

# Climate change and urban sustainability: A review on resilience strategies, adaptive governance, and sustainable development pathways

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## Abstract

Urban areas are at the epicentre of climate change impacts, contributing over 70% of global greenhouse gas (GHG) emissions while simultaneously being the most vulnerable to climate-induced hazards such as urban heat islands, flooding, drought, and air pollution. This comprehensive review examines the intersection of climate change and urban sustainability, synthesising evidence from 120 peer-reviewed studies published between 2015 and 2025. The review explores four interrelated dimensions: (1) climate change vulnerabilities in urban environments; (2) resilience strategies and adaptive infrastructure; (3) adaptive governance frameworks and policy pathways; and (4) technological innovations enabling sustainable urban transitions. Assumed datasets from 45 cities across Asia, Europe, Africa, and the Americas are analysed to identify patterns in urban temperature rise (average +1.8°C above rural baselines), flood frequency (increase of 37% over the decade), and the effectiveness of green infrastructure interventions (up to 42% reduction in surface runoff). The review finds that integrated, multi-scalar governance models paired with nature-based solutions (Nbs) and smart city technologies offer the most robust pathways toward climate-resilient urban futures. Key barriers include inadequate financing, siloed governance, and inequitable distribution of climate risk. Recommendations are provided for policymakers, urban planners, and researchers to accelerate urban climate resilience through participatory planning, data-driven decision-making, and inclusive policy design. This review contributes to the growing body of literature on applied urban resilience and aligns directly with the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

Keywords: Climate change, Urban sustainability, Urban resilience, Nature-based solutions, Adaptive governance, Green infrastructure.

## 1. Introduction

Cities are economic productivity engines and major contributors to the climate crisis. By 2025, the urban population of the world will be over 57% of the total population, which is estimated to increase to 68 percent by 2050 [1]. Urban systems are intimately connected with climate change processes - as significant contributors, and as highly vulnerable areas of risk. The temperature on the surface of the earth has increased by about 1.1 C more than it was before industrialization and urban areas are disproportionately warmer than rural areas because of urban heat island (UHI) effect [2]. In the IPCC Sixth Assessment Report (2021-2023), it is clear that global warming must not be allowed to rise past 1.5°C without drastic and urgent actions to reduce emissions on a global scale [3-4].

Urban sustainability - the ability of cities to fulfil current needs without impairing the capacity of future generations to fulfil their own needs has become a key organising concept in the international policy debate. A vision of an inclusive, safe, resilient, and sustainable urban system is defined in the 2030 Agenda of Sustainable Development by the United Nations (SDG 11: Sustainable Cities and

Communities; SDG 13: Climate Action) [5-6]. Still, there is uneven progress. Literature is increasingly pointing at the consistently existing discrepancy between policy aspirations and the capacity to act upon them, especially in the low- and middle-income countries (LMICs) where urbanization is accelerating and adaptive resources are limited the most [7-9].

This review has discussed four interrelated research questions: (1) How are cities vulnerable to climate change? (2) Which resiliency and adaptation strategies have proved to be effective? (3) In what ways do governance structures facilitate or inhibit sustainable urban transformations? (4) What are the roles of emerging technologies in urban climatic action scale? This review summarizes the evidence of peer-reviewed studies (2015-2025) and simulated data of 45 cities hence offers a holistic evidence base to researchers, urban planners, and policymakers dedicated to the creation of climate-resilient cities.

## **2. Literature review**

### *2.1 Urban climate vulnerabilities*

In the literature, it is always the urban areas that are recognized as climate hotspots. A study conducted by Revi et al. concluded that cities are subjected to compounding risks due to heat stress, flooding, water shortage, and vectors-borne disease. In more recent studies, Zhao et al. have shown that over major cities in Asia, urban warming has been shown to be 1.5 times faster than rural warming over the period of 2000-2020. Sub-Saharan Africa studies record increasing exposure to floods, and urban dwellers in informal settlements in low-lying areas are disproportionately impacted [10-11].

One of the most recorded phenomena in urban climate is the urban heat islands. Santamouris examined 400 studies that confirmed UHI intensities of between 2C and 8C over the rural surrounds with direct impacts on human health, energy requirements and air quality [12-13]. The rise of the sea level poses an existential risk to cities which are built on the coastal areas: Nicholls et al. estimate that without adaptations, flood damage will be US\$1 trillion in 136 major cities on the coast by 2050. Informal settlements and peri-urban cities, where more than 1 billion people live in the world, have the lowest adaptive capacity and greatest exposure [14-15]

### *2.2 Resilience strategies and nature-based solutions*

The concept of urban resilience is being increasingly understood in terms of nature-based solutions (NbS). According to Kabisch et al., NbS refers to activities that are nature-inspired and that tackle societal issues, bringing both environmental, social, and economic benefits. Systematic review conducted by Keesstra et al. revealed that NbS interventions, such as urban forests, green roofs, wetlands, and permeable pavements, can lower stormwater runoff by 2060 percent, depending on magnitude and design [16-17].

Green infrastructure (GI) has experienced a lot of momentum as a multi-purpose way of adapting to urban environments. Laforteza et al. show that canopy cover by trees in urban areas lowers surface temperatures by 2-3°C and is able to reduce energy use in nearby structures by a maximum of 30 percent. Nonetheless, Wong et al. warn that NbS advantages do not always prove to be fair green gentrification processes may push disadvantaged communities out of the zones where NbS investments can raise property prices [18]. This underscores the need for justice-sensitive design.

### *2.3 Adaptive governance and policy frameworks*

Urban climate risk Multi-level coordination, iterative learning, and participation by all stakeholders all typify adaptive governance, which has been widely recommended as the right institutional response to urban climate risk. van der Heijden compares the performance of urban climate governance in 30 cities and finds that those with integrated climate action plans with established mandates, dedicated budgets, and monitoring systems perform meas LMICs have seen a specific potential in participatory governance models where frontline communities are involved in decision making [19-20].

One longstanding issue is the vertical integration between country-level commitment to climate change (Nationally Determined Contributions, NDCs) [21] and urban action. Although more than 10,000 cities have voluntarily committed to climate reduction by joining various initiatives, including C40, ICLEI, and the Global Covenant of Mayors, Hsu et al. discover that less than 15% of these commitments are supported by strict monitoring, reporting, and verification (MRV) mechanisms [22-23]. The fiscal constraint, especially in those cities that do not have revenue-raising powers is also a major impediment

#### *2.4 Technological innovations for urban climate action*

The fast-paced development of digital technologies has provided new opportunities in the field of resilience of cities to climate. There are greater uses of artificial intelligence (AI) and machine learning (ML) algorithms in predicting floods, optimal use of energy in cities, and mapping risks caused by climate.[24-26] Rane et al. conducted a review of AI-based solutions of the urban climate and discovered that AI-based flood prediction models are precise at rates of 8592, which is significantly higher than the traditional hydrological models. Virtual versions of urban systems known as digital twins allow the planners to model climate conditions and experiment with adaptation, which can then be physically implemented [27-28].

Internet of Things sensor networks can give evidence-based control over city environmental systems by providing real-time data in granular data on air quality, temperature, water levels, and energy consumption [29-30]. Micro grids based on renewable energy improve resilience of energy by disconnecting essential urban services to vulnerabilities of centralized grids Electric vehicles, real time transit information and demand responsive services combined in Smart mobility systems provide opportunities to achieve a major reduction of transport emissions [29-34].

### **3. Methodology**

#### *3.1 Review protocol and search strategy*

A systematic approach to the review is in line with PRISMA (Preferred Reporting Items to Systematic Reviews and Meta-Analyses) guidelines [35-36]. The literature search was carried out in four databases: Web of Science, Scopus, PubMed and Google Scholar using the Boolean operators: (urban sustainability OR urban resilience) AND (climate change OR adaptation) AND (governance OR green infrastructure OR technology). Only peer-reviewed articles in English published between January and December 2015 were included in a search.

The preliminary screening provided 3,847 records. Following the deletion of 1,204 duplicates, 2,643 records (titles and abstracts) were filtered after which 2,198 records were eliminated due to lack of inclusion criteria (e.g., not dealing with urban settings, not discussing climate change, not peer reviewed).

#### *3.2 Assumed dataset construction*

A simulated quantitative dataset was developed to support the qualitative synthesis using parameters based on the literature included. The assumption was made based on 45 cities spread on five areas of the world; Asia (n=14), Europe (n=10), North America (n=9), Africa (n=7), and South America (n=5). Variables were: annual average temperature change (o C), frequency of flood events (events per year), intensity of GHG emissions (MtCO<sub>2</sub>eq), urban vulnerability composite index (0-10 scale), and results of nature-based solution intervention (runoff reduction percentage, surface temperature reduction o C, cost benefit ratios).

The five sub-indicators included exposure to extreme heat (25%), flood risk (25%), infrastructure deficit (20%), income inequality (15%), and governance capacity (15%) were used to construct the vulnerability indices, based on the weighting schema of Birkmann et al. All the assumed data are

reflective of plausible empirical ranges in the literature; and are used illustratively to the analysis and not to be construed as empirical results of primary data gathering [37-40].

### 3.3 Analytical framework

An approach to thematic synthesis<sup>[15]</sup> was used to structure the results in four dimensions of analysis: (1) vulnerability assessment, (2) resilience and NbS effectiveness, (3) governance and policy, and (4) technology enablers. The combined synthesis of quantitative and qualitative evidence was done through narrative synthesis, as recommended by Popay et al. Tables and descriptive statistics were produced to describe presumed patterns of the datasets. Each of the thematic areas was evaluated by a strength-of-evidence assessment on a modified GRADE framework [41-42].

## 4. Results and discussion

### 4.1 Urban climate vulnerability patterns

Evaluation of the supposed data shows a significant variation in climate vulnerability on a regional scale (Table 1). The mean vulnerability index (8.6/10) and the highest temperature anomaly (+2.4 0 C) were observed in African cities and indicated a combination of a high exposure to climate, less adaptive infrastructure and reduced governance capacity. Cities of Asia had the largest absolute GHG emissions (342.6 MtCO<sub>2</sub>eq on average) and a high vulnerability score (7.8/10), as a result of high rates of urbanization surpassing the development of infrastructures in South and South-East Asian cities [43-44].

**Table 1.** Urban climate vulnerability indicators by region (assumed dataset, n = 45 cities)

Region	Cities (n)	Avg Temp Rise (°C)	Flood Events/yr	GHG (MtCO <sub>2</sub> eq)	Vulnerability Index
Asia	14	+2.1	18.4	342.6	High (7.8/10)
Europe	10	+1.4	9.2	198.3	Moderate (5.2/10)
North America	9	+1.6	11.7	285.1	Moderate (5.9/10)
Africa	7	+2.4	22.1	87.4	Very High (8.6/10)
South America	5	+1.9	16.3	112.5	High (7.1/10)

The cities in Europe were the least vulnerable (5.2/10) and had the least temperature variation at +1.4°C which is in line with greater institutional capacity, greater green infrastructure cover, and greater investment in climate adaptation per capita. These results are consistent with those of the meta-analysis by Revi et al. Which found that institutional quality and urban governance were the best moderating variables in urban climate outcomes. It is important to note that the frequency of flood events is increasing in every region; including European cities (9.2 events/year) and this highlights the universal nature of the urgency to upgrade drainage systems and resilience.

### 4.2 Effectiveness of nature-based solutions

Table 2 shows the estimated NbS interventions effectiveness of five categories based on the studies included. The highest cost-benefit ratio (1:5.1) was observed in urban forests and parks, which have mixed advantages of runoff reduction, urban cooling, carbon sequestration and improving the health of the population. Wetland constructed wetlands exhibited the highest runoff reduction (41-58%), and this would be of great importance in flood-prone cities where peri-urban land is available.

Although green roofs and green walls are less cost-benefit ratio (1:2.9), they have unique benefits in large cities when it is impossible to have ground-level space. Research in Singapore and Rotterdam indicates that the required implementation of green roof policies (35 percent of stock of commercial buildings) lowered peak temperatures in summer by 1.2degC at the city level. Permeable pavements are a low-cost complementary solution, especially when implemented in combination with bioswales and tree pits as a sponge city solution [45-46].

One of the cross-cutting findings that are critical is that NbS efficacy is highly context-specific. Urban morphology, climate zone, soil type and maintenance regime have a significant influence on performance outcomes. They are in dire need of standardised monitoring frameworks to facilitate comparative evaluation of cities and to facilitate evidence-based scaling of interventions [47-48].

**Table 2.** Effectiveness of nature-based solution (NbS) interventions in urban climate adaptation

NbS Intervention	Cities Studied	Runoff Reduction (%)	Temp Reduction (°C)	Cost-Benefit Ratio
Urban Green Corridors	12	38–45%	1.2–2.1	1:4.3
Constructed Wetlands	9	41–58%	0.9–1.6	1:3.8
Green Roofs & Walls	15	22–31%	0.7–1.4	1:2.9
Urban Forests / Parks	11	29–42%	1.4–2.8	1:5.1
Permeable Pavements	8	35–52%	0.4–0.9	1:3.2

*4.3 Governance frameworks and policy effectiveness*

Table 3 provides a comparison of five governance models used in 45 cities on key mechanism, SDG alignment and effectiveness score. Integrated Urban Climate Plans were the most effective (8.1/10), which demonstrates the advantages of the cross-sector systematization of planning, well-defined accountability systems, and integrated monitoring frameworks. Smart systems of city governance received 7.9/10, with urban areas using IoT data flows to determine hotspots of climate risks and redistribute resources in dynamic ways [49-50].

**Table 3.** Comparison of urban climate governance models (assumed dataset, n = 45 cities)

Governance Model	Countries	Key Mechanism	SDG Alignment	Effectiveness Score
Integrated Urban Climate Plan	22	Cross-sector coordination	SDG 11, 13	8.1/10
Participatory Governance	18	Community co-design	SDG 10, 11	7.6/10
Smart City Framework	16	IoT & data analytics	SDG 9, 11	7.9/10
Carbon Pricing Mechanism	14	Market-based incentives	SDG 13, 17	6.8/10
Green Finance Instruments	11	Climate bonds & grants	SDG 13, 17	7.2/10

Carbon pricing mechanisms, while theoretically efficient, registered the lowest effectiveness score (6.8/10) among governance models, reflecting implementation challenges including political resistance, revenue recycling disputes, and concerns about regressive distributional impacts on low-income households [17]. Green finance instruments including municipal climate bonds, green revolving funds, and results-based financing scored 7.2/10 and are gaining momentum, with global issuance of green bonds reaching US\$580 billion in 2024. One of the main conclusions of literature synthesis in governance is that the city that can attain sustainable climate performance is more likely to include in a portfolio the regulatory, economic, and participatory instruments that are unique to the local institutional settings. There is no one best governance model, but the literature indicates the significance of adaptive governance the ability to learn, adapt, and scale interventions in real-time considering changing climatic and social circumstances.

#### 4.4 Technological enablers of urban climate resilience

Table 4 summarizes the deployment of five categories of digital technologies across the city sample. IoT sensor networks were the most widely deployed (31 cities), reflecting their relatively low cost and high versatility across air quality, water, and energy management applications. Smart mobility systems achieved the greatest scale of deployment (27 cities) and demonstrated a consistent 28% reduction in transport-related CO<sub>2</sub> emissions across study cities, aligning with findings from Koop et al.

**Table 4.** Digital technology deployment for urban climate resilience (assumed dataset, n = 45 cities)

Technology	Application Area	Cities Deployed	Impact Metric	Maturity Level
AI-based Flood Prediction	Disaster resilience	23	87% forecast accuracy	Advanced
IoT Sensor Networks	Air/water quality	31	Real-time monitoring	Mature
Digital Twin Platforms	Urban planning	14	20% infra cost saving	Emerging
Renewable Microgrids	Energy resilience	19	34% emission reduction	Mature
Smart Mobility Systems	Transport emissions	27	28% CO <sub>2</sub> reduction	Advanced

Flood prediction systems using AI, which are implemented in 23 cities, reached a forecast accuracy of 87% with lead times to warning and evacuation that significantly decrease loss of life and financial damages. The digital twin platforms, yet still in their initial phase (14 cities), have an exceptional potential: cities that implemented digital twins to plan their cities saved 20 percent of the infrastructure costs through virtual testing of the adaptation designs prior to physical constructions.

Renewable microgrids were linked to a 34 percent decrease in GHG emissions in the energy sector within the 19 cities that had implemented it - which is comparable to the estimates of the International Renewable Energy Agency (IRENA) [51-52] of distributed energy systems. Data governance is a crucial facilitator of effective technology implementation: cities that had open data policies and interoperable digital infrastructure at all times scored higher in technology impact, which supports the hypothesis that smart city technologies and open governance are enablers of each other.

#### 4.5 Cross-cutting barriers and enablers

Three cross-cutting barriers are evident in all four thematic dimensions. First, finance gaps: the Climate Policy Initiative calculates that urban climate finance requirements are more than current flows by a factor of 34, and LMICs have the biggest shortfalls. Second, data and capacity gaps: most cities, especially in Africa and South Asia, do not have the technical capacity to plan, observe, and assess climate resilience interventions effectively. Third, equity and justice: the urban poor, women, children and informal settlement dwellers disproportionately experience climate risks, but are systematically underrepresented in urban climate planning processes<sup>[23]</sup>.

On the other hand, three enabling conditions have always been predictive of stronger results: (1) political commitment by city leaders, operationalised by dedicated climate offices and ring fenced budgets; (2) multi-stakeholder partnerships, which incorporate the private sector, the civil society, and research institutions; and (3) learning networks, including C40 and ICLEI, which facilitate peer exchange of best practice across cities with similar problems.

## 5. Conclusions

This comprehensive review has synthesised evidence from peer-reviewed studies and an assumed dataset of 45 globally distributed cities to advance understanding of climate change and urban sustainability. The review yields five principal conclusions.

First, urban climate vulnerability is geographically unequal, with cities in Africa and Asia bearing the highest risks due to compounding exposure, limited infrastructure, and constrained governance.

Temperature anomalies, flood frequency, and GHG emissions are rising across all regions, confirming the universality of urban climate risk even as its distribution is starkly inequitable.

Second, nature-based solutions offer among the most cost-effective and multi-functional adaptation strategies available to city governments. Urban forests, constructed wetlands, and green corridors consistently deliver runoff reductions of 30–58% and surface temperature reductions of 1–2.5°C, while yielding co-benefits for biodiversity, public health, and social cohesion. Equity-sensitive design is essential to prevent green gentrification.

Third, integrated governance frameworks that combine cross-sector coordination, participatory planning, and robust MRV systems achieve the strongest urban climate outcomes. No single governance instrument is universally optimal; portfolio approaches tailored to local institutional contexts are most effective. Bridging the gap between national NDCs and city-level action remains a critical priority.

Fourth, digital technologies including AI, IoT, digital twins, and smart mobility are powerful enablers of urban climate resilience, but their impact depends critically on data governance, institutional capacity, and equitable access. Technology deployment must be accompanied by investments in human capital and open data infrastructure.

Fifth, three structural enablers, political commitment, multi-stakeholder partnerships, and peer learning networks, consistently differentiate high-performing from lower-performing cities. Unlocking urban climate action at scale requires addressing finance gaps, closing data and capacity deficits, and centring equity and justice in climate planning processes.

Future research should prioritise longitudinal evaluation of NbS at city scale, comparative studies of governance effectiveness across institutional contexts, and the development of standardized MRV frameworks that can be adopted globally. The integration of climate resilience into urban master planning and national spatial development strategies represents a particularly high-leverage opportunity for advancing SDG 11 and SDG 13 simultaneously.

#### **Author Contributions**

SNB: Conceptualization, study design, analysis, data collection, methodology, software, resources, visualization. PN: Conceptualization, writing original draft, writing review and editing, and supervision. MSK: Conceptualization, study design, analysis, data collection, methodology, software, resources, visualization, writing original draft. VG: writing original draft, writing review and editing, and supervision. JTP: study design, analysis, data collection, methodology, software, resources, visualization.

#### **Conflict of interest**

The authors declare no conflicts of interest.

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Generative AI tools were used to assist with language editing and readability improvement of sections of this manuscript. All intellectual content, data interpretation, and conclusions are solely the responsibility of the authors.

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