awareness of cultural heritage benefits among climate change policymakers (Fatorić and Egberts, 2020).

6.3.4 Adaptation Through Nature-Based Solutions

Well-functioning ecosystems can play a significant role in buffering cities, settlements and infrastructure from climate hazards at multiple scales (*robust evidence*, *high agreement*). Nature-based solutions (NBS) are actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham et al., 2016). Widely recognised as low-regret measures for disaster risk reduction and climate change adaptation, green and blue infrastructure investments and natural area conservation in cities can provide NBS across scales to reduce temperature shocks and provide natural flood defences among other adaptation and resilience benefits (McPhearson et al., 2018; Andersson et al., 2019; Frantzeskaki et al., 2019). Blue infrastructure, for example, provides ecological and hydrological functions (e.g., evaporation, transpiration, drainage, infiltration, detention) critical to sustainable urban water management (Iojă et al., 2021). Public parks, urban forests, street trees and green roofs, as well as lakes, ponds and streams are widely documented for providing local cooling, grass and riparian buffers, forested watersheds can enhance flood and drought protection for cities and settlements, and mangrove stands and wetlands in coastal areas can reduce storm surges. Despite increasing knowledge about NBS (here encompassing literature on ecosystem services for climate change adaptation and resilience, ecosystem-based adaptation, and benefits of green and blue infrastructure for adaptation), recent studies indicate that nature-based approaches to adaptation and resilience are still under-recognised and under-invested in urban planning and development (Matthews, Lo and Byrne, 2015; Geneletti and Zardo, 2016; Frantzeskaki et al., 2019), despite the potential scale of benefits, for example, a recent study covering 70 cities in Latin America calculated that 96 million people would benefit from improving main watersheds with green infrastructure (Tellman et al., 2018).

Grey infrastructure often damages or eliminates biophysical processes (e.g., through soil sealing, stream burial or altered hydrology) necessary to sustain ecosystems, habitats and livelihoods, where urban ecological infrastructure (Childers et al., 2019) can be more flexible and cost effective for providing flood risk reduction and other benefits (Palmer et al., 2015). Hybrid approaches are emerging that integrate ecological and grey (engineered) infrastructure in adaptation planning and hazard protection (Grimm et al., 2016; Depietri and McPhearson, 2017). Explicit policy uptake by city authorities is increasing (Hansen et al., 2015; Hölscher et al., 2019), such as in New York where in 2010 the city committed to a hybrid infrastructure plan for storm water management, investing USD 5.3 billion over 20 years, of which USD 2.4 billion was targeted for green infrastructure investments (NYC, 2010). A subset of services from urban ecosystems are being increasingly invested in as NBS for climate adaptation pathways (Keeler et al., 2019; Kabisch et al., 2016) and included as regulatory drivers through flood management, hazard mitigation and air pollution regulations that encourage or enforce the implementation of green infrastructure practices (Davis et al., 2020).

Development and climate mitigation co-benefits of NBS is an additional reason that NBS are being increasingly taken up by cities, including for improving health and livelihoods, particularly for poor, marginalised groups (Poulsen et al., 2015; Poulsen, Neff and Winch, 2017; Maughan, Laycock Pedersen and Pitt, 2018; Simon-Rojo, 2019; Cederlöf, 2016). Co-benefits include a wide range of social and environmental benefits (Brink et al., 2016; Alves et al., 2019) for human physical and mental health (Kabisch, van den Bosch and Lafortezza, 2017; Sarkar, Webster and Gallacher, 2018; Engemann et al., 2019; Rojas-Rueda et al., 2019), climate mitigation (De la Sota et al., 2019) and as habitat for local biodiversity (Ziter, 2016; Knapp, Schmauck and Zehnsdorf, 2019). At the same time, concerns about the unintended consequences of investing in green infrastructure for NBS, such as how it may contribute to gentrification (Turkelboom et al., 2018; Anguelovski et al., 2018; Haase et al., 2017), create more public use, increase water demand (Nouri, Borujeni and Hoekstra, 2019) or contribute to criminal activity (Cilliers and Cilliers, 2015) underlines the challenges of investing in adaptation in complex urban systems (see Section 6.2.6). Additionally, more place-based analyses of the efficacy of NBS for reducing climate impacts across varying urban contexts and future climate scenarios are needed to better understand the cost effectiveness of investing in NBS to provide disaster risk reduction and deliver critical co-benefits for human well-being. Cooperation between scientists, decision-makers and Indigenous knowledge-holders can supplement current efforts and ensure that investments in NBS do not negatively impact indigenous communities (Ban et al., 2018; Seddon et al., 2021; Townsend, Moola and Craig, 2020).

6.3.4.1 Temperature Regulation

Nature-based strategies, including street trees, green roofs, green walls and other urban vegetation, can reduce heat and extreme heat by cooling private and public spaces (*robust evidence*, *high agreement*). Shading and evapotranspiration are the primary mechanisms for vegetation-induced urban cooling (Coutts et al., 2016). Shading reduces mean radiant temperature, which is the dominant influence on outdoor human thermal comfort under warm, sunny conditions (Thorsson et al., 2014; Viguié et al., 2020). Outdoor green space and parks may also slightly reduce indoor heat hazard (Viguié et al., 2020). Apart from lowering temperature, NBS may also contribute to lower energy costs by reducing extra demand for conventional sources of cooling (e.g., air conditioning) (Viguié et al., 2020; Foustalieraki et al., 2017), especially during peak demand periods. Homes with shade trees that are located in cities where air conditioning systems are common can save over 30% of residential peak cooling demand (Zardo et al., 2017; Wang et al., 2015). Green roofs have been shown to significantly lower surface temperatures on buildings (Bevilacqua et al., 2017) and modelling suggests that green roofs, if employed widely throughout urban areas, have the potential to impact the regional heat profile of cities (Bevilacqua et al., 2017; Rosenzweig, Gaffin and Parshall, 2006). Community or allotment gardens, backyard greening and other types of low vegetation, as well as lakes, ponds, rivers and streams, can also provide local cooling benefits to nearby residents (Gunawardena, Wells and Kershaw, 2017; Larondelle et al., 2014; Santamouris, 2020).

Urban climate models show that increased vegetation cover results in reducing both mean air temperatures and extreme temperatures during heatwaves (Heaviside, Cai and Vardoulakis, 2015; Ferreira and Duarte, 2019; Schubert and Grossman-Clarke, 2013). Greater density and more canopy coverage relative to other built and paved surfaces increases shade provision and evapotranspiration (Hamstead et al., 2016; Grilo et al., 2020; Herath, Halwatura and Jayasinghe, 2018; Knight et al., 2021). However, local cooling by vegetation depends on regional climate context, geographic setting of the city, urban form, the density and placement of the trees, in addition to a variety of other ecological, technical, and social factors, such as local stewardship (Salmond et al., 2016). Green spaces less than 0.5–2.0 ha may have negligible cooling effects at regional scales, but impacts of shading can have microscale cooling benefits (Gunawardena, Wells and Kershaw, 2017; Zardo et al., 2017). Vegetation impacts on day versus night-time cooling varies (Imran et al., 2019) as does cooling potential in temperate versus tropical climates. The supply of cooler air from surrounding peri-urban and rural areas can impact cooling in the urban core suggesting that regional adaptation planning for NBS is important to maintain or extend ventilation paths from the urban fringe into the city centre (Schau-Noppel, Kossmann and Buchholz, 2020).

To maximize the adaptation benefits of NBS for regulating urban heat, it can be helpful to prioritise tree planting and other urban greening investments in areas where heat vulnerability and risk are the highest, especially communities that lack urban tree canopy or accessibility to parks to cool off during hot days or heatwaves (Ziter et al., 2019). Planting trees closely together or in partly permeable vegetated barriers along streets can improve local cooling benefits. Additionally, choosing tree species with leaves that have the greatest leaf area index or the largest leaves can improve cooling performance, as those trees have the greatest shading and evapotranspiration benefits that, in turn, provide the greatest cooling effects (Keeler et al., 2019). Drought-resistant trees, often native trees, are ideal to avoid high watering costs, though dry or water scarce areas may limit adoption of urban vegetation as an NBS strategy (Coutts et al., 2013). Native trees and permaculture can provide additional benefits for local biodiversity as shown in study in Melbourne, Australia which found that increasing vegetation from 10% to 30% increased occupancy of bats, birds, bees, beetles and bugs by up to 130% (Threlfall et al., 2017), with particularly high impact on native species.. Additionally, planting fruit or nut trees can provide co-benefits for local food production, and yet choice of species and placement is important to consider with respect to local cultural needs and norms (Adegun, 2018; Adegun, 2017).

6.3.4.2 Air Quality Regulation

NBS in cities can help regulate air quality by absorbing air pollutants (*medium evidence*, *medium agreement*). For example, planting trees or vegetated barriers along streets or in urban forests can reduce particulate matter, the ambient air pollutant with the largest global health burden (Janhäll, 2015; Tiwary, Reff and Colls, 2008; Matos et al., 2019; McDonald et al., 2016). However, findings show that trees can also positively affect ground-level ozone (Calfapietra et al., 2013; Kroeger et al., 2014), airborne pollen concentrations (Willis and Petrokofsky, 2017) and indirectly affect air quality through reduced emissions from energy production offset by shade provision (Keeler et al., 2019). Certain tree species however can also be detrimental to urban ozone formation by emitting significant amounts of reactive biogenic volatile organic compounds (VOCs). Decreasing urban emissions of VOCs is an increasingly important ozone mitigation strategy in urban areas (Fitzky et al., 2019).

Trees can also have negative effects by increasing pedestrian exposure to pollution if they are introduced in heavily travelled street canyons where air pollutants can be trapped (Vos et al., 2013; Gromke and Blocken, 2015). To maximise the adaptation benefits of NBS for improving air quality, planners and managers can target tree selection for species with low VOC emissions, low allergen emissions and high pollutant deposition potential (Keeler et al., 2019), and combine with low pollution transportation policies. Studies suggest sensitive planting of roadside tree canopies can have positive effects on air pollutants (Beckett, Freer Smith and Taylor, 2000; Yang, Chang and Yan, 2015). For example, Xue et al. (2021) found that the PM2.5 reduction between 2013 and 2017 in China was associated with a saving of approximately USD 111 billion yr^{-1} nationally. Tree planting near schools, nursing homes and hospitals can ensure that benefits provided by trees are delivered to the local populations that stand to benefit the most from improved air quality, but species need to be adapted to regional climate to provide benefits over time (Donovan, 2017; Nowak et al., 2018).

6.3.4.3 Stormwater Regulation and Sanitation

Urban parks and open spaces, forests, wetlands, green roofs and engineered stormwater treatment devices help manage stormwater and wastewater by reducing the volume of stormwater runoff, reducing surface flooding, and reducing contamination of runoff by pollutants (*robust evidence*, *high agreement*). Engineered devices include bioswales, rain gardens, and detention and retention ponds, and are becoming common and standard approaches to mitigate the negative effects of impervious surfaces on stormwater quality and surface flooding in cities (Zhou, 2014; McPhillips et al., 2020). Allotment gardens, street trees, green roofs and urban forests may also help reduce runoff and provide a stormwater retention service (Pennino, McDonald and Jaffe, 2016; Berland et al., 2017; Gittleman et al., 2017). Modelling and empirical studies show that NBS at small spatial scales lead to improvements in water quality and reduction of peak flows (Moore et al., 2016; Keeler et al., 2019; Webber et al., 2020). Peak flow reductions are greatest for small rain events. For example, D-Ville et al. (2018) observed a 30–70% reduction in peak flow for the 1-in-30 year storm, but performance reduces for more intense rainfall or if saturated (Garofalo et al., 2016). Employing NBS to reduce flooding on roads can be an important adaptation mechanism for reducing the impact of flooding events on traffic flows (Pregnolato et al., 2016).

During periods with intense precipitation, low-lying urban parks and open space, engineered devices and wetlands can play an important role in reducing stormwater runoff volumes by providing places for water to be stored and infiltrate during heavy storms (Moore et al., 2016). However, the magnitude of the runoff reduction service will depend on the total area of green infrastructure, vegetation type and its position on the landscape. There is less evidence of the effectiveness of NBS at larger temporal and spatial scales (Pregnolato et al., 2017; Jefferson et al., 2017). The performance of NBS depends on the degree to which their extent and spatial configuration in the city are optimised to capture runoff (Fry and Maxwell, 2017). Investing in a diversity of NBS types may be important to maximise stormwater management and flood regulation, as different types of engineered NBS have different strengths and weaknesses.

Overall, NBS are attractive adaptation options for stormwater management and to reduce impacts of pluvial and fluvial flooding in cities (Rosenzweig et al., 2018a) compared, and in combination, with grey infrastructure. Cities with combined sewer infrastructure are *likely* to see benefits from NBS due to reductions in stormwater quantity and reduced sewage overflows. Cities where a large proportion of residents lack access to piped infrastructure and drink surface water may see large benefits, especially to human health, from NBS investments (Keeler et al., 2019). Where future large-scale upgrades or installation of grey infrastructure will be necessary, new and growing cities may have more opportunity to realise large net benefits from investments in NBS. Older cities, and new, rapidly urbanising areas that lack large-scale water infrastructure may see the greatest benefits from enhanced NBS, relative to cities where heavy investments infrastructure upgrades have already been made. Cities facing climate changes that include more frequent or extreme precipitation may also see large water quality benefits from investment in NBS (Keeler et al., 2019). Overall, there is increasing evidence that NBS for addressing stormwater is cost effective (Bixler et al., 2020; Kozak et al., 2020; Mguni, Herslund and Jensen, 2016), especially in cities facing a need to update current infrastructures.

6.3.4.4 Coastal Flood Protection

Coastal ecosystems including coral and oyster reefs, coastal forests including mangroves and other tree species, salt marshes and other types of wetland habitat, seagrass, dunes and barrier islands can reduce impacts of coastal flooding and storms (*robust evidence*, *high agreement*) (Zhao, Roberts and Ludy, 2014; Boutwell and Westra, 2016; Narayan et al., 2017; Yang, Kerger and Nepf, 2015; Bridges et al., 2015; World Bank, 2016) (see also Section CCP2 Cities and Settlements by the Sea). Recent literature highlights the value of nature-based approaches for coastal protection in terms of avoided damages and human well-being (Narayan et al., 2017; Silva et al., 2016a). NBS can protect coasts from flooding through reducing the wave energy by drag friction, reducing wave overtopping by eliminating vertical barriers, and absorbing floodwaters in soil (Arkema, Scyphers and Shepard, 2017; Dasgupta et al., 2019; Zhu et al., 2020). For example, coastal and marine vegetation and reefs can dissipate wave energy, attenuate wave heights and nearshore currents, decrease the extent of wave run-up on beaches, and trap sediments (Ferrario et al., 2014; Bridges et al., 2015). These effects result in lower water levels and reduce shoreline erosion, which in turn has potential to save lives and prevent expensive property damages (Narayan et al., 2017).

Researchers, practitioners and policy-makers are increasingly calling for the use of nature-based approaches to protect urban shorelines from coastal hazards (Cunniff and Schwartz, 2015; Bilkovic et al., 2017). The expectation is that coastal ecosystems can help stabilise shorelines, protect communities against storm surge and from tidal-influenced flooding, while providing other co-benefits for people and ecosystems. However, vegetation along protected coastlines with higher frequency, lower intensity coastal hazards (National Research Council, 2014) may be more effective for stabilising shorelines and reducing risk to coastal communities and properties, and benefits will depend on local hydrology of the coastal region. Narayan et al. (2017) estimate that coastal wetlands alone reduced direct flood damages by USD 625 million during Hurricane Sandy in the USA in 2012. Similarly, researchers found that villages with wider mangroves between them and the coast experienced significantly fewer deaths than villages with narrow or no mangroves during a 1999 cyclone in India (World Bank, 2016). Recently, Arkema et al. (2017) noted that the number of people, poor families, elderly and total value of residential property most exposed to hazards along the entire coast of the USA can be reduced by half if existing coastal habitats remain fully intact.

Coastal habitats also have limitations in their ability to protect coasts from extreme events. Some studies suggest reduced effectiveness of vegetation and reefs for coastal protection from large storm waves and surge (Möller et al., 2014; Guannel et al., 2016) and there is active debate in the literature about the ability of ecosystems to mitigate the impact of tsunamis (Gillis et al., 2017). Further research is needed to understand and quantify coastal protection services provided by these hybrid green-grey solutions, especially in urban areas (Bilkovic et al., 2017). Additionally, in some coastlines, water may be too deep or waves too high for some species such as mangroves to grow, thrive and provided needed NBS.

Maximising the adaptation benefits of NBS for improving coastal flood protection research requires that cities seek to restore and conserve the vegetation and reef types that are appropriate for the exposure setting and in sufficient abundance to be effective. In particular, planners and managers can use vegetation in protected bays as alternatives to hard infrastructure for shoreline stabilisation. However, the influence of ecosystems on flooding and erosion is variable and depends on a suite of social, ecological and infrastructural factors that vary within and among urban areas (Narayan et al., 2017; Ruckelshaus et al., 2016; Bridges et al., 2015). Additionally, long-term planning to restore or ensure resilience of individual species and ecosystems that may themselves be damaged or destroyed during extreme events is needed in order for urban green and blue infrastructure to continue providing NBS over the longer term.

6.3.4.5 Riverine Flood Impact Reduction

NBS reduce both the volume of floodwater and the impact of floods (*medium evidence*, *medium agreement*). NBS reduce the volume of runoff by increasing infiltration and water storage (Shuster et al., 2005; Salvadore, Bronders and Batelaan, 2015), and affect the production and impact of flood waters through reducing river energy and flow speed through physical blockage, stabilising riverbanks during flood events, creating space for floodwaters to expand and combating land subsidence (Palmer, Filoso and Fanelli, 2014; Ahilan et al., 2018). Installing NBS to increase infiltration on low slopes and high-permeability soils can reduce the impacts of potential increases in urban flooding driven by climate change, especially for small- to medium-scale flood events (lower than 20% mean annual flood) (Moftakhari et al., 2018).

Source reduction strategies include creating permeable areas such as parks and open spaces, as well as engineered devices such as raingardens, bioswales and retention ponds that help retain stormwater runoff from impervious areas. River restoration can reduce flood peak flow and provide space for floodwaters to expand. Planting and maintaining vegetation along riverbanks, often in the form of parks or river restoration, maintains structural integrity during flood events. Wetland construction and improved connectivity to floodplains also reduces flood peaks. Efforts to restore floodplains are important to create space for floodwaters and reduce exposure by moving people out of the hazard zone. Floodplain restoration also provides access to the river that has multiple benefits including recreation, access to water for domestic use and other cultural ecosystem services. A key adaptation strategy is to reduce streambank erosion (a result of high peak flow) using riparian vegetation to stabilise riverbanks during flood events.

Cities manage flood risk using different types of adaptation and regulatory mechanisms (Naturally Resilient Communities, 2017). Built flood-control infrastructure, such as levees and stream channelisation, reduces the demand for nature-based flood impact reduction. Cities facing flood risk that do not currently have extensive grey flood-mitigation infrastructure may find NBS to be an appealing, lower cost solution (Keeler et al., 2019). In cities where flood-control grey infrastructure already exists, there is less demand for NBS of flood protection, but NBS may provide important back up, especially in a changing climate that may increase flood hazards (City of Los Angeles, 2017; Elmqvist et al., 2019). Overall, city and basin-wide NBS for riverine flood impact reduction can reduce the generation of new hazards by making space for water which can reduce the potential for a false sense of security provided by traditional flood management approaches (Ruangpan et al., 2020; Turkelboom et al., 2021).

6.3.4.6 Water Provisioning and Management

The role of NBS has been increasingly recognised for improving urban water management, emphasising it's contribution for climate-adapted development and sustainable urbanisation (*robust evidence*, *high agreement*) (Wong and Brown, 2009). NBS that protect or restore the natural infiltration capacity of a watershed can increase the water supply service to various extents, improving drought protection and providing resilient water supply (Drosou et al., 2019; Krauze and Wagner, 2019), although different forms of NBS (e.g., street trees, parks and open space, community gardens, and engineered devices such as rain gardens, bioswales or retention ponds) contribute in different ways to increasing stormwater infiltration. Additional sources of water may be available to replace the water supplied by NBS, such as rainwater harvesting, inter-basin transfers or desalination plants. Reliance on naturally sourced, locally available surface water and groundwater is more energy efficient and economical than desalination or water reuse for potable use (Boelee et al., 2017), while rainwater harvesting is even more economical. Increasing the amount of green space in urban areas can secure and regulate water supplies, improving water security (Liu and Jensen, 2018; Bichai and Cabrera Flamini, 2018). However, Bhaskar et al. (2016) reviewed the effect of urbanisation and NBS on baseflow and suggest that the confounded effects of infiltration and evapotranspiration losses, combined with the subsurface infrastructure (sewer systems) and geology, makes it difficult to predict the magnitude of baseflow enhancement resulting from the implementation of NBS in cities.

To maximise the adaptation benefits of NBS for urban water supply research suggests that managers and planners consider NBS as alternatives to traditional stormwater management techniques, where possible, since these solutions can promote groundwater recharge. As green infrastructure is increasingly being used for stormwater absorption in cities (McPhillips et al., 2020), rain gardens, wetlands, or engineered infiltration ponds and bioswales are the NBS most likely to promote recharge, reduce evapotranspiration and contribute to water provisioning.

6.3.4.7 Food Production and Security

Urban agriculture can serve as a NBS for food security (*medium evidence*, *medium agreement*) across a range of urban contexts (Lwasa and Dubbeling, 2015; Nogeire-McRae et al., 2018; Pourias, Aubry and Duchemin, 2016) by contributing to food provisioning as well as providing co-benefits including for recreation, place making and mental health (Petrovic et al., 2019; Soga, Gaston and Yamaura, 2017; Goldstein et al., 2016b).

Urban agriculture among poorer communities in lower income areas is already an important source of food supply for those communities, contributing to food security and health (Orsini et al., 2013). However, potential for expanding open air urban food production may be practically constrained by land availability (Badami and Ramankutty, 2015; Martellozzo et al., 2014). This is particularly true in some lower-income countries where rapid urbanisation is occurring, which compounds existing food insecurity (Satterthwaite, McGranahan and Tacoli, 2010; Vermeiren et al., 2013). Land availability and suitability for gardens can be further constrained by land use history, including past industrial uses that can contaminate soils with pollutants such as lead.

At the same time, investments in vertical agriculture continue to expand, such as in Singapore where private investment in food production is occurring in high rise buildings (Wong, Wood and Paturi, 2020). Not all cities can benefit similarly from vertical agriculture since higher heating costs to produce vegetables indoors during northern winters consumes considerable amounts of energy and may generate fossil fuel emissions depending on the energy source (Goldstein et al., 2016a; Mohareb et al., 2017). Some regions can benefit from more traditional outdoor urban farming, such as in South and Southeast Asia, which can support multiple growing cycles per year for some crops, particularly in tropical areas where irrigation is available. Light availability, soil health and water availability will impact food production in urban areas. For example, a study conducted in Vancouver, Canada, demonstrated that light attenuation from buildings and trees can reduce both crop yield and water demand for crop growth (Johnson et al., 2015).

Climate change may have important impacts on urban food production and food security. While urban agriculture may provide benefits in terms of stability of food access in low-income households in some regions of the Global South where the climate is warmer, the shorter growing seasons in colder climates will reduce the role of outdoor urban agriculture in year-round food supply and diets. Though urban agriculture constitutes a small fraction of total food consumption in some urban areas, several studies have attempted to estimate the extent to which urban agriculture could theoretically meet urban total food or vegetable demand (Badami and Ramankutty, 2015;

McClintock, 2014; Hara et al., 2018). Maximising the adaptation and resilience benefits of NBS for food production and security suggests the need to embrace the multi-functionality of urban agriculture, rather than viewing it as solely concerning food production (Barthel, Parker and Ernstson, 2015).

6.3.5 Adaptation Through Grey/Physical Infrastructure

Globally, it is estimated that as much as USD 94 trillion of investment is required between 2016 and 2040 to replace, upgrade and extend the world's physical infrastructure (Oxford Economics, 2017), much of which is ageing and will require replacement. Given the typical lifespan of infrastructure, this is both an opportunity and an imperative to ensure this investment is low carbon and resilient to climate change risks (Grafakos et al., 2020). 'Grey' or physical infrastructure is a priority for adaptation because its performance is sensitive to climate (particularly extreme events) and decisions on design and renovation have long-lasting implications and are hard to reverse (Ürge-Vorsatz et al., 2018). Avoiding longer-term impacts on society, the economy and the environment will require future investment and retrofitting of existing infrastructure, to be undertaken in the context of the risks of climate change (Dawson et al., 2018; Rosenzweig et al., 2018b). However, evidence from Africa shows that the benefits of pro-active adaptation measures and policies for infrastructure can result in net savings depending on the country context (Section 9.8.5).

Engineered measures for hazard mitigation such as seawalls, slope revetments and river levees, as well as air conditioning are increasingly implemented in urban centres, but many engineering interventions are less affordable and accessible in LMICs because of high construction and maintenance costs. These adaptive measures can also counter mitigation objectives because of reliance on climate-polluting energy sources. Despite this, engineering measures such as seawalls for tsunami protection and cooling areas in cities provide critical hazard reduction functions in urban contexts (Depietri and McPhearson, 2017). As Pelling et al. (2018) highlight, sustainable risk reduction can be better achieved where these engineering measures include the at-risk poor majority and inclusive planning to support pro-poor risk reduction. Inclusive design and management of physical infrastructure can enhance contributions to climate resilient development (Table 6.6 and Supplementary Material). This section covers urban morphology and built form, building design, information and communication technology, energy, transport, water and sanitation, and coastal management. All these domains of physical infrastructure will require adaptation to cope with a changing climate; many of them can also contribute to broader adaptation for cities and settlements.

6.3.5.1 Urban Morphology and Built Form

Urban morphology describes the overall status of cities as physical, environmental and cultural entities. Cities interact with surrounding environmental processes, for example, as documented in Section 6.2 by influencing urban temperature, but also precipitation and through coastal and riverine development fluvial and coastal sedimentary regimes of erosion and deposition that impact on flood risk. Rapid, increased urbanisation has contributed to observed flood risks in recent decades (see Section 5 4.2.4; Tramblay et al., 2019). The design process for physical infrastructure projects and significant construction (e.g., residential or industrial estates and large industrial development) typically includes risk assessments and social and environmental impact assessments that consider neighbouring land uses and connected infrastructure. Land use planning can consider diverse land uses and their interactions at the neighbourhood level (Section 6.3.2.1). Resilience planning aims to bring together integrated, systemic views and enable joined-up planning at the city level (as well as lower scales) (Section 6.3.2.1). There is however a lack of long-term studies that assess the climate change impacts on urban form, including informal settlements (Bai et al., 2018; Ramyar, Zarghami and Bryant, 2019), leading to impact assessments that often overlook urban form (Ramyar, Zarghami and Bryant, 2019). Additionally, context-specific spatial tools and community based approaches lack a precise connection to urban morphology. For example, there is a need for further studies that connect solar radiation, urban morphology (e.g., aspect and plot ratio), and the urban heat island spatio-temporal variability (Giridharan and Emmanuel, 2018; Li et al., 2019c).

Several tools and models have emerged in response to recommendations from AR5, including models that assess the impacts of urban heat island (Ramyar, Zarghami and Bryant, 2019), climatic uncertainty (Dhar and Khirfan, 2017), flood vulnerability (Abebe, Kabir and Tesfamariam, 2018) and inundation (Barau et al., 2015; Ford et al., 2019). For example, findings from Kano, Nigeria, reveal that a lack of distribution of certain urban morphological features, including open spaces and streets (both pervious and impervious), roof and building materials (e.g., concrete and metallic) and urban ecological features (e.g., urban ponds and ecological basin), exacerbates inundations and their associated impacts (Barau et al., 2015). Also, findings about the urban forms of coastal settlements, particularly in small islands, reveal that they often experience severe beach erosion due to wave action, sea level rise and storm surge that leads to landward retreat of coastline which threatens their social and economic activities (Dhar and Khirfan, 2016; Lane et al., 2015; Khirfan and El-Shayeb, 2019). Despite these examples, very limited research is available to offer assessments of different urban scale morphologies and urban scale adaptation planning, including planning adaptation across supply chains and networked relationships with distant urban and rural places connected through trade and resource (financial, human and material) or waste flows.

Interventions in the morphology and built form of cities can contribute to the reduction of the urban heat island effect and reduce the consequences of urban heatwaves. These can include installing air conditioning, establishing public cooling centres (i.e., for use during heatwaves), pavement watering (Parison et al., 2020a) and increasing surface albedo through 'cool roofs' (i.e., with high-reflectance materials) and walls. Air conditioning can significantly increase the local urban heat island (Salamanca et al., 2014; Wang et al., 2019a) and the choice of refrigerant has a significant impact on global warming potential (McLinden et al., 2017). The relative efficiency of cool roofs compared with green roofs is variable, because while white roofs have similar potential to reduce the urban heat island (Li, Bou-Zeid and Oppenheimer, 2014), they can quickly turn grey due to dust and air pollution, losing their effectiveness (Gunawardena, Wells and Kershaw, 2017), although these effects are now well studied and newer performance standards should account for ageing and soiling effects on reflectivity (Paolini et al., 2014). Ageing of 'cool pavements' is more complex, which makes their long-term performance less reliable to predict (Lontorfos, Efthymiou and Santamouris, 2018). The cooling performance of green roofs is highly variable and depends on the actual water content of the green roof substrate, with dry vegetation performing poorly in terms of cooling (Parison et al., 2020b). This holds true for regular vegetation and NBS in general (Daniel, Lemonsu and Viguie, 2018). For all built environment adaptations, changes are locked-in for a long time, and are likely to be expensive so that care is needed to avoid potential negative impacts on social equity (Cabrera and Najarian, 2015; Romero-Lankao et al., 2018; Fried et al., 2020; Rode et al., 2017) and carbon-intensive construction (Bai et al., 2018; Seto et al., 2016).

6.3.5.2 Building Design and Construction

Architectural and urban design regulations at the single-building scale (building codes and guidelines) facilitate climate responsive buildings that adapt to a changing climate and have the potential to collectively change user behaviour during extreme weather events (Osman and Sevinc, 2019). They include buildings that are adaptive to ensure user comfort during extremes of hot and cold as well as to floods (e.g., building on stilts and amphibian architecture). Changes to design standards can scale quickly and widely, but retrofit of existing buildings is expensive, so care must be taken to avoid potential negative impacts on social equity (Schünemann et al., 2020; Matopoulos, Kovács and Hayes, 2014; Ajibade and McBean, 2014; Bastidas-Arteaga and Stewart, 2019). Buildings can be adapted to the negative consequences of climate change by altering their characteristics, for example increasing the insulation values (e.g., van Hooff et al., 2014; Makantasi and Mavrogianni, 2016; Fisk, 2015; Fosas et al., 2018; Barbosa, Vicente and Santos, 2015; Invidiata and Ghisi, 2016; Pérez-Andreu et al., 2018; Taylor et al., 2018; Triana, Lamberts and Sassi, 2018), adding solar shading (e.g., van Hooff et al., 2014; Makantasi and Mavrogianni, 2016; Barbosa, Vicente and Santos, 2015; Invidiata and Ghisi, 2016; Pérez-Andreu et al., 2018; Taylor et al., 2018; Triana, Lamberts and Sassi, 2018; Dodoo and Gustavsson, 2016; Osman and Sevinc, 2019), increasing natural ventilation, preferably during the night (e.g., van Hooff et al., 2014; Makantasi and Mavrogianni, 2016; Pérez-Andreu et al., 2018; Triana, Lamberts and Sassi, 2018; Dodoo and Gustavsson, 2016; Osman and Sevinc, 2019; Mulville and Stravoravdis, 2016; Cellura et al., 2017; Fosas et al., 2018; Dino and Meral Akgül, 2019), solar orientation of bedroom windows (Schuster et al., 2017), applying high-albedo materials for the building envelope (van Hooff et al., 2014; Invidiata and Ghisi, 2016; Baniassadi et al., 2018; Triana, Lamberts and Sassi, 2018), altering the thermal mass (van Hooff et al., 2014; Mulville and Stravoravdis, 2016; Din and Brotas, 2017), adding green roofs/facades to poorly insulated buildings (Geneletti and Zardo, 2016; Skelhorn, Lindley and Levermore, 2014; van Hooff et al., 2014; de Munck et al., 2018; Feitosa and Wilkinson, 2018) and for water harvesting (Sepehri et al., 2018).

In general, the most promising adaptation measures are a combination of solar shading with increased levels of insulation and ample possibilities to apply natural ventilation to cool down a building (e.g., van Hooff et al., 2014; Makantasi and Mavrogianni, 2016; Fosas et al., 2018; Barbosa, Vicente and Santos, 2015; Taylor et al., 2018; Triana, Lamberts and Sassi, 2018; Dodoo and Gustavsson, 2016). However, it must be noted that the cooling potential of natural ventilation will decrease in the future because of increasing outdoor air temperatures (Gilani and O'Brien, 2020). Increased insulation (including through green solutions) without shading and ventilation can also lead to adverse impacts through the lowering of nighttime cooling (Reder et al., 2018). Similarly, air conditioning performance also decreases with increasing outdoor temperatures, in addition to being maladaptive where use increases anthropogenic heat emissions into the urban area, and global greenhouse gas emissions if powered by carbon intensive energy systems (Wang et al., 2018c).

Passive cooling is a design-based, widely used strategy to create naturally ventilated buildings, making it an important alternative to address the urban heat island for residential and commercial buildings (Al-Obaidi, Ismail and Rahman, 2014). Generally, passive cooling is achieved by controlling the interactions between the building envelope and the natural elements. Façade fixes such as overhangs, louvres and insulated walls are effective at shading buildings from solar radiation, while complex ones such as texture walls, diode roofs and roof ponds are effective at minimising heat gains from solar radiation and ambient heat (Oropeza-Perez and Østergaard, 2018). Passive cooling is inspired also by traditional design forms, for example from Mediterranean, Islamic and Mughal architecture in the Indian sub-continent (Di Turi and Ruggiero, 2017; Izadpanahi, Farahani and Nikpey, 2021).

In addition, wind towers, solar chimneys and air vents are features that facilitate cool air circulation within buildings while dissipating heat (Bhamare, Rathod and Banerjee, 2019). These features may be arranged to address hotspots or highly frequented spaces within buildings. Similar to NBS, the effectiveness of passive cooling to ameliorate the urban heat island varies widely depending on the location of the sun, wind direction and the type of strategy used. For instance, natural ventilation strategies (e.g., wind towers, solar chimneys, etc.) have shown temperature reductions of up to 14°C (Bhamare, Rathod and Banerjee, 2019; Calautit and Hughes, 2016; Rabani et al., 2014). Shading strategies alone can reduce indoor temperatures by 3°C, while heat sinks (in which heat is directed at a medium such as water) may result in indoor temperatures up to 6°C lower than the outdoor temperature (Oropeza-Perez and Østergaard, 2018). More systemic interventions, such as altering urban form through urban planning, can mitigate the urban heat island across suburbs and cities (Lee and Levermore, 2019; Takkanon and Chantarangul, 2019; Yin et al., 2018; Liang and Keener, 2015; Emmanuel and Steemers, 2018). Experience in Kano (Nigeria) has shown that incorporating Indigenous knowledge into building design and urban planning can increase resilience to heat and flood risks (Barau et al., 2015). A review by Lemi (2019) suggests that traditional ecological knowledge can provide wider climate change adaptation benefits.

Limits on housing and building adaptation include failure of regulatory systems so that formal design standards are not followed even when legally required (Arku et al., 2016; Durst and Wegmann, 2017; Pan and Garmston, 2012; Awuah and Hammond, 2014). This can be a result of pressures from clients for cheaper structures, developers illegally cutting costs or regulators lacking capacity for enforcement. Technological innovation can also be slow to embed itself in building norms and standards. Innovation also lies outside the formal sector and can include artisanal building techniques that may have adaptive value. Examples from Latin America demonstrate how initiatives in informal settlement improvement associated with housing policy, guaranteeing access to land and decent housing, show the opportunity for overarching policies encompassing development, poverty reduction, disaster-risk reduction, climate-change adaptation and climate-change mitigation (see Section 12.5.5).

6.3.5.3 Information and Communication Technology

Information and communication technologies (ICTs) are deeply intertwined with the functioning of urban and infrastructure systems, and are at the core of the 'smart city' concept (Angelidou, 2015). ICT is more flexible than other physical infrastructure, although as other sectors are increasingly reliant on ICT, it is creating new climate-related failure mechanisms (Norman, 2018; Maki et al., 2019). ICT assets and networks in urban, national and international communications systems will need to be strengthened to enable ICT infrastructure to better cope with climate change, and to enable ICT infrastructure to support the resilience of cities, settlements and other infrastructure. The increased pervasiveness of ICT in smart cities, smart infrastructure and day-to-day living, will evidently have long-term implications for exposure to climate change risks and how cities manage those risks (Norman, 2018; Maki et al., 2019). For example, even if the ICT network is resilient to heatwaves, it is dependent on the electricity network to power it. Conversely, other networks are dependent upon ICT for control systems, for example smart grids for energy. There is limited information on how these interdependencies, and associated risks, will evolve.

Although networked like many other infrastructure systems, ICT components have some distinctive properties. They are relatively cheap, and the advent of wireless communications has enabled ICT to have the widest reach of all infrastructures. Components can be rapidly deployed or repaired, and generally ICT networks are therefore built with inherent redundancy and flexibility (Sakano et al., 2016). Components have a wide range of expected lifetimes which leads to faster cycles of innovation. There is therefore greater potential to accelerate uptake of climate resilience in this infrastructure sector, but conversely, this can increase waste and (energy intensive) resource consumption. For example, mobile phones and computers may last as little as a year, cables and switching units may be moved and upgraded to improve bandwidth every few years, poles and masts are typically designed to last several decades, whilst exchanges and other critical nodes can be in use for over half a century.

ICTs are playing an increasing role in resilience building and enabling climate change adaptation. They are enabling access to information needed for decision making, facilitating learning and coordination among stakeholders, and building social capital, as well as helping to monitor, visualise and disseminate current and future climate impacts (Eakin et al., 2015; Heeks and Ospina, 2019; Haworth et al., 2018; Imam, Hossain and Saha, 2017). Advocacy and awareness raising through ICTs, such social media applications, can influence behaviours and attitudes in support of adaptive pathways (Laspidou, 2014).

ICTs play a role in adaptive responses to both short-term shocks and long-term trends associated with climate change. Timely access to information (e.g., early warning, temperature and rainfall, agricultural advice) through ICTs (e.g., mobile devices, SMS, radio, social media) can be crucial to respond and mitigate the impact of emergencies such as floods and drought, for identifying pest and disease prevalence, and for informing livelihood options, key in adaptation pathways of vulnerable communities (Devkota and Phuyal, 2018; Panda et al., 2019).

In addition to contributing to the robustness and stability of the critical infrastructure in the event of disasters, ICTs can strengthen other attributes of resilient urban systems by enabling learning and community self-organisation, cross-scale networks and flexibility, helping vulnerable stakeholders, in particular, to adjust to change and uncertainty (Heeks and Ospina, 2015; Heeks and Ospina, 2019). Big data is being used to inform responses to humanitarian emergencies (Pham et al., 2014; Ali et al., 2016), as well as to generate new forms of citizen engagement and reporting (e.g., community-based maps of flood-prone areas) that can help to inform coping and adaptive responses (Ogie et al., 2019).

The selection and use of ICTs for adaptation needs to be fairly grounded in the broader socio-cultural, economic, political and institutional context, to ensure that these tools effectively help address existing, emerging and future adaptive needs. Typically, ICT is inadequate on its own to make a significant difference (Toya and Skidmore, 2015). The role of ICTs in adaptive pathways is influenced by the availability of locally relevant information (e.g., weather-based advisory messages, local market prices), the accessibility of information by all members of the community (e.g., using various text, audio and visual content, local languages, addressing gender-related exclusion, cost and digital competencies) and the applicability of information at the appropriate scale (local, regional or national), including data quality and verification (Namukombo, 2016; Haworth et al., 2018).

Information privacy and security, as well as the unintended impacts of ICTs on inequality, spread of misinformation and on widening existing gaps (e.g., due to poverty, gender and power differentials), can also constrain the contribution of ICTs to urban adaptation (Haworth et al., 2018; Coletta and Kitchin, 2017; Leszczynski, 2016) and are among the key challenges that need to be addressed in order to fully realise their potential.

6.3.5.4 Energy

A number of measures are available to adapt existing energy infrastructure to climate change. These typically involve changing engineering design codes and upgrading facilities to cope with new climatic conditions, building redundancy and robustness into systems, and preparation to ensure continued operation following extreme events. Adapting low carbon energy infrastructure improves its climate resilience whilst simultaneously delivering mitigation goals (Kemp, 2017; Feldpausch-Parker et al., 2018), benefitting all other sectors (Dawson et al., 2018; Pescaroli and Alexander, 2018; Kong, Simonovic and Zhang, 2019).

Hall et al. (2019) identified 4223 GW of global power generation at risk of flooding. If these assets were protected by 0.5 m flood protection, ~700 GW would be at risk from the 1-in-100 year flood. Many assets can be strengthened, relocated or replaced with new equipment built to higher standards. An example of this is in the UK where a total of £172 million is being invested between 2011 and 2023 to raise flood protection of substations to be resilient to the 1-in-1000 year flood (ENA, 2015). Electricity cables can be upgraded in anticipation of reduced efficiency in a warmer climate, although in many locations this may be achieved autonomously to meet growth in electricity demand (Fu et al., 2017).

Fuels, including oil, natural gas, hydrogen, biomass and CO_2 prior to sequestration are delivered and distributed by pipeline or transportation by road, rail and shipping. In addition to engineering improvements, adaptation measures also include planning and preparation for service disruption by changing transport patterns, increasing local storage capacities and identifying and prioritising protection of critical transport nodes (Wang et al., 2019b; Panahi, Ng and Pang, 2020).

Several options are available to reduce the impacts of reduced cooling water for thermoelectric power generation, increases in water temperature and lower flows for hydropower generation. These include (i) switching from freshwater to seawater (if available) or air cooling; (ii) replacing once-through cooling systems with recirculation systems; (iii) replacing fuel sources for thermoelectric power generation; (iv) increasing the efficiency of hydro and thermoelectric power plants; (v) relaxing discharge temperature rules to allow warmer water to enter rivers; (vi) installation of screens to stop algae or jellyfish blooms clogging intakes; (vii) reducing power production and managing demand; and (viii) changing reservoir operation rules (where available). Shreshta et al. (2021) show that changing reservoir operation rules can offset reduced water availability under RCP8.5 until 2050, but is insufficient by the 2080s. van Vliet et al., (2016) showed that a 10% increase in hydroelectric generation efficiency can compensate for reduced water availability in most regions. Higher efficiency thermoelectric plans offset impacts under lower climate change scenarios but are shown to be inadequate under RCP8.5 by the 2080s; whereas a switch to seawater and dry (air) cooling provides a net increase under this scenario. However, these technologies can increase costs. Increasing the temperature of water discharged from the power station can have negative environmental impacts (Thome et al., 2016; Yang et al., 2015).

Longer term systemic strategies could include a combination of increased network redundancy and decentralisation of generation locations (Fu et al., 2017), or the use of 'defensive islanding' which involves splitting the network into stable islands to isolate components susceptible to failure and subsequently trigger a cascading event (Panteli et al., 2016). Smart grids are being increasingly deployed within municipalities to provide more efficient management of supply and demand and mitigate greenhouse gas emissions, however, there is limited understanding of their performance and reliability during floods and other extreme weather events (Vasenev, Montoya and Ceccarelli, 2016; Feldpausch-Parker et al., 2018).

Adaptation and preparedness at the household level can minimise impacts during power outages, but neighbourhood-level assistance may be more appropriate to ensure support for vulnerable households and coordination of action and information (Ghanem, Mander and Gough, 2016). More generally, it is important for responder organisations to integrate energy needs in disaster preparedness and response plans. Whilst over the longer term, reducing household and industrial demand for energy supply will reduce the need for capital investments and upgrades (Fu et al., 2017).

Providing a reliable and resilient power supply is crucial to economic and social development (Fankhauser and Stern, 2016). Furthermore, there are co-benefits from the use of low carbon energy systems (Chapter 8, WGIII AR6). For example, solar-charged street lamps and household lighting gives reliable nighttime lighting, providing safety, security and resilience to disruption of network power supplies (Burgess et al., 2017). At larger scales, deploying solar power on building roofs reduces energy demand for cooling by 12% and lowers the urban heat island, and thereby has health benefits (Masson et al., 2014a). In the USA, construction of solar panels over 200 million parking spaces would generate a quarter of the country's electricity supply (Erickson and Jennings, 2017).

As presented in Table 6.3, access to energy supply varies considerably. In particular, many African countries require substantial energy infrastructure to support their economic development. The combination of smart technologies with solar and other renewable generation provides a huge opportunity (Anderson et al., 2017; Kolokotsa, 2017). However, care must be taken in rapidly developing cities, as failure to ensure energy access during urbanisation can reduce resilience (Ürge-Vorsatz et al., 2018).

6.3.5.5 Transport

A wide range of adaptation options are available for transport infrastructure and most provide a good benefit cost ratio (Doll, Klug and Enei, 2014; Forzieri et al., 2018). Options include upgrading infrastructure (which can often be achieved autonomously as part of standard repair and replacement schedules) and strengthening or relocating (critical) assets. Adaptation of road and rail networks in Australasia includes re-routing, coastal protection, improved drainage and upgrading of rails (Table 11.7.) In areas with substantial infrastructure deficits, such as much of Africa, investments in public transport and transit-oriented development are highlighted as desired mitigation-adaptation interventions within cities of South Africa, Ethiopia and Burkina Faso (Section 9.8.5.3). Adapting low carbon transport infrastructure will be crucial to ensure resilience to climate change impacts whilst simultaneously delivering mitigation goals (Shaheen, Martin and Hoffman-Stapleton, 2019; Costa et al., 2018).

Wright et al. (2012) calculated that strengthening bridges in the USA would cost USD 140–250 billion by 2090 (or several billion dollars a year), but costs are reduced by 30% if interventions are made proactively. Koks et al. (2019) calculate a benefit–cost ratio of greater than one for over 60% of the world's roads exposed to flooding. The greatest benefits from adaptation of the global road network are in LMICs where reductions in flood risk are typically between 40% and 80%. Pregnolato et al. (2017) showed that in the city of Newcastle upon Tyne (UK), two carefully targeted interventions at key locations to manage surface water flooding reduced the impacts of the 1-in-50 year event in 2050 by 32%. In permafrost regions, geo-reinforcement, foundation and piles can be strengthened (Trofimenko, Evgenev and Shashina, 2017), whilst passive cooling methods, including high-albedo surfacing, sun-sheds and heat drains can cool infrastructure (Doré, Niu and Brooks, 2016).

Hanson and Nicholls (2020) calculate the total global investment costs for port adaptation to sea level rise and provision of new areas at USD 223–768 billion by 2050. However, adaptation of existing ports is only 6% of this. Yesudian and Dawson (2021) estimate the cost of maintaining present levels of flood risk in 2100 for the global air network will cost up to USD 57 billion (Monioudi et al., 2018; Esteban et al., 2020b).

New technologies and design innovations can improve the resilience of cars, trains, boats and other vehicles to cope with more extreme weather. Mobility transitions have the potential to improve mobility and accessibility, to influence urban form and to reduce vehicular use (and thereby infrastructure degradation), vehicle miles travelled and vehicle-based emissions (Sperling, Pike and Chase, 2018). For example, use of electric vehicles, hydrogen vehicles and greater uptake of public transport and other vehicles that reduce exhaust head emissions reduces the urban heat island (Kolbe, 2019). Carsharing can reduce carbon emissions by over 50% (Shaheen, Martin and Hoffman-Stapleton, 2019). Ride hailing, matching non-professional drivers of private vehicles with paying passengers, positively impacts low-income, low-car ownership households in Los Angeles (Brown, 2018), and fills market gaps in cities where public transit infrastructure is inadequate, unreliable or unsafe (Suatmadi, Creutzig and Otto, 2019; Vanderschuren and Baufeldt, 2018), but can also create a precarious and insecure job market that impacts well-being (Fleming, 2017). Whether the resulting impacts are positive or negative, largely depends on local, national and international policy and practices.

Safe and convenient walking and cycling (and public transport) infrastructure in cities reduces carbon emissions and urban heat island intensity, but also improve cardiovascular capacity which reduces heat stress (Schuster et al., 2017). In some regions, warmer weather may bring opportunities for increased uptake of cycling and walking, though precipitation or thermal discomfort caused by high temperature and humidity can reduce the use of active travel modes for commuting and recreation (Chapman, 2015). Shaded pavements and lanes, and measures to mitigate the urban heat island can reduce risks to disruption of active travel thereby also enhancing mitigation (Wong et al., 2017).

Full system re-design may enable the greatest resilience but it does not usually have a good benefit–cost ratio (Doll, Klug and Enei, 2014). Moreover, Caparros-Midwood et al. (2019) show that transport infrastructure planners will not always be able to resolve trade-offs between managing climate risks and mitigating greenhouse gases without tackling other sectors. However, infrastructure planners should continually seek opportunities for positive infrastructure lock in where available (Ürge-Vorsatz et al., 2018).

6.3.5.6 Water and Sanitation

Adaptation to water scarcity can be through measures to increase supply (e.g., water storage, rainwater harvesting, desalination, river basin transfers, increased abstraction, reduced pollution of water sources), or manage demand (e.g., reduce leakage lower consumption, use of water efficiency devices, greywater reuse, behaviour change). A combination of these measures is usually required (e.g., Ives, Simpson and Hall, 2018; Dirwai et al., 2021; Wang et al., 2018a). Reliable and well-adapted water and sanitation services support economic growth, public health, reduce marginalisation and poverty, and can lower energy use and improve water quality (Campos and Darch, 2015; Miller and Hutchins, 2017; Jeppesen et al., 2015; Hamiche, Stambouli and Flazi, 2016).

Globally, water sector adaptation costs are estimated to be USD 20 billion yr^{-1} by 2050 (Fletcher, Lickley and Strzepek, 2019). Globally, the budget required by 2030 for water infrastructure (new and refurbishment) is more than half of the budget required for all infrastructure (Koop and van Leeuwen, 2017). For OECD countries, water adaptation increases costs by 2%, but this proportion is far higher for developing nations (Olmstead, 2014).

A number of adaptation actions are available to reduce the impacts of floods on water and sanitation infrastructure. Active management reduces blockages in water infrastructure and protects related services such as roads and culverts which are essential to ensure the operation of onsite sanitation infrastructure (Capone et al., 2020). The impact of floods for onsite or sewerage systems can be lowered by reducing or eliminating excreta from the environment through regular maintenance, cleaning and clearing of blockages (O'Donnell and Thorne, 2020; Borges Pedro et al., 2020).

Infrastructure to protect key assets such as water and wastewater treatment plants or pumping stations has a high cost but benefits all connected households and reduces pollution from flood events. In well-regulated water sectors, there has been an increasing focus on such investments (Campos and Darch, 2015). Whereas more diffused cheaper interventions can reduce flood water ingress to domestic toilets (Irwin et al., 2018). Luh et al. (2017) found that protected dug wells were one of the least resilient technologies, whereas piped, treated, utility managed surface water systems had higher resilience.

Protecting water sources from pollution is even more important in a warmer climate that increases the frequency of algal blooms. Individual assets such as water intake pipes can be protected using screens (Kim et al., 2020a), whereas basin-scale land management is required to reduce nutrient load from runoff (Me et al., 2018), whilst injecting water or installing barriers can protect coastal aquifers from salinisation (Siegel, 2020).

More radical structural interventions may be needed in the longer term, but would need to be planned and delivered in coordination with investments in other sectors, particularly housing (Lüthi, Willetts and Hoffmann, 2020). As an interim measure, sanitation services with a lower reliance on fixed infrastructure, or container-based sanitation could be appropriate in many urban areas that are badly affected by flooding (Mills et al., 2020).

Other actions include use of adaptive planning (Evans, Rowell and Semazzi, 2020), integration of measures of climate resilience into water safety plans (Prats et al., 2017), as well as improved accounting and management of water resources (Lasage et al., 2015). Policy prescriptions on technologies for service delivery and changes in management models offer potential to reduce risks, particularly in low-income settings (Howard et al., 2016). Where formal sewerage provision is lacking, community based adaptation that incorporates both the function of the sanitation system and the vulnerability of users (e.g., women, children, elderly, ill or disabled) into the design is essential (Duncker, 2019).

6.3.5.7 Flood Management

Cities are deploying a broad range of strategies to adapt infrastructure to flooding, with hard engineering approaches (e.g., dikes and seawalls) increasingly complementing soft approaches, including planning and use of nature-based solutions, that emphasise natural and social capital (Jongman, 2018; Sovacool, 2011). The infrastructure can alter downstream risks and lead to increased residual risk by encouraging more floodplain construction (Miller, Gabe and Sklarz, 2019; Ludy and Kondolf, 2012). Physical infrastructure is highly cost effective for large settlements, but not always for small settlements (Tiggeloven et al., 2020) and can be inaccessible to poorer communities (Sayers, Penning-Rowsell and Horritt, 2018; Van Bavel, Curtis and Soens, 2018). It is often inflexible once installed but new designs and adaptive pathways are emerging (Anvarifar et al., 2016; Kapetas and Fenner, 2020).

As urban areas have expanded, so too have the number of vulnerable assets, and efforts may now emphasise reducing construction in high-risk regions (Paprotny et al., 2018a). The National Flood and Coastal Erosion Risk Management Strategy for England, for example, calls for reductions in inappropriate developments in floodplains (Kuklicke and Demeritt, 2016; UK Environment Agency, 2020). Because climate change increases the flood risk profile of certain regions, reconsideration of design criteria has become more common (Ayyub, 2018). New York City now requires the sewer system currently designed for hydraulic capacity in 5-year design life should be designed for 50-year design life, taking into account climate changes over that period (NYC, 2019).

Adaptation strategies are diverse and often involve hybrid physical and NBS, and increasingly integrated management plans that consider both flood prevention and designing infrastructure and supporting people to cope with floods when they occur. Adaptation typically focuses on (i) increasing the standard of protection to compensate for the increased magnitude of extreme events; (ii) increased maintenance to cope with increased frequency of extremes and changes in ambient conditions; (iii) changed maintenance regimes from narrower maintenance windows, for example as assets are used more frequently (Sayers, Walsh and Dawson, 2015); (iv) land use planning and management to reduce exposure and manage hydrological flows; and (v) raising awareness, preparedness and incident management. In high population areas, hard interventions such as dikes and levees are generally cost effective (Jongman, 2018; Ward et al., 2017).

Prevention or attenuation solutions include: rooftop detention, reservoirs, bioretention, permeable paving, infiltration techniques, open drainage, floating structures, wet-proofing, raised structures, coastal defences, barriers and levees, and have been deployed in diverse configurations and environments around the world (Matos Silva and Costa, 2016). Barcelona (Spain) reached 90% impermeable surface cover by the 1980s, and has recently begun implementing artificial detention, underground reservoirs and permeable pavement technologies (Favaro and Chelleri, 2018; Matos Silva and Costa, 2016). Florida Power and Light (USA), which provides service to approximately 10 million people, is investing USD 3 billion in flood protection and the hardening of assets (for example, upgrading wooden poles to steel and concrete) (Brody, Rogers and Siccardo, 2019). The City of Seattle recommends increasing preventative maintenance activities, the regular review of appropriate pavement technologies and modifications to subgrades and drainage facilities for high-risk areas (City of Seattle, 2017), whilst also providing benefits to transport disruption (Arrighi et al., 2019). Adaptation in African cities is often dominated by informal responses (Owusu-Daaku and Diko, 2018). In the absence of centralised responses, low-income residents in Nairobi (Kenya) dig trenches and construct temporary dikes to protect homes, and in Accra (Ghana) the community has developed a range of social responses, including communal drains and local evacuation teams, to help protect people and critical valuables, although these innovations require connection to city-wide infrastructure to effectively reduce widespread risk (Amoako, 2018).

More recent developments include sensor arrays to catalogue a river's reach and how changing hydraulics interact with roadways (Forbes et al., 2019). Kuala Lumpur's (Malaysia) stormwater management and road tunnel (SMART) during extreme rain events transitions the motorway to a stormwater conduit, an example of multifunctionality enabling agility (Isah, 2016; Markolf et al., 2019). Smart stormwater control systems are starting to use real-time control to dynamically manage the retention and movement of water during storms, though uptake at large scales which provide the greatest improvements in performance have been limited (Xu et al., 2020b).

In contrast to a 'fail-safe' approach to design which emphasises strengthening infrastructure against more intense environmental conditions, 'safe-to-fail' flood strategies allow infrastructure to fail in its ability to carry out its primary function but control the consequences of the failure. Examples include the use of a bioretention basin in Scottsdale (Arizona, USA) to accommodate excess runoff and help drain the city; a subsidy for affected farmers for lost crop production as part of the Netherlands' Room for the River programme; targeted destruction of a levee to control flooding in the Mississippi River Valley in 2011 (Kim et al., 2019). Water-sensitive urban design, low-impact development, sponge cities, sustainable urban drainage and natural flood management involve deployment of systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater to protect water quality and associated aquatic habitat. These are being designed and implemented at increasingly ambitious scales. For example, China's Sponge City initiative sets a goal of 80% of urban land able to absorb or reuse 70% of stormwater through underground storage tanks and tunnels, and use of pervious pavements, in addition to NBS (Chan et al., 2018; Muggah, 2019). Similarly, several thousand water-sensitive urban design interventions have been implemented across the city of Melbourne (Kuller et al., 2018).

6.3.5.8 Coastal Management

Physical coastal management infrastructure has significant benefits in reducing flood and erosion losses and damage from storms. Physical infrastructure includes seawalls, dikes, breakwaters, revetments, groynes and tidal barriers. Adapted infrastructure can alter risks in morphologically connected areas, and lead to increased residual risk by encouraging more construction in the coastal zone (Miller, Gabe and Sklarz, 2019; Ludy and Kondolf, 2012). The infrastructure is highly cost effective for large settlements, but not always for small settlements (Tiggeloven et al., 2020) and can be inaccessible to poorer communities (Fletcher et al., 2016; Pelling and Garschagen, 2019).

Anticipated costs for this vary widely. For example, Hinkel et al. (2014) calculate that adaptation costs to maintain current global levels of coastal flood protection would be 1.2–9.3% of gross world product but protect assets in human settlements of USD 21–210 billion; Tiggeloven et al. (2020) calculate the cost of adaptation to be USD 176 billion (although this would provide a benefit–cost ratio of 106 under RCP8.5); while Nicholls et al. (2019) estimate that global coastal protection would cost substantially more, up to USD 18.3 trillion between 2015 and 2100 for RCP8.5 (this includes ranges of unit costs and maintenance costs which have often been ignored).

Coastal protection infrastructure such as dikes and sluice gates can inhibit salinity intrusion through careful management of water levels, this can provide co-benefits for flood risk reduction and agricultural productivity, but can also have negative impacts on ecosystems (Renaud et al., 2015). Managed aquifer recharge can be effective if the objective is to secure freshwater drinking supply (Hossain, Ludwig and Leemans, 2018).

Physical infrastructure can provide substantial benefits, be constructed quickly and has enabled coastal cities and settlements around the world to flourish and grow. Multifunctional physical infrastructure can also provide economic and social co-benefits. These include integration of transport, recreation, agriculture (e.g., cattle pasture), founding for wind turbines, housing, office or industry into the coastal management infrastructure (Anvarifar et al., 2017; Kothuis and Kok, 2017). However, physical infrastructures can also disrupt natural processes, often leading to undesirable impacts such as pollution, degradation of ecosystems and displacement of erosion and flood risk to other locations (Wang et al., 2018b; Dawson, 2015; Nicholls, Dawson and Day, 2015). Coastal management strategies that take a hybrid approach, integrating physical and natural infrastructure, provide the best opportunities for managing risk and achieving wider socioeconomic and environmental benefits (Depietri and McPhearson, 2017; Morris et al., 2018; Schoonees et al., 2019; Powell et al., 2019).

6.3.6 Cross-Cutting Themes

This section builds on 6.3.4 to offer two entry points for assessing urban adaptation that extend beyond individual infrastructure types and that demonstrate the interdependent and dynamic natures of urban systems.

6.3.6.1 Equity and Justice

Questions of equity and justice influence adaptation pathways for cities, settlements and infrastructure (see also Chapter 8). Although infrastructure, ranging from social to ecological and physical to digital, can help to reduce the impacts of climate change (Stewart and Deng, 2014; Baró Porras et al., 2021), there is *limited evidence* of how infrastructures, implemented to reduce climate risk, also reduce inequality. Rather, there is more evidence to suggest that both adaptation plans and associated infrastructure implementation pathways are increasing inequality in cities and settlements (Chu, Anguelovski and Carmin, 2016; Anguelovski et al., 2016; Romero-Lankao and Gnatz, 2019). Social, economic and cultural structures that marginalise people by race, class, ethnicity and gender all contribute in complex ways to climate injustices and need to be urgently addressed for adaptation options to shift to benefit those most vulnerable, rather than mainly benefitting the already privileged and maintaining the status quo (Thomas et al., 2019; Porter et al., 2020; Ranganathan and Bratman, 2019). Innovation and imagination are needed in adaptation responses to ensure that cities and settlements shift from perpetuating structural domination and inequality to fairer cities (Porter et al., 2020; Henrique and Tschakert, 2019; Parnell, 2016b). To support these possibilities, this section explores adaptation through the lens of distributive and procedural justice. Although not expanded on here, spatial and recognition injustices are equally important (Fisher, 2015; Chu and Michael, 2018; Campello Torres et al., 2020). Recognition can be supported through a capabilities approach that helps to bring attention to past cultural domination and enable citizens to develop the functioning life they choose (Schlosberg, Collins and Niemeyer, 2017). This brings a focus on local action, emphasising the relevance to vulnerability reduction and resilience building of individual and local/community capacities and supporting structures. This blurs the distinction between climate change adaptation and community development, with the former firmly embedded in the latter. Struggles for recognition are deeply political and central to adaptation responses which requires increased focus on power to support more equitable and just adaptation (Nightingale, 2017). Justice questions are not static, Box 6.4 overviews the implications of COVID-19 for urban justice and vulnerability.

Distributive justice calls attention to unequal access to urban services, land, capital and technology. Related to this, exposure to health, flooding and drought risks of people living in low-income and informal settlements is a growing concern, as is disaster preparedness and the ability to support the needs of vulnerable groups such as the elderly, children and disabled, where data is often lacking (Lilford et al., 2016; Castro et al., 2017). There are also differences in who benefits from infrastructures, as they are inherently political, embedded in social contexts, politics and cultural norms (McFarlane and Silver, 2017) and often tend to benefit those already privileged (Henrique and Tschakert,

Box 6.4 | Adapting to Concurrent Risk: COVID-19 and Urban Climate Change

COVID-19 impacts have highlighted the depth and unevenness of systemic social vulnerability and the compounding characteristics of contemporary development models, with direct relevance to climate change risk accumulation and its reduction (Patel et al., 2020b; Manzanedo and Manning, 2020; Bahadur and Dodman, 2020). This is plain at the global level: of the estimated 119–124 million additional people induced into poverty by COVID-19 in 2020, South Asia and sub-Saharan Africa each contribute two-fifths (Lakner et al., 2021). These are rapidly urbanising and highly climate-hazard-exposed world regions, indicating COVID-19 impacts may further concentrate risk in these regions. Within cities, COVID-19 and climate change risk and loss is concurrent by gender, race and income or livelihood, for example, when vulnerable elderly populations are simultaneously exposed to COVID-19 and heatwave risk. Globally, in 2020, about 431.7 million vulnerable people were exposed to extreme heat during the COVID-19 pandemic, including about 75.5 million during the July and August 2020 European heatwave, with an excess mortality of over 9000 people arising from heat exposure (Walton and van Aalst, 2020).

The pandemic has demonstrated the multiple, often reinforcing, ways in which specific drivers of vulnerability interact both in generating urban risk and shaping who is more or less able to recover (Phillips et al., 2020; Honey-Rosés et al., 2020) (see Section 6.2). Again, this is not a new lesson for urban climate change adaptation, but it is a lesson that has not yet been seen to enter into routine practice for urban adaptation. Two key challenges for climate change adaptation are the associations between COVID-19 risk and urban connectivity and overcrowding. Connectivity has been presented in urban adaptation policy as a virtue, a means to share risk and diversity inputs (Ge et al., 2019; Kim and Bostwick, 2020), COVID-19 has surfaced the unevenness with which people and places are connected and also the need to balance connectivity against risk transfer, through the failure of food supply chains or remittance flows, as well as by the direct transfer of disease (Challinor et al., 2018). High-density living has advantages for urban resource efficiency including benefiting climate change mitigation. When high-density living is not supported by adequate access to critical infrastructure (sufficient internal living space, access to potable water and sanitation, access to open green space), this exacerbates overcrowding and generates vulnerability to multiple risks, including climate change hazards and communicable disease (Bamweyana et al., 2020; Hamidi, Sabouri and Ewing, 2020; Peters, 2020; Satterthwaite et al., 2020). Where overcrowding coincides with precarious livelihoods, for example in informal settlements, risk is further elevated (Wilkinson, 2020). Neighbourhood associations (a benefit of high-density living) have been an important source of resilience through providing trusted information, access to food and water for washing during the pandemic and serving populations unable to access government or market provision (Pelling et al., 2021). Here local organising has not only met gaps in service provision, but opened dialogue to vision and organise for alternative development futures. These distinctly urban challenges should be read as a sub-set of wider cross-cutting lessons for recovery from COVID-19 (see Cross-Chapter Box COVID in Chapter 7).

Where responses to COVID-19 include addressing inequities in social infrastructure, this opens a considerable and potentially society-wide opportunity to reduce social vulnerability to climate change risks (see Cross-Chapter Box COVID in Chapter 7).

2019). As an example, fixing water leaks can depend as much on the politics of who is involved and whose knowledge is prioritised as on the technical aspects (Anand, 2015).

The quality and maintenance of infrastructure is often unequal across cities, benefiting some and increasing vulnerability of others. Some property is seen as dangerous and of lower value if highly exposed to risk (Wamsley et al., 2015). Similarly, areas suffering from disinvestment in infrastructure might have a high risk of flooding (Haddock and Edwards, 2013). Zoning and land use trade-offs have been seen to be unequally skewed in favour of prime real estate and economically valuable assets (e.g., protecting factories and refineries from flooding) (Anguelovski et al., 2016; Carter et al., 2015). Urban planning reforms are therefore central to building a fairer urban adaptation response (Parnell, 2016b).

Infrastructure is often not adequately implemented in low-income urban areas and not equally accessible to all (Meller et al., 2017). For example, low-income neighbourhoods often have less green space and therefore less associated cooling benefits. Even in high-income areas, there is often unequal access to services. For example, an assessment of sustainable urban mobility plans in Portugal showed that some areas have considered equity in their plans and increased access for disadvantaged users including the elderly and disabled, but in other cities this is lacking (Arsenio, Martens and Di Ciommo, 2016). Understanding who has access to what infrastructure can help to redress the drivers of social vulnerability that are central to just urban adaptation (Michael, Deshpande and Ziervogel, 2018; Shi et al., 2016).

Changing land use and increasing green spaces to reduce climate risks and attract investments and job opportunities has increased real estate values, triggered climate gentrification in some areas (Keenan, Hill and Gumber, 2018) and decreased access to affordable housing in other areas (Larsen, 2015; Carter et al., 2015). Displacement through evictions and relocations linked to land use conversion and resettlement in the name of adaptation has also increased people's vulnerability (Anguelovski et al., 2016; Henrique and Tschakert, 2019).

Understanding social and economic elites and their investment in infrastructure has implications for distributive justice, particularly when there is secession from public infrastructure services that has financial implications for viability (Romero-Lankao, Gnatz and Sperling, 2016). In the case of the 2015–17 Cape Town drought, wealthy households secured their water needs through off-grid technologies such as rainwater tanks and boreholes. Although this resulted in more water being available in the dams, it also led to less revenue being collected for municipal water and less ability to cross-subsidise water for poor households (Ziervogel, 2019b; Simpson, 2019; Bigger and Millington, 2019). More attention needs to be paid to how shifts in infrastructure are serving the interests of urban elites, often driven by the state, and failing to adequately consider the needs of the disadvantaged (Bulkeley, Castán Broto and Edwards, 2014; Ajibade, 2017; Shi et al., 2016). Equally, more risk-reducing infrastructure is needed across all urban areas (Reckien et al., 2018a).

Procedural justice, which focuses on the institutional processes by which adaptation decisions are made, brings attention to the lack of opportunity for engaging in political decision making and limited representation of diverse voices in cities and settlements, and in relation to investment in infrastructure (Coates and Nygren, 2020; Henrique and Tschakert, 2019). Even when inclusive adaptation processes are run, they seldom produce procedurally just outcomes (Malloy and Ashcraft, 2020). Understanding who is excluded and included is important (Sara, Pfeffer and Baud, 2017). One example is the increasing numbers of migrants who are confronted with lack of access to citizenship rights and housing tenure (Romero-Lankao and Norton, 2018). Often, migrants are not allowed to formally claim public provisions in health, finance and shelter (Chu and Michael, 2018). Further, migrants and their settlements are likely unrecognised in spatial or infrastructure development plans. In this context, social infrastructure, zoning and land use planning for climate adaptation has triggered inequity through omission, as some planning process have been racialised and excluded groups such as migrants and ethnic minorities (Anguelovski et al., 2016). Urban adaptation policy-making processes that explicitly integrate multiple stakeholder interests can help to balance top-down solutions (Reckien et al., 2018a).

Identifying who is least able to adapt to climate risks sufficiently is important (Thomas et al., 2019). Some people may have few opportunities to relocate away from flooded areas in the long term or to evacuate in the short term. It is also harder for many from low-income areas to rebuild after an extreme event. Lack of housing tenure and sub-standard housing has been shown to limit the ability of residents to improve and manage their landscapes and therefore it is hard for them to enhance energy efficiency (Dempsey et al., 2011). Access to information is critical for adapting to climate risk and reducing vulnerability to hazards, yet access to this information is often not equally available (Ma et al., 2014). For example, low literacy can hamper ability to respond to early warning information (Dugan et al., 2011). In other instances, racial violence has surfaced during disasters, with Black victims' lives being seen as less important than others (Anderson et al., 2020).

When looking at justice issues in urban adaptation, it is important to recognise that the adaptation of one individual or household may lead to maladaptation and negative impacts elsewhere (Holland, 2017; Limthongsakul, Nitivattananon and Arifwidodo, 2017; Atteridge and Remling, 2018). For example, the case of an area of peri-urban Bangkok experiencing localised flooding due to unregulated private sector development saw households take both individual (building flood walls around homes, digging temporary drainage swales in the carriageway) and collective action (petitioning authorities, pumping water into vacant land). These actions, to a certain extent, merely displaced the flood water to other areas, or created new problems by damaging the carriageway, creating negative impacts on other households and the wider community. However, ultimately, it was the actions of improperly regulated private sector developers driving the need for this autonomous adaptation (Limthongsakul, Nitivattananon and Arifwidodo, 2017).

One of the tensions that emerge when addressing injustice is that the global provision of modern infrastructure is increasingly seen as unfeasible. It is unfeasible, both in terms of the current high emissions associated with infrastructure (World Bank, 2017) and the centralised, high standard ideal (Lawhon, Nilsson and Silver, 2018; Coutard and Rutherford, 2015). Decentralisation is increasingly needed, which the urban poor already engage in through their use of 'informal' infrastructure technologies, given their limited access to infrastructure networks. Transformative adaptation pathways that reduce climate risk whilst reducing inequity require an approach that sees infrastructure as inherently social and political.

6.3.6.2 Mitigation and Adaptation

As analytical concepts, mitigation and adaptation have helped, over the years, to structure thinking and action around climate change. However, since AR5 there has been a growing debate about the adequacy of a neat separation between adaptation and mitigation (Castán Broto, 2017).

The delivery of climate change action has revealed numerous co-benefits between adaptation and mitigation, around diverse areas such as implementing NBS and delivering health and development benefits (Ürge-Vorsatz et al., 2014; Suckall, Stringer and Tompkins, 2015; Puppim de Oliveira and Doll, 2016; Spencer et al., 2017). There has been a strong interest in delivering development benefits alongside climate mitigation, thus benefiting the overall infrastructure base (Suckall, Stringer and Tompkins, 2015). Some of these co-benefits have also emerged in experiences of urban planning, pointing toward the dilemma of separating adaptation and mitigation in a context in which integration, rather than an analytical differentiation, was seen as being required to transcend work in silos (Aylett, 2015). Because urban planning needs to carefully consider long time scales, the neat separation between mitigation and adaptation runs counter to integrated forms of planning that can consider scales (time and space) carefully and that are aimed to deliver the sustainable city as a whole (Solecki et al., 2015; Grafakos et al., 2020).

For example, the ideas of climate resilient development and climate compatible development help planners to consider the simultaneous wins that emerge between adaptation, mitigation and development, requiring institutional building and partnerships to deliver triple win solutions (Stringer et al., 2014; Seo, Jaber and Srinivasan, 2017; Mitchell and Maxwell, 2010). While the evidence base for the actual possibility of achieving such triple wins remains scarce (Tompkins et al., 2013; Sharifi, 2020), emerging examples show important developments. For example, establishing safe and convenient walking and cycling infrastructure can lead to improvements in population health, thereby highlighting the close interaction between urban land use, infrastructure and population health (Schuster et al., 2017), while clean cooking has the potential to deliver positive health outcomes alongside improvements in air quality and emissions reductions and through reducing pressure on woodland as a fuel source for expanding urban populations (Msoffe, 2017). Furthermore, active transport infrastructure reduces air pollution and related health risks, and helps to mitigate further climate change (Schuster et al., 2017). These are supported by city networks such as the C40 Clean Air Cities Declaration and the Clean Air Coalition that complements WHO guidelines and standards, for example through the Breathe Life Campaign. In conclusion, in both urban environments and infrastructural sectors, triple wins are only realisable through broader perspectives that link climate compatible development to institutional change or the achievements of wider welfare objectives such as those enshrined in the United Nations 2030 Agenda of Development (Castán Broto et al., 2015; England et al., 2018) (*medium evidence*, *high agreement*).

The aspiration to deliver climate change action within a broader agenda of transformative change, introduced in the SREX report, received renewed attention after the publication of IPCC Special Report on Global Warming of 1.5°C, which argues for a focus on urban transformations and highlighted that informal settlements were vital for understanding the delivery of these transformations. Deep decarbonisation has emerged as a new idea that regards the development of low or zero carbon pathways as a condition for good adaptation in the long term. Decarbonisation becomes urgent in the face of growing impacts attributable to climate change (Ribera et al., 2015; Bataille et al., 2016; Wesseling et al., 2017). Urbanisation opens opportunities for deep mitigation in low-impact developments, and hence, it is imperative to understand the implications of those opportunities for climate action (Mulugetta and Broto, 2018). These gains are not limited to urban areas. The reliance on connected urban–rural systems for water, food and fuel has led to city government and urban-based businesses supporting landscape adaptations in rural hinterlands with strong potential for mitigation and rural development co-benefits. Water Funds bring downstream urban public and private finance to support upstream rural residents to make land use and agricultural management decisions to avoid damaging runoff, soil erosion and downstream sedimentation with reduction in water quality and increased flood risk. There are more than 30 Water Funds in Latin America and sub-Saharan Africa. These operate at landscape scale; the Upper Tana-Nairobi Water Fund, Kenya (Vogl et al., 2017), planned for a USD 10 million investment in Water Fund-led conservation interventions, with a projected return of USD 21.5 million in economic benefits over a 30-year timeframe (Apse and Bryant, 2015). However, these investments do not occur where communities lack funding or the institutions to direct funding from downstream beneficiaries to upstream residents (Brauman et al., 2019).

6.3.7 Climate Resilient Development Pathways

Table 6.6 represents the contribution of 21 adaptation measures identified in this chapter to 17 components of climate resilient development (CRD). CRD brings together the aims of climate adaptation, climate mitigation, sustainable development and social justice (Singh and Chudasama, 2021). This provides a first assessment of the viability of adaptation to cities, settlements and key infrastructure as a part of global transition to sustainability (see also Cross-Chapter Box FEASIB in Chapter 18).

Two overarching messages and one key consequence for planning arise from Figure 6.4. First, urban adaptation measures can offer a considerable contribution to CRD. Second, this potential is realised by adaptations that extend predominant physical infrastructure approaches to also deploy nature-based solutions and social interventions. The consequence for planning is support for comprehensive monitoring and joined-up evaluation across the multiple components of CRD, as well as between the sectors that contribute to adaptation.

Table 6.6 shows that adapting key grey/physical infrastructure (built form and design, ICT, energy, transport, water and sanitation) is fundamental to CRD. This provides resilience to a range of hazards, with benefits to livelihoods, social capital and health, and provides benefits for the adaptation of other, connected infrastructure systems. Challenges to the contributions of grey/physical infrastructure, where adaptation through nature-based solutions and social policy offer alternatives are a lack of flexibility post-deployment constraining ability to flex as climate and vulnerability change; risk transferred to other people/places, not resolved; negative ecological consequences; and *limited evidence* of targeting marginality and inequality.

The significance of a CRD lens for the evaluation of adaptation strategy can be seen in approaches to riverine and coastal flooding. This viewpoint brings physical (e.g., embankments and defenses), nature-based (e.g., mangrove stands) and social policy (livelihood and social protection) options together. The benefits of physical infrastructure interventions for strengthening existing livelihoods and protecting health, for being deployable at scale and supporting other infrastructures to adapt are recognised and set these against challenges including hazard generation and risk transfer, limited flexibility, ecological harm, carbon costs and an undermining of social inclusion and accountability. Final evaluations will be determined by individual contexts, raising the importance of comprehensive monitoring of existing urban systems adaptation interventions and their association with ongoing development processes and outcomes (see Section 6.4).

The most consistent limit for all urban systems infrastructure types is in risk transfer. Current adaptation approaches in cities, settlements and key infrastructure have a tendency to move risk from one sector or place to others. With the exception of social infrastructure, the observed contribution of adaptation to social transformation is also limited. There are consequences for equity and sustainability as the impacts of climate change increase, and implications for evaluation and planning to work across adaptation interventions and connect with social and environmental policy and practice.

Table 6.6 | Urban climate resilient development

Risk coverage				Benefits to Human			Benefits to eco-system services	Potential effectiveness				Con-tribution to GHG emission reduction	Equity benefits		Transformation towards sustainable development (human systems fundamental change + impact on wider system)		Inf. Systems	Adaption Measure
Multi-climate Hazard	Systemic vulner-ability reduction	Reduces new hazard exposure generated	Transfer risk or impact to other people or places	Social capital	Liveli-hood	Health	Eco-logical	Flexibility post de-ployment	Deploy at scale	Benefit to other inf. systems adapta-tion	Eco-nomic feasi-bility	Mitiga-tion co-benefit	Targets pov-erty and margin-ality	Inclusive and locally account-able	Social transfor-mation	Eco-logical transfor-mation		
HA-RE	HA-RE	HA-RE	HA-RE	HA-RE	HA-RE	HA-RE	HA-RE	HA-RE	HA-ME	HA-ME	HA-RE	HA-RE	MA-LE	HA-ME	HA-ME	HA-ME	Social Inf.	Land-use planning 6.3.2.1
HA-ME	HA-RE	HA-ME	HA-LE	HA-LE	HA-ME	HA-LE	LA-LE	MA-ME	HA-ME	HA-LE	MA-ME	LA-LE	HA-ME	MA-RE	MA-ME	LA-LE		Livelihoods and social protection 6.3.2.2
HA-ME	MA-ME	MA-ME	HA-ME	HA-ME	HA-ME	HA-ME	HA-ME	MA-ME	MA-ME	HA-ME	HA-ME	HA-ME	MA-ME	MA-ME	MA-ME	MA-ME		Emergency management and security 6.3.2.3
HA-RE	HA-RE	HA-ME	HA-ME	HA-ME	HA-ME	HA-RE	MA-ME	MA-ME	HA-RE	MA-ME	MA-ME	MA-ME	HA-RE	MA-ME	LA-LE	LA-LE		Health 6.3.2.4
HA-ME	MA-ME	MA-ME	MA-ME	HA-RE	HA-ME	HA-ME	HA-LE	HA-ME	MA-LE	LA-LE	LA-LE	HA-ME	MA-ME	MA-ME	HA-ME	MA-RE		Education & Comms. 6.3.2.5
HA-ME	MA-ME	MA-LE	HA-ME	MA-ME	MA-RE	HA-ME	MA-LE	MA-ME	LA-LE	MA-LE	HA-ME	MA-LE	MA-LE	HA-ME	HA-RE	HA-RE		Cultural heritage & institutions 6.3.2.6
HA-RE	LA-ME	LA-LE	LA-LE	HA-ME	HA-ME	HA-ME	HA-ME	MA-LE	HA-ME	MA-ME	HA-ME	HA-RE	MA-LE	MA-LE	LA-LE	HA-ME	Nature based solu-tions	Temp. regulation 6.3.3.1
HA-ME	MA-LE	MA-LE	LA-LE	HA-ME	MA-ME	HA-ME	MA-ME	HA-ME	MA-ME	MA-LE	MA-ME	HA-ME	LA-LE	MA-LE	LA-LE	MA-LE		Air quality regulation 6.3.3.2
HA-ME	MA-ME	MA-LE	HA-ME	MA-ME	MA-LE	HA-LE	HA-ME	MA-ME	MA-LE	HA-ME	HA-ME	HA-ME	MA-LE	MA-LE	LA-LE	MA-ME		Stormwater and sanitation 6.3.3.3
HA-ME	MA-ME	HA-LE	LA-LE	MA-LE	MA-RE	HA-LE	HA-ME	HA-LE	MA-LE	HA-ME	HA-ME	MA-ME	MA-LE	LA-LE	MA-LE	MA-ME		Coastal flood protection 6.3.3.4
HA-RE	MA-ME	MA-ME	HA-ME	HA-ME	LA-ME	HA-ME	HA-RE	MA-LE	MA-ME	MA-ME	LA-ME	HA-RE	LA-ME	MA-LE	LA-LE	MA-ME		Riverine flood impact reduction 6.3.3.5
HA-RE	MA-LE	MA-LE	MA-LE	MA-LE	MA-ME	HA-ME	HA-RE	MA-ME	HA-ME	MA-ME	HA-RE	HA-ME	LA-LE	MA-LE	HA-LE	HA-ME		Water provisioning and management 6.3.3.6
HA-ME	HA-ME	MA-LE	LA-LE	MA-ME	MA-ME	MA-ME	HA-ME	MA-ME	HA-ME	MA-ME	HA-ME	MA-ME	MA-ME	MA-LE	HA-ME	MA-ME		Food production and security 6.3.3.7
HA-RE	HA-RE	HA-RE	MA-LE	LA-LE	MA-ME	HA-RE	MA-ME	HA-RE	HA-RE	LA-LE	LA-LE	MA-ME	LA-LE	LA-LE	LA-LE	MA-ME	Grey/ Physical Inf.	Built form 6.3.4.1
HA-RE	HA-RE	HA-RE	MA-ME	LA-LE	MA-ME	HA-RE	LA-LE	HA-RE	HA-RE	MA-LE	MA-ME	MA-ME	MA-ME	MA-ME	MA-ME	MA-ME		Housing and building design 6.3.4.2
HA-RE	HA-ME	LA-LE	LA-LE	HA-RE	HA-ME	LA-LE	LA-LE	HA-RE	HA-ME	HA-RE	HA-ME	MA-ME	LA-ME	LA-ME	MA-ME	LA-LE		ICT 6.3.4.3
HA-RE	HA-ME	LA-LE	LA-LE	HA-LE	HA-RE	LA-LE	LA-LE	HA-ME	MA-ME	HA-RE	MA-ME	HA-RE	MA-ME	MA-ME	LA-LE	LA-LE		Energy Inf. 6.3.4.4
HA-RE	HA-ME	LA-LE	LA-LE	HA-LE	HA-RE	LA-LE	LA-LE	HA-ME	MA-ME	MA-ME	MA-ME	MA-LE	MA-ME	MA-ME	LA-LE	LA-LE		Transport 6.3.4.5
HA-RE	HA-LE	MA-ME	LA-ME	HA-LE	HA-RE	HA-RE	HA-RE	HA-ME	MA-ME	HA-RE	MA-ME	HA-ME	MA-RE	MA-ME	LA-LE	HA-RE		Water and sanitation 6.3.4.6
HA-RE	HA-ME	HA-ME	HA-RE	MA-ME	HA-RE	HA-RE	MA-ME	HA-ME	HA-RE	HA-RE	HA-RE	HA-LE	MA-ME	LA-ME	LA-LE	MA-LE		Flood management 6.3.4.7
HA-RE	HA-ME	HA-ME	HA-RE	MA-ME	HA-RE	HA-RE	MA-ME	HA-ME	HA-RE	HA-RE	HA-RE	HA-LE	MA-ME	LA-ME	LA-LE	MA-LE		Coastal management 6.3.4.8

Key:

Climate Resilient Development Contribution

Negative High	Negative Moderate	Negative Small	Neglible negative	Nil	Positive Neglible	Positive Small	Positive Moderate	Positive High	No data

Confidence

HA-LE *High agreement – limited evidence*	HA-ME *High agreement – medium evidence*	HA-RE *High agreement – robust evidence*	MA-LE *Medium agreement – limited evidence*	ME-ME *Medium agreement – medium evidence*	MA-RE *Medium agreement – robust evidence*	LA-LE *Low agreement – limited evidence*	LA-ME *Low agreement – medium evidence*	LA-RE *Low agreement – robust evidence*

Overall confidence: ***Medium agreement—medium evidence***. Supplementary Material provides a detailed analysis including definitions for each component of climate resilient development and for each of the 357 entries an underlying explanatory statement linked to key evidence. Analysis was by Chapter 6 Lead and Contributing Authors.

6.4 Enabling Conditions for Adaptation Action in Urban Areas, Settlements and Infrastructure

This section assesses the effectiveness of efforts to create enabling conditions for adaptation. New policy innovations such as National Urban Policies are emerging to address the multi-level governance demands of climate change (UN-Habitat, 2020; Kinyanjui, 2020). There is no one-size-fits-all approach to deliver adaptation that will fit every case, because the local conditions of implementation bear a strong influence on adaptation's feasibility and impacts (Archer et al., 2014). Ways to foster adequate enabling conditions for adaptation are well-documented (IPCC, 2018 Ch.4). These often include integrated planning, multi-agency working and multi-scale and sector action. Existing techniques can be shared and new innovations taken up (Maxwell et al., 2018).

Adaptation in urban areas and settlements can be *incremental* (when it addresses the causes of problems but without fundamentally changing the social and political structures that drive it, for example through planning or new regulations), *reformist* (when it changes the features that cause problems but without fundamentally changing the structures) or *transformative* (when it addresses fundamental systems attributes and outcomes such as reducing inequality in political and socioeconomic structures or enhancing well-being [Mendizabal et al., 2018; Rosenzweig and Solecki, 2018] which change the situation completely) (Heikkinen, Ylä-Anttila and Juhola, 2019; Roberts and Pelling, 2020; O'Brien, Selboe and Hayward, 2018). In the context of the SGDs mission to leave-no-one behind, transformative adaptation addresses fundamental systems' functions to enable enhanced social justice and socio-ecological well-being. Incremental adaptation actions seek to maintain the essence and integrity of a system or process at a given scale (see Annex II: Glossary). Adaptation that seeks only to defend existing development status will not contribute to enhanced well-being and is not transformative, even if fundamental infrastructure engineering or legislative systems are changed to maintain the status quo in the face of increasing risk (Mendizabal et al., 2018).

City populations and non-state actors, together with local and regional governments, can play an essential role in creating enabling conditions for action, including, for example, civil society mobilising concerns of marginalised voices and future generations, as indicated in the worldwide student mobilisations against climate change (Wood, 2019; Maor, Tosun and Jordan, 2017; Cloutier, Papin and Bizier, 2018; Prendergast et al., 2021), which may then be prioritised by local and regional governments. National governments also play a crucial role, for example in facilitating resources and finance for urban adaptation actions, alongside financial organisations and the business sector (see Section 6.4.5). This section starts assessing adaptation experiences in cities, settlements and infrastructures since the AR5, before reviewing evidence of how to foster enabling conditions for adaptation through institutionalisation, governance capacity, finance, evaluation and social learning.

6.4.1 Adaptation Experiences in Cities, Settlements and Infrastructures

Since AR5, there is increasing evidence that successful adaptation to climate change is context-specific and responsive to the particular needs of urban locations. This section assesses the contributions of key urban actors, local government, civil society and the local private sector, in enabling adaptation. Wider influences from national government cross cut this and are discussed with the role of international agencies, and finance which is assessed in Section 6.4.5.

The literature on the governance of adaptation has grown since the AR5, though with few cases from cities and settlements in the Middle East, North Africa, Central Asia and former USSR countries. Potential reasons for the continued lack of studies in these areas include the centralised character of decision making systems in countries in these regions and the early stage of adaptation planning in these urban areas (Clar, 2019; Mitchell and Laycock, 2019; Olazabal et al., 2019a).

Flexible institutions that allow for both top-down and bottom-up action can bring capacities together from across levels of government and actors within a settlement (Sharifi and Yamagata, 2017). Predominant planning and capacity-building strategies, however, lack the flexibility to address the needs of a rapidly changing environment (Carter et al., 2015; Dhar and Khirfan, 2017; Juhola, 2016). Efforts to adapt to new challenges may have to speed up. This is especially true in urban areas and settlements with lower levels of development and experiencing rapid urbanisation, growing inequality and exposure to multiple hazards (Dulal, 2019; Grafakos et al., 2019; Solecki et al., 2018). Even within cities that share similar characteristics, there are considerable differences in the level of investment in adaptation (Georgeson et al., 2016). There is also a danger that uncoordinated actions for climate change mitigation and adaptation may constrain future adaptation opportunities or create maladaptation (Juhola et al., 2016). The evidence emerging since the AR5 suggests that institutional change can be accelerated by closer collaboration between the diverse actors and deployment of the diverse approaches that can deliver adaptation.

6.4.1.1 Experiences of Adaptation Action in Sub-national Governments

The assessment of cases of local adaptation demonstrates that most urban adaptation is led by local governments (although the local government is also a heterogeneous category and local governance arrangements may vary across administrative and political contexts) (*high confidence*) (Amundsen et al., 2018; Lesnikowski et al., 2021). Local government reform at different levels can improve local adaptation, whether this is by strengthening specific teams or building cross-departmental linkages (*high confidence*) (Paterson et al., 2017; Shi, 2019; Wamsler and Raggers, 2018). Adaptation success often depends on having political champions driving the adaptation agenda alongside measures such as access to a knowledge base, resources at hand, political stability and the presence of dense social networks that can be supported through local government reform (Pasquini et al., 2015). Aligning adaptation objectives with other potential benefits of sustainable development also supports adaptation. Specifically, policies and plans that link adaptation to the objectives of Agenda 2030 supports action at the local level (UN-Habitat, 2016b). Showing the economic benefits of adaptation is a strategy for local institutions to gain support for adaptation action. For example, local governments in Surat, Indore and Bhubaneswar in India linked adaptation to local development needs in experiments that facilitated accessing human and finance resources, at the local, national and international levels (Chu, 2016). However, linking adaptation to co-benefits may also divide efforts and reduce the effectiveness of adaptation actions. For example, urban land use planning and management in Ambo town, Ethiopia, resulted in the implementation of urban greening projects, but these projects did not directly address the climate-related disaster risks affecting the settlement, including urban flooding, water stress, water shortages, increased urban heat, wind and dust storms (Ogato et al., 2017).

Multi-level governance measures that support local governments can foster robust adaptation approaches and address risks and vulnerabilities across scales (*high confidence*) (Westman, Broto and Huang, 2019; Hardoy et al., 2014; Romero-Lankao and Hardoy, 2015). Effective action by local government requires national government's support (*medium confidence*). For example, Araos et al. (2017) documents the case of Dhaka, Bangladesh, where a national plan prioritises measures for protecting coasts and agricultural production. In this context, the local government has minimal access to human and financial resources. Without national support, the local government struggles to coordinate action among different stakeholders. National urban adaptation directives can influence municipal governments' action and planning, but evidence suggests that national policy alone is not sufficient to deliver action on the ground without understanding local conditions (*high confidence*) (Archer et al., 2014; Lehmann et al., 2015).

There are barriers for municipal adaptation plans to deliver effective adaptation outcomes and implemented actions often diverge from plans (see Section 6.4.6). For example, a comparison of adaptation plans and budget expenditures of six metropolitan cities in South Korea between 2012 and 2016 showed that the implementation of adaptation programmes diverged substantially from the original plans, both in terms of total and sector-specific spending (Lee and Kim, 2018). Often, a focus on institutional change and reform limits attention to more practical aspects of adaptation that improve communities' resilience (Castán Broto and Westman, 2020). Adaptation actions, even where financed effectively, do not always deliver positive outcomes (*high confidence*) (Reckien et al., 2015; Woodruff and Stults, 2016; Uittenbroek, 2016; Aguiar et al., 2018; Reckien et al., 2018a; Olazabal et al., 2019b; Campello Torres et al., 2021) (see also Section 6.4.7).

6.4.1.2 The Role of Non-State Actors in Local Adaptation

There are multiple actors, other than local governments, that can deliver adaptation action, including businesses, not for profit organisations and trade unions (*high confidence*) (Giordano et al., 2020; Eakin et al., 2021). Empirical evidence since the AR5 highlights the role of communities, universities, the private sector and transnational networks in adaptation (Hunter et al., 2020; Bäckstrand et al., 2017). Non-state actors are particularly important in enabling adaptation by linking government agencies with low-income and marginalised communities, including those living in informal settlements (Kuyper, Linnér and Schroeder, 2018; Khosla and Bhardwaj, 2019).

Since AR5, civil society and private actors have emerged as core knowledge holders and drivers of experimentation, even succeeding in changing public policy in the process (Klein, Juhola and Landauer, 2017; McKnight and Linnenluecke, 2016; Mees, 2017). Previous IPCC Assessment Reports noted that civil society actors enable local risk awareness, sensitisation and adaptive capacity, and generate locally based innovation (e.g., through community based adaptation programmes).

Community based adaptation includes a range of initiatives that put communities at the centre of planning for adaptation, often led by communities themselves (Reid, 2016). Community based adaptation is a comprehensive and effective strategy to deliver resilience at a human scale (Trogal et al., 2018; Greenwalt et al., 2020). Many community based responses to climate impacts represent coping strategies developed within households with a small effect on adaptation capacities beyond incremental improvements. Residents adopt private coping strategies to reduce exposure to and the impacts of heat, floods, flash floods, landslides, storms and diseases on their lives (Hambati and Yengoh, 2018). These coping strategies include the construction of physical protection against flooding, reforestation, the construction of terraces, flood diversion measures and interventions to protect houses (such as raised doorsteps or use of sandbags and adoption of building techniques for making homes resilient to storms and landslides), ventilation of houses, urban agriculture and redefinition of daily practices and livelihoods (Navarro et al., 2020; Malabayabas and Baconguis, 2017; Apreda, 2016; de Andrade and Szlafsztein, 2020; Sahay, 2018; Bausch, Eakin and Lerner, 2018).

Individual coping strategies are generally ineffective in reducing extreme risks and they rarely address the underlying structural causes of vulnerability (*high confidence*) (Sahay, 2018; Rözer et al., 2016; Jay et al., 2021). Expending resources on private coping strategies in some cases may divert resources and capacity for wider community adaptation efforts (de Andrade and Szlafsztein, 2020). However, individual coping strategies can provide foundations for the implementation of collaborative action in communities, building on people's experiences, in ways which may have a longer-term, durable impact on developing resilience (*high confidence*) (McEwen et al., 2018). Community based adaptation can be effective at different scales, whether this is to manage transboundary issues (Limthongsakul, Nitivattananon and Arifwidodo, 2017), support the replication of local solutions (Danière et al., 2016), increase the uptake of adaptation measures (Liang et al., 2017) or inform the design of more effective policies for resilience (Berquist, Daniere and Drummond, 2015; Odemerho, 2015). Community action may be mediated by NGOs or third sector organisations who play a coordinating or enabling role, particularly where other local government mechanisms are absent.

6.4.1.3 The Role of the Private Sector in Local Adaptation

There is weak evidence of private sector involvement in urban adaptation (Pauw, 2015; Heurkens, 2016). The absence of private sector investment in adaptation is particularly visible in rapidly urbanising countries (Nagendra et al., 2018). Business continuity describing private sector preparedness notes that firms underestimate the impacts of climate risks on their business models (Goldstein et al., 2019; Forino and von Meding, 2021; Korber and McNaughton, 2017; Crick et al., 2018b). There is little research on how businesses can play a leading role in urban adaptation (Klein et al., 2018). A global assessment of the private sector's role in urban adaptation using data from 402 cities shows that most adaptation projects focus on the public sector and do not address private sector concerns or local people's participation (Klein et al., 2018). Recorded private sector action is recognised through partnerships and participation (Peterson and Hughes, 2017; Hughes and Peterson, 2018). There are a few examples of studies of private sector-led adaptation action which adopts a national focus (Crick et al., 2018a; Crick et al., 2018b). This lack of evidence contrasts with a well-developed body of literature on private sector-led mitigation (Averchenkova et al., 2016).

Businesses have an essential role in urban adaptation actions, through the collective formulation of adaptation strategies, the provision of critical adaptive interventions and collaboration in partnerships. Businesses in the property sector, such as real estate developers, are on the frontline of climate change impacts but display differing attitudes toward climate adaptation. A study of property businesses in cities in Australia (Taylor et al., 2012) showed that speeding up planning approval processes facilitated adaptation actions, and joint private–public decision-making was the preferred mode of governance for responding to climate concerns. Property businesses in cities in Sweden had a limited and reactive engagement in climate issues and resisted regulation (Storbjörk et al., 2018). Corporate, private sector interventions in urban risk reduction more broadly remain limited, with a mix of public and private responsibility for planning, implementing and maintaining adaptations in the built environment, and yet limited engagement of private sector actors in providing healthcare measures for heat prevention (*medium confidence*) (Mees, 2017).

There is little published literature documenting the heterogeneity of business and the private sector's responses to climate impacts (Linnenluecke, Birt and Griffiths, 2015; Doh, Tashman and Benischke, 2019). Firms have varying abilities to introduce climate adaptation measures related to staff availability, levels of awareness, perceptions of responsibility and duration of contracts (short-term projects implies less interest in adaptation outcomes) (Shearer et al., 2016). The impact of COVID-19 has serious but uncertain implications for both access to finances for sustainable development by LMICs and sub-national governments, and the possibility of stimulating maladaptive infrastructure and policy responses (OECD, 2020; Sovacool, Del Rio and Griffiths, 2020). The response of businesses to disasters influences the resilience in the communities in which they operate (McKnight and Linnenluecke, 2016; Linnenluecke and McKnight, 2017). However, at the same time there is a growing literature that warns against the conflict interests that businesses may have in their adaptation strategies. For example, real estate responses to flooding have led to processes of climate gentrification, whereby lower income populations are displaced toward higher risk areas which stablishes racialised and class-based patterns of inequality of exposure to risk, with hard evidence rapidly growing specially in US cities (Keenan, Hill and Gumber, 2018a; Shokry, Connolly and Anguelovski, 2020; De Koning and Filatova, 2020; Aune, Gesch and Smith, 2020). Private-sector participation in adaptation solutions depend on having mechanisms to enable transparency and open reporting on the nature of support and the solutions proposed. For example, businesses adopting 'community-centric' disaster management strategies can assist local recovery efforts by protecting employment, provision of emergency supplies and participation in reparations (McKnight and Linnenluecke, 2016). Private sector actors engaged in community climate responses can play a role in funding and managing programmes that address public health and education concerns. The potential of ecopreneurship, social enterprises, cooperatives and other sustainability-oriented business models (Schaltegger, Hansen and Lüdeke-Freund, 2016; Lopes et al., 2020; Battaglia, Gragnani and Annesi, 2020) for urban adaptation remains under-explored in the literature on urban climate governance.

The private sector also constitutes a key stakeholder group involved in collaborative processes to develop adaptation strategies. The inclusion of private sector actors in deliberative policy-making processes in urban adaptation can lead to higher procedural legitimacy levels, as witnessed in Rotterdam's case (Mees, Driessen and Runhaar, 2014). Rotterdam has created an institutional environment that favours eco-innovation (Huang-Lachmann and Lovett, 2016). The municipal government works directly with the private sector to enhance protection against flooding constructing a marketing strategy around a 'floating city' concept. A 'floating housing' market has expanded, with benefits for the local real estate and construction industries and knowledge-exporting businesses that provide consultation expertise, delta technologies and architectural models. Nevertheless, these new trends raise new governance challenges to deliver adaptation.

There are obstacles associated with reconciling private sector interests with public priorities and justice agendas in local climate programmes. The involvement of the private sector in adaptation actions may lead to the appropriation of land and natural resources, and to the exclusion of vulnerable populations (Anguelovski et al., 2016; Rumbach, 2017; Scoppetta, 2016) (see also Section 6.4.4.2). Navigating the inclusion of businesses in urban planning processes requires local authorities to engage in ongoing negotiations, to reflect on constantly shifting power balances and to move delicately between the role of regulator and facilitator in the process of defining and maintaining long-term objectives (Storbjörk, Hjerpe and Glaas, 2019b; Storbjörk, Hjerpe and Glaas, 2019a).

6.4.1.4 Partnerships for Adaptation

Multi-level governance remains an influential paradigm that recognises government institutions' influence at different scales and the diversification of actors intervening in public issues from the private sector and civil society (*robust evidence*, *high agreement*). Establishing linkages between multiple organisations can help deliver coordinated action. Multi-level governance includes mechanisms for multiple actors to engage in local adaptation strategies through collaborative processes of planning, learning, experimentation, capacity building, construction of coalitions and communication channels (Barton, 2013; Jaglin, 2013; Reed et al., 2015; Restemeyer, van den Brink and Woltjer, 2017; Melica et al., 2018). Many of these studies directly focus on institutional arrangements that facilitate interaction between communities and civil society, experts, government representatives, firms and international organisations. Box 6.5 demonstrates the decisive role that community activists can play in building resilience over long periods.

Institutional fragmentation reduces the capacity to deliver adaptation (Den Uyl and Russel, 2018) Multi-level governance shows a commitment to tackling fragmented and complex policy issues through collaboration between national governments and non-state actors, as explained in the 2030 Development Agenda, especially SDG17 ('Revitalize the global partnership for sustainable development'). Multi-level governance is particularly important to deliver adaptation at the metropolitan scale, that require coordinating actions across different institutions in inter-municipal institutions (Lundqvist, 2016). Gaps in knowledge remain regarding the effectiveness of multi-level governance actions in different contexts and the extent to which multi-level governance strategies transfer the brunt of responsibility for adaptation action to less-resourced local governments (Hale et al., 2021).

Public–private partnerships are increasingly relevant for collaborative development of urban adaptation (Klein et al., 2018). Partnerships can deliver infrastructure, coordinate policy and support learning. The main limitation of partnerships is scale, as partnership action is usually limited to discrete projects or objectives. Partnerships tend to be linked to reactive (rather than proactive) adaptation projects and the deviation of objectives away from adaptation concerns (Harman, Taylor and Lane, 2015). Partnerships can support capacity building in public and private organisations and facilitate networking efforts that extend beyond the private sector to communities and NGOs (Bauer and Steurer, 2014; Castán Broto et al., 2015). Public actors can benefit from the private sector's innovation and implementation capacity, and businesses can de-risk investments. Still, partnerships can also strengthen the ideologies of growth and managerialism within the operations of the local government (Taylor et al., 2012). Reconciling divergent norms and routines within public and private organisations remains one of the challenges to establishing successful public–private partnerships for adaptation (Lund, 2018). Administrative and political culture influences the nature of interactions between public and private sector actors in urban adaptation agendas (Bauer and Steurer, 2014), with negative consequences such as the imposition of vertical chains of commands on horizontal collaborations, and the need to formalise contractual relations (Klein and Juhola, 2018).

Local authorities are an important enabling actor that can guide the private sector and communities to take responsibility for creating policy and regulatory environments that encourage private sector participation aligned with the SDGs' equity and ecological sustainability principles (*high confidence*). For example, Frantzeskaki et al. (2014) report a port relocation project in the Netherlands where sustainability principles drove private sector participation. Klein et al. (2017) cite examples from two cities—Helsinki and Copenhagen, where local authorities have shifted adaptation responsibilities to private actors through regulation and public problem ownership. In Mombasa, private companies provide green infrastructure to match local government requirements, in what has frequently been cited as an example of NBS (Kithiia and Dowling, 2010; Kitha and Lyth, 2011).

Box 6.5 | Building Water Resilience in Urban Areas through Community Action and Activism

In Bengaluru, India, communities have traditionally managed a network of water tanks of immense ecological importance. However, in the last half-century, urban development has increasingly threatened this blue network (Unnikrishnan and Nagendra, 2015). Today's Bengaluru depends on long-distance water transfers that create political conflict and a dense network of private boreholes that are depleting the city's water resources. The restoration of the existing community managed water tanks network offers a more sustainable and socially just alternative for managing water resources.

Unnikrishnan et al. (2018) have documented how the colonial and postcolonial history of water management in Bengaluru shapes the water infrastructure and provision systems today. Water access inequalities can be traced to the patterns of spatial development developed by colonial policies. Records from the sixth century onwards show how city rulers invested in an interconnected, community managed network of tanks and open wells, regularly recharged through harvested rainwater. The water system was changed at the end of the 18th century, as first the colonial state, then the post-independence government of Karnataka took responsibility for water management. Ideas of modernist planning influenced the development of new water infrastructure and piped networks, including the first piped infrastructure, bringing water from sources 30 km away, including the Hesaraghatta and then the TG Halli reservoirs. The old network of tanks gradually deteriorated as tanks became disused, polluted or built over. More prolonged and costly water transfers took place in the post-colonial period, delivering water from the Cauvery River in a massive engineering project with a high energetic cost and enmeshed in inter-state conflicts over water use (Castán Broto and Sudhira, 2019). Scarcity is still a problem in Bengaluru. The citizen response has been an activist movement to reclaim the city's tanks, accompanied by a plea to reconsider current water uses within the city, including actions to protect and rejuvenate water wells (Nagendra, 2016). Unnikrishnan et al. (2018) document different actions led by citizen-led collectives, including projects for lake rejuvenation, filtering technologies to treat sewage, recovering the value of lakes through a share of photos and art projects, and involvement of local knowledge in-tank restoration. Those efforts suggest an untapped potential to deliver adaptive green spaces through the recovery of Bengaluru's tanks.

6.4.1.5 Trans-national Municipal Networks

Since the late 1990s, transnational municipal networks (TMNs) have increased awareness of climate change and served as a bridge for cities to access critical financial resources from private and philanthropic sources (Rashidi and Patt, 2018; Fünfgeld, 2015). Recently, TMNs have taken on more programmatic functions, working with cities to strategise, plan and incrementally improve their organisation functions in the face of climate change. For example, the Rockefeller Foundation's 100 Resilient Cities program (2014–2019) provided a two-year salary for a Chief Resilience Officer (CRO) to be situated in a municipal authority to bridge silos, incentivise change and develop development strategies for resilience (Bellinson and Chu, 2019; Spaans and Waterhout, 2017). In these cases, external actors have enabled broad organisation change, resource mobilisation pathways and alternative forms of agenda-setting in cities (Chu, 2018; Hakelberg, 2014) (see also Case Study 6.2, Semarang).

A range of TMNs also support and encourage cities and settlements to plan and implement adaptation actions. ICLEI-Local Governments for Sustainability has developed protocols and implemented projects for member cities. The C40 Climate Leadership Group has facilitated the coordination of both local governments and business actors at a global scale (Gordon, 2020). Policy coordination has been central to the signatories of the Covenant of Mayors (Domorenok et al., 2020). Such networks can encourage the sharing of information about appropriate practices between urban areas; contribute to goal setting; support experimentation and development of new policy instruments; enhance stakeholder engagement; institutionalise climate agendas; and encourage policy integration across governance levels and sectors (Bellinson and Chu, 2019; Busch, Bendlin and Fenton, 2018; Fünfgeld, 2015; Busch, 2015; Papin, 2019; Rashidi and Patt, 2018). However, participation in TMNs is biased toward cities in the Global North (Bansard, Pattberg and Widerberg, 2017; Haupt and Coppola, 2019). A recent comparative study of 337 cities found out that cities that participation in TNMs are more likely to take adaptation action and that being part of multiple networks leads to higher levels of adaptation planning (Heikkinen et al., 2020).

6.4.2 Institutional Change to Deliver Adaptation in Cities, Settlements and Infrastructure

The main barriers to urban climate adaptation, and strategies to address them, relate to institutional change (*high confidence*) (see Table 6.7). Institutions include legislative and policy frameworks and guidelines intended to direct the action of government, civil society and private sector organisations and extend into informal and customary practices that shape individual behaviour. Many of the barriers that inhibit institutions acting in ways that can support action for inclusive and sustainable adaptation have historical roots, grounded in complex political and social relations and can be reinforcing (Table 6.7). Overcoming these barriers requires coordinating the activities of multiple actors who can facilitate institutional and political change (Eisenack et al., 2014).

Institutional change is needed to open new options for inclusive and sustainable adaptation and to integrate adaptation and mitigation (*robust evidence*, *high agreement*) (see also Section 6.3.5).

Institutional change refers to processes that aim to shift existing norms and practices within organisations to deliver more effective action for adaptation. Institutional change at the local level can be achieved with diverse strategies (Patterson, de Voogt and Sapiains, 2019). Table 6.7 illustrates various instruments that enable the institutionalisation of climate adaptation concerns into policy and planning. As Table 6.7 shows, institutional change is often used as synonymous with mainstreaming. Both terms refer to the integration of climate adaptation concerns into other areas of work and as part of practical routines and arguments (Chu, Anguelovski and Carmin, 2016; Storbjörk and Uggla, 2015; Runhaar et al., 2018; Uittenbroek et al., 2014). Early assessments understood mainstreaming as activities that integrate climate adaptation into long-range and sectoral plans (Anguelovski and Carmin, 2011; Aylett, 2015). Since then, efforts to mainstream climate adaptation have grown into agendas around the community and economic development (Ayers et al., 2014), climate mitigation (Göpfert, Wamsler and Lang, 2019), spatial and infrastructure planning (Anguelovski, Chu and Carmin, 2014), urban finance (Musah-Surugu et al., 2018; Keenan, Chu and Peterson, 2019), public health (Araos et al., 2015), environmental management (Wamsler, 2015; Kabisch et al., 2016) and multi-level decision making (Ojea, 2015; Visseren-Hamakers, 2015). Such efforts require various degrees of regulatory or programmatic action to integrate adaptation with other concerns (Wamsler and Pauleit, 2016). However, institutional change has a broader remit than mainstreaming adaptation, as it may include, for example, changing the organisations already dealing with climate adaptation and make them more effective including changes in inputs, procedures and options (Patterson, de Voogt and Sapiains, 2019).

6.4.2.1 Input-Driven Institutional Change

Input-driven institutional change creates incentives to deliver adaptation action. An input view focuses on the intrinsic capacities of a given organisation. Input indicators are often referred to as political capital (Rosenzweig and Solecki, 2018; Diederichs and Roberts, 2016), existing or endogenous resources (Moloney and Fünfgeld, 2015; Wamsler and Brink, 2014), or local drivers for adaptation (Dilling et al., 2017). ReResearch conducted across two municipalities in Western Cape, South Africa, showed the importance of a dedicated environmental champion, access to a knowledge base, the availability of resources, political stability and the presence of dense social networks (Pasquini et al., 2015). Research from São Paulo, Brazil, showed how intrinsic political capacities and contextual factors, such as the political ideology of elected officials, shaped opportunities for embedding adaptation into ongoing urban agendas (Di Giulio et al., 2018).

Networks, interactions and actor coalitions shape options for institutional change. Aylett (2015) noted the importance of internal networks between municipal departments, including informal communication channels, cultivating personal contacts and trust between the person or team responsible for climate planning and staff within other local government agencies. Internal networks can facilitate the commitment of local elected officials (Hughes, 2015), support higher municipal expenditures per capita and foster perceptions that climate adaptation is needed (Shi, Chu and Debats, 2015). Collective decision-making can integrate multiple types of information with moral concerns and provide key rationales that enable adaptation action (Carlson and McCormick, 2015). In urban areas in Africa, research on internal networks has also investigated how informal arrangements shape action possibilities (Satterthwaite et al., 2020). For example, in Zimbabwe, informal, traditional and civil society institutions are core arenas for issue discussion because of lower public sector capacities (Mubaya and Mafongoya, 2017). In Durban, South Africa, local governments rely considerably on shadow systems and informal spaces of information and knowledge exchange across their operations to introduce and sustain new ideas (Leck and Roberts, 2015). In the metropolitan area of Styria, Austria, informal cooperation has supported the development of rural–urban partnerships for the formulation of common goals (Oedl-Wieser et al., 2020). In Arkansas, USA, informal governance structures support planning to manage wildfires (Miller, Vos and Lindquist, 2017).

Cities can leverage input-driven institutional change even without national support for climate change adaptation or mitigation. For example, where cities have defined policymaking and budget raising powers, city level political leadership can support adaptation action going beyond national policy (Hamin, Gurran and Emlinger, 2014; Shi, Chu and Debats, 2015; Carlson and McCormick, 2015). Examples include the Surat Climate Change Trust in Surat, India (Chu, 2016) and Initiative for Urban Climate Change and Environment in Semarang, Indonesia (Taylor and Lassa, 2015). In Saint Louis, Senegal, support from national and state-level actors enabled local institutional change (Vedeld et al., 2016). Processual levers may be also mobilised in situations of political instability (which disrupts patterns in champions and networks), clientelism (which can cause environmental projects to be discontinued) (Pasquini et al., 2015) or in contexts where there are high political and socioeconomic inequalities (Harris, Chu and Ziervogel, 2018; Chu, Anguelovski and Carmin, 2016).

6.4.2.2 Output-Driven Institutional Change

Output-driven institutional change is shaped by organisational products such as strategies, plans, policies and evaluative metrics (Patterson and Huitema, 2019; Bellinson and Chu, 2019) (See Table 6.8). There are numerous examples of institutional change through planning outcomes. For example, Manizales, Colombia has included climate adaptation into long-established environmental policy (Biomanizales) and a local environmental action plan (Bioplan), which follows on from a long coherent trajectory of climate change policy (Hardoy and Velásquez Barrero, 2014). A significant number of North American cities have integrated adaptation into long-range plans, while fewer cities integrate adaptation in sustainable development plans or sectoral plans (Aylett, 2015). Canadian cities are more likely to have a plan specifically focused on adaptation rather than having adaptation integrated into municipal long-range planning (Aylett, 2015). In the European Union, adaptation plans depended on national climate legislation or, in fewer cases, the influence of an international climate network (Reckien et al., 2018b). A comparative report from the Covenant of Mayors, however, suggests that the adaptation pillar needs development to demonstrate the effectiveness of adaptation responses and their integration with mitigation goals (Bertoldi et al., 2020). Municipalities in Sweden have been called 'pre-reactive' because adequate strategic guidelines are in place to frame the accessibility, aesthetics and adaptability of waterfront developments (Storbjörk and

Table 6.7 | Barriers to climate adaptation

Examples of barriers to climate adaptation	Institutional changes to overcome those barriers	Examples	Evidence
Lack of financial resources	Strategic combination of municipal, regional and national level funds Access to multiple financing mechanisms	In European countries, large cities tend to fund their own adaptation, while smaller settlements depend on regional or national funding	Aguiar et al. (2018); Moser et al. (2019)
Lack of human resources and capacities	Development of formal and informal partnerships, cooperative agreements and inter-agency arrangements	International cooperation programmes for adaptation in urban areas in the Global South are most likely to succeed if they can align their objectives with local priorities and capacities	UN-Habitat (2016b)
Political commitment and willingness to act	Use of policy windows and extreme events to generate interest and create lasting responses	In Germany, responses to flooding were strongly shaped by public perceptions of safety during the electoral cycle, leading to inadequate responses	Gawel et al. (2018); Di Giulio et al. (2018)
Uncertainty about future impacts and dynamic interactions	Develop institutional arrangements that acknowledge and reduce uncertainty Facilitate the development of bottom-up initiatives that relate directly to the context of action	Power plant operators and the federal state of Baden-Württemberg negotiated the minimum power plant concept ('Mindestkraftwerkskonzept', MPP), a contract to establish more predictable and workable procedures for curtailment in the event of severe heatwaves	Eisenack (2016); Thaler et al. (2019)
Institutional fragmentation and unclear responsibilities	Evaluation of existing institutions to diagnose miscoordination Creation of policy networks that address emerging interdependences	In settlements in Languedoc, France, decentralisation adds complexity to the ongoing challenges of population growth and climate change	Therville et al. (2019)
Legal issues and regulations	Address the legal hurdles to create frameworks that allow for experimental action	Policymakers in the San Francisco Bay Area, USA, reported that minor changes could have a definitive influence in delivering regulatory changes to support adaptation action In the Netherlands, a lack of climate change adaptation policy for cultural heritage hamper adaptation of cultural heritage to current and projected climate risks	Ekstrom and Moser (2014); Fatorić and Biesbroek (2020)
Competition of adaptation with other policy agendas and polarisation	Prioritisation and development of synergies across sectors Mainstreaming adaptation into other sectors	In European cities, for example, urban planning is strongly correlated with water management strategies	Aguiar et al. (2018); Sieber, Biesbroek and de Block (2018)
Lack of data, knowledge generation capacity and knowledge exchange	Mobilise multiple strategies for the use of climate information in local decision making Involve a wide range of stakeholders, with different values and knowledge, in decision making	In Scotland, Hungary and Portugal, local decision makers use high-end climate change (HECC) scenarios, but most often as background data Sharing knowledge alongside the supply chain favours adaptation for both multinationals and small and medium-sized enterprises (SMEs)	Lourenço et al. (2019); Herrmann and Guenther (2017); Gotgelf, Roggero and Eisenack (2020); Wamsler (2017)

Uggla, 2015). Some Asian cities also report high output effectiveness, where they are more likely to indicate senior local government officials' performance management contracts, the budgeting procedures of local government agencies and the procedures that local government agencies use for budgeting infrastructure spending (Aylett, 2015). Despite this evidence, there is a gap in understanding the general trends of planning and institutional change in Africa, Asia, East Europe and the Middle East.

Institutional change processes are complex, contested and sporadic (Patterson, de Voogt and Sapiains, 2019). Such processes are often inhibited by unclear planning mandates, conflicting development priorities, lack of leadership and resource and capacity shortfalls (Anguelovski et al. 2014). There is no one size fits all approach to institutional change, which works *in situ*, and benefits from clearly defined plans and an incremental approach to revising new elements and addressing gaps or failures (Beunen et al., 2017). A longitudinal view of institutional change allows for assessing actors and dynamics involved in integrating adaptation into the sectoral agendas or governance arrangements mentioned above (Patterson and Huitema, 2019).

6.4.3 Solution Spaces to Address the 'Policy Action Gap'

A policy action gap arises when administrative, communication, financial and other organisational blockages and inertia interrupt implementation of policy, the intent of political leadership and delivery of adaptation interventions on the ground (Ampaire et al., 2017; Bell, 2018; Shi, 2019). Political and policy confidence are key enabling conditions for adaptation decision making. As the AR5 already acknowledged, political inaction can arise where there is *low confidence* that adaptation actions can deliver a safer future for all (Chan et al., 2015a). For example, in some administrative jurisdictions (most of them local governments), calls by social movements for the adoption of Climate Emergency Declarations were addressed, however, practical outcomes in terms of adaptation have been limited, and may have foreclosed other future local actions (Nissen et al., 2020; Ruiz Campillo, Castán Broto and Westman, 2020) and raised concerns about maladaptation (Long and Rice, 2019). Political inaction for climate justice is particularly visible in contexts of informality (Ziervogel, 2020). Studies of city and local authority decision-making in South America (Di Giulio et al., 2019), Asia (Araos et al., 2017) and Europe (Lesnikowski et al., 2021) indicate that where there is

Table 6.8 | Examples of institutional and policy instruments to enable adaptation

Objective	Type of instrument	Description	Examples	Assessment
Policy	Information instruments	A diverse range of activities such as training, research and development, and awareness campaigns to produce and share information	Urban-LEDS II Capacity Building Workshop for cities in Laos arranged for local government by ICLEI Southeast Asia Secretariat and UN-Habitat (UN-Habitat, 2019)	Information instruments tend to be low-cost and low-risk options, but their impact is unpredictable and the effects may be uneven (Henstra, 2016). In the example of the workshops in Laos (UN-Habitat, 2019), the result was to map vulnerable sectors and build capacity for mainstreaming
	Voluntary instruments	Practices such as codes, labelling, management standards or audits, voluntarily, that can provide incentives for adaptation	Singapore's National Water Agency's Voluntary Water Efficiency Labelling Scheme (Voluntary WELS) (Tortajada and Joshi, 2013)	A problem with voluntary instruments is that implementation varies. Uptake is likely to be more common among organisations self-identifying as 'champions' and less effective among other actors to bring about far-reaching change (Haug et al., 2010)
	Economic instruments	Taxes or subsidies can be used to promote adaptive activities	US Office for Coastal Management NOAA Coastal Resilience Grants Program (NOAA, 2019)	Economic incentives can be effective as they 'engage local stakeholders and provide price signals that stimulate individual adaptation' (Filatova, 2014). However, uptake of incentives may be low (Sadink, 2013; Henstra, 2016) and resource intensiveness and potential regressive effects (equity impacts) must be considered (Henstra, 2016)
	Regulatory instruments	These include a range of mandatory requirements through controls, bans, quotas, licensing, standards often applied when a specific outcome is required	Building codes to enhance structural stability for storm resilience in Moore, Oklahoma (US) (Ramseyer, Holliday and Floyd, 2016)	Regulatory instruments can be effective in changing and institutionalising adaptation behaviours (Nilsson, Gerger Swartling and Eckerberg, 2012; Henstra, 2016), but outcomes depend on the strength of implementation (e.g., monitoring, transparency, mechanisms for accountability)
Process	Visioning	Events that bring together different stakeholders to produce a city vision	Rotterdam Resilient City participatory processes to create resilience strategies (Resilient Rotterdam, 2016)	There may be challenges in translating complex climate science into understandable and meaningful forms (Sheppard et al., 2011) and creating inclusive processes that allow for co-creation of visions, for example, by involving new digital platforms (Baibarac and Petrescu, 2019)
	Baseline studies	Focus on understanding the current conditions in a neighbourhood or city from an interdisciplinary perspective	*Flood Risks, Climate Change Impacts and Adaptation Benefits in Mumbai,* an OECD assessment study (Hallegatte, Ranger and Bhattacharya, 2010)	Baseline studies can be mobilised to track the progress of adaptation actions in multiple sectors over time. In the example of the study in Mumbai (Hallegatte, Ranger and Bhattacharya, 2010), the analysis includes different climate scenarios and quantification of how adaptation could reduce economic loss
	Development priorities	Specific methods to ensure an open definition of multiple priorities and contrasting values that will inform the planning process	Participatory housing upgrading through the Baan Mankong Program in Bangkok (Thailand) (Berquist, Daniere and Drummond, 2015)	Participatory planning can help navigate which action to take to build resilience and, at the same time address prioritised social concerns (Cloutier et al., 2015). As with all participatory processes, issues of recognition, access/inclusion and potential capture of the process by actors in power must be considered
Planning	Profiles	Develop a common understanding of how different sectors interact with adaptation and the governance capacity	New York City Panel on Climate Change 2019 Report (Nycpcc, 2019)	As with baseline studies, the development of profiles can inform plans for adaptation action, which considers social priorities and synergies across various sectors. Multiple forms of knowledge should be considered in the development of profiles (Codjoe, Owusu and Burkett, 2014)
	Risk assessment	This includes a range of instruments to evaluate the impact of risk	Climate risk assessment for Buenos Aires, conducted by the World Bank (Mehrota et al., 2009)	Risk assessments can be a useful starting point for adaptation. However, assessments do not directly prescribe adaptation options but must be seen as the basis for debate (Yuen, Jovicich and Preston, 2013). A common challenge is a lack of data at the city level (Maragno, Dalla Fontana and Musco, 2020; Cloutier et al., 2015)
	Impact assessment tools	Tools such as strategic impact assessments or sustainability assessments provide a means to assess the impact of specific policies and programmes concerning adaptive capacity	Economic Impact Assessment of Climate Change in Key Sectors in Nepal (Government of Nepal, 2014)	Embedding climate risks into impact assessment tools (either mandatory or voluntary) builds resilience by integrating climate objectives into plans and specific projects (Richardson and Otero, 2012), and they are seen as a legitimate tool in many contexts (Runhaar, 2016)
	Monitoring systems and indicators	Systems to take measurements at regular intervals to specify progress against objectives and revise the planning process	Climate Change Adaptation Indicators for London (London climate change partnership, 2018)	Monitoring systems are essential to make sure that formal objectives are met. However, many urban climate adaptations do not have monitoring and evaluation components (Woodruff and Stults, 2016) and there is no standard set of indicators to monitor adaptation or resilience (Brown, Shaker and Das, 2018; Ford and Berrang-Ford, 2016)
Management	Budgets and audits	Methods for the periodic revision of adaptation plans and policies	Helsinki metropolitan area climate change adaptation monitoring strategy (HSY, 2018)	As with monitoring, budgets and audits can be incorporated into the adaptation planning process to ensure reflexivity and accountability. Low levels of implementation and monitoring of adaptation plans suggest that the uptake may be low (although the evidence is limited)

insufficient political will (that is lack of prioritisation of the issue and inadequate allocation of resources including staffing and finance) and lack of inclusive, coordinated leadership, it can be difficult to overcome inaction, generating a policy action gap.

Multiple actors contribute to deliver climate change adaptation (Chan et al., 2015a; Bäckstrand et al., 2017). There are also multiple scales of action, from the provision of local services to large infrastructures of national or even international significance. Figure 6.5 provides an insight into the challenges that shape the policy action gap and a range of strategies that can help bridge policy action gaps. Effective adaptation governance will depend on the compound impact of the actions of multiple agents operating at different scales (*medium confidence*, *medium agreement*) (Di Giulio et al., 2019; Hale et al., 2021; Zwierzchowska et al., 2019).

6.4.3.1 Delivers on the Needs of the Most Vulnerable

Success in urban adaptation is most often understood as requiring measurable outcomes and evaluation (see also Section 6.4.6). However, many adaptation outcomes are not measurable (*medium evidence*, *medium agreement*) (Béné et al., 2018). Adaptation action solely focused on action tends to ignore areas in the city for which there is no existing data even though actions in these areas may play an essential role in shaping resilience and its limits. Informal settlements and informal economies, which are integral in managing urban resources for effective climate adaptation, are not routinely included in formal urban and national monitoring(Guibrunet and Castán Broto, 2016). The resulting understanding and monitoring of city needs, capacities and actions that feed into policy is incomplete. The innovation, as well as particular concerns and capacities of the informal sector, which is often highly gendered, are not always measured (Brown and McGranahan, 2016). An emphasis on measurable adaptation outcomes may lead to prioritising techno-economic measures to adaptation at the local level. Technocratic approaches to environmental policy continue to shape local sustainability politics (Bulkeley, 2015). The deployment of such technocratic approaches at the local scale is detrimental for democratic and collaborative practices (Metzger and Lindblad, 2020). For example, while China has received praise in terms of delivering urban policies that put climate change at its core, thus suggesting its role providing leadership in climate change debates (Liu et al., 2014; Wang and He, 2015; Fu and Zhang, 2017), other analyses suggest that processes of planning should take greater account of certain groups and interests (Westman and Broto, 2018). Urban sustainability policy may, as a result, fail to deliver collaborative social and environmental objectives, and this is maladaptive in terms of CRD.

6.4.3.2 Moves from Mainstreaming to Transformative Adaptation

Two forms of mainstreaming are usually found in urban policy: incorporating climate adaptation into different sectors or incorporating climate adaptation in holistic sustainability or resilience plans, linking climate adaptation objectives with other social and development objectives (Reckien et al., 2019; Fainstein, 2018). The integration of climate adaptation in local policies in cities and settlements has often been seen as maintaining business-as-usual and not always aligned with transformative efforts to address structural drivers of vulnerability (*high confidence*). For example, mainstream actions that seek to advance other development objectives, as explained above, may reduce adaptation to 'low-hanging fruits', which may maintain business-as-usual practices without any fundamental transformation of the social, institutional and economic systems that drive vulnerabilities (Aylett, 2014). However, as explained above, mainstreaming can also generate wider processes of institutional change (Section 6.4.2). Mainstream strategies may help to demonstrate how policy and frameworks can produce practical outcomes on the ground (Biesbroek and Delaney, 2020). However, previous experiences in other sectors, such as gender mainstreaming, have shown the limitations of the mainstreaming approach, particularly in terms of addressing the structural drivers of inequality and vulnerability, and in achieving justice for those who suffer most (Moser, 2017). Local governments in particular, can link mainstreaming efforts with specific strategies that support justice in adaptation, including redistribution efforts to address vulnerabilities (see Section 6.3.2), representation in local institution and deliberative processes, and recognition of the conditions for self-realisation, including personal and collective safety (Agyeman et al., 2016; Castán Broto and Westman, 2017; Castán Broto and Westman, 2019; Hess and McKane, 2021).

6.4.3.3 Facilitates Coordination Across Separate Actors and Interests

Coordination of adaptation policy goals cuts across cities to integrate them into international processes of climate policy formulation; coordination in cities produces effective collective outcomes, cementation of common standards and methodologies for climate action (e.g., emission inventories) (*high agreement*, *medium evidence*) (Gordon and Johnson, 2017; Hsu and Rauber, 2021). A collective global response has become a significant concern in international climate policy (Chan et al., 2015a). The UNFCCC has adopted a role as an orchestrator, including providing framework for city governments (Bäckstrand and Kuyper, 2017). Within cities, coordination can arise from active programming; for example, in Rotterdam and New York City, local authorities adopted long-term objectives and conditions for action, bringing together a multiplicity of actors across sectors to orient contributions, share knowledge and coordinate actions (Hölscher et al., 2019). Where national politics is supportive, coordination between city and national government is an asset (Chan and Amling, 2019; Inch, 2019). The use of social media and digital mechanisms for coordination with public interest is ambiguous: in China, Weibo has facilitated an expansion of public engagement, although it remains top down and dominated by a few influencial actors (Liu and Zhao, 2017; Yang and Stoddart, 2021). The pilot project #OurChangingClimate is one example of engaging youth with an understanding of their communities and their resilience or vulnerability to climate change (Napawan, Simpson and Snyder, 2017).

6

6.4.3.4 Enables the Co-production of Adaptation Strategies with Citizens

Co-production can advance urban sustainability and social justice in cities and settlements to provide infrastructure adapted to the human scale and advancing SDGs (*medium confidence*) (McGranahan, 2015;

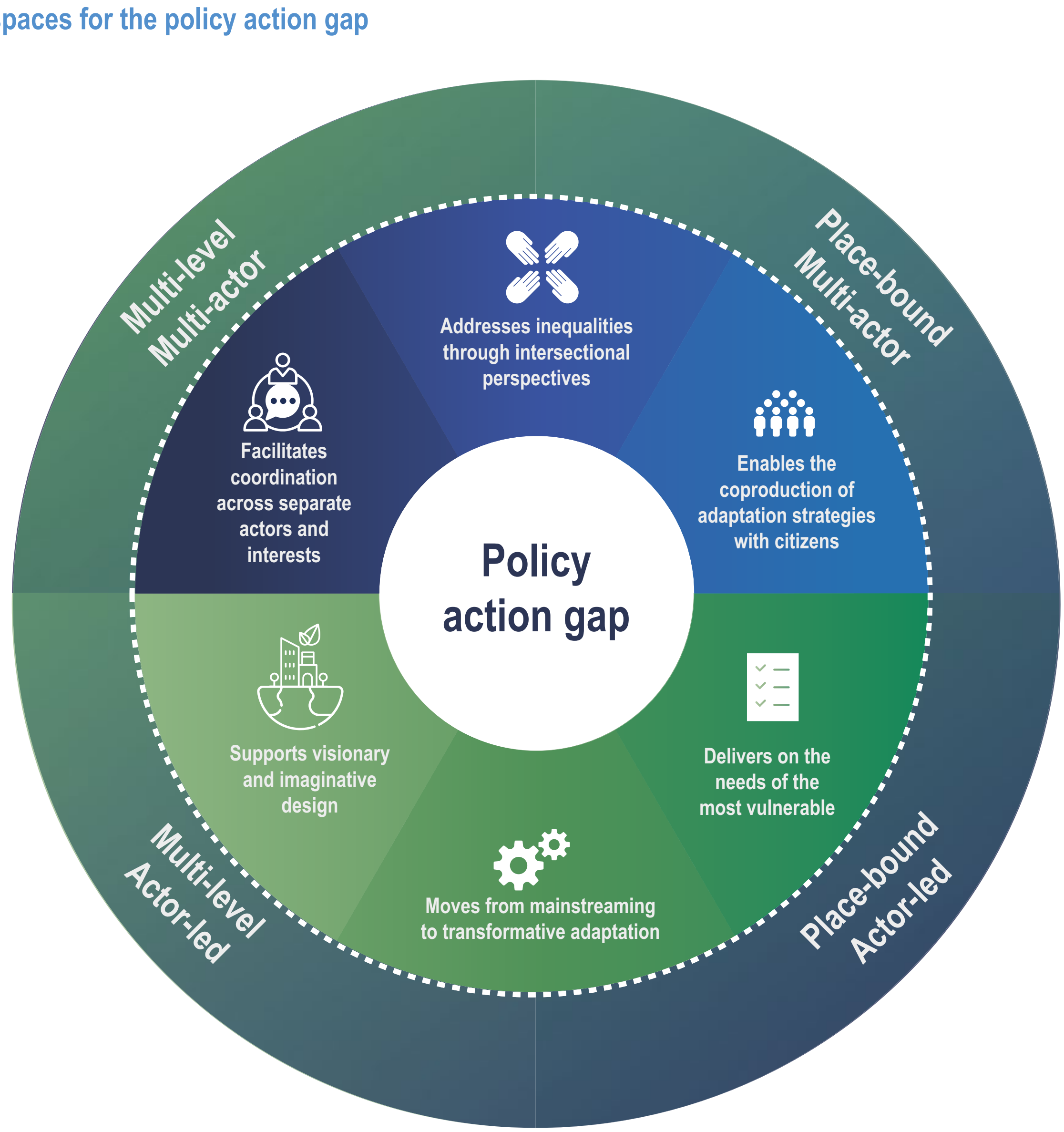

Figure 6.5 | Solution spaces for the policy action gap. The categories in the outer circle represent the tension that shape the policy action gap. On the one hand, there is a tension between the need to deliver action at scale (multi-level) and the need to mobilise the capacities in a given place (place-bound). On the other hand, there is a tension between the need to facilitate collaborations among multiple actors (multi-actor) and the fundamental impact that leadership can have in actor-led initiatives (actor-led). These two tensions interact creating different possibilities for transformative adaptation. The inner ring represents different areas of intervention that configure the solution space to tackle the policy action gap and that bridge these two tensions.

McGranahan and Mitlin, 2016; Chowdhury, Jahan and Rahman, 2017; Moretto and Ranzato, 2017; Nastiti et al., 2017). Co-production involves the active involvement of citizens and citizens' organisation in iterative public service planning and delivery, and has become increasingly central in climate change responses alongside other bottom-up, community-led strategies (Bremer et al., 2019; Vasconcelos, Santos and Pacheco, 2013).

Co-production builds on public participation that brings together diverse sets of citizen interests, values and ideas to inform change and solve problems relating to a collective adaptation challenge (Archer et al., 2014; Bisaro, Roggero and Villamayor-Tomas, 2018; Sarzynski, 2015), and is increasingly important in environmental policy more widely (McGranahan, 2015; Moretto and Ranzato, 2017). For example, in three cities across the Czech Republic, stakeholder participation exercises were used to prioritise climate change risks, provide impetus and opportunity for knowledge co-production, and support adaptation planning (Krkoška Lorencová et al., 2018). In municipalities in Malaysia, stakeholders and citizens are active in the adaptation policy cycle (Palermo and Hernandez, 2020). In Quebec, Canada, citizens collaborated with the municipal authority to bring together climate science and 'ordinary' urban management and design solutions (Cloutier et al., 2015). Service co-production enables integrating multiple actors in the management and delivery of public services (Pestoff and Brandsen, 2013; Pestoff, Brandsen and Verschuere, 2013). Civil society-driven, co-productive approaches can pioneer new forms of institutional relations and practices filling gaps where the public sector is absent or retreating (Frantzeskaki et al., 2016).

A co-production approach to climate change governance addresses the increasing public interest on climate change (Davies, Broto and Hügel, 2021). Youth movements such as Forum for Future have joined forces with other environmental and Indigenous organisations to lobby governments and institutions to action (Kenis, 2021; Fisher and Nasrin, 2021; Davies and Hügel, 2021; Hayward, 2021). These movements have built momentum moving local governments and other institutions to declare a climate emergency and have supported the creation of new forums where climate change can be addressed collectively, such as citizens' assemblies. In the UK, for example, initial scepticism has led to the proliferation of citizen-centric Climate Assemblies at the local level (Sandover, Moseley and Devine-Wright, 2021).

Cooperative governance models provide insights for designing forms of participatory and collaborative planning through which communities and state actors can identify concrete actions and resources to improve services and mitigate structural vulnerabilities to disasters (Castán Broto et al., 2015). Experiences of co-production of sanitation services show how co-production may improve outcomes, while at the same time opening up avenues for grassroots organisations to claim political influence (McGranahan and Mitlin, 2016). Co-production may change institutions in response to external interventions (Das, 2016). Although there are drawbacks in terms of the extent to which co-production can be used to legitimise unfair interventions within a given context, co-production may also be a tool for improving the accountability of dominant groups to vulnerable sectors of the population (Nastiti et al., 2017). There are limitations to co-production. The city of Barcelona, Spain, used co-production methodologies to develop the Barcelona Climate Plan. However, policymakers and civil servants were reluctant to use lay knowledge from participants and political deadlines constrained the time dedicated to deliberation (Satorras et al., 2020).

6.4.3.5 Addresses Inequalities through Intersectional Perspectives

Inclusive and sustainable adaptation can address the causes of systemic vulnerability (*medium evidence*, *high agreement*). This points to the fundamental requirements of adaptation action in line with the Universal Declaration of Human Rights. Climate justice theories draw on the environmental justice movement experiences at the local level (Bickerstaff, 2012; Bickerstaff, Walker and Bulkeley, 2013; Perez et al., 2015; Hall, Hards and Bulkeley, 2013). Slogans such as 'leave no one behind' embedded in international policy for cities and settlements recognise the connection between systems of oppression and exclusion that reproduce and perpetuate urban inequality and the delivery of urban services and security (Kabeer, 2016; Stuart and Woodroffe, 2016).

Intersectional strategies of action seek to consider the multiple forms of structural oppression experienced at the local level (Grunenfelder and Schurr, 2015) and, in the context of adaptation, explain how they produce or exacerbate vulnerabilities. For example, intersectionality ties with the idea of how multiple deprivations shape access to services (from sanitation to health and education) and the exposition to environmental risks (Sicotte, 2014; Lau and Scales, 2016; Van Aelst and Holvoet, 2016; Lievanos and Horne, 2017; Raza, 2017; Yon and Nadimpalli, 2017; European Environment Agency, 2020) (see Box 6.6 on the participation of women in local decision making bodies). For example, fisherwomen in the western coast of India rely on a complex arrangement of relationships around categories of class, caste and gender that shapes their possibilities to draw political resources to maintain their livelihoods and, hence, influence the dynamics of transformation (Thara, 2016). Intersectionality is central to build resilience across communities, rather than in particular areas (Khosla and Masaud, 2010; Reckien et al., 2017). Including intersectionality deliberately in partnerships with communities can empower socially excluded groups and highlight justice issues while aligning agendas with local development priorities (Castán Broto et al., 2015a). Despite the *high confidence* on the growing importance of intersectionality concerns in the delivery of just environmental policies, there is *limited evidence* of its explicit inclusion in adaptation policies.

Box 6.6 | Invisible Women: Lack of Women's Participation in Urban Authorities

Women are under-represented internationally in governance structures (Prihatini, 2019; Gonzalez-Eiras and Sanz, 2018; Rashkova and Zankina, 2017; Koyuncu and Sumbas). This situation is reflected in urban authorities where participation by those who identify as women is low (Williams, Devika and Aandahl, 2015; Kivoi, 2014). Das (2014) reports deep-rooted economic inequalities are barriers for women's participation in Indore, India, and that women's collective empowerment could increase their bargaining power within households as well as in the community and state. Kivoi (2014) draws a similar conclusion presenting experiences from Kenya. The big question is how to make women more visible in the urban governance process?

What are the barriers women face and how do we increase their participation so that urban governance become more inclusive? Escalante and Valdivia (2015) show the participatory tools that can be used at different stages of planning for women's empowerment using bottom-up planning models. Using these tools makes planning processes more inclusive. Araujo and Tejedo-Romero (2016) show from Spanish local councils that women's political representation in municipalities has a positive influence on the level of transparency, increasing information transparency and reducing information asymmetry. In Myanmar, Minoletti (2014) increased levels of women's participation in urban authorities helped to improve the quality of governance such as reducing corruption and conflicts, and improving service delivery.

People traditionally excluded from climate change governance, such as children, are also more likely to have their needs and priorities considered in urban planning for adaptation where there are national advocacy bodies, for example, Commissions for Future, or Children's commissions (Nordström and Wales, 2019; Watts et al., 2019; Hayward, 2021). An emphasis on procedural justice in decision-making has potential to produce transformational outcomes where these are defined as significantly reducing inequality (Holland, 2017). In this light, emerging evidence suggests transformative adaptation is more likely

Box 6.7 | The Role of Urban Design in Local Adaptation

Since AR5, there has been a growing literature about the role of urban design, creating new opportunities for both incremental and transformative adaptive responses to climate change (*medium evidence*, *high agreement*). For example, some of these creative design approaches compliment and extend regulatory and land use planning approaches such as form-based codes and established certifications such as Leadership in Energy and Environmental Design–Neighbourhood Design (LEED-ND) (Garde, 2018; Garde and Hoff, 2017) and the USA's Sustainable Sites Initiative (SITES) (Valente, 2014). Emphasis on sufficiency has also influenced urban design, for example, with the mobilisation of 'doughnut' economics that emphasise both a social foundation and an environmental ceiling, for example Amsterdam (Raworth, 2017). However, such cases are rare, substantial public investment is often required (*high confidence*, *high agreement*) (see also Section 6.4.7 on finance and insurance). Other approaches underscore innovation and creativity, at the essence of which are context-specific interventions that draw on a compendium of urban design principles such as indeterminacy (to accommodate climate uncertainty), polyvalency and diversity, and harmony with nature (Dhar and Khirfan, 2017). Creative interventions include the daylighting of buried streams to create climate adaptive public realms (Khirfan et al., 2020; Khirfan, Mohtat and Peck, 2020). For example, the demolition of a major expressway and the restoration of the Cheonggyecheon Stream reorganised downtown Seoul, South Korea, and significantly contributed to climate change adaptation through stormwater management and reducing the urban heat island effect (Kim and Jung, 2019). Biomimicry and ecological infrastructure are design features that governance bodies can use to reshape space and contribute to place making (Santos Nouri and Costa, 2017; Prior et al., 2018). For example, urban metabolism and local ecological knowledge has constituted the essence of urban design interventions on the Island of Tobago in ways that capitalise on the contiguous relationship between ecosystems (e.g., the mangrove forest) and human actions (rainwater harvesting and grey water management) (Khirfan and Zhang, 2016). While lack of funding or design capacity, restrictive planning regulations, inequality and competing urban agendas can create barriers for the implementation of creative design solutions. Transition architecture movements are also driving local urban adaptation experiments and exploring ways local learning can be scaled up (Tubridy, 2020; Irwin, 2019).

to occur if people have the agency to influence decisions and enact change (Archer and Dodman, 2015). Cities are also more likely to build and develop infrastructure that serves the needs of disadvantaged groups when urban climate governance encourages wider community participation and inclusion (Ziervogel, 2019a; Hölscher et al., 2019; Anguelovski et al., 2016). This can help to stimulate innovation, shift power relations and address diverse needs (Martel and Sutherland, 2019; Chu, Schenk and Patterson, 2018). Experiments in including marginalised groups in adaptation planning are starting to emerge in places such as Quito (Ecuador), Lima (Peru), Manizales (Colombia) and Surat (India), where disadvantaged youth, informal settlers and other vulnerable communities are included in discussions of short-/long-term adaptation needs and fair distribution of adaptation resources (Chu, Anguelovski and Carmin, 2016; Sara, Pfeffer and Baud, 2017; Hardoy and Velásquez Barrero, 2014). These processes can also support citizens to manage risks as they encounter them in their everyday life (Ziervogel et al., 2017).

To respond to urban injustices, attention needs to be paid to both the local level and to broader system-wide governance issues (that are unpacked further in Section 6.4). At the local level, it is important to understand who is most vulnerable to climate risk, which is likely to be related to class, race, gender, ability and age (Wilby and Keenan, 2012; Ranganathan and Bratman, 2019; Thomas, Cretney and Hayward, 2019). Factors such as age and levels of ability, as well as those pursuing outdoor livelihoods, have a direct link to higher vulnerability to heat stress (Conry et al., 2015). In least-developed countries, less than 60% of the urban population have access to piped water which impacts on health and well-being, and emphasises the importance of alternative resources for these households (World Health Organization, Nations and Fund, 2017).

6.4.3.6 Supports Visionary and Imaginative Design

The failure to deliver inclusive and sustainable adaptation contributes to a collective inability to mobilise the power of creative community vision (*medium evidence*, *high agreement*). Urban design plays a central role to support creative adaptation strategies (Box 6.7). Much adaptation action repeats previous experiences. However, the potential for building resilience to deliver adaptation, especially transformative adaptation, requires an articulation of collective visions of the future and the imagination of new or alternative urban futures (Glaas et al., 2018), including through design and deliberate engagement with cultural artefacts, technologies and performances (Jordan, 2020). Social movements can be powerful sources of such alternative visions of the future, as exemplified by recent Youth Climate Strikes and Extinction Rebellion (*limited evidence*, *medium agreement*). Community protest such as Youth Climate Strikes have influenced urban climate policy agendas including the declaration of climate emergency in municipalities worldwide, fostering a new debate on climate change, although their impact on local policy is ambiguous (Davidson et al., 2020; Thomas, Cretney and Hayward, 2019; Prendergast et al., 2021; Ruiz Campillo, Castán Broto and Westman, 2020). Social movements on climate mitigation, such as the Transition Movement and Transition Towns (Feola and Nunes, 2014), and school strikes may serve as an example for mobilisations more specifically about climate adaptation and the way new, networked, grassroots citizen activism and community organisations can encourage urban institutional change (Gunningham, 2019; Jordan et al., 2018; Wahlström et al., 2019). Other strategies such as cultural production and exhibitions may also have an impact (Stripple, Nikoleris and Hildingsson, 2021).

6.4.4 Limits of Adaptation Capacity at the Institutional Level

In delivering adaptation in cities, settlements and infrastructure, however, there is a need to understand and measure the adaptive capacity and limits to manage future risks in communities, institutions and organisations (Filho et al., 2019). However efforts to track urban adaptation lack consistent methods, metrics and data gathering (Olazabal et al., 2019b). The scale of complex, cascading challenges, limited finance and governance capacity, combined with the impacts of growing social inequality and sustainable development priorities can result in both soft and hard limits on cities government's capacity to adapt to climate change (Chanza, 2018; Sanchez Rodriguez, Ürge-Vorsatz and Barau, 2018; Lehmann et al., 2015; Di Giulio et al., 2018). Hard limits to adaptation are identified when it is unfeasible to avoid severe risks, while soft limits exist when technological and socioeconomic options are not immediately deployable (IPCC, 2014). In urban contexts, soft limits may become hard limits when large numbers of people are unable to avoid severe climate-related risks of loss and damage (Mechler et al., 2020). Climate change-related loss and damage that are intangible also require more caution in assessment processes (Roberts and Pelling, 2018; Andrei et al., 2015; Barnett et al., 2016; Thomas and Benjamin, 2018). Incorporating Indigenous knowledge can identify people-oriented and place-specific scenarios, leading to development of urban adaptation policies that foster identity, dignity, self-determination and better collective decision making/capacity to act (McShane, 2017; Preston, 2017), and are also sensitive to the local context and limits of community adaptation (Makondo and Thomas, 2018).

Urban transformations represent forms of adaptation that challenge the principles in which a society is established (Pelling, O'Brien and Matyas, 2015) and can be deployed to go beyond the existing limits of development justice and climate change adaptation capacity. While not all adaptation will be transformative, transformative capacities support both ongoing adaptation efforts and the broader systemic change processes that align adaptation efforts with decarbonisation requirements and the delivery of SDGs. 'Urban transformative capacity' focuses on understanding what elements of a system to respond to external changing conditions in a manner that transforms the system toward a more sustainable state (Ziervogel, Cowen and Ziniades, 2016). The capacities required to deliver adaptation action in cities and settlements are 'transformative capacities', because they move away from thinking of adaptation as an adjustment to a changing external environment to think instead of it as a reconfiguration of infrastructures and institutions to build resilience in the surrounding environment (Pelling, 2010; Matyas and Pelling, 2015). Reflective and iterative learning is integral to fostering transformative capacity (c.f. Luederitz et al., 2017). Transformative capacity extends across multiple agency levels or geographical locations, as well as various domains (Wilson et al., 2013; Olsson, Bodin and Folke, 2010; Keeler et al., 2019b). The components of transformative capacity in cities and settlements can be grouped into three categories (see Table 6.9): (1) agency and forms of interaction, (2) development processes and (3) relational dimensions (Wolfram, 2016). Alongside different forms of technical expertise, there is a need to broaden the interventions of disadvantaged populations in urban sustainability (Wolfram, Borgström and Farrelly, 2019).

Table 6.9 presents a defined framework of ideas that local institutions, mostly local governments, can put into practice to improve their adaptive capacity. Enabling transformative capacity requires novel governance arrangements based on broad participation, a diversity of actor networks, socially embedded leadership and empowerment of communities, alongside an understanding of the system dynamics, which refers to system awareness, collective visions, practical experimentation, reflexivity, capacity building, institutional mainstreaming and the multiple levels of agency or scales (Ziervogel, Cowen and Ziniades, 2016; Ziervogel, 2019a; Wolfram, 2019; Hölscher and Frantzeskaki, 2020; Castán Broto et al., 2018). Many of the transformative capacity components are already visible in local adaptation actions, but many efforts emphasise one element at the expense of others without delivering a systemic perspective. In particular, measures to facilitate the empowerment of communities, reflexivity and social learning are rare but often point toward heightened capacities for transformative, alongside incremental, adaptation (Castán Broto et al., 2018). Transformative capacity frameworks may foster inclusive governance to deliver risk management that works for the poor in countries such as South Africa (Ziervogel, 2019a).

6.4.5 Financing Adaptation in Cities, Settlements and Infrastructures

The amount invested in urban adaptation is limited. The Cities Climate Finance Leadership Alliance tracked USD 3.7 billion of investments in adaptation projects in 2017–2018, of which only 3–5% had an urban component (Richmond et al., 2021). Cities and settlements frequently face barriers of inadequate financing for climate adaptation and mitigation (Cook and Chu, 2018). Finance barriers interact with economic barriers and socioeconomic conflicts and need to be considered within an integrated perspective (Hinkel et al., 2018).

Many early leaders in climate adaptation are, therefore, perhaps unsurprisingly, political capitals or financial centres in the Global North with much larger resource envelopes and well-developed fiscal and financing capacities (Westerhoff, Keskitalo and Juhola, 2011; Shi, Chu and Debats, 2015).

The funding required to deliver climate change adaptation will depend on choices made about climate mitigation (IPCC, 2018). Still, the cost of adapting to a global temperature increase of 1.5°C will be a fraction of the cost of adapting to a global temperature increase exceeding 3°C (IPCC, 2019a; IPCC, 2019b; Hoegh-Guldberg et al., 2018). It will also depend on selected adaptation options, as they have different capital requirements, operating costs and returns on investment (See 6.3). Finally, costs depend on financing sources and mechanisms selected.

Broadly, there are two options for adaptation investment: funding, direct expenditure in preparation for or response to climate change impacts, and financing, the deployment of market-based instruments to attract third-party resources to an adaptation action (Keenan, 2018; Banhalmi-Zakar et al., 2016). Using funding can be a lower-cost strategy, as there is no third party expecting a return on investment. However, using financing can expand the total resources available for adaptation (White and Wahba, 2019).

Table 6.9 | Components of urban transformative capacity with broader relevance for multiple forms of adaptation (Wolfram, 2016).

Component		Manifests in…
Agency and interaction	**Inclusive, multiform urban governance (C1)** Participation/inclusiveness (C1.1)	Citizens and/or civil society organisations participating directly in planning and/or decision making processes.
	Diverse governance modes / Networks (C1.2)	Different and various stakeholders working together and building connections between sectors in different manners.
	Sustained intermediaries and hybridization (C1.3)	An intermediary positioned between the stakeholders of a project.
	Transformative leadership (C2)	Leadership acting as a collaborative driving force in an initiative.
	Empowered communities (C3) **Social needs (C3.1)**	Either analysing or addressing social needs.
	Autonomous communities (C3.2)	Integrating into the design of the project different aspects of community empowerment.
Development processes	**System awareness (C4)** Baseline analysis and system(s) awareness (C4.1)	Agendas aiming to tackle sustainability challenges after deliberate analysis of urban systems.
	Recognition of path dependencies (C4.2)	Explicitly tackling systemic barriers to change.
	Foresight (C5) Co-production of knowledge (C5.1)	Involvement of various and multiple stakeholders in knowledge production processes.
	A collective vision for change (C5.2)	An explicit future vision shared among stakeholders as a means for motivating partners and fostering commitments.
	Alternative scenarios, future pathways (C5.3)	Comparative scenarios that evaluate the mutual shaping of social, ecological, economic and technological dimensions.
	Experimentation with disruptive solutions (C6)	The deliberate use of experiments or ideas that seek to challenge the existing landscape of established policies, technologies or social practices.
	Innovation embedding (C7) Resources for capacity development (C7.1)	Project stakeholders sharing resources for capacity development outside the project to disseminate and multiply results.
	Mainstreaming transformative action (C7.2)	Attempts to generalise the project operation or results beyond the initial context of an application.
	Regulatory frameworks (C7.3)	A new regulation was established as a result of the project or as part of the project activities.
Relational dimensions	**Reflexivity and social learning (C8)**	Stakeholders reflecting on learning and capacity building processes.
	Working across human agency levels (C9)	Project activities contributing to capacity development across human agency levels.
	Working across levels and scales (C10)	Project activities contributing to building capacity across geographical or political–administrative levels.

The choice of funding and financing mechanism is often based on implicit economic world views (Keenan, Chu and Peterson, 2019) or on the technical support available to sub-national governments, such as preparing municipal bonds or contracting for public–private partnerships (Bisaro and Hinkel, 2018). The urban finance literature has long called for critical interrogation of these choices, as adaptation finance has profound justice implications (Khan et al., 2020). However, the literature on adaptation investments is limited (Harman, Taylor and Lane, 2015; Keenan, Chu and Peterson, 2019). The use of municipal debt such as green bonds, for example, intensify the financial and environmental risks borne primarily by the poor, the working class or people discriminated against because of race, sexual orientation or ability (Bigger and Millington, 2019).

The climate imperative has not yet fundamentally changed urban infrastructure investment (White and Wahba, 2019). Mobilising adaptation investment in urban areas continues to depend on strengthening public finance capacities (particularly evaluating and integrating climate risk into economic decisions) and meeting private investors and lenders' expectations. Climate change creates new investment risks and physical risks (Martimort and Straub, 2016), and highlights the limitations of current models to account for risk and uncertainty when pricing investments (Keenan, 2018). Private investors and lenders do not seem ready to provide adaptation finance on significantly easier or cheaper terms than conventional finance (White and Wahba, 2019). However, a variety of means for financing climate change adaptation in urban areas exist (Table 6.10).

6.4.5.1 Urban Adaptation Financing Gap

Cities and settlements in higher-income countries typically have access to funding that could be used to enhance resilience and build adaptive capacity; this includes both the private resources of individual households and firms (which varies significantly within and among cities) and public budgets of different government tiers (see Table 6.10).

Depending on fiscal devolution levels within a country, public revenues may be collected and managed primarily at the national, state, metropolitan or local level. In federal countries, sub-national governments collect an average of 49.4% of public revenues, compared with only 20.7% in unitary countries (OECD/UCLG, 2019). For example, sub-national revenues represent over a quarter of total public revenues in Belgium, Canada and Denmark, but less than 5% in Greece, Ireland and New Zealand (OECD/UCLG, 2019). The share of the national revenue transferred to sub-national governments also varies significantly among countries: grants and subsidies account for over

Table 6.10 | Finance instruments to deliver adaptation in urban areas. Source: adapted from Richmond et al. (2021) and UN-Habitat (2016b)

Type of finance	Finance source	Instruments	Examples of specific instruments in urban settings
Public	Municipal government	Local revenue generation	Utility fees Open space funds/land value capture General obligation bonds Local property, income and sales taxes
	State/Provincial government National government	Grants, incentives, technical assistance funds	Insurance Tax advantages Low-cost project debt Infrastructure investment funds Shared taxes Intergovernmental funding transfers/revenue sharing
Public finance	National development finance institutions (DFIs) Bilateral DFIs Multilateral DFIs	Grants, project debt (low-cost market rate), technical assistance, risk instruments	Risk mitigation support of PPP Project level debt Project preparation facilities and other technical advisory Insurance
	Climate funds	Grants, debt, equity, guarantees	Dedicated climate fund
Private	Commercial FIs	Project debt and equity (market rate), guarantees	Internal climate risk mitigation PPP financing Climate loans
	Private equity (PE)/infrastructure funds	Project equity (market rate)	Direct urban infrastructure investments Corporate equity investment
	Institutional investors	Project debt and equity (market rate)	Direct urban infrastructure investment Corporate debt and equity investments
	Private insurance	Insurance	Public and private risk mitigation Catastrophe bonds Parametric insurance
	Corporate actors	Balance sheet financing and project equity (market rate)	Internal risk mitigation Leasing PPP
	Household	Balance sheet financing	Internal climate risk mitigation
	Non-profits, philanthropies and foundations	Grants, technical assistance, donations	Microfinance Impact investment
	Communities	Grants and collective support	Risk sharing Upgrading funds Community development funds Crowdfunding

three-quarters of sub-national government revenue in Malta, but less than a quarter of sub-national revenue in Iceland (OECD/UCLG, 2019). A local government's capacity to collect revenues is further mediated by incomes within a city (which dictates the prospective tax base) and the capacity of civil servants to administer taxes, fees and charges. The result is that metropolitan and local governments' budgets vary dramatically, across and within countries. For example, per capita municipal budgets vary from USD 1114 in Saskatoon and USD 2682 in Peterborough (Canada), USD 2635 in Leipzig and USD 3638 in Freiburg (Germany), to USD 4907 in Bristol and USD 5612 in Aberdeen (UK) (Löffler, 2016).

Revenue streams are often insufficient relative to the scale of adaptation requirements. For example, Kano, Nigeria, is a large urban area that urgently needs investment in human development and climate resilience but where a fragmented local government has little capacity to finance their climate plans (Mohammed, Hassan and Badamasi, 2019). Many local governments are unable to mobilise funds for adaptation as they face competing priorities, meaning that resources for resilience must be allocated by higher levels of government (Hughes, 2015), which also perceive opportunity costs to adaptation investments. Funding from non-state actors is, therefore, proving important. For example, in the USA, private foundations and non-profit organisations account for 17% and 16%, respectively, of adaptation support in urban areas (Carmin, Nadkarni and Rhie, 2012). However, tapping into these funding sources raises complex questions about accountability and ownership of urban adaptation (Chu, Schenk and Patterson, 2018). Land reclamation may foster real estate markets and mobilise finance for adaptation, as shown in Germany, the Netherlands and the Maldives (Bisaro et al., 2019).

City governments need to anticipate climate shocks and stresses, and design their operating models and investment plans accordingly to ensure financial resilience (Clarvis et al, 2015). Climate risks threaten fiscal models, for example, a drought may disrupt water revenues by reducing total water consumption and incentivising households and firms to invest in independent water storage or supply infrastructure (Simpson et al., 2019). Storm surges and sea level rise may threaten

Table 6.11 | Barriers to finance adaptation in urban areas (Richmond et al., 2021)

Barrier application to urban adaptation Barriers to adaptation finance	
Poor policy environment	Municipal policy environment lacks conditions supportive to private adaptation investment (e.g., lack of requirements that private sector organisations operating in cities implement climate risk mitigation strategies or invest in systemic resilience).
Poor institutional environment	Legal and regulatory infrastructure in the city lacks clarity of purpose toward addressing urban climate risks (e.g., no limitations on development in high climate risk areas).
Poor market environment	Market environment is unsupportive toward adaptation investment (e.g., lack of creditworthy partner municipalities for private sector engagement).
High cost of projects and unknown value add	The value or benefit of the technology is uncertain; private sector actors do not sufficiently consider climate risk in decisions; upfront costs of technology are high.
Lack of technical capacity	Prospective users of technology do not have technical capacity to implement (e.g., limited or siloed expertise in implementing resilient urban infrastructure solutions).
Limitations of private insurance	Insurance has to date largely not been engaged in cities to efficiently transfer risk or incentivise adaptive action and the private insurance industry is facing considerable risk associated with the accelerating impacts of climate change in.

sunk investments in revenue-generating infrastructures such as toll roads or electricity generation and transmission systems. .

6.4.5.2 Barriers to Adaptation Investments

Common sources of adaptation finance might include donor agencies including the Green Climate Fund, sovereign funds (e.g., the Bangladesh Climate Change Resilience Fund) and private finance from commercial banks, investment companies, pension funds and insurance companies (Floater et al., 2017). These capital sources have different risk–return expectations and investment horizons, so they will suit different types and stages of projects. Many sub-national governments in the Global North have access to well-developed domestic, if not global, capital markets to raise and steer finance for urban investment (Banhalmi-Zakar et al., 2016).

However, investments in *ex ante* urban climate adaptation may prove less attractive to these financiers than other opportunities because of their long maturities and high risk (Keenan, Chu and Peterson, 2019) (see also Table 6.11). Many generate economic returns primarily through avoided losses from climate impacts, which are difficult to measure and are, in any case, more attractive to funders than financiers (Kaufman, 2014). *Ex post*, insurance already plays a critical role in protecting urban households, firms and other stakeholders from the full economic costs of high-severity, low-frequency events by sharing risk over time and space. Insurance can also be designed to incentivise risk-reducing behaviours and investments (Banhalmi-Zakar et al., 2016; Paddam and Wong, 2017). Some researchers suggest that, in urban environments, insurance practices are helping to establish adaptation and risk as a new area of public health and public protection. For example, local governments are using new risk transfer instruments, such as re-insurance and catastrophe bonds, to fund investments in resilience projects and disaster recovery (Collier and Cox, 2021). However, the commercial feasibility of private sector insurance depends on more robust estimates of current and future risks, and premiums commensurate with the ability and willingness of consumers to pay. Therefore, *ex ante* investments must complement insurance schemes to improve climate modelling and reduce climate risk (Surminski, Bouwer and Linnerooth-Bayer, 2016). The private sector also faces practical barriers to invest in adaptation.

National governments typically determine the fiscal transfers that sub-national governments receive and the taxes, fees and charges they permit to collect (see for example CBO, 2016). Local governments may strengthen their own source revenue collection and management capacities to better exploit these funding streams and improve their balance sheets, but their total budget will be limited to these funding sources (Ahmad et al., 2019). The amount of local public funding available for urban adaptation depends on the relationships across different government levels.

Similarly, mobilising private finance for urban adaptation projects demands robust institutional, fiscal and regulatory frameworks, which are typically national authorities' responsibility. For local governments to access private finance for adaptation may require national (or in federal countries, state) governments to reform policies and rules governing municipal borrowing, public–private partnerships, land value capture instruments and other financing mechanisms (Ware and Banhalmi-Zakar, 2017). Such fiscal reforms tap into fundamental political and policy issues, such as local governments' autonomy or the tariff-setting powers of national ministries (Gorelick, 2018; White and Wahba, 2019).

Access to private finance can support infrastructure development through private provisioning, public–private partnerships (PPP) and public debt arrangements (*high confidence*) (see also Section 6.4.1.2). Private provisioning attracts coastal adaptation investment when returns are high (e.g., when there is a real estate market associated with it) (Bisaro and Hinkel, 2018). Public–private partnerships attract investments from dredging and construction companies that involve a large share of operational costs (Bisaro and Hinkel, 2018). Public debt instruments appear less successful in supporting investment in adaptation infrastructure. Real estate firms focus on adaptation actions if they perceive climate change impacts such as flooding may impact their activity, mostly focusing on adaptation action as a means to gain competitive advantage (Teicher, 2018).

There have been numerous attempts to innovate in climate finance, for example, mobilising community and cooperative forms of finance, or crowdfunding, which have already proven effective in the context of mitigation (De Broeck, 2018). A well-studied instrument in urban

Box 6.8 | Challenges to Investment in Adaptation in African Cities

In Africa, new investment in institutions can support other enabling conditions for climate-resilient urban development (Robins, 2018). While several studies reveal the net economic benefit of climate-resilient, low-carbon African cities (Global Commission on Economy and Climate, 2017), structural impediments remain to the mobilisation of investment for the types of public good infrastructure that would unlock this benefit (Dodman et al., 2017).

Since the 1960s, gross capital formation (sometimes called Gross domestic investment) has been less than 22% in Africa, whilst in East Asian countries, it has risen to 42% (OECD, 2016). Africa faces an estimated 40% infrastructure financing gap, but this gap is almost certainly higher in the continent's rapidly growing cities (Baker and McKenzie, 2015). Relative poverty, weak or absent local fiscal systems, and contested tenure that prevents land being used as collateral, have restricted investment in African cities (Berrisford, Cirolia and Palmer, 2018; Dodman et al., 2017). Sub-Saharan African countries are reaching the 40% urban threshold at national per capita incomes of around USD 1000 per annum, significantly poorer than South-East Asian and Latin American cities at the same level of urbanisation (Freire, Lall and Leipziger, 2014). Absolute poverty, in conjunction with weak revenue collection and low levels of investment, render conventional infrastructure finance difficult (Smolka, 2013; Global Commission on Economy and Climate, 2017; Berrisford, Cirolia and Palmer, 2018; Cirolia and Mizes, 2019). Sprawled urban development in Africa might make the provision of public services both more energy intensive and three times more expensive than high-density developments (Collier and Venables, 2016).

Data on private finance in African cities are inadequate (OECD, 2017), but all of Africa secured just 3.5% (USD 46 billion) of global foreign direct investment (FDI), despite a 10.9% increase in 2018 (UNCTAD, 2019). Mining and the extraction and processing of fossil fuels accounted for almost a third of greenfield FDI in Africa in 2018 (UNCTAD, 2019). The FDI secured by cities has tended to serve an urban elite and has been used to build shopping malls, housing settlements and airlines (Watson, 2015). It is also unevenly distributed across the continent and within cities. Five countries; Egypt, South Africa, Congo, Morocco and Ethiopia, accounted for more than half the total FDI in 2018 (UNCTAD, 2019), leaving large parts of Africa's growing cities described by financiers as 'high risk' and their citizens deemed 'unbankable' (UCLG, 2016).

Private financiers have begun entering public–private partnerships with African cities, often supported by bilateral agreements between the respective countries, including the growing number of Asian and Middle-Eastern countries contributing to infrastructure in African cities (Cirolia and Rode, 2019). In the absence of enforceable spatial plans and strong urban governance, the risk remains that individual investment projects that are completed will aggregate to create urban systems that are at risk from climate change through the locking-in of inequality, urban sprawl, flooding and greenhouse gas emissions (Dodman et al., 2017; Wachsmuth, Cohen and Angelo, 2016). These risks will constitute a future burden for asset owners, financiers and insurers, and cause a progressive hemorrhaging of economic opportunities in Africa's urban centres (UCLG, 2016).

Securing climate finance for urban development is contingent upon robust multi-level governance arrangements (Tait and Euston-Brown, 2017; OECD/UN-Habitat, 2018). Such investments are needed for cities that do not yet have the balance sheets or rate-paying citizens required to enter financial markets on favourable terms. Similarly, Central Banks have a crucial role in managing the transition risks within cities and limiting the systemic impact of stranded urban assets due to technology shifts or sea level rise (Safarzyńska and van den Bergh, 2017).

New energy, water and sanitation technologies alter the public good nature of urban services and offer novel opportunities for private sector financiers and blended finance. Still, financial sector innovation remains necessary if technological innovation is to be scaled (Cities Climate Finance Leadership Alliance, 2015; European Environment Agency, 2020). UNEP has cited anecdotal evidence of a 'quiet revolution' toward a more developmental and sustainable global finance sector, in part due to global environmental, social and governance requirements, and industry initiatives within the financial and insurance sectors (UNEP, 2015). Scope remains to strengthen Development Finance Institutions programmes, such as the World Bank's City Creditworthiness Programme and the activities of China's ExIm Bank, with a bespoke urban climate dimension.

environments is land-value capture. Land-value capture refers to communities' ability to capture the benefit of increased land values that result from public investment or other government actions (Germán and Bernstein, 2020). There is considerable potential to mobilise land-value capture for adaptation (*limited evidence*, *medium agreement*), but its potential remains unexplored (Dunning and Lord, 2020). While there are numerous examples of the mobilisation of land-value capture to finance sustainable development action (Li and Love, 2019; Wang, Samsura and van der Krabben, 2019), there is *limited evidence* of its use in climate adaptation (see Case Study 6.2). These innovations are particularly important in contexts where resources are very constrained, such as in the financing of adaptation in African cities (See Box 6.7).

Corruption in urban adaptation and disaster risk management finance is a considerable but little researched challenge observed from all world regions (Sanderson et al., 2021). Corruption generates maladaptation, increasing risk, for example where infrastructure is constructed with faulty design, substandard materials and inadequate maintenance (Kabir et al., 2021). More widely, corruption increases vulnerability and reduces capacity by damaging the body politic, distorting markets and reducing economic growth (Alexander, 2017). The construction and infrastructure industries are repeatedly identified as sources of corruption (GIACC, 2020; Chan and Owusu, 2017; Sanderson et al., 2021). Corruption and misuse of climate finance is exacerbated by limited public access to information, political considerations in finance decision making and lack of accountability for decisions and actions (Kabir et al., 2021). In construction, Owusu et al. (2019) found causes included too-close relationships, poor professional ethical standards, negative industrial and working conditions, negative role models and inadequate sanctions throughout the phases of construction. Post-disaster response and reconstruction, and periods of surge funding following international or national policy priorities are especially vulnerable to corruption, with increased funding and pressure to lower norms of financial management (Imperiale and Vanclay, 2021). Mixed delivery mechanisms have been shown to reduce corruption, for example where civil society organisations are involved in project approval stages, although there is also a risk that civil society organisations will themselves become entangled in corruption. International donors have a role to play in working with government and civil society to promote wider scrutiny and transparency of financing processes and project delivery through promoting media and press freedom and legislation for access to information to reduce corruption by enhancing transparency and accountability (Kabir et al., 2021).

Expanding the resource envelope available for adaptation investment is often beyond the authority or competency of city governments. Sovereign and state governments have critical roles to play in providing funding or securing finance for adaptation investments. Such a role is particularly important where the impacts of climate change are distributed inequitably across a country, so that the costs borne by a city may exceed local budgets.

6.4.6 Monitoring and Evaluation Frameworks for Adaptation Used in Cities, Settlements and Infrastructures

Urban adaptation plans can focus attention on the needs of marginalised or vulnerable communities including the elderly, children and the disabled (Dahiya and Das, 2020; Yang, Lee and Juhola, 2021). However, monitoring and evaluation (M&E) frameworks for adaptation are far from being fully developed and operationalised both in theory and in practice for cities, settlements and infrastructures. See also Section 17.5 for an assessment of monitoring and evaluation in climate adaptation. Despite significant experience on the application in other sectors (e.g., health, water, industry or business) or with other climate change objectives (e.g., emissions reduction), the assessment of adaptation efforts has been to date under-theorised in current urban adaptation literature (Berrang-Ford et al., 2019; Leiter et al., 2019; Olazabal et al., 2019b). There is also limited evaluation of new social innovations of the last two decades, including participatory budgeting, social financing, crowdfunding and low-cost urban infrastructure that can be enabling conditions for transformative urban adaptation (Dahiya and Das, 2020; Caprotti et al., 2017).

The challenges related to the evaluation of adaptation progress (lack of methods, agreed metrics, data and definitions, including the ambiguity of the concept of 'adaptation') have been widely recognised after the Paris Agreement by multiple organisations, including the OECD, the World Bank, the European Environment Agency and the Global Environment Facility (Ford et al., 2015; Magnan, 2016; Bours, McGinn and Pringle, 2014). Monitoring and evaluation systems in urban areas will necessarily be incremental and additive, and will have to build on existing indicator systems (Solecki and Rosenzweig, 2020). There is a need to develop practical and efficient frameworks to assess adaptation progress across all levels of public and private decision making. This should include the assessment and consideration of top-down adaptations alongside informal, bottom-up community actions, or corporate-led programmes developed to reduce vulnerabilities and climatic risks and increase resilience (*high confidence*, *high agreement*).

On the one hand, there is a need to guarantee that planned adaptation actions are efficient, just and equitable (Olazabal et al., 2019b), including being able to disaggregate, for example by gendered impacts. On the other hand, there is a need to observe if and how environmental, social and economic vulnerability and climatic risk conditions evolve with time. Surveillance, monitoring and evaluation facilitate adaptation decision making by linking three aspects (Berrang-Ford et al., 2019): (1) changing vulnerabilities and risks, (2) established adaptation goals and targets, and (3) adaptation efforts put in place. The process will help evaluate whether current adaptation efforts are sufficient or adequate, thus enabling the learning process that adaptation action requires (Haasnoot, van't Klooster and Van Alphen, 2018; Klostermann et al., 2018).

Monitoring and evaluation of government-led urban adaptation in major cities around the globe is largely missing (Araos et al., 2017; Olazabal et al., 2019a). This reveals: (1) a lack of awareness by local adaptation managers about the critical importance of monitoring and evaluation systems in adaptation decision making, (2) inadequacy, irrelevancy or underuse of available monitoring and evaluation resources, or (3) a lack of knowledge, capacity and resources to make monitoring and evaluation work in practice at city scale.

Olazabal et al. (2019b) argue that six components are at least required to make monitoring and evaluation operational for urban adaptation planning: (1) the definition of a context-specific tailored system adapted to existing local institutions, (2) the definition of a responsible party (public authority, department, group or organisation) that will be in charge of monitoring and evaluation system management, (3) the definition and assignation of the appropriate budget over time, (4) the identification of monitoring objectives and indicators, (5) the definition of a method and process to evaluate outcomes of the monitoring process and finally, (6) the reporting process (how and who the outputs will be reported to). Klostermann et al. (2018) emphasise the importance of learning through iterative cycles of selection of monitoring objectives, procedures, data collection and evaluation, and inputs to adaptation policy and planning processes (see also discussion of evaluation and learning in Section 17.5.1.7). Yet practical exemplary approaches are still missing.

The IPCC's Fifth Assessment Report acknowledged the lack of standard metrics to measure and monitor success in urban adaptation and suggested a list of indicators that could be developed, while also taking note of the localised nature of adaptation (see also (Rufat et al., 2015)). However, predominant approaches are typically not conducted at the appropriate scale to inform adaptation decision-making (Ford et al., 2018). While some scholars advocate the use of a unifying indicator of social vulnerability (Spielman et al., 2020), others propose to develop flexible sets of comparable indicators that can be adjusted to different contexts (Leiter et al., 2019). Risk-based approaches are seen as an alternative in a context where the monitoring of decision-relevant variables in urban climate adaptation planning is essential to link climatic risk assessment and action (Hallegatte and Engle, 2019; Kingsborough, Borgomeo and Hall, 2016; McDermott and Surminski, 2018). Because of the need to define normative frameworks for risk evaluation, what is acceptable, for what purpose and for how long (Galarraga et al., 2018), these approaches may offer an opportunity for the generation of a shared understanding on goals and limitations of adaptation (McDermott and Surminski, 2018). However, risk-based indicators may also create a bias toward quantifiable variables that tend to be based on climatic modelling outputs, engineering or financial assessments. Based on this and various examples of urban development projects, Hallegatte and Engle (2019) claim it is important to consider output-based indicators and process-based indicators that talk about government, voice and empowerment. Overall, dozens of indicator-based approaches to assess climate adaptation have been proposed across the scientific and policy literature, especially in the broader framework of (community) resilience assessment tools (Sharifi, 2016; Feldmeyer et al., 2019), and in different sectors, for example the climate benefits of NBS (Kabisch et al., 2016; Donatti et al., 2020). Although these efforts may help to mainstream the evaluation of adaptation in current city evaluation initiatives, the development of comprehensive monitoring and evaluation systems is lacking.

There is little evidence on how best to make monitoring and evaluation approaches practical at the local scale. Cities worldwide face important social, environmental and economic conflicts related to resource inequality, poverty, environmental pollution and social tensions that coexist with climatic risks. It makes sense to integrate climate change adaptation assessment goals and needs into existing frameworks for the sake of efficiency. This will benefit small urban areas and cities in developing regions that often face data scarcity and may also find available indicators irrelevant to their realities and, thus, be required to adjust them (Simon et al., 2016). Efforts to coordinate frameworks for the assessment of sustainability (e.g., Local Agenda, sustainability appraisals), resilience (e.g., 100 Resilient Cities, new standards for urban resilience), greenhouse gas (GHG) emissions reporting (e.g., Global Covenant of Mayors for Energy and Climate) can be deployed to learn about contexts. However, they need to be applied with caution as enforcing external requirements may lead to local tensions during their application (for example Roberts et al., 2020). In a context where adaptation efforts need to be aggregated and evaluated across nations (Magnan, 2016) and their implications on wider objectives such as sustainable development and social justice need to be assessed (Long and Rice, 2019), urban adaptation monitoring and evaluation can inform national and international processes that enable a global stocktake of adaptation.

6.4.7 Enabling Transformations

Growing awareness of the interlocking of drivers of urban change and vulnerability has motivated an interest in transformational approaches to adaptation action in cities, settlements and infrastructure. While the idea of transformation has been adopted across the field, there is no consensus about what an urban transformation that addresses adaptation means. There is no one single transformative solution or approach relevant in every case (Chu, Schenk and Patterson, 2018; Shi, 2019; Goh, 2019). What constitutes 'urgent' and 'far-reaching' transformation depends on the local community's expectations and ideas (Choko et al., 2019).

Transformation is often approached as a process of institutional transformation, akin to the process described in Section 6.4.2 (see, for example, Duijn and van Buuren, 2017). Transformation engages with critiques of adaptation or risk reduction as an individual responsibility (Sou, 2018). The idea is to use transformation to focus on coordinating collective efforts (Haque et al, 2014). The coordination of multiple actors is a condition to enable transformative institutions (Torabi et al, 2018) and link adaptation action to development efforts (Chu et al, 2017; Roberts and O'Donoghue, 2013). The role of communities and citizens in such an approach to transformation is ambiguous. Sometimes communities and citizens are presented as critical agents of transformation (Limthongsakul et al, 2017). Other times, however, they are simply situated within strong and durable networks that provide the institutional setting to build resilience (Danière et al., 2016). Despite the political nature of transformative approaches and the evidence that transformative approaches rely on protest and political activism, few authors recognise this strategy (but see Bahadur and Tanner, 2014; Chu, Anguelovski and Roberts, 2017; Dierwechter and Wessells, 2013).

Transformation is also more than a single instance of institutional change. Historical perspectives on transformation enable an understanding of the chain of institutional changes that ultimately lead to significant or far-reaching reconfiguration of infrastructure and service provision (Rojas et al, 2015). Paradigm changes, such as new engagements with nature and green infrastructure, will improve adaptation outcomes (Roberts et al., 2012). Changes of paradigms, however, are not inherently positive and may clash with existing interests or involve trade-offs with other priorities. When care is taken to ensure greater inclusion in urban decision-making, disadvantaged, vulnerable communities are less likely to be disadvantaged. For example, indigenous traditions of nature management provide entry points for the sustainable management of resources, such as seed banks, urban agriculture and the local management of watersheds and floods, may be at odds with conventional structures of expert knowledge (Cid-Aguayo, 2016; Chandra and Gaganis, 2016). These traditions are vital both because of the solution space that they open in the local context and how they serve to create resilience through collective and intergenerational learning (Chandra and Gaganis, 2016).

While aspects of transformative capacity identified in the literature may facilitate far-reaching change, there is *limited evidence* of actual transformations as an outcome of adaptation. While community led resilience agendas may tackle poverty related issues, they struggle to tackle city-wide structural forms of inequality (Chu, Schenk and Patterson, 2018). Processes of shared learning and co-production of knowledge can reinforce existing power dynamics and be limited by technical framings of vulnerability that marginalise political issues (Orleans Reed et al., 2013). These issues are especially acute in relation to land use decisions where short-term fiscal and commercial interests conflict with long-term vulnerability reduction objectives (Brown, Dayal and Rumbaitis Del Rio, 2012). It can be difficult for adaptation actions to target cities' underlying political–economic structure, such as entrenched political–economic interests, elite influence over decision making or neoliberal planning logics that maintain and reproduce inequality (Chu, Anguelovski and Roberts, 2017). Urban resilience plans may be formulated in disconnection from broader development strategies, which leads to a limited ability to tackle underlying structures of political power and urban development practices (Weinstein et al., 2019). Evidence from Kolkata demonstrates the limitations of resilience plans to address underlying conditions of vulnerability, including the commodification of hazardous land, under-provision of informal settlements and spatial segregation of the urban poor (Rumbach, 2017).

Planning for transformative adaptation is more *likely* where communities can learn collectively (*medium evidence*, *medium agreement*) (Restemeyer, van den Brink and Woltjer, 2017; Kabisch et al., 2017; Fraser et al., 2017; Putri, Dalimunthe and Prasojo). Greater citizen engagement facilitates implementing specific measures for radical policymaking or the mainstreaming of environmental knowledge into adaptation practices (Reed et al, 2015). Do it yourself (DIY) planning, in which stakeholders focus on creating and improving specific urban spaces they inhabit, has led to urban greening experiments led by civil society that change paradigms of urban and environmental management (Cloutier, Papin and Bizier, 2018). Social learning may occur through combinations of activism and collaboration with and between informal settlement dwellers, as shown in adaptation experiences in informal settlements in Hanoi and Bangkok (Danière et al., 2016).. The adaptation process can benefit from the inclusion of multiple sources of knowledge for social learning, including universities but also communities and citizens (Chu, Schenk and Patterson, 2018). Citizens assemblies are increasingly recognised as spaces for transformative adaptation (Muradova, Walker and Colli, 2020), although their potential influence at different government levels is still not fully understood.

The integration of multiple forms of knowledge leads to social learning (*medium evidence*, *high agreement*). Indigenous knowledge and local knowledge can provide essential insights into community needs and experiences of housing and urban infrastructure to inform climate adaptation, including improper waste disposal, inadequate drainage and poor sanitation, but there is significant variation in community knowledge networks (Roy et al., 2018b; Douglas et al, 2018; Waters and Adger, 2017). It is important to identify and address barriers to the incorporation of Indigenous knowledge and local knowledge, such as the dominance of scientific knowledge, oppression and/or racism, and fragmentation of knowledge including gender and generational divides (see Burke and Heynen, 2014; Whyte, 2017; Victor, 2015; Lövbrand et al., 2015; Kelly, 2019).The incorporation of Indigenous knowledge in urban decision making requires a constructive dialogue with scientists and urban planners.

Indigenous knowledge and local knowledge have an important role to play in urban planning and management. They can support impact detection and evaluation in urban areas (Codjoe et al, 2014), weather forecasting in urban areas (Magee et al., 2016; Ebhuoma and Simatele, 2019), climate change adaptation in urban agriculture (Wahab and Popoola, 2018; Solomon et al., 2016), urban food security (Simatele and Simatele, 2015), planning and managing urban solid waste (Kosoe et al, 2019), urban flood management (Thorn et al, 2015; Jameson and Baud, 2016; Hooli, 2016), drought perception and coping strategies (Saboohi et al., 2019), and ecological restoration and urban commons management (Nagendra, 2016; Nagendra and Mundoli, 2019). They can help define baselines for past climate and ecological change, providing a historical perspective on changes in urban commons such as lakes and trees (Nagendra, 2016), as well as past climatic changes or climate baselines (Ajayi and Mafongoya, 2017) and shifting baseline syndrome (Fernández-Llamazares et al., 2015; Soga and Gaston, 2018; see Businger et al., 2018 for a review of hurricane history in Hawaiian newspapers; also Wickman, 2018). Incorporating Indigenous knowledge and local knowledge can help generate more people-oriented and place-specific approaches, leading to adaptation policies that foster identity, dignity, self-determination and better collective decision making and capacity to act (Preston, 2017; McShane, 2017) (see also Section 6.1).

Envisioning development alternatives through adaptation as a first step toward transformative adaptation can leverage social learning. Experiences of migration, length of residence and the density of local social-networks impact social learning opportunities and underscore why context-specific social education is vital (Waters and Adger, 2017; Karunarathne and Lee, 2020). Learning across and between communities can be enhanced when care is taken to understand local challenges. Given power relationships, cultural needs and community aspirations, a top-down approach to information sharing is generally less effective than community partnerships and co-created knowledge at surfacing visions and strategies for getting past baked-in, unequal and unsustainable development assumptions and practices (*medium evidence*, *high agreement*) (Clemens et al., 2016; Thi Hong Phuong, Biesbroek and Wals, 2017; Fitzgerald and Lenhart, 2016; Fisher and Dodman, 2019). Social learning in formal and informal urban contexts is also enhanced when care is taken to ensure multiple stakeholders have opportunities to understand a variety of viewpoints, values, resources and ideals, and that these viewpoints are clearly identified in decision-making (Thi Hong Phuong, Biesbroek and Wals, 2017). However much social learning still happens only after a crisis, for example in urban water adaptation, and new knowledge is often frustrated by the lock in of powerful local institutions and groups (Johannessen et al., 2019). Social learning is, however, only one component of the development of climate-resilient pathways. System perspectives theorise the possibility of tipping points, leverage points or disruptive technologies to challenge the stable regime to create a broader reconfiguration (Chapter 17; O'Neill et al., 2018).

Case Studies

Case Study 6.1: Urbanisation and Climate Change in the Himalayas: Increased Water Insecurity for the Poor

The Hindu Kush Himalayan region extends over roughly 3500 km covering eight countries: Afghanistan, Pakistan, Nepal, China, India, Bhutan, Bangladesh and Myanmar. Projections show that by 2050, more than 50% of the population in Hindu Kush countries will live in cities (UNDESA, 2014). The region is home to 10 major river basins that feed south and south-east Asia. In 2017, the total population in the 10 major river basins with their headwaters in the region was around 1.9 billion, including 240 million in the mountain and hills of the Hindu Kush (Wester et al., 2019). The region is characterised by unique mountain topography, climate, hydrology and hydrogeology. Each one of these factors plays an important role in determining the availability of water for people living in the Himalayas (Nepal, Flügel and Shrestha, 2014; Scott et al., 2019; Prakash and Molden, 2020). The total landmass that can support physical infrastructure for towns to develop is much less in the Hindu Kush Himalayan region as compared with the plains. Due to this physical constraint, the process of urbanisation is slow in the region. Only 3% of the total population in the region live in larger cities and 8% in smaller towns (Singh et al., 2019b). However, there has been an increase in urbanisation, largely due to regional imbalances in providing economic opportunities for the poor. People from rural areas are flocking to the nearest urban centres in search of employment and other economic opportunities (Singh and Pandey, 2019). As a result, the share of urban population is increasing in the region, while that of the rural population is declining.

One of the major challenges of urbanisation in the Himalayas is sprawling small towns with populations of under 100,000 (see Figure 6.6). These towns are expected to become major urban centres within a decade because of high growth rate. A recent study by Maharjan et al. (2018) on migration documented that 39% of rural communities have at least one migrant, of whom 80% are internal and the remaining 20% are international. Around 10% of the migration is reported as environmental displacement. Males account for the majority of the migration, which forms an important aspect of gendered vulnerability (Sugden et al., 2014; Goodrich, Prakash and Udas, 2019). The ever-expanding urban population in the Himalayas generates many challenges, especially in the context of climate change adaptation. First, unplanned urbanisation is causing significant changes in land use and land cover, with recharge areas of springs being reduced. Most of the towns in Hindu Kush Himalayan region meet their water needs using supplies from springs, ponds and lakes which are largely interlinked systems. Water insecurity in hill towns are becoming the order of the day (Virk et al., 2019; Bharti et al., 2019; Singh et al., 2019a; Sharma et al., 2019). Second, climate-induced changes in the physical environment include increased rainfall variability. Due to this, heavy rains are becoming frequent and are leading to more landslides. Third, global warming has increased the average temperature in the Himalayas which has caused glacier melt and subsequent change in hydrological regimes of the region. One of the contributing factors of glacial decline is also the deposition of black carbon (Gautam et al., 2020; Gul et al., 2021) which is contributed by burning of crop residue in Punjab (Kant et al., 2020). These critical stressors, climatic and non-climatic, are adversely affecting the socioecology of urban conglomerations in the region (Pervin et al., 2019). Encroachment or degradation of natural water bodies and the disappearance of traditional water systems such as springs are evident (Shah and Badiger, 2018; Sharma et al., 2019). While water availability in these towns has been adversely affected by the climatic and socioeconomic changes, demand for water has increased greatly (Molden, Khanal and Pradhan, 2018). Some of the towns are major tourist attractions that create a floating population in peak tourist seasons, challenging the

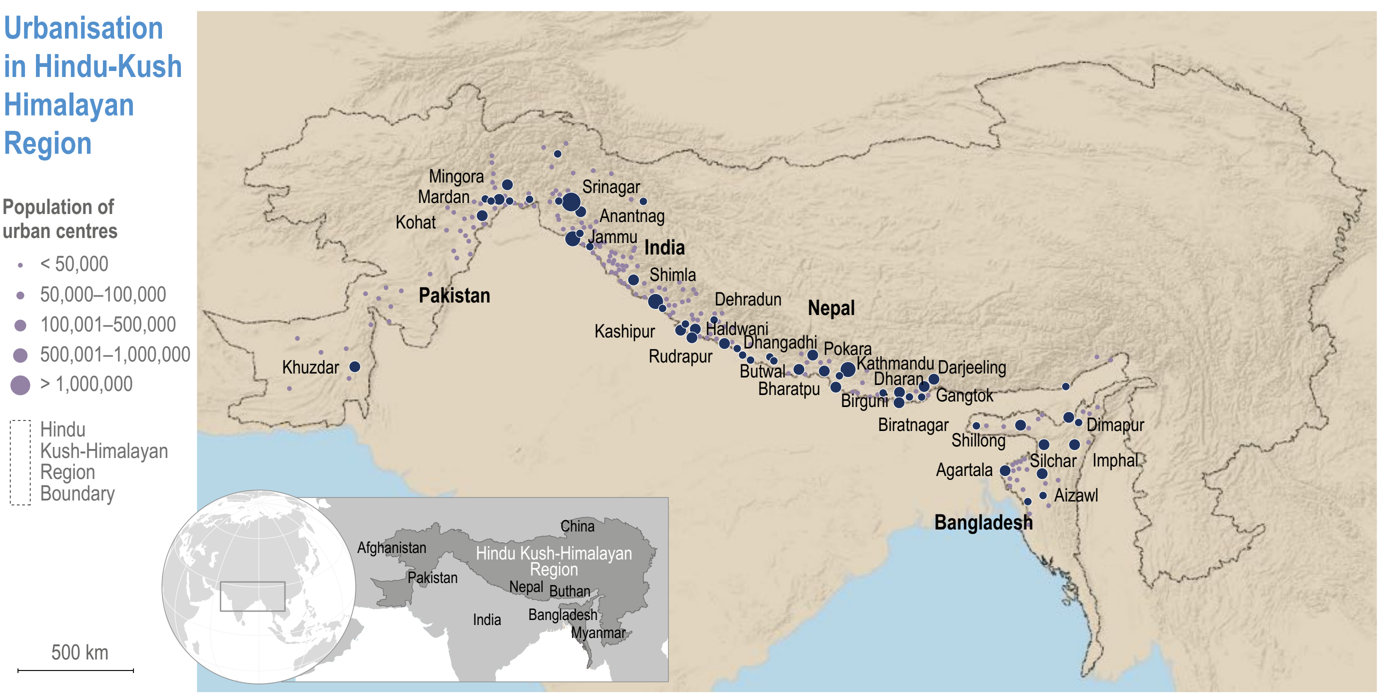

Figure 6.6 | Urbanisation in Hindu Kush Himalayan Region. Figure based on Singh et al. (2019b)

carrying capacities of the towns. The residents must cope with water scarcity as the demand for water increases in peak seasons and water distribution through the public water supply systems becomes highly inequitable (Raina, Gurung and Suwal, 2018). The usual challenges of utilities being inefficient also applies in these areas, though it becomes much more critical as the sources of water are limited and the local geology limits the ability to access groundwater. All these processes are resulting in increased water insecurity for the poor and marginalised in urban towns of Hindu Kush (Prakash and Molden, 2020). To cope with the scarcity situation, people are adapting through various means such as rationing of intra-household water access and groundwater extraction to access water supply (Virk et al., 2019; Bharti et al., 2019; Sharma et al., 2019). This is due to lack of long-term strategies and options provided by utilities.

Case Study 6.2: Semarang, Indonesia

The City of Semarang, on the northern coast of Central Java in Indonesia, has a population of nearly 1.8 million (CBS, 2019). The city has experienced rapid urbanisation over last three decades, with the population almost doubling and density reaching 4650 people per square kilometre (Handayani and Rudiarto, 2014; Handayani et al., 2020b). Semarang is vulnerable to sea level rise, tidal flooding and inundation (Suhelmi and Triwibowo, 2018; Yuniartanti, Handayani and Waskitaningsih, 2016), risks which are worsened by land subsidence along the coast (Abidin et al., 2013). Globally, land subsidence is a notable compounder of climate change-induced sea level rise and coastal flooding (Bagheri et al., 2021). In Semarang, the land subsidence rate is projected to be up to 60 mm yr^{-1} (Abidin et al., 2013; Bott et al., 2021). Approximately 20% of the city's coastline is characterised as extremely vulnerable because of sea level rise and enhanced land subsidence (Husnayen et al., 2018), with the north-eastern portions of the city experiencing larger subsidence than the rest (Yastika, Shimizu and Abidin, 2019). Associated public health and sanitation risks are also evident, including increasing outbreaks of dengue fever and diarrhoea (Pratama et al., 2017; Indonesia Ministry of Health, 2020).

The City of Semarang first engaged with climate change in 2009, when the Rockefeller Foundation launched the Asian Cities Climate Change Resilience Network (ACCCRN), an initiative to develop resilience capacity across secondary and rapidly growing cities in South and Southeast Asia (Reed et al., 2015). Semarang was a pilot city for ACCCRN from 2009 to 2016, when it introduced a participatory approach to planning and decision making that challenged the government-dominated tradition in the city, and in turn played a key role in Semarang's climate adaptation and resilience planning process (Orleans Reed et al., 2013; Moench, 2014; Kernaghan and Da Silva, 2014). A City Team was formed in 2010 consisting of City Environmental Agency (BLH; *Badan Lingkungan Hidup*), Regional Disaster Management Agency (BPBD; *Badan Penanggulangan Bencana Daerah*), Water Resources Management Office (PSDA; *Kantor Dinas Pengelolaan Sumber Daya Air*), Regional Planning and Development Agency (BAPPEDA; *Badan Perencanaan Pembangunan Daerah*), local universities and NGOs such as the Bintari Foundation, with technical support from Mercy Corps Indonesia (Nugraha and Lassa, 2018).

The City Team was first established within the City Environment Agency (BLH) but was then transferred to the Development and Planning Agency (BAPPEDA) (Lassa, 2019). This corresponded to a shift in framing of climate change from an environmental priority to encompassing broader development issues such as economic development, housing and infrastructure delivery. By asserting that climate change affects the operations of every critical sector across the city, the number of municipal agencies involved in climate change programming increased significantly (Setiadi, 2015). Most notably, this approach helped the municipal health agency to recognise the relationship between climate change and health (Setiadi, 2015), and helped to shift the emphasis of dengue fever management toward a more proactive community-based health early warning system (Pratama et al., 2017). In 2017, these measures helped to reduced dengue fever infection rates by 56% compared with 2011–2016 levels (Indonesia Ministry of Health, 2020). ACCCRN also supported policy experimentation through implementing rainwater harvesting facilities and a community-based flood early warning system (Archer and Dodman, 2015; Yuniartanti, Handayani and Waskitaningsih, 2016; Sari and Prayoga, 2018). These projects were designed in conjunction with national government investments in flood management infrastructure, which led to a reduction in the city's inundated area by 24% or approximately 1% of the total urban area (Semarang City Government, 2016).

Building on Semarang's ACCCRN experience, the city then became a member of the Rockefeller Foundation's 100 Resilient Cities (100RC) programme between 2016 and 2018. As in ACCCRN, this new process emphasised stakeholder involvement, with the previous City Team recast as a team of City Resilience Officers (CRO), which was in turn led by the City Mayor and received strategic advisory support from the City Secretary. Semarang synthesised its experiences in climate adaptation planning through the *Resilient Semarang Strategy* published in May 2016 (Semarang City Government, 2016). The *Resilient Semarang Strategy* (2016) acknowledged that urban resilience must be pursued in a comprehensive and inclusive manner and highlighted 18 strategies across 6 themes: water and new energy, new economy, disaster and disease, integrated mobility, transparency of public information and competitive human resource, to be mainstreamed into the revision of the Mid-Term Regional Development Plan (RPJMD, *Rencana Pembangunan Jangka Menengah Daerah*) of 2016–2021. City Resilience Officers were formally appointed to serve on the RPJMD team, thereby formalising climate resilience as a critical item on the RPJMD programme list.

Engagement with 100RC allowed Semarang's resilience programmes to appear on 100RC's 'marketplace' of municipal projects, allowing them to be connected with bi-/multi-lateral donor resources, while continuing to align projects with goals articulated within the Mid-Term Regional Development Plan. The 100RC marketplace is a *resilience platform* that showcases particular initiatives of 100RC network cities to potential *resilience partners*, thereby attracting investment and donor support to Semarang's resilience programmes. Examples include the Water as Leverage (WaL) project that has been working to conserve urban water resources in the face of climate change since 2018 (Handayani et al., 2020a; Laeni et al., 2021) and the Transboundary Flood Risk Management through Governance and Innovative Information Technology Program (TRANSFORM) that has been helping Semarang tackle flood risks beyond city boundaries through reforestation and development of dry wells and swales in upstream areas, as well as promoting cross-region dialogue (Global Resilience Partnership, 2018). Other collaborations focused on developing resilience indicators (ARUP, 2018; Rangwala et al., 2018). For example, the Zurich Flood Resilience Program implemented resilience measurement tools in 16 sub-districts along the East Flood Canal. Results of the assessment were then used to develop local disaster contingency plans (Rangwala et al., 2018).

The conclusion of the Rockefeller Foundation's formal engagement in Semarang in 2018 has brought forth questions about continued financial and institutional support for climate adaptation action in the city. Increasing land subsidence will also *likely* overwhelm current efforts to incrementally adapt to sea level rise and coastal flooding (Abidin et al., 2013). Still, the Semarang case study does highlight several key lessons for urban climate governance in secondary rapidly urbanising cities in the Global South. First, transnational institutions and partnerships are critical enablers (Aisya, 2019; Setiadi, 2015; Chu, Hughes and Mason, 2018; Handayani et al., 2020a). Institutions such as the Rockefeller Foundation foster programmes and investment in the city, leverage access to adaptation funding, accelerate climate mainstreaming into wider urban sectors, and promote better knowledge management (Setiadi, 2016). However, such opportunities are also supported by the city's ability to further mobilise its own resources in the long term and remove its dependency on the national government and transnational supporters (Handayani et al., 2020a). Second, scaling up of programmes and replication of adaptation actions are increasingly important to close the gap between planning and implementation (Setiadi, 2016). It is evident that increased community empowerment and participation can help fill this gap (Hadi, 2018; Miladan, 2016), but this must also be evidence-based to ensure its applicability and effectiveness (Suarma et al., 2018). Questions remain around how to determine and assess evidence-based participatory adaptation at the local level. Third, sustainable financing (from both external and internal sources) to support proposed adaptation strategies is essential as it allows for more capacity building, technology transfer and programme implementation in the long run (Handayani et al., 2020a; Laeni et al., 2021; Hadi, 2017). An example is the development of a water retention on the eastern coast of Semarang using a collaborative financing model, which helped further adaptation by protecting water resources for local industries as well as promote the idea of land value capture for community residents.

Case Study 6.3: Institutional Innovation to Improve Urban Resilience: Xi'xian New Area in China

Located in Northwest China and the Silk Road Economic Belt, Xi'Xian covers a total of 882 km^2 of the border zone of two cities of Xi'an and Xianyang, Shaanxi province. Xi"xian accommodates a registered population of 1.06 million, with a planned area of 272 km^2 reserved for urban development. As a new engine for promoting the West Development Strategy and people-centred urbanisation in the northwest China, Xi'xian has paved the way for China's ecological city agenda since January 2014.

Xi'xian aimed to build a 'modern garden city' when it was selected as national demonstration sites for Sponge City (SC) during 2015–2018 and Climate Resilient City (CRC) during 2017–2020. Under the changing climate, the old cities of Xi'xian suffers urban heat island, drying and water scarcity, heavy rains and waterlogging, thunderstorms and so on, which bring adverse effects to transportation, construction, cultural relics tourism resources and other industries (Ma, Yan and Zeyu, 2021). SC status requires innovation to reduce flood risk through design to absorb, store and purify rainfall and storm water in an ecologically friendly way that reduces dangerous and polluted runoff. When required, the stored water is released and added to the urban water supply (MoHURD, 2014). As a CRC, the aim is to adapt to climate risk and environmental change by integrating climate resilience into urban renewal and revitalisation.

In practice, building ecological cities in China has primarily focused on hard measures (Li et al., 2020). Key areas of development include stakeholder engagement and horizontal coordination (Li et al., 2016). Among one of 19 national-level New Areas in China, Xi'xian enjoys special preferential policies in the fields of fiscal autonomy, investment and tax policy, and permission in land utility for industrial development purpose. These policy freedoms allow Xi'Xian to explore adaptation options. This has opened engagement with business through an urban construction investment group sponsored and invested in jointly by Xi'Xian Management Committee (administrative authority) and local enterprises (Wei and Zhao, 2018). Second, the municipal government has simplified administrative systems to reduce the project waiting period from evaluation to approval to 50 d. Third, a green financial mechanism creates a leverage effect for national funding, including the first provincial Green Sponge Development Fund (RMB 1.2 billion) and in Shaanxi, special funding from the Urbanization Development Fund (RMB 2.64 billion). Furthermore, a public–private partnership model with a whole-lifecycle-management approach has been introduced, raising funding of RMB 1.24 billion with a packaged project including public pipelines and sewage water treatment facilities.

Such institutional and financial support have allowed Xi'xian to implement a Pilot Construction Plan and Three-year Action Plan for Adapting to Climate Change. In 2020, Xixian formed an urban ecology system including 21 m^2 of green space per capita. The old cities' underground drainage pipe network has been replaced by sponge designs such as green corridors, grass ditches, water storage gardens and recessed green spaces. The 10 waterlogging prone points in Xi'xian New Area have been eliminated and the green area has alleviated urban heat, with average temperature about 1°C lower than the neighbouring densely populated mega-cities of Xi'an and Xianyang. Groundwater in the New Area has also risen by 3.43 m compared with 2015.

At the end of 2020, Xi'xian New Area has built 2.4 million m^2 of modern garden cities, more than 50 km of sponge roads, 1.4 million m^2 of resilient park green space and established a green coverage of more than 50% of the urban space. The target of becoming a green city in which everyone can 'see green in 100 meters, step into garden every 300 meter' has been realised (Ma et al., 2021). The urban parks and green spaces play a role in regulating local microclimate and also improve the urban environmental amenities for residents. In a comprehensive performance assessment for the Climate Resilient Cities facilitated by the Climate Change Department of the Ministry of Ecology and Environment (MEE), the Xi'xian ranked number 9 among all of the 28 pilot cities.

Case Study 6.4: San Juan: Multi-Hazard Risk and Resilience in Puerto Rico and Its Urban Areas

This case study illustrates multi-hazard risk and reviews the formation of a multi-stakeholder adaptation governance regime as one response to this.

In two weeks in 2017, Puerto Rico experienced two powerful hurricanes, Irma (category 5) and María (category 4). The compound effects decimated the island's power, water, communications and transportation infrastructure, and an estimated 2975 people lost their lives (Irvin-Barnwell et al., 2020; Santos-Burgoa et al., 2018). Soon after, while many homes still had no electricity or roofs and the tree canopy was still bare, Puerto Ricans were faced with cascading effects including environmental health impacts from air pollution, extreme heat and mosquitoes (Ortiz et al., 2020). In 2020, while still recovering, Puerto Ricans experienced earthquakes, extreme African dust events, intense coastal and urban floods, and the COVID-19 pandemic (Keck, 2020; NASA Explore Earth, 2020; NASA/JPL-Caltech, 2020). These events continue to unveil unresolved conditions of social vulnerability and its root causes in economic poverty, social inequities, aged and deteriorating infrastructure, and population loss (Bonilla and LeBrón, 2019). Combined with limited past investment in climate change adaptation and underlying governance challenges including corruption, bankruptcy and political crisis (Holladay et al., 2019), this has constrained a more CRD for Puerto Rico.

It is in this context that government, academic institutions and local civil society have taken important steps and often joint action toward mitigation and adaptation. Federal funding included USD 20 billion of disaster recovery funding with USD 8 billion allocated for adaptation and resilience projects, such as flood risk mitigation. During the year 2020, the Federal Emergency Management Agency (FEMA) approved USD 13 billion to rebuild the power grid and education system (Delgado, 2020). These programmes allow communities and local governments to plan and implement strategies and build new infrastructure that reduces risks and builds long-term adaptive capacities. The Government of Puerto Rico also approved two key climate adaptation policies in 2019. The Puerto Rico Mitigation, Adaptation and Resilience to Climate Change Law (Law 33, Senate Bill PS 773) established, for the first time in the island's history, a legal framework that acknowledges that the climate is changing and threatens the quality of life. The law recognises important scientific projections for the island, including an increase of 0.5 to 1 m in sea levels by 2015, maximum temperatures of up 2.5°C and precipitation decrease of up to 50% by 2100 (Gould et al., 2018). The law generated the formation of an Expert and Advisory Committee on Climate Change to develop the plan with specific recommendations and present it to the Legislature within a year of the passing of the law in 2020. Along with strategies to specifically protect and build the resilience of urban and rural communities to future climate disasters, the law establishes SDGs, including water and food security, urban planning and densification, and transition to renewable and alternative forms of energy. The energy target is reinforced by another key state policy approved in 2019 in response to the failed energy infrastructure during Hurricane María, the Puerto Rico Energy Public Policy Act (Senate Bill PS 1121). This law calls for a transition to 100% renewable and alternative energy by 2050.

Puerto Rico has a strong science base that produced extensive knowledge on climate change and sustainability long before Hurricane María. The Puerto Rico Climate Change Council has collected and synthesised scientific information for Puerto Rico since before its formation in 2009. Many Puerto Rican scientists were also editors and authors on Chapter 20: US Caribbean Region for 4th US National Climate Assessment (Gould et al., 2018). The National Institute of Island Energy and Sustainability (INESI in Spanish) recently published a catalogue with more than 60 scientists and experts working on energy and sustainability innovations in the University of Puerto Rico (UPR) system. The scientific community became very active after the hurricane in efforts to empower local groups and communities to build more sustainable and resilient futures. UPR environmental health scientists worked with communities to design and implement risk reduction action plans, including NBS , through the Community Climate Actions Plans and the Puerto Rico Community Resiliency Initiative sponsored by Fundación Comunitaria de Puerto Rico and Education Development Center-Regional Education Laboratories, Northeast and Islands. A successful example of these alliances is the development of the first solar power community in Toro Negro, Puerto Rico. These initiatives were inspired by principles of human-centred design, a problem-solving approach that starts with the people impacted the most by the problem to be solved. In San Juan, the capital and major urban centre of the island, scientists from UPR and the US Forest Service International Institute of Tropical Forestry worked with local stakeholders and communities to develop sustainable and transformative urban futures with the support of the Urban Resilience to Extreme Events Sustainability Research Network (UREx SRN). The UREx SRN is a knowledge network of 10 cities in the USA and Latin America and 20 other institutions building scientific knowledge, models and participatory tools to build resilience and transformative capacities for cities.

Perhaps the greatest source of adaptive capacity that emerged after the hurricane came from the civic sector and community-based organisations, and local residents. Hundreds of non-profit and grassroots organisations became active in disaster recovery and are now catalysing actions to advance social transformation and sustainable development. In the energy sector, numerous communities and NGOs developed new action plans to promote transitions to renewable energy and community-based microgrids, such as the Queremos Sol initiative (https://www.queremossolpr.com/), and the establishment of solar panels in community centres and residences by the Puerto Rico Community Foundation and Resilient Power Puerto Rico. The San Juan Bay Estuary Program, an NGO in the San Juan metropolitan area, launched alongside the Clinton Global Initiative the development of a watershed-based multi-jusrisdictional hazard mitigation plan, the first watershed-based plan for the metro region. The organisation has established resilience hubs to support the community with critical resources, communications and energy supply during an emergency. In many of the most isolated areas across the island where government aid did not reach them for months, the communities that self-organised during recovery are also leading examples of community social–ecological resilience. In Utuado, one of the hardest hit areas by the hurricane, their main community organisation known as COSSAO (Corporación de Servicios de Salud y Desarrollo Socioeconómico, El Otoao) emerged from the hurricane with a strong and holistic sustainable development vision, the Tetuan Reborn initiative, to improve the socioeconomic status and health of community members while building capacity for disaster resilience through various initiatives. The long-term outcome of this initiative is to support efforts toward self-empowerment within neighbourhoods by identifying and designing viable solutions to hurricane-related and economic development challenges specific to the local context, including constructing a primary health care clinic, a public health promoter programme, pursuing farms rehabilitation, and promoting agritourism, agrotherapy and education (Holladay et al., 2019).

Adaptation efforts, however, continue to face many governance hurdles. Up to 2020, only 2–3% of the USD 20 million Federal Government recovery funds had been spent with hundreds of families that lost their homes or roofs in 2017 yet to receive the help they need (Colón Almenas, 2020). Lack of administrative capacities, coordination across sectors and efforts, transparency and accountability are some of the governance barriers that keep recovery and transformation efforts from materialising (Lamba Nieves and Marxuach, 2020). Puerto Ricans are now contending with the reality that the disaster they are experiencing is not an outcome of a singular event but of multiple hazards converging with pre-existing vulnerabilities and low adaptive capacities creating severe multi-hazard risk to the island (Eakin, Muñoz-Erickson and Lemos, 2018; Gould et al., 2018). Many Puerto Ricans now question when the disaster began and when it ended because they have been living in a state of chronic crisis (Bonilla and LeBrón, 2019).

Case Study 6.5: Climate-Resilient Pathways in Informal Settlements in Cities in Sub-Saharan Africa

Informal settlements account for over three-quarters of residential areas in sub-Saharan Africa and have grown rapidly over the last three decades (Visagie and Turok, 2020). Informal settlements will remain home to a significant proportion of the urban population of this region which is projected to grow by 2.5 times between 2020 and 2050 (UNDESA, 2018), driven by a complex set of underlying factors including socioeconomic conditions, inadequate planning systems, local and foreign investment patterns, and rural-to-urban migration (De Longueville et al., 2020). Yet residents of informal settlements are often excluded from macro-level visions and policies that seek to make cities safer and improve resilience (Adenle et al., 2017; Pelling et al., 2018). This case study compares the experience of collective action to manage risk in the informal settlements of Freetown, Sierra Leone, with other cases in Sub-Saharan Africa. These examples show how local knowledge and capacity, engagement of policymakers in meaningful ways with residents of informal communities, and institutional change, can combine to deliver adaptation outcomes at a city scale (Kareem et al., 2020).

Despite their diversity and differences across the continent (Kovacic et al., 2019), informal settlements are frequently located in hazard-prone areas, with residents living in precarious housing conditions on marginal lands (Badmos et al., 2020; Kironde, 2016), lacking essential services and risk-reducing infrastructure, and often developing outside the legal systems intended to record land tenure and ownership (Satterthwaite et al., 2020; Adelekan et al., 2015). Consequently, they are particularly vulnerable to climate change, and the urban poor residents suffer disproportionate burdens and losses from natural hazards, which undermines urban resilience (Williams et al., 2019). Recent impacts from flooding have brought wide-spread devastation to urban poor residents in major coastal urban centres including Accra, Lagos, Freetown, Maputo and Dar es Salaam, resulting in injury and death, displacement of people, loss of assets, destruction of public infrastructure and disruption to livelihoods and economies (Douglas et al., 2008; Adelekan, 2010; Yankson et al., 2017; Allen et al., 2017). Flooding and long-term inundation also lead the spread of diseases and health risks (Sverdlik, 2011; Zerbo, Delgado and González, 2020). Climate change will also bring stresses such as city-wide reductions in freshwater availability, and heatwaves that have particularly severe consequences for residents of poorly built homes in informal settlements (Pasquini et al., 2020; Kayaga et al., 2021; Wilby et al., 2021).

In response to these risks, a wide range of adaptation efforts have been implemented in cities across sub-Saharan Africa (Hunter et al., 2020). In Freetown, informal settlement residents have led data generation efforts that capture the value of local knowledge in understanding climate risk. Through partnerships with NGOs and research institutions, informal settlement residents have mapped climate hazard hotspots using geo-referenced tools, producing both digital and hardcopy outputs that serve as a blueprint for climate-informed community development discourses (Allen et al., 2020b; Visman et al., 2020). Similarly, residents of informal settlements in Dar es Salaam, Tanzania, have profiled community climate and health risks by using an adaptation of the 'Action at the Frontline' methodology developed by the Global Network of Civil Society Organisations for Disaster Reduction (GNDR). Locally informed risk profiles support the development of community action plans based on prioritisation and ranking of scaled-down interventions that communities can collectively do on their own (Osuteye et al., 2020). This process highlights the lived experiences of climate change, and allows communities to develop deliberation spaces, communal solidarity and cohesion, and share adaptation strategies (Sakijege et al., 2014). Such sharing and peer-to-peer learning is particularly useful because adaptive capacities are unevenly distributed among exposed populations (Ajibade and McBean, 2014). The community-generated assessments and data consider the range of environmental, socioeconomic and political factors that contribute to a better understanding of how climate change affects the vulnerability of low-income urban residents, and how this changes over time.

Data that is generated and owned by residents of informal settlements provides a basis for making the risks facing these neighbourhoods more visible to city planners, and for enabling collaboration between a range of urban stakeholders (Dobson, 2017). In Freetown, this process has been led by the Federation of the Urban and Rural Poor (FEDURP) and the Centre for Dialogue on Human Settlement and Poverty Alleviation (CODOHSAPA). The FEDURP belongs to the global Slum Dwellers International network, committed to empowering poor residents in urban spaces, and has a presence in several other African cities (Macarthy et al., 2017). With the support of CODOHSAPA, FEDURP coordinates community development committees (CDC) and community disaster management committees (CDMC) in nearly all the informal settlements in the city. Both CODOHSAPA and FEDURP work closely with the local research institution, the Sierra Leone Urban Research Centre (SLURC). SLURC has played an essential role in curating spaces for continuous learning and relationship-building between FEDURP and community residents, including the formation of 'Community Learning Platforms' (CLP) for mixed groups of community actors (City Learning Platform, 2019) to build their capacities to address climate risk collectively. This is done by drawing on the data, agency and mobilisation potential of community organisations in informal settlements. In the coastal settlement of Cockle Bay at the western end of the city, uncontrolled traditional land reclamation ('banking') along the shores progressively exposed residents to perennial floods from tidal surges, and the settlement received regular threats of evictions from city authorities. However, residents have drawn on their climate risk knowledge and hazard profiling to self-manage a process of action planning resulting in a decision to prohibit further land reclamation. It also identified and demarcated an exterior boundary of the settlement and planned and constructed new drainage channels to carry away runoff water within the community (Allen et al., 2017). The community organisations have subsequently successfully negotiated with the Ministry of Environment to formalise this new exterior boundary, which has led to the authorities dropping their threats of evictions.

The approach taken in Freetown demonstrates a pathway to adaptation that is based on a more people-centred approach to urban planning that understands the aspirations of urban residents, addresses climate risk and advances sustainable development (Woodcraft et al., 2020; Fraser et al., 2017). It further provides an example of the ways in which different sources and scales of data can be co-produced (Kovacic et al., 2019) and targeted interventions can be co-designed with community residents (Musango et al., 2020). The community-generated data on climate and health risks and the subsequent strategic action plans developed through local community organisations' work have been recognised and incorporated into a new city-wide initiative led by the Office of the Mayor, dubbed Transform Freetown (Allen et al., 2020a). The action has expanded the political space for the urban poor's collectives to strategically engage in urban resilience planning, highlighting the value and potential of participatory processes and community-generated data.

Cross-Working-Group Box URBAN | Cities and Climate Change

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Introduction

This Cross-Working Group Box on Cities and Climate Change responds to the critical role of urbanisation as a megatrend impacting climate adaptation and mitigation. Issues associated with cities and urbanisation are covered in substantial depth within all three Working Groups (including WGI Box TS.14, WGII Chapter 6 'Cities, settlements and key infrastructure'; WGII regional chapters; WGII Cross-Chapter Paper 'Cities and settlements by the sea'; WGIII Chapter 8 'Urban systems and other settlements'). This Box highlights key findings from Working Groups II and III and substantial gaps in literature where more research is urgently needed relating to policy action in cities. It describes methods of addressing mitigation and adaptation in an integrated way across sectors and cities to advance sustainable development and equity outcomes; and assesses the governance and finance solutions required to support climate resilient responses.

Urbanisation: A Megatrend Driving Global Climate Risk and Potential for Low-Carbon and Resilient Futures

Severe weather events, exacerbated by anthropogenic emissions, are already having devastating impacts on people who live in urban areas, and on the infrastructure that supports these communities and those of many other distant places (*high confidence*) (Cai et al., 2019; Folke et al., 2021). Between 2000 and 2015, the global population in locations that were affected by floods grew by 58–86 million (Tellman et al., 2021). The direct economic costs of all extreme events reached USD 210–268 billion in 2020 (Aon, 2021) or about USD 0.7 billion d^{-1}; this figure does not include knock-on costs in supply chains or days off work lost so that the actual economic costs could be far higher. Depending on RCP, between half (RCP2.6) and three-quarters (RCP8.5) of the global population could be exposed to periods of life-threatening climatic conditions arising from coupled impacts of extreme heat and humidity by 2100 (see Section 6.2.2.1; WGII Figure 6.3; Mora et al., 2017; Zhao et al., 2021; Huang et al., 2019).

The interdependencies between infrastructure, services and networks driven by urban production and consumption mean that urban systems are now global; remittance flows and investments reach into rural places shaping natural resource use far from the city and bring risk to the city when these places are impacted by climate change. This urbanisation megatrend (Kourtit, Nijkamp and Scholten, 2015) amplifies and shapes the potential impacts of climate events. It provides the economic and institutional framework for integrating the aims and approaches that can deliver mitigation, adaptation and sustainable development (*medium evidence*, *high agreement*) (Zscheischler et al., 2018; Dawson et al., 2018; Tsavdaroglou et al., 2018). For cities facing flood damage, wide-ranging impacts have been recorded on other urban areas (Simpson et al., 2021; Carter et al., 2021) as production and trade is disrupted (Shughrue et al., 2020).

Cross-Working Group Box (continued)

In the absence of integrated mitigation and adaptation across and between infrastructure systems and local places, impacts that bring urban economies to a standstill can extend into supply chains or across energy networks causing power outages.

Urban settlements are drivers of climate change, generating about 70% of global CO_2-eq emissions (*high confidence*) (WGI Box TS.14; WGIII 8 ES; WGII 6.1, WGII 6.2). This global impact feeds back to cities through the exposure of infrastructure, people and business to the impacts of climate-related hazards. Especially in the larger cities, this climate feedback is exacerbated by local choices in urban design, land use, building design and human behaviour (Viguié et al., 2020) that shape local environmental conditions. Local and global conditions influence the nature of hazards in urban centres: urban form can add up to 2°C to warming, concretisation of open space can increase runoff and building height and orientation influences wind direction and strength (WGII 6.3).

Building today for resilience and lower emissions is far easier than retrofitting tomorrow. As urbanisation unfolds, its legacy continues to be the locking in of emissions and vulnerabilities (*high confidence*) (Ürge-Vorsatz et al., 2018; Seto et al., 2016). Retrofitting, disaster reconstruction and urban regeneration programmes offer scope for strategic direction changes to low-carbon and high-resilience urban form and function if they are inclusive in design and implementation. Rapid urban growth means new investment, new buildings and infrastructure, new demands for energy and transport and new questions about what a healthy and fulfilling urban life can be. The USD 90 trillion expected to be invested in new urban development by 2030 (NCE, 2018), is a global opportunity to place adaptation and mitigation directly into urban infrastructure and planning, and social policy including education and health care and environmental management (Ürge-Vorsatz et al., 2018). If this opportunity is missed, if business as usual urbanisation persists, then social and physical vulnerability will be not be so easily confronted.

The benefits of actions taken to reduce greenhouse gas (GHG) emissions and climate stressors diminish with delayed action, indicating the necessity for rapid responses. Delaying the same actions for increasing the resilience of infrastructure from 2020 to 2030 is estimated to have a median cost of at least USD 1 trillion (Hallegatte et al., 2019), while also missing the carbon emissions reductions required in the narrowing window of opportunity to limit global warming to 1.5°C (WGI). In contrast, taking integrated actions toward mitigation, adaptation and sustainable development will provide multiple benefits for the health and well-being of urban inhabitants and avoid stranded assets (WGII 6.3, WGII 17; WGIII 5; WGIII 8.2; Cross-Chapter Box FEASIB in Chapter 18).

The Policy-Action Gap: Urban Low-Carbon and Climate Resilient Development

Cities are critical places to realise actions on both adaptation and mitigation simultaneously, with potential co-benefits that extend far beyond cities (*medium evidence*, *high agreement*) (Grafakos et al., 2020; Göpfert, Wamsler and Lang, 2019). Given rapid changes in the built environment, transforming the use of materials and the land intensiveness of urban development including in many parts of the Global South in the next decades will be critical, as well as mainstreaming low-carbon development principles in new urban development in all regions. Much of this development will be self-built and 'informal', and new modes of governance and planning will be required to engage with this. Integrating mitigation and adaptation now rather than later, through reshaping patterns of urban development and associated decision making processes, is a prerequisite for attaining resilient and zero carbon cities.

While more cities have developed plans for climate adaptation and mitigation since AR5, many remain to be implemented (*limited evidence*, *high agreement*) (Araos et al., 2017; Olazabal and De Gopegui, 2021; Aguiar et al., 2018). A review of local climate mitigation and adaptation plans across 885 urban areas of the European Union suggests mitigation plans are more common than adaptation plans, and that city size, national legislation and international networks can influence the development of local climate plans with an estimated 80% of cities with above 500,000 inhabitants having a mitigation and/or an adaptation plan (Reckien et al., 2018b).

Integrated approaches to tackle common drivers of emissions and cascading risks provide the basis for strengthening synergies across mitigation and adaptation, and managing possible trade-offs with sustainable development (*limited evidence*, *medium agreement*) (Grafakos et al., 2019; Landauer, Juhola and Klein, 2019). Analysis of 315 local authority emission reduction plans across the European Union reveals that the most common policies cover municipal assets and structures (Palermo et al. 2020). Estimates of emission reductions by non-state and sub-state actors in 10 high-emitting economies projected GHG emissions in 2030 would be 1.2–2.0 $GtCO_2$-eq per year or 3.8–5.5% lower compared to scenario projections for current national policies (31.6–36.8 $GtCO_2$-eq per year) if the policies are fully implemented and do not change the pace of action elsewhere (Kuramochi et al. 2020). The value of integrating mitigation and adaptation is underscored in the opportunities for decarbonising existing urban areas, and investing in social, ecological and technological infrastructure resilience (WGII 6.4). Integrating mitigation and adaption is challenging (Landauer, Juhola and Klein, 2019) but can provide multiple benefits for the health and well-being of urban inhabitants (Sharifi, 2020).

6

Cross-Working Group Box (continued)

Effective climate strategies combine mitigation and adaptation responses, including through linking adaptive urban land use with GHG emission reductions (*medium evidence*, *high agreement*) (Xu et al., 2019; Patterson et al., 2021). For example, urban green and blue infrastructure can provide co-benefits for mitigation and adaptation (Ürge-Vorsatz et al., 2018) and is an important entry point for integrating adaptation and mitigation at the urban level (Frantzeskaki et al., 2019). Grey and physical infrastructure such as sea defences can immediately reduce risk, but can also transfer risk and limit future options. Social policy interventions including social safety nets provide financial security for the most at risk and can manage vulnerability determined both by specific hazards and independently. Hazard-independent mechanisms for vulnerability reduction, such as population-wide social security, provide resilience in the face of unanticipated cascading impacts or surprise and novel climate-related hazard exposure. Social interventions can also support, or be led by, ambitions to reach the Sustainable Development Goals (Archer, 2016). Climate resilient development invites planners to plan interventions and monitor the effectiveness of outcomes beyond individual projects and across wider remits that reach into sustainable development. Curbing the emission impacts of urban activities to reach net zero in the next decades while improving the resilience of urban areas necessitates an integrated response now.

Key gaps in knowledge include urban enabling environment; how smaller settlements, low-income communities living in slums and informal settlements, but also those in rental housing spread across the city, and actions to reduce supply chain risk can be supported to accelerate equitable and sustainable adaptation in the face of financial and governance constraints (Birkmann et al., 2016; Shi et al., 2016; Dulal, 2019; Rosenzweig et al., 2018b).

Enabling Action

Innovative governance and finance solutions are required to manage complex and interconnected risks across essential key infrastructures, networks and services and meet basic human needs in urban areas (*medium confidence*) (Moser et al., 2019; Colenbrander, Dodman and Mitlin, 2018). There are many examples of 'ready-to-use' policy tools, technologies and practical interventions for policymakers seeking to act on adaptation and mitigation (Keenan, Chu and Peterson, 2019; Bisaro and Hinkel, 2018; Chirambo, 2021). Tax and fiscal incentives for business and individuals can help support city-wide change behaviour toward low carbon and risk reducing choices. Change can start where governments have most control; in public sector institutions and investment, but the challenge ahead requires partnership with private sector and community actors acting at scale and with accountability. Urban climate governance and finance needs to address urban inequalities at the forefront if the urban opportunity is to realise the ambition of the Sustainable Development Goals.

Increasing investment at pace will put pressure on governance capability and transparency and accountability of decision making (*medium confidence*) (WG II 6.6.4.5). Urban climate action that actively includes local actors and is built on an evidence base open to independent scrutiny is more likely to avoid unintended, negative maladaptive impacts and mobilise a wide range of local capacities. In the long run, this is also more likely to carry public support, even if some experiments and investments do not deliver the intended social benefits. Legislation, technical capacity and governance capability is required to be able to absorb additional finance. About USD 384 billion yr^{-1} of climate finance has been invested in urban areas in recent years. This remains at about 10% of the annual climate finance that would be necessary for low-carbon and resilient urban development (Negreiros et al., 2021). Rapid deployment of funds to stimulate economies in recovery from COVID-19 have highlighted the pitfalls of funding expansion ahead of policy innovation and capacity building. The result can be an intensification of existing urban forms, exactly the kinds of choices and preferences that contribute to risk creation and its concentration among those with little public voice or economic power.

Iterative and experimental approaches to climate adaptation and mitigation decision making co-generated in partnership with communities, can advance climate-resilient decarbonisation (*medium evidence*, *high agreement*) (Caldarice, Tollin and Pizzorni, 2021; Culwick et al., 2019; van der Heijden and Hong, 2021). Conditions of complexity, uncertainty and constrained resources require innovative solutions which are both adaptive and anticipatory. Complex interactions among multiple agents in times of uncertainty makes decision making about social, economic, governance, and infrastructure choices challenges, and can lead decision makers to postpone action. This is the case for those balancing household budgets, residential investment portfolios and city-wide policy responsibilities. Living with climate change requires changes to business-as-usual design making. Co-design and collaboration with communities through iterative policy experimentation can point the way toward CRD pathways (Ataöv and Peker, 2021). Key to successful learning is transparency in policymaking, inclusive policy processes and robust local modelling, monitoring and evaluation, which are not yet widely undertaken (Ford et al., 2019; Sanchez Rodriguez, Ürge-Vorsatz and Barau, 2018).

The diversity of cities' experiences of climate mitigation and adaptation strategies brings an advantage for those city government and other actors willing to 'learn together' (*limited evidence*, *high agreement*) (Bellinson and Chu, 2019; Haupt and Coppola, 2019). While contexts are varied, policy options are often similar enough for the sharing of experiments and policy champions. Sharing expertise can

Cross-Working Group Box (continued)

build on existing regional and global networks, many of which have already placed knowledge, learning and capacity building at the centre of their agendas. Learning from innovative forms of governance and financial investment, and strengthening co-production of policy through inclusive access to knowledge and resources, can help address mismatches in local capacities, strengthen wider Sustainable Development Goals and COVID-19 Recovery agendas (*limited evidence*, *medium agreement*). Perceptions of risk can greatly influence the reallocation of capital and shift financial resources (Battiston et al., 2021). Coupling mitigation and adaptation in an integrated approach offers opportunities to enhance efficiency, increases the coherence of urban climate action, generates cost savings and provides opportunities to reinvest the savings into new climate action projects to make all urban areas and regions more resilient.

Local governments play an important role in driving climate action across mitigation and adaptation as managers of assets, regulators, mobilisers and catalysts of action, but few cities are undertaking transformative climate adaptation or mitigation actions (*limited evidence*, *medium agreement)* (Heikkinen, Ylä-Anttila and Juhola, 2019). Local actors are providers of infrastructure and services, regulators of zoning, and can be conveners and champions of an integrated approach for mitigation and adaptation at multiple levels (*limited evidence*, *high confidence*). New opportunities in governance and finance can enable cities to pool resources together and aggregate interventions to innovate ways of mobilising urban climate finance at scale (White and Wahbah, 2019; Simpson et al., 2019; Colenbrander, Dodman and Mitlin, 2018). However, research increasingly points toward the difficulties faced during the implementation of climate financing *in situ*, such as the fragmentation of structures of governance capable of managing large investments effectively (Mohammed et al., 2019).

Scaling up transformative place-based action for both adaptation and mitigation requires enabling conditions including land-based financing, intermediaries and local partnerships (*medium evidence*, *high agreement*) (Tirumala and Tiwari, 2021;). Governance structures that combine actors working at different levels with different mixes of tools are effective in addressing challenges related to implementation of integrated action, while cross-sectoral coordination is necessary (Singh et al., 2020). Joint institutionalisation of mitigation and adaptation in local governance structures can also enable integrated action (Göpfert et al., 2020; Hurlimann et al., 2021). However, the proportion of international finance that reaches local recipients remains low, despite the repeated focus of climate policy on place-based adaptation and mitigation (Manuamorn, 2019). Green financing instruments that enable local climate action without exacerbating current forms of inequality can jointly address mitigation, adaptation and sustainable development. Climate finance that also reaches beyond non-state enterprises, including SMEs, communities and NGOs, and is responsive to the needs of urban inhabitants, including disabled individuals and different races or ethnicities, is essential for inclusive and resilient urban development (Colenbrander, Dodman and Mitlin, 2018Frenova, 2020). Developing networks that can exert climate action at scale is another priority for climate finance.

The urbanisation megatrend is an opportunity to transition global society. Enabling urban governance to avert cascading risk and achieve low-carbon, resilient development will involve co-production of policy and planning, rapid implementation and greater cross-sector coordination, monitoring and evaluation (*limited evidence*, *medium agreement)* (Grafakos et al., 2019; Di Giulio et al., 2018). New constellations of responsible actors are required to manage hybrid local-city or cross-city risk management and decarbonisation initiatives (*limited evidence*, *medium agreement*). These may increasingly benefit from linkages across more urban and more rural space as recognition of cascading and systemic risk brings recognition of supply chains, remittance flows and migration trends as vectors of risk and resilience. Urban governance will be better prepared in planning, prioritising and financing the kind of measures that can reduce GHG emissions and improve resilience at scale and pace when considering a view of cascading risks and carbon lock-ins globally, while acting locally to address local limitations and capacities, including the needs and priorities of urban citizens (Colenbrander, Dodman and Mitlin, 2018).

Frequently Asked Questions

FAQ 6.1 | Why and how are cities, settlements and different types of infrastructure especially vulnerable to the impacts of climate change?

Cities, settlements and infrastructure become vulnerable when investment decisions fail to take the risks of climate change fully into account. Such failures can result from a lack of understanding, competing priorities, a lack of finance or access to appropriate technology. Around the world, smaller cities and poorer populations are often most vulnerable and suffer the most over time, while large cities can register the greatest losses to individual events.

The world is urban. Billions of people live in towns and cities. Hardly anyone, even in remote rural locations, is separated from the flows of trade that connect the world and are held together by networks of transport and communication infrastructure systems. Connected networks once broken can cascade out, multiplying impacts across urban and rural areas. When major manufacturing centres or regionally important ports are impacted, global trade suffers. For example, flooding in Bangkok in 2011 led to a global shortage in semiconductors and a slowdown in global computer manufacturing.

Despite cities generating wealth, additional vulnerability to climate change is being created in urban areas every day. Demographic change, social and economic pressures, and governance failures that drive inequality and marginality mean that increasing numbers of people who live in towns and cities are exposed to flooding, temperature extremes and water or food insecurity. This leads to an adaptation gap, where rich neighbourhoods can afford strategies to reduce vulnerability while poorer communities are unable to do the same. Although this would be so even without a changing climate, climate change increases the variability and extremes of weather, exposing more people, businesses and buildings to floods and other events. The combination of rising vulnerability and increasing exposure translates to a growth in the number of people and properties at risk from climate change in cities worldwide.

Around the world, vulnerability is rising but differs considerably between and within urban areas. Settlements of up to 1 million people are the most rapidly expanding and also among the most vulnerable. These settlements often have limited community level organisation and might not have a dedicated local government. Coping with rapid population growth under conditions of climate change and constrained capacity is a major challenge. For large cities, multiple local governments and well-organised community-based organisations interact with large businesses and national political parties in a complicated cocktail of interests that can interfere with planning and action to reduce vulnerability.

For the poorest living in urban slums, informal settlements or renting across the city, lack of secure tenure and inadequate access to basic services compound vulnerability. But even the wealthy in large cities are not fully protected from climate change-related shocks. Just like breaks in infrastructure between towns and rural settlements, big city infrastructure can be broken by even local landslides, floods or temperature events, with consequences cascading across the city. Electricity blackouts are the most common and can affect water pumping, traffic regulation and streetlights, as well as hospitals, schools and homes. Still, it is the urban poor and marginalised who experience the greatest exposure, most vulnerability and least capacity to cope.

Rounds of exposure and impact can reduce the capacity of survivors to cope with future events. As a result, the already vulnerable and exposed become more vulnerable over time, increasing urban inequalities. But this need not be the case. Focussing on vulnerability reduction is not easy, it requires joined-up action across social and economic development sectors, together with critical infrastructure planning. It often also means partnering local government with informal and community-based actors. But there is considerable experience globally on what works and how to deliver reduced vulnerability for the urban poor and for cities as a whole. The challenge is to scale up this experience and accelerate its application to keep pace with climate change and address the adaptation gap.

Frequently Asked Questions

FAQ 6.2 | What are the key climate risks faced by cities, settlements and vulnerable populations today, and how will these risks change in a mid-century (2050) 2°C warmer world?

Climate change will interact with the changing physical environment in cities and settlements to create or exacerbate a range of risks. Rising temperatures and heatwaves will cause human illness and morbidity, as well as infrastructure degradation and failures, while heavy rainfall and sea level rise will worsen flooding. Low-income groups and other vulnerable populations will be affected most severely because of where they live and their limited ability to cope with these stresses.

Cities and settlements are constantly changing. Their populations grow and shrink, economic activities expand or decline, and political priorities shift. The risks that cities and their residents face are influenced by both urban change and climate change. The seriousness of these risks into the 21st Century will be shaped by the interactions between drivers of change including population growth, economic development and land use change.

In a warming world, increasing air temperature makes the urban heat island effect in cities worse. One key risk is heatwaves in cities that are *likely* to affect half of the future global urban population, with negative impacts on human health and economic productivity. Heat and built infrastructure such as streets and houses interact with each other and magnify risks in cities. For instance, higher urban temperatures can cause infrastructure to overheat and fail, as well as increase the concentration of harmful air pollutants such as ozone.

The density of roads and buildings in urban areas increases the area of impermeable surfaces, which interact with more frequent heavy precipitation events to increase the risk of urban flooding. This risk of flooding is greater for coastal settlements due to sea level rise and storm surges from tropical cyclones. Coastal inundation in the Miami-Dade region in Florida, USA, is estimated to have caused over USD 465 million in lost real estate value between 2005 and 2016, and it is *likely* that coastal flood risks in the region beyond 2050 will increase without adaptation to climate change.

Within cities, different groups of people can face different risks. Many low-income residents live in informal settlements alongside coasts or rivers, which greatly heightens exposure and vulnerability to climate-driven hazards. In urban areas in Ghana, for example, risks from urban flooding can compound health risks, and have resulted in outbreaks of malaria, typhoid and cholera. Those outbreaks have been shown to disproportionately affect poorer communities.

Severe risks in cities and settlements also arise from reduced water availability. As urban areas grow, the amount of water required to meet basic needs of people and industries increases. When increased demand is combined with water scarcity from lower rainfall due to climate change, water resource management becomes a critical issue. Low-income groups already face major challenges in accessing water, and the situation is *likely* to worsen due to growing conflicts over scarce resources, increasing water prices and diminishing infrastructure provisions in ever-expanding informal settlements.

These key risks already differ greatly between cities, and between different groups of people in the same city. By 2050, these discrepancies are likely to be even more apparent. Cities with limited financial resources, regulatory authority and technical capacities are less equipped to respond to climate change. People who already have fewer resources and constrained opportunities face higher levels of risk because of their vulnerability. As a result of this, key risks vary not only over time as climate change is felt more strongly, but also over space, between cities exposed to different hazards and with different abilities to adapt, and between social groups, meaning between people who are more or less affected and able to cope.

Frequently Asked Questions

FAQ 6.3 | What adaptation actions in human settlements can contribute to reducing climate risks and building resilience across building, neighbourhood, city and global scales?

Settlements bring together many activities, so climate action will be most effective if it is integrated and collaborative. This requires (i) embedding information on climate change risks into decisions; (ii) building capacity of communities and institutions; (iii) using both nature-based and traditional engineering approaches; (iv) working in partnership with diverse local planning and community organisations; and (v) sharing best practice with other settlements.

Settlements bring together people, buildings, economic activities and infrastructure services, and thus integrated, cross-sector, adaptation actions offer the best way to build resilience to climate change impacts. For example, actions to manage flood risk include installing flood proofing measures within and outside properties, improving capacity of urban drainage along roads, incorporating nature-based solutions (NbS) within the urban areas, constructing flood defences and managing land upstream of settlements to reduce runoff.

Adaptation actions will be more effective if they are implemented in partnership with local communities, national governments, research institutions, and the private and third sector. Climate action should not be considered as an additional or side action to other activities. Rather, climate action should be mainstreamed into existing processes, including those that contribute to the UN Sustainable Development Goals (2015) and New Urban Agenda adopted at the UN Conference on Housing and Sustainable Urban Development (Habitat III) in 2016. Cities are already coming together through international networks to share good practice about adaptation actions, speeding up the dissemination of knowledge.

This integrated approach to adaptation in human settlements needs to be supported by various other actions, including potential co-benefits with carbon emissions reductions, public health and ecosystem conservation goals. First, information on climate risks needs to be embedded into the architectural design, delivery and retrofitting of housing, transportation, spatial planning and infrastructure across neighbourhood and city scales. This includes making information on climate impacts widely available, updating design standards and strengthening regulation to avoid development in high-risk locations. Second, the capacity of communities needs to be strengthened, especially among those in informal settlements, the poorest and other vulnerable groups including minorities, migrants, women, children, elderly, disabled and people with serious health conditions such as obesity. This involves raising awareness, incorporating communities into adaptation processes, and strengthening regulation, policies and provision of infrastructure services. Third, nature-based solutions should be integrated to work alongside traditional 'grey' or engineered infrastructure. Vegetation corridors, greenspace, wetlands and other green infrastructure can be woven into the built environment to reduce heat and flood risks, whilst providing other benefits such as health and biodiversity.

Although even the largest city covers only a small area of the planet, all settlements are part of larger catchments from which people, water, food, energy, materials and other resources support them. Actions within cities should be mindful of wider impacts and avoid displacing issues elsewhere.

Frequently Asked Questions

FAQ 6.4 | How can actions that reduce climate risks in cities and settlements also help to reduce urban poverty, enhance economic performance and contribute to climate mitigation?

If carefully planned, adaptation actions can reduce exposure to climate risk and reduce urban poverty, advance sustainable development and mitigate greenhouse gas emissions. When adaptation responses are equitable, and if a range of voices are heard in the planning process, the needs of the disadvantaged are more likely to be addressed and wider societal benefits can be maximised.

Urbanisation is a global trend which is interacting with climate change to create complex risks in cities and settlements, especially for those that already have high levels of poverty, unemployment, housing informality and backlogs of services. Many cities and settlements are seeing increasing action to manage climate risks. On top of reducing communities' exposure to climate risk, adaptation actions can have benefits for reducing urban poverty and enhancing economic performance in ways that reduce inequality and advance sustainability goals. Adaptation actions, however, can also have unintended consequences. That is why care needs to be taken to ensure climate adaptation planning and development of new infrastructure does not exacerbate inequality or negatively impact other sustainable development priorities. Climate adaptation planning is most effective when it is sensitive to the diverse ways that low-income and minority communities are more *likely* to experience climate risk, including women, children, migrants, refugees, internally displaced peoples and racial/ethnic minority groups, among others.

Adapting to climate change can have benefits for reducing greenhouse gas (GHG) emissions and urban inequalities. In cities where growing numbers of people live in informal settlements, introducing risk-reducing physical infrastructure such as piped water, sanitation and drainage systems can enhance the quality of life of the community. At the same time, those measures can increase health outcomes and reduce urban inequalities by reducing exposure to flooding or heat impacts. In less developed countries, less than 60% of the urban population have access to piped water which, in turn, impacts their health and well-being. Increasingly, housing is being built better to manage heat risk through insulation or changing building orientation, or to flood risk by raising structures, which then contributes to well-being and ability to work. Improvements to early warning systems can help people evacuate rapidly in case of storm surges or flooding. Although the most vulnerable often do not get these warnings in time.

Carefully planned nature-based solutions (NbS), such as public green space, improved urban drainage systems and storm water management, can deliver both health and development benefits. When these adaptation actions succeed, water, waste and sanitation can be improved to better manage climate risk and provide households and cities with better services. Many nature-based solutions entail bringing back plants and trees into cities, which also helps to reduce the concentration of heat-trapping GHGs in the atmosphere.

When care is taken to ensure that adaptation responses are equitable, and that a range of voices are heard in planning, the needs of the disadvantaged are more likely to be addressed. For example, a study that looked at transport plans across 40 cities in Portugal saw that some urban communities have prioritised the needs of disadvantaged users such as the elderly and disabled, while at the same time reducing urban transport emissions and enhancing public well-being and equity of transport. On the other hand, in some cities, there is evidence of emerging trade-offs associated with climate adaptation actions where sea walls and temporary flood barriers were erected in economically valuable areas and not is less well-off areas. Going forward, it is important to ensure that vulnerable groups' needs are carefully considered, both in terms of climate and other risks, as this has not been sufficiently done in the past.

Frequently Asked Questions

FAQ 6.5 | What policy tools, governance strategies and financing arrangements can enable more inclusive and effective climate adaptation in cities and settlements?

Inclusive and effective climate adaptation requires efforts at all levels of governance, including the public sector, the private sector, the third sector, communities and intermediaries such as universities or think tanks. Inclusive and effective adaptation requires action fit for the diverse conditions in which it is needed. Collaborative dialogues can help to map both adaptation opportunities and potential negative impacts.

There is no one-size-fits-all approach to ensure that climate adaptation efforts have positive results and include the concerns of everyone affected. Cities and local communities are diverse, and thus they have diverse perspectives on what responses to prioritise. Moreover, adaptation efforts may impact people's lives in very different ways. Policy tools, strategies and financial arrangements for adaptation can include all society sectors and address socioeconomic inequalities. Planning and decision making must respond to marginalised voices and future generations (including children and youth).

Efforts to adapt to climate change can be incremental, reformist or transformational, depending on the scale of the change required. Incremental action may address specific climate impacts in a given place, but do not challenge the social and political institutions that prevent people from bouncing back better. Reformist action may address some of the social and institutional drivers of exposure and vulnerability, but without addressing the underlying socioeconomic structures that drive differential forms of exposure. For example, social protection measures may improve people's capacity to cope with climate impacts, but that improved capacity will depend on maintaining such protection measures. Transformative action involves fundamental changes in political and socioeconomic systems, oriented toward addressing vulnerability drivers (e.g., socioeconomic inequalities, consumption cultures). All forms of adaptation are relevant to deliver resilient futures because of the variability of conditions in which adaptation action is needed.

Local and regional governments play an essential role in delivering planning and institutional action suited to local conditions in cities and settlements. Potential strategies can span multiple sectors and scales, ranging from land use management, building codes, critical infrastructure designs and community development actions, to different legal, financial, participatory decision making and robust monitoring and evaluation arrangements. NGOs or third sector organisations can also play a coordinating role by building dialogues across governments, the private sectors and communities through effective communication and social learning. Local action tends to falter without the support of national governments as they are often facilitators of resources and finance. They can create institutional frameworks that facilitate (rather than impede) local action. National governments also play a crucial role in the development of large-scale infrastructures.

Private actors can also drive adaptation action. The evaluation of private-led infrastructure and housing projects suggests that the prioritisation of profit, however, may have a detrimental impact on the overall resilience of a place. New institutional models such as public–private partnerships respond to the shortcomings of both the public and private sectors. Still, the evidence of them facilitating the inclusion of multiple actors is mixed.

The private sector can mobilise finance. However, the forms of finance available for adaptation are limited and directed to huge projects that do not always address local adaptation needs. Private actors tend to join adaptation projects when there is an expectation of large profits, such as in interventions that increase real estate value. Private-led adaptation can lead to 'gentrification' whereby low-income populations are relocated from urban centres and safer settlements. Models that enable the collaboration between public, private and civil society sectors have greater potential to mobilise adaptation finance in inclusive ways.

Forms of collaborative planning and decision making can create dialogues for a sustainable future in cities, settlements and infrastructure systems. Adaptation action needs multiple approaches. For example, adaptation needs both actions that depend on dialogues between multiple actors (e.g., urban planning and zoning) and action that follows strong determination and leadership (e.g., declarations of emergency and target commitments). There are adaptation actions that depend on place-based conditions (e.g., flood defences) and those that require considering interactions across scales (e.g., regulatory frameworks). The growth of adaptation capacities, fostering dialogues, empowered communities, multi-scalar assessments and foresight within current institutions can support effective and inclusive adaptation action that is also sustained in the long term.

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