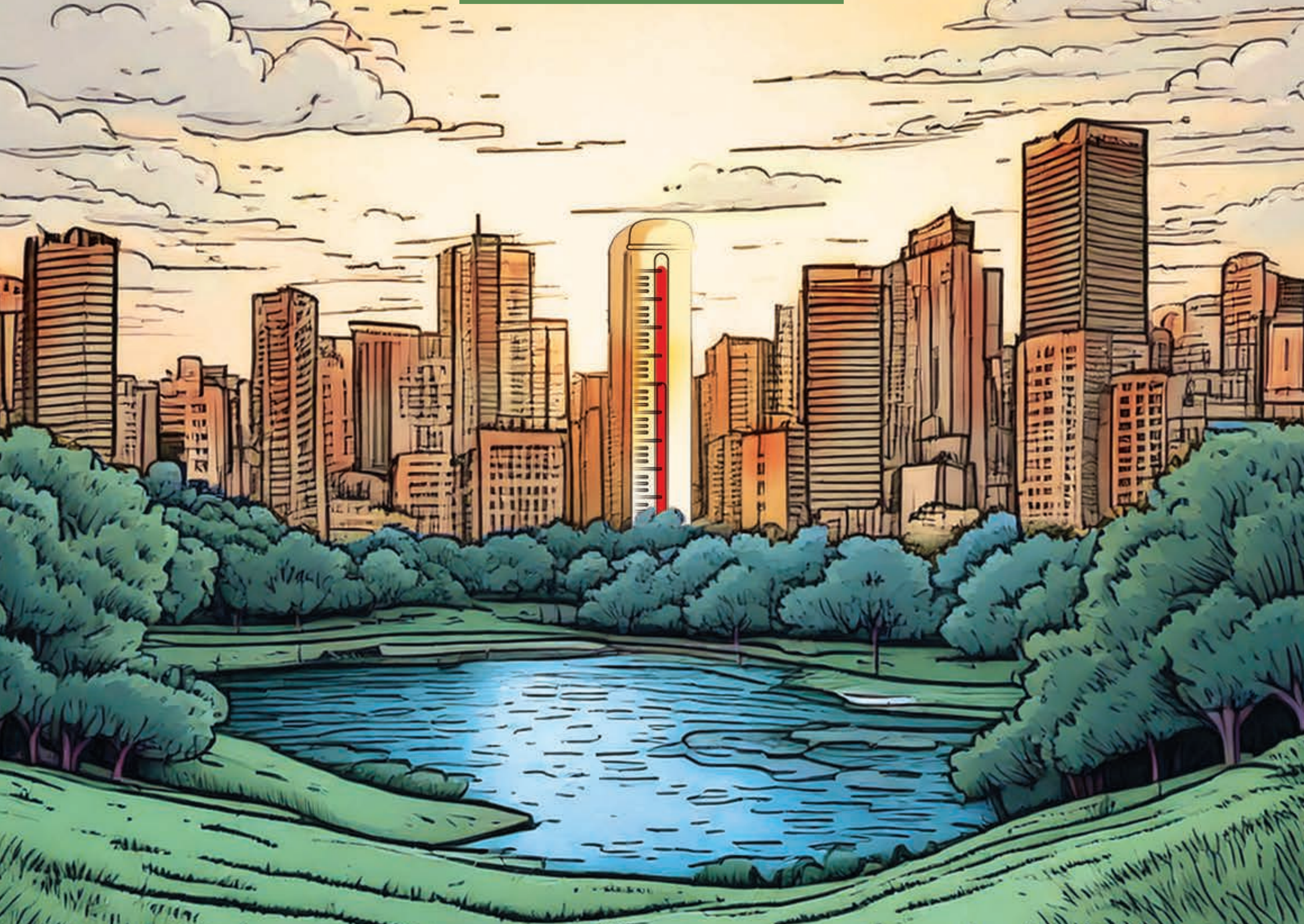
PLANNING AND DESIGNING HABITAT IN CLIMATE-RISKED TIMES

HEAT TOOLKIT



PLANNING AND DESIGNING HABITAT IN CLIMATE-RISKED TIMES

HEAT TOOLKIT

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Foreword

PRESIDENT
Institute of Town Planners, India

It gives me immense pleasure that Centre for Science and Environment, New Delhi, and Institute of Town Planners, India have prepared this toolkit titled *Planning and Designing Habitat in Climate-Risked Times*. It comes at an urgent time when India is rapidly urbanizing and the biggest of its cities are searing in heat every summer. Increasing concretization and decreasing natural heat sinks are not only making cities trap more heat but also pushing them towards other climate vulnerabilities like flooding. Therefore, both new and existing cities need to safeguard themselves from a warming environment through appropriate and guided development that this toolkit enables.

Cities are preparing climate action plans. While most of these are big cities, I am excited to take this toolkit to tier 2 and tier 3 towns where such assessments can avert the ongoing heat crisis. These towns have great potential to become models of a heat-resilient development. I also expect the findings of the spatial and temporal heat assessment that is guided in this toolkit to crucially inform new master plans or amendments in building bylaws. The Urban and Regional Development Plan Formulation and Implementation Guidelines 2014 have received an Addendum that recommends integrating heat-related interventions with master plans such as urban forestry, cool roofs, water-sensitive urban design, cool materials, etc. This assessment enables identification of areas that need these interventions the most.

Cities are now witnessing not one but multiple urban heat islands. This means that certain areas in a city are more exposed to heat than others. This raises concerns of inequitable planning. The vulnerability assessment provided in the toolkit is crucial to bridge this disparity driven by the urban form. It is also important to prioritize heat action in cities.

Finally, I am delighted that this toolkit will equip all generations of planners who are policymakers, office bearers or private practitioners in making our cities heat resilient. This is a big step in urban planning practice that comes when India is embarking upon its development curve and also contributes towards global climate commitments. This toolkit will be very useful to all built environment professionals working in small towns or municipalities.

Shri N.K. Patel
President, Institute of Town Planners, India

Foreword

EXECUTIVE DIRECTOR
Centre for Science and Environment, India

Every year India is battered by extreme weather events that impose very high social, economic and environmental costs. This is a lasting reminder of the challenge of climate change and developing within the climate-constrained world and the devastating consequences that are likely to happen if the global temperature rise exceeds 1.5°C.

The world is witnessing record-breaking summers and rising heat year after year. The predictions are that the global population exposed to deadly heat waves will more than double by 2100 under a growing emission scenario. Cities are particularly vulnerable. By 2070, over 30 per cent of the global poor population will be living outside human thermal comfort, beyond adaptive capacity. Frequent heat episodes and heatwaves are expected to worsen in tropical countries like India. In 2024 alone, several Indian cities experienced record-breaking temperatures exceeding the 50°C mark. This can have serious health consequences. Cities are particularly more vulnerable as urban areas trap more heat due to the heat island effect. Concretization, depleting waterbodies and green cover, and waste heat generation from vehicles, buildings, air conditioning and industries etc. contribute to this trend. Cities can be 10–15°C hotter than their rural surroundings.

Due to inadequate interventions, lack of mainstreaming of heat management in urban infrastructure and maladaptation making cities more vulnerable. Cities and the urban population are not able to adapt to the rising heat and build adequate safeguards for the population, especially the vulnerable population—the urban poor, elderly, children, women etc.

Solutions need to roll and accelerate immediately. Several policies and regulations, including urban development codes and model building bylaws and, Urban and Regional Development Plan Formulation and Implementation Guidelines, among others are integrating provisions for interventions. The India Cooling Action Plan (ICAP) 2019 has sought mitigation of heat and sustainable cooling solutions. But these need to add up to create a cohesive framework for accelerated adoption of energy efficiency measures, adaptive thermal comfort standards, and low-energy not-in-kind cooling technologies. On the other hand, at the city scale, resource-sufficiency measures, urban forestry, water-sensitive urban design and planning, cool materials, and passive architecture among others require implementation pathways for heat resilience and promote climate-appropriate planning in cities.

City-specific heat management plans need to go much deeper than the immediate emergency response to help cope with specific heat events during summer and prevent heat lock-in. To support and enable this process in cities, the Centre for Science and Environment (CSE) has prepared *Planning and Designing Habitat in Climate-Risked Times: Heat Toolkit*. This toolkit is a step-by-step method to help cities assess the extent of heat stress in a city, map out heat centres, estimate areas under vegetation and waterbodies, and identify factors responsible for local heat generation and growing vulnerability of the exposed population. It is based on CSE's deep-dive field investigation in nine cities from different climatic zones of India, and is designed to identify solutions for implementation.

This toolkit aims to promote sustained action on heat generators to heat proof the city and undertake heat mitigation, along with monitoring, to improve the adaptive thermal comfort, reduce heat and heat exposures, especially for vulnerable communities and occupationally exposed groups in cities.

Anumita Roychowdhury
Executive Director, Centre for Science and Environment, India

1 WHY THIS TOOLKIT?

Global exposure to deadly heatwaves is expected to more than double by 2100; many cities could warm by as much as 4°C by 2100. Tropical regions such as India face the greatest risk.

Cities are losing their ability to adapt to rising heat. Creating safeguards and mitigating rising heat by reducing energy guzzling is urgently needed.

Climate-responsive urban planning and design can reverse the heat crisis. Master plans and buildings bylaws are now integrating heat resilience in accordance with the addendums to the Urban and Regional Development Plan Formulation and Implementation Guidelines 2014 and Model Building Bye Laws 2016 respectively.

This toolkit provides a methodology for understanding the extent and drivers of heat stress in cities. This methodology has been executed for nine cities located in three out of five climate zones of India.

Some components of the methodology include evaluation of land surface temperatures, identification of heat centres, calculation of green and blue spaces, identification of drivers of local heat and vulnerability assessment.

The world is witnessing record-breaking summers year after year. Research suggests that it is warming at a pace at which the global population exposed to deadly heatwaves would more than double (from 30 per cent to 74 per cent) by 2100 under a growing emission scenario.[1,2] According to the UN, many cities could warm by as much as 4°C by 2100.[3] This has many repercussions, from public health to growing emissions. By 2070, over 30 per cent of the global poor population will be living outside human thermal comfort, beyond adaptive capacity.[4]

Tropical countries—where mercury touches or even crosses 50°C during frequent episodes of heatwaves—have it harder. In 2024, several Indian cities experienced record-breaking temperatures exceeding the 50°C mark.[5] According to the IMD database, May 2024 saw 26 out of 31 days of heatwaves across plains, hills and coastal areas of India alike. These prolonged heatwaves had severe human impacts, with the Union Ministry of Health and Family Welfare reporting 374 deaths and 67,637 cases of suspected heatstroke during March 1, 2024–July 27, 2024 across 37 cities in 17 states.[6] Independent research suggests a higher toll of 733 deaths.[7] Such episodes of extreme heat intensify in urban areas as they trap more heat due to rampant concretization and depleting natural cover, i.e. water and greens. Due to the urban heat island effect, cities can be 10–15°C hotter than their rural surroundings, exacerbating the effects.[8] Finding solutions in energy-intensive air conditioners only adds to the problem, along with other anthropogenic activities such as the use of motorized transport and industrial emissions. Under this phenomenon, cities are losing their ability to adapt to rising heat. Cities urgently need to create safeguards and mitigate it by reducing energy guzzling.

On the one hand, the India Cooling Action Plan (ICAP) 2019 recognizes the need to mitigate heat by providing sustainable cooling solutions. It guides a framework that includes adoption of building energy codes, development of adaptive thermal comfort standards, improving energy efficiency of cooling equipment and promoting low-energy not-in-kind cooling technologies as key strategies. On the other hand, an addendum to the Urban and Regional Development Plan Formulation and Implementation Guidelines 2014 and an addendum to Model Building Bye Laws 2016 have laid down the need for cities to act towards heat through urban forestry, water-sensitive urban design and planning, cool materials, and passive architecture among others. These addendums are calling cities to integrate heat resilience with master plans and building bylaws through such strategies.

These guidelines collectively highlight the potential of the built environment to cool itself down and prevent heat-trapping by appropriate planning and design. Climate-appropriate planning and a blend of modern and traditional architecture can enhance overall thermal conditions both indoors and outdoors. Cool roofs and reflective paint are examples of roofing interventions that can lower indoor air temperatures by 2.1–4.3°C. Shaded walkways can reduce air temperatures by 0.64–2.52°C compared to unshaded areas, and surface temperatures by 3.28–8.07°C.[9,10,11] These temperature reductions show opportunities to prevent heat-trapping by the built environment which leads to less active cooling and therefore lower emissions.

According to the Bureau of Energy Efficiency (BEE), energy conservation measures in buildings (such as shading, insulation and ventilation) can save up to 40 per cent of energy consumption as compared to conventional buildings in India.[12] According to the State Energy Efficiency Index 2023 report, over 20 states have notified the Energy Conservation Building Code (ECBC) 2017, which establishes minimum energy performance standards for commercial buildings to promote energy efficiency and reduce energy consumption. While 17 states have initiated steps to notify the Eco-Niwas Samhita, a code designed to improve energy efficiency in residential buildings (which form the majority of the city), it has yet to be mandated.[13] While the need to include heat resilience in statutory documents like master plans and building bylaws has been established, how to address it in cities is a road still untraversed for policymakers.

Deliberate actions so far that address heat involve preparation and implementation of heat action plans (HAP) that mainly include adaptation strategies like deployment of early warning systems and public awareness in the event of heatwaves. At present, 23 states that are prone to high temperatures leading to heat-wave conditions, have prepared and implemented Heat Action Plans (HAPs).[14] Another action involves construction of cool roofs such as by Telangana under its cool roof policy and Ahmedabad.[15] Cities need more than this. Preventive strategies that increase the ability of a city to withstand heat and reduce its impact on public have become key.

With this backdrop, understanding the extent and drivers of heat stress in the city is the first step. CSE has developed a methodology to determine the extent of heat stress in a city and its contributors. This methodology has been executed for nine cities that are located in three out of five climate zones of India. This has not only provided an overview of the extent of the problem but also led to measures needed to institutionalize heat resilience in cities.

This toolkit elaborates this methodology step-by-step, with a view to guide planners and policymakers on integration of heat resilience with master plans and building bylaws. Some of the components include evaluation of land surface temperatures, identification of heat centres, calculation of green and blue spaces, identification of drivers of local heat and vulnerability assessment. This toolkit also brings out the parameters crucial for heat management and its standardization for different kinds of development.

While the focus of this toolkit remains on safeguarding the built environment through informed planning and design, ambient heat can be mitigated further by innovation and technology as, for instance, harnessing waste heat from air-conditioning and using it for purposes such as heating water. CSE's Anil Agarwal Environment Training Institute (AAETI) campus, uses a heat pump to recycle the heat rejected by air conditioners to meet the campus's hot-water needs.[16] District cooling technologies can improve energy efficiency compared to room air conditioners, and offer opportunities to repurpose waste heat. The International Energy Agency (IEA) forecasts that active intervention through district energy models and improved building designs could reduce peak energy demand and greenhouse gas emissions by up to 55 per cent.[17] Mitigation of heat from other sources like landfill sites, open burning of waste, traffic congestion and industrial emissions opens up new avenues of research and will be covered in the second part of this heat management toolkit series.

Indian cities have a great opportunity for co-mitigation of heat with air pollution abatement action. A total of 134 cities have prepared and are implementing their clean air action plan that comprises strategies such as augmentation of green areas and waterbodies, curbing open waste burning and bio-remediation of landfill sites, enabling modal shift from motorized transport to public and non-motorized transport, installation of street fountains, vertical gardens among others.[18] Such action combined with deliberate and informed heat management strategies can deliver heat resilience in cities at speed and scale. This will not only reduce the effect of heat on public health but will also be a key contributor to India's net-zero goals.

2 PARAMETERS AND CHALLENGES ASSOCIATED WITH URBAN HEAT

CSE's analysis shows that nine major Indian cities, home to over 50 million people, are experiencing extreme heat stress, with surface temperatures reaching up to 50°C.

Cities are characterized by dense building fabric, limited green-blue spaces, inadequate ventilation and heat-retaining materials, which exacerbate the Urban Heat Island (UHI) effect.

Indian cities have traditionally safeguarded themselves against heat through climate-appropriate materials, colours, building geometry, layouts, clustering and adiabatic cooling.

Urban morphology, aspect ratio, sky view factor, materials fabric density and vegetation cover are some parameters that can regulate heat. Anthropogenic activities such as transportation, use of air conditioners and industries denote metabolism of a city comprising largely waste heat.

Urban heat presents challenges that threaten human life and the environment as rising temperatures and frequent heatwaves become common. Indian cities are transforming into virtual heat chambers, driven by climate change, development that is not climate-appropriate, and human activities. In the past two years, Indian cities have experienced extreme heat, with temperatures reaching 45–50°C, and summers arriving earlier and lasting longer. A CSE analysis of nine Indian cities, spanning various climatic zones—hot and dry, warm and humid, and composite—over the past decade reveals that all of the cities are experiencing heat stress. These cities collectively house around 50 million people, making them vulnerable to heatwaves.

Climate-inappropriate urban planning and design worsen the heat crisis. Dense grey infrastructure, few blue-green spaces, and heat-retaining materials intensify the Urban Heat Island (UHI) effect, causing temperatures to rise both in the ambient environment and indoors. The built environment suffers from poor planning and design choices, such as inadequate ventilation and heat-absorbing surfaces, which trap heat and increase discomfort.

Indian cities have traditionally been effective at safeguarding against heat through climate-appropriate materials, colours, geometry, layouts, clustering, and adiabatic cooling. These methods have always remained vital in our ways of development. However, this wisdom has not cascaded well into modern city-planning concepts.

The key now is to return to climate-appropriate planning and design, as we did traditionally. Without this approach, today's cities are boiling, discomfort is profound, and heat-related miseries are increasing. Every now or then, we hear that summer holidays are extended, a new format of shelters to safeguard outdoor workers from heat is introduced, and heat action plans are becoming a new emergency reality. We often mistakenly attribute this solely to climate change, which surely is an additional dimension in city design.

CSE dove deep into nine heat-centric cities and found that still there are substantial steps to be taken in three dimensions, i.e. how we design, how we calibrate modern requirements with traditional science, and how our choices impact this new additionality of heat.

Contributors to heat in urban areas

Urban heat is a multifaceted phenomenon influenced by a wide range of factors. These factors can be broadly categorized into three main levels: urban cover, urban structure, and urban metabolism.

CHALLENGES DUE TO URBAN HEAT

Deterioration in public health

High temperatures can cause a range of heat-related illnesses, including heatstroke, heat exhaustion and dehydration. This particularly impacts vulnerable groups like the elderly and children. Extreme heat also exacerbates respiratory conditions such as asthma and cardiovascular diseases, especially in people with preexisting health issues.

High humidity combined with heat can lead to discomfort and trigger skin diseases, asthma, migraines, stress and hay fever, further hindering daily activities. Prolonged exposure to heat may also lead to mental health problems, such as anxiety and depression.

Additionally, rising temperatures increase the transmission of vector-borne diseases like malaria and dengue, as conditions become favourable for disease-carrying insects. A nationwide survey across 20 states and Union territories by the Centre for Rapid Insights (CRI) showed that 45 per cent of the households reported at least one member getting sick from the heat during May 2024.[19]

Loss of working hours and productivity

High heat and elevated humidity create sultry conditions that affect both mental and physical performance, impacting overall productivity. According to The Lancet, India lost 191 billion potential work hours in 2022 due to heat exposure. This represents a 54 per cent increase compared to 1991–2000.[20]

This loss equated to US $219 billion in potential income, which is 6.3 per cent of India's GDP. It is anticipated that by 2041–60, even if the temperature rise is limited to 2°C, the annual loss of work hours will double compared to the period from 1995–2014. Without additional mitigation efforts, this loss could increase nearly 2.5 times.

Disproportionate impact on vulnerable groups

Urban heat disproportionately impacts vulnerable populations, such as economically weaker communities, the elderly, children, outdoor workers and individuals with chronic health conditions. The elderly are particularly at risk, due to their slower adaptation to temperature changes and underlying health conditions. Since the 1990s, heat-related deaths among adults over 65 have risen by 85 per cent, according to the 2023 report of *The Lancet Countdown on Health and Climate Change*.

Children are vulnerable due to their inability to regulate body temperature (due to underdeveloped sweat glands) and reliance on adults for hydration. Women, especially those in outdoor occupations, face unique health challenges due to heat exposure, including high blood pressure, delayed menstrual cycles, and physical discomfort.

Economically weaker populations, often living in congested and polluted areas, are at higher risk due to limited access to electricity, water, sanitation and healthcare.[21] Moreover, using heat-absorbing roofing materials like tarpaulin and tin sheets exacerbate this issue. Outdoor workers, such as street vendors and labourers, are exposed to extreme heat daily for a long duration, which can lead to serious health problems.

Rise in energy demands

Rising urban temperatures affect energy demand, particularly for cooling systems like air conditioning. As extreme heat intensifies, the need for cooling escalates, leading to higher electricity consumption and increased energy costs for residents. According to the India Energy Demand 2021 report,[22] the country's energy consumption has more than doubled since 2000, putting immense pressure on the power grid.

This surge in energy consumption raises household electricity bills and adds to greenhouse gas emissions, exacerbating climate change. The strain on energy infrastructure often results in load shedding and power system failures, particularly in states like Haryana, Punjab, Rajasthan and Uttar Pradesh, where peak energy demand exceeds supply.[23]

Pressure on infrastructure

High temperatures damage critical infrastructure like roads, railways and electrical grids. Roads and railways can buckle under extreme heat, leading to costly repairs and transportation disruptions. Power outages also become more frequent as electrical grids struggle to meet the rising demand for cooling. These outages disrupt public services and strain city budgets with repair and restoration costs.

Housing infrastructure, in the form of poorly insulated buildings and inadequately designed structures, becomes heat traps. This raises indoor temperatures and increases reliance on mechanical cooling systems. These challenges hinder economic productivity and highlight the vulnerability of urban infrastructure to the rising impacts of extreme heat.

Water scarcity and increasing drought-like conditions

Higher temperatures increase water demand for drinking and irrigation, which can stress urban water supplies and exacerbate water scarcity. Additionally, higher heat disrupts the natural water cycle by altering precipitation and evaporation rates, which can lead to water crises.

In 2024, water scarcity affected around 330 million people, with half the country's land area experiencing drought conditions.[24] Several states, including Andhra Pradesh, Arunachal Pradesh, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Karnataka, Maharashtra, Uttarakhand and Tamil Nadu, experienced severe droughts, worsening the challenges to urban resilience.[25]

Decline in agricultural productivity

Extreme heat poses challenges to the agricultural sector, resulting in reduced crop yields and affecting livestock health. As temperatures rise, crops struggle to grow, and livestock suffer from heat stress, leading to lower agricultural output. This can increase food prices and worsen food security, especially in heat-affected urban areas. The impact extends beyond the agricultural sector, as reduced productivity leads to higher costs for consumers.

Degraded air quality

Urban heat raises energy consumption for cooling and deteriorates air quality by promoting the formation of ground-level ozone and other pollutants.[26] Research from American conservation news web portal Mongabay[27] highlights that 110 out of 131 Indian cities that exceed safe air quality limits are in heat-prone states. This highlights a link between rising temperatures and increasing air pollution.

Impact on tourism

Extreme heat affects the tourism sector, a source of revenue for many Indian cities. Heatwaves deter tourists from visiting, leading to fewer tourists and less revenue for hotels, restaurants, and other businesses, affecting the hospitality and retail sectors. As cities become less attractive due to heat, the impact on the local economy grows worse.

Figure 1: Urban cover

Source: CSE

URBAN COVER

Urban cover refers to the broad types of surfaces or overall fabric that make up a city. It includes green, blue and grey infrastructure (see *Figure 1: Urban cover*).

Blue-green infrastructure

Blue-green infrastructure, such as waterbodies and green spaces, helps manage urban heat. Waterbodies cool the air through evaporation, while green spaces offer shade and provide cooling through evapotranspiration, aiding in the regulation of the urban microclimate.

Grey infrastructure

Grey infrastructure, such as buildings and utility infrastructures, largely impacts urban heat dynamics. In densely built areas with few blue-green spaces, heat is trapped and released gradually at night, creating the urban heat island effect. Open surfaces, including both pervious areas like bare ground and dry open fields, as well as impervious surfaces such as asphalt roads and parking lots, absorb and store heat, making cities even hotter. This makes grey infrastructure a major contributor to elevated heat levels in cities, impacting the local climate.

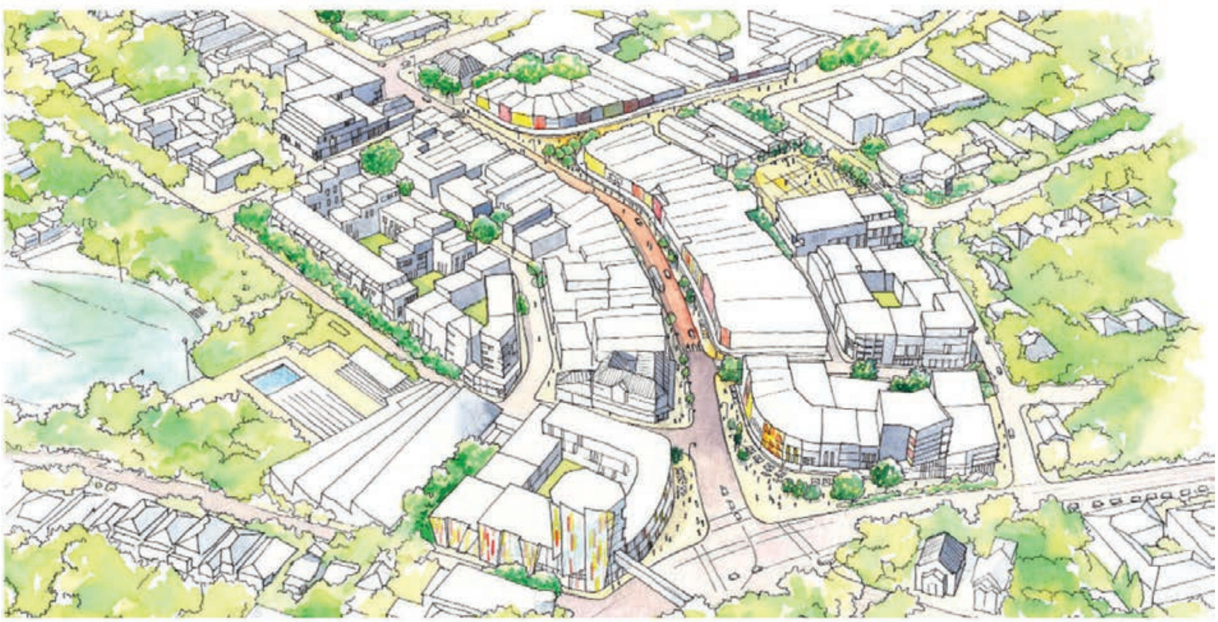
URBAN STRUCTURE

Urban structure refers to the geometry and configuration of a city at the neighbourhood level. This includes the clustering, layout, shape, size and physical arrangement of buildings and public spaces (see *Figure 2: Urban structure*). Characteristics of the urban structure include distance between building, their height, street width, vegetation, construction materials, facades, housing types, and street designs, among others. These factors influence how heat is absorbed, retained and dissipated in urban areas, and the likelihood of heat accumulation, especially in regions exposed to high temperatures.

Urban morphology

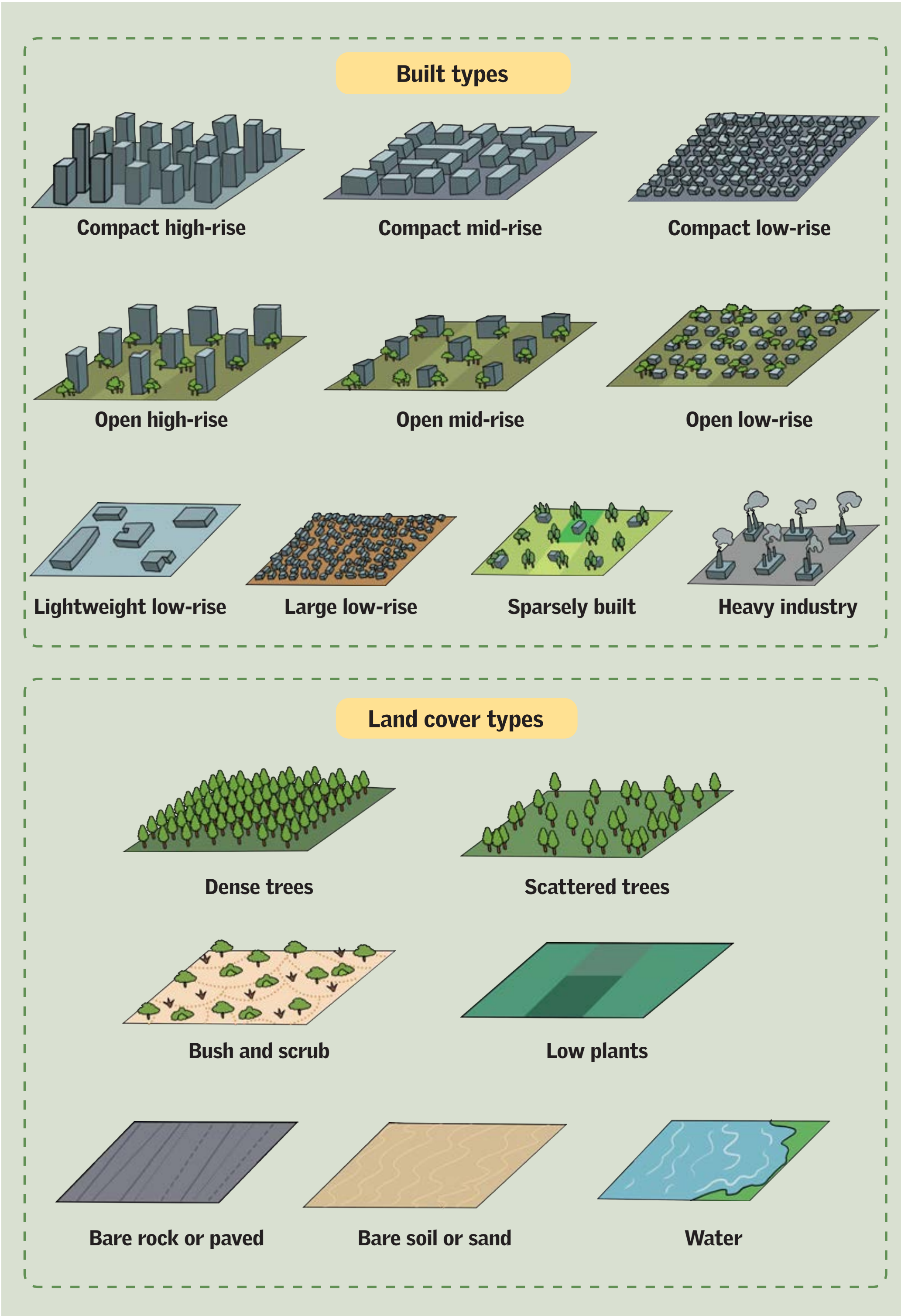
Urban morphology refers to how cities are physically laid out and organized, with a foundation of local climatic zones. It looks at how buildings, streets, open spaces and other parts of a neighbourhood are arranged. Key factors include building height, density, street patterns and block sizes. These factors determine how close together or far apart buildings are and how tall they are. This layout shapes the area and affects the local climate, especially in managing heat and using available space.

Figure 2: Urban structure



Source: https://www.atlasurban.com/page-lane-cove

Figure 3: Urban morphologies



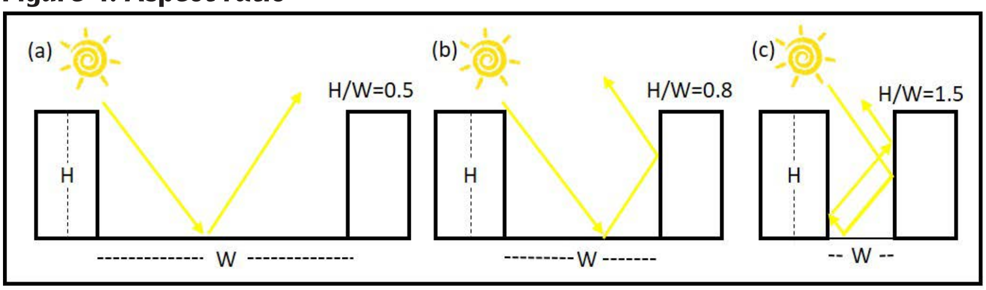
Source: Stewart and Oke (2012)

Cities can have different urban morphologies (UMs), including built types such as compact high-rise, compact mid-rise, compact low-rise, open high-rise, open mid-rise, open low-rise, lightweight low-rise, large low-rise, sparsely built and heavy industry; as well as land cover types like dense trees, scattered trees, bush/scrubs, low plants, bare rocks/paved, bare soil/sand and water. The schematic representation of each type of UM is illustrated below (see *Figure 3: Urban morphologies*). If not designed appropriately, compact morphologies can lead to reduced air circulation and trap more heat, worsening microclimatic conditions.

Aspect ratio

Aspect ratio (AR) is the ratio of building height to street width (see *Figure 4: Aspect ratio*). It plays an important role in urban heat management. AR determines how much shade buildings provide and the extent of direct sunlight exposure on the street. A higher AR can result in narrower streets, which contributes to less heat absorption, as buildings create shade and reduce direct sun exposure. However, narrower streets can hinder airflow, which is crucial for thermal comfort. Therefore, optimizing aspect ratios requires careful consideration of various factors based on specific urban conditions.

Figure 4: Aspect ratio

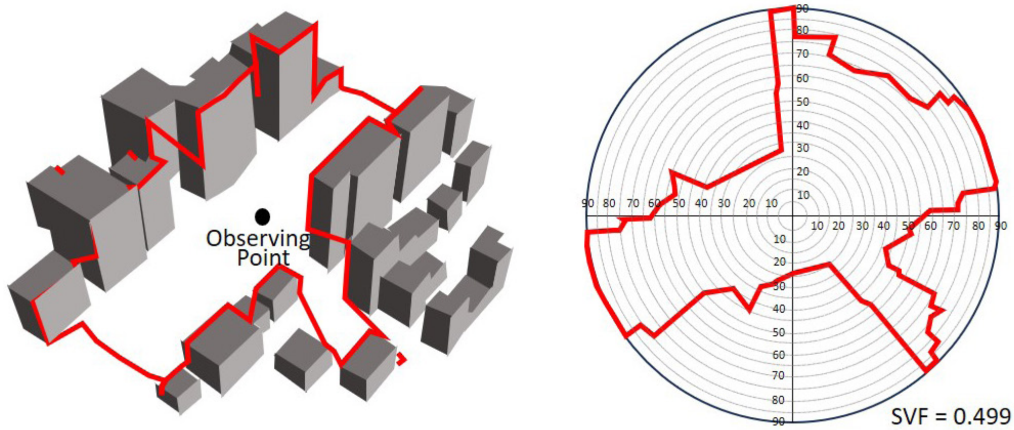


Source: Mutani, G., and Todeschi, V. (2020). The effects of green roofs on outdoor thermal comfort, urban heat island mitigation and energy savings

Sky view factor

Sky view factor (SVF) measures how much sky is visible from a certain point when looking straight up, representing a worm's eye view (see *Figure 5: Sky view factor*). It affects heat management by determining how much heat is absorbed and how air flows. SVF determines how much surface is exposed to heat during the day and how much heat can escape at night. A higher sky view factor means more heat is absorbed during the day but also allows more heat to be released at night. Therefore, optimizing SVF is important for managing heat.

Figure 5: Sky view factor



Source: Park, C., Ha, J., and Lee, S. (2017). Association between three-dimensional built environment and urban air temperature: Seasonal and temporal differences. Sustainability, 9(8), 1338.

Street orientation

Street orientation affects heat gains in urban areas by influencing shade/exposure, heat absorption and airflow. It serves as a secondary factor in defining heat absorption alongside aspect ratio and sky view factor. North–south-oriented streets typically receive more sunlight, while east–west-oriented streets may benefit from shading.

Effective vegetation cover

The presence and quality of vegetation at the building and neighbourhood level can improve the microclimate. It regulates temperature and humidity, while absorbing and decomposing pollutants, thereby improving air quality. Green spaces also provide shade and other benefits. However, the effectiveness of these benefits varies with the type of vegetation. Dense tree foliage can improve the microclimate more than low foliage trees, shrubs or grass.

Materials

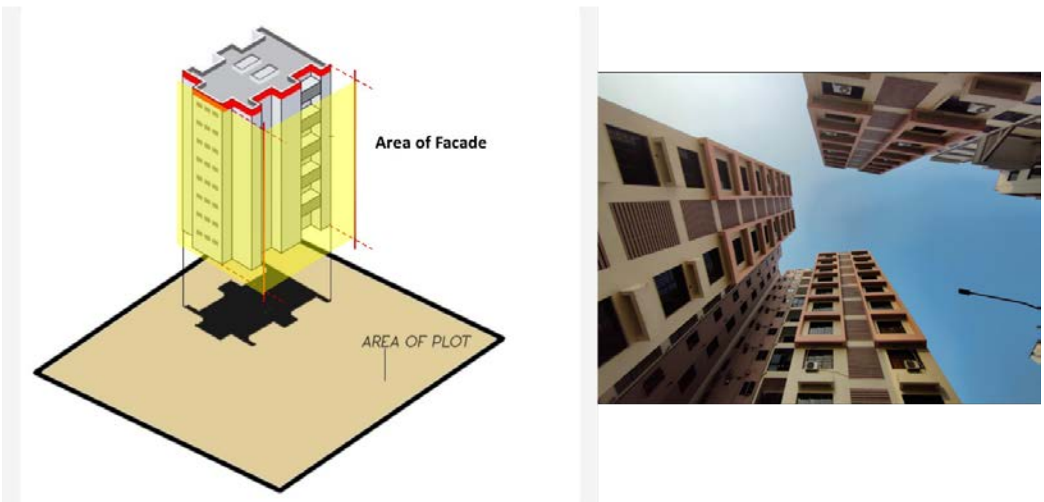
The material choice affects how heat is managed in cities. Light-coloured materials reflect sunlight and absorb less heat, keeping surfaces cooler. Dark materials like asphalt absorb heat and make surfaces warmer. Materials with high thermal mass, like concrete, store and slowly release heat, raising temperatures during both day and night. Permeable surfaces and green roofs allow for cooling through evaporation. Well-insulated buildings reduce the transfer of heat, leading to lower energy use for cooling. By choosing climate-appropriate materials, cities can effectively manage heat, reduce energy demand, and build resilience against rising temperatures.

Fabric density ratio

Fabric density ratio (FDR) is the ratio of vertical built area to total ground area (see *Figure 6: Fabric density ratio in a building*). It shows the total facade (exterior walls) area exposed to heat. Taller buildings, in particular high-rise constructions, have more surface area exposed to sunlight, which leads to higher heat absorption.

Buildings with larger facades, especially if made of materials with high thermal mass, absorb and re-radiate more solar radiation, making local temperatures rise. The colour and type of façade materials also matter, with lighter colours reflecting more heat. High FDR can increase the temperature of both the building and the surrounding area. This leads to higher energy use for cooling, which then adds more heat back into the environment.

Figure 6: Fabric density ratio in a building



Source: Understanding Floor Area Ratio (https://rerafiling.com/real-estate-articles-detail.php/9/understanding-floor-area-ratio-far)

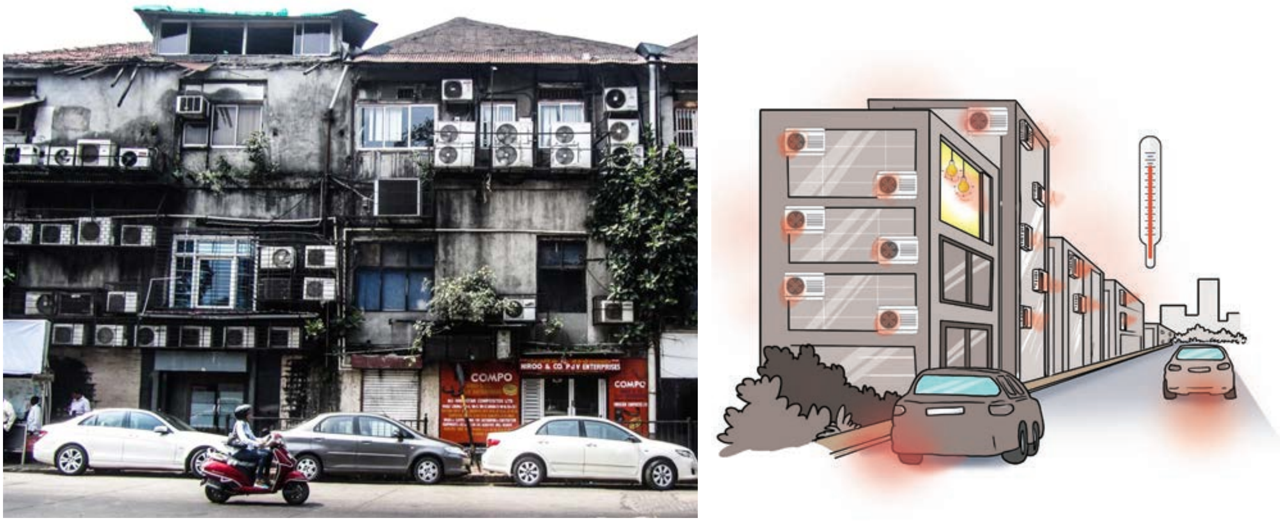
Floor area ratio

The floor area ratio (FAR) measures the density of development on a piece of land. A higher FAR means denser development, which can result in taller or more closely spaced buildings. This can result in more heat being absorbed and released, contributing to elevated heat levels.

URBAN METABOLISM

Urban metabolism describes how energy, heat and resources flow in a city. It is largely the resultant/waste heat generated by anthropogenic activities (see *Figure 7: Urban metabolism*). It focuses on the heat generated by activities like air

Figure 7: Urban metabolism



Source: *Down to Earth* and CSE

conditioner usage, vehicular emissions, and industrial processes that is released in the environment. Even in well-planned areas, high temperatures can persist due to these anthropogenic activities. They add heat and pollutants, which influence the local climate and raise temperatures

Number of air conditioners

Air conditioning units primarily transfer heat from inside buildings to the outside, raising the local air temperatures. In densely populated urban areas, many AC units run simultaneously, which increases ambient temperatures. The heat released by these units can exacerbate energy consumption during peak hours. This leads to higher greenhouse gas emissions, which intensifies the heat. On-site validation can show that this is a major factor in increasing local temperatures.

Vehicular density and traffic congestion

Vehicles release heat through their exhaust systems, particularly in areas with heavy traffic. This exhaust heat can significantly elevate local temperatures, while tailpipe emissions contribute to increased greenhouse gases, further intensifying heat. Additionally, running engines generate heat that radiates into the surrounding environment. Roads and pavements absorb and retain solar heat, and the high density of vehicles amplifies this effect by warming the road surfaces. Consequently, these surfaces re-radiate heat into the air, resulting in elevated ambient air temperatures and land surface temperatures.

Industrial activities

Industries and manufacturing units add to urban heat. They generate large amounts of heat during operations, which goes into the environment and worsens urban heat island effect. These units also release pollutants that can trap heat and contribute to air pollution, intensifying the heat problem in urban areas.

3

URBAN HEAT ASSESSMENT

TOOLS AND TECHNOLOGIES

Around 80 per cent of the geographical area in major Indian cities face heat stress.

A two-decade spatial analysis of major Indian cities reveal a decline in green spaces by up to 47.74 per cent and blue spaces by up to 42.90 per cent.

The quality of green cover is crucial for cooling, with dense tree canopies reducing surface temperatures by up to 10°C, and smaller canopies by 4–5°C.

Optimizing materials, urban morphology, aspect ratio and sky view factor can regulate land surface temperatures by up to 8°C.

Analysis highlights green-blue infrastructure and materials as major drivers of heat gains, while factors such as urban morphology, aspect ratio and sky view factor serve as key influencers.

Summer 2024 data shows that cities with high humidity, such as Chennai, experienced extreme discomfort daily from March to July.

Vulnerability assessments evaluate heat exposure, sensitive populations and adaptive infrastructure, identifying high-risk groups and aiding interventions. In Kolkata, nearly half the wards face moderate to high heat vulnerability.

Building on the understanding of urban heat, this section offers a methodology for assessing urban heat. This methodology explores parameters that act as heat sources or sinks, along with their impacts. The section outlines a step-by-step process to access data and tools for assessing urban heat at both city and granular scales. This assessment identifies key parameters that exacerbate or alleviate urban heat. The entire process aids in identifying areas that need urgent action as they may include vulnerable groups, weak safeguards or intensive anthropogenic activities. Therefore, this toolkit empowers stakeholders to make informed decisions and implement policy interventions aimed at heat mitigation and creating climate-responsive cities. It also allows city managers to build resilience and strengthen preparedness towards extreme heat events.

Methodology

Urban heat assessments can be conducted at different scales using different methods and indicators. This toolkit encompasses two key analyses: measuring the severity of urban heat and exploring the relationship between urban heat and public health (see *Table 1: Components for assessment of heat and health*). Urban heat assessment involves categorization at city, neighbourhood and local scale. This method helps identify heat pockets or small heat islands across the city as well as what is trapping heat in these pockets. It also provides performance indicators for a city, for instance, the percentage of green area in a city.

CSE conducted the citywide analysis using remote sensing and ground truthing to validate the findings and identify drivers of local heat. This methodology was applied to nine Indian cities to develop case examples. These cities include Kolkata, Pune, Chennai, Bhubaneswar, Delhi, Nagpur, Hyderabad, Jaipur and Ahmedabad. In-situ data collection, analysed alongside corresponding temperatures, provided insight into probable parameters. For the heat–health relationship, an assessment provides heat vulnerability for the wards of Kolkata.

With this backdrop, this toolkit aims not only to enhance the heat resilience of cities but also to reduce the public health impact of heat within communities. By analysing different components, it reveals heat-affected regions and identifies factors contributing to heat increases or reductions. It supports the implementation of tailored strategies that address urban heat challenges, fostering more comfortable environments.

Table 1: Components for assessment of heat and health

Level	Analysis	Tools and data sources
Measuring the severity of urban heat		
Urban cover (spatial analysis): involves assessing the overall distribution of heat-stressed areas and availability of blue-green infrastructure.	Spatial analysis of heat and identification of heat-stressed areas	Geographic Information Systems Dataset: remote sensing
	Influence of blue-green infrastructure on temperatures	Geographic Information Systems Dataset: Remote sensing
Urban structure (spatial and in situ): focuses on understanding the parameters contributing to increases or decreases in heat.	In-depth analysis of shade and exposure elements	Geographic Information Systems Dataset: remote sensing and in-situ measurements
Urban metabolism: provides information on anthropogenic sources of heat such as air conditioning, traffic congestion, industrial processes, etc.		Dataset: in-situ measurements
Urban heat and health: an interface		
City level	Heat index analysis: a measure of real feel	Dataset: India Meteorological Department (IMD), in-situ measurements and simulations/ empirical formulas
Granular level	Heat vulnerability assessment	Dataset: IMD, Census of India, Municipal corporations/municipalities, etc.

Source: CSE

This toolkit comprises several analyses (see *Figure 8: Methodological framework for heat toolkit*) including spatial analysis of heat and identification of heat-stressed areas; influence of blue-green infrastructure on temperatures; in-depth analysis of shade and exposure elements; heat index analysis, a measure of real feel; and heat vulnerability analysis.

Measuring the severity of heat

ANALYSIS OF URBAN COVER

Heat assessment of urban cover includes a city-scale analysis of the wide urban fabric. This involves identifying heat-affected areas and assessing blue and green infrastructure. The results provide insights into locations experiencing heat stress and the presence of micro-climatic enhancers, such as blue-green infrastructure, in the surrounding areas.

Figure 8: Methodological framework for heat toolkit

Spatial analysis of heat and identification of heat-stressed areas

Why? Provides information of heat hotspots

How?

Estimation of land surface temperature (Landsat series)	Selecting threshold for heat affected areas (in-situ field survey, statistically-based techniques, IMD defined heat wave)	Heat centres and heat-stressed areas

Influence of blue-green infrastructure on temperatures

Why? Understanding the adaptive capacity of land use in coping with heat hotspots. Highly beneficial when green-blue infrastructure is evenly distributed

How?

Estimation of bue and green infrastructures (manual digitization, open street maps, remote sensing data)	Selecting threshold for extracting vegetated and water spaces Using band ratio and combination methods (visual interpretation, statistical measure)	Green and blue areas across the city

In-depth analysis of shade and exposure elements

Why? Understanding the elements that contribute to making a location a significant heat hotspot and identifying the most significant element at each specific location.

How?

Field analysis (urban morphology, effective vegetation cover, choice of materials, building height, street width, aspect ratio, sky view factor, street orientation, fabric density ratio, anthropogenic heat sources)	Analysis of shade and exposure components Elements of shading—sky view factor, aspect ratio, tree canopy cover Elements of exposure—building/materials, impervious open surfaces, barren areas, waterbodies, surface greens	Heat pyramid—contribution of each parameter

Heat Index analysis—a measure of real feel

Why? Provides information on health related vulnerability. Also aids in identifying emergency response, its timing and intensity

How?

Data required (source of data) • Ambient air temperature (IMD) • Relative humidity (IMD) • Black globe temperature (in situ) • Wind speed (IMD) • Mean radiant temperature (empirical formula or simulations)	Estimation of heat index • National Oceanic and Atmospheric Administration Heat Index • Universal Thermal Climate Index • Wet Bulb Globe Temperature • Tropical Summer Index • Physiological Equivalent Temperature	Real feel of temperature

Heat vulnerability assessments—ward level

Why? To understand the impact of heat at localized level. Aids in making and improving policies and investments decisions

How?

Selecting and quantifying indicators/sub-indicators under each of the components • Exposure—reduced green and blue infrastructure • Sensitivity—below poverty line, 0–6 age group, elderly population, women population, slum population • Adaptation—access to information, access to electricity, access to tap water, number of primary healthcare centres, number of primary schools, thermal performance of roofing material	Estimation of vulnerability index • Exposure—vulnerable land/area • Sensitivity—Most vulnerable population • Adaptation—Adaptive capacity	Vulnerable wards and population

Source: Created by CSE

Spatial analysis of heat and identification of heat-stressed areas

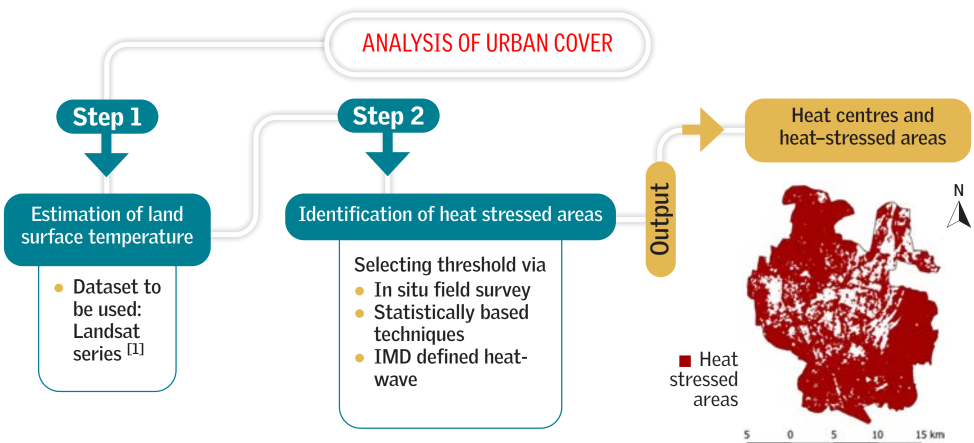
Spatial analysis of heat in urban areas provides information for urban planning, public health, infrastructure design, energy management, environmental monitoring and disaster preparedness. It involves mapping and understanding temperature variations across built-up areas, waterbodies, green spaces and barren lands, among others.

By leveraging the Geographic Information System (GIS) and remote sensing, heat-stressed areas in urban environments can be identified. This helps in creating strategies to improve microclimates in the most affected regions. Heat-stressed areas are linked to health risks such as heatstroke and dehydration, making it important to develop targeted interventions for vulnerable populations.

This analysis can help in formulating climate adaptation strategies and reducing energy requirements for cooling. The insights from heat maps guide in choice of materials and designs that minimize heat absorption. It allows authorities to predict the impact of extreme heat and devise response plans, including early warning systems and emergency responses.

The analysis involves two steps: a) Estimating land surface temperature (LST), and b) Identifying heat centres and heat-stressed areas (recurrent heat centres over the years) (see *Figure 9: Methodology and output: Spatial analysis of heat and identification of heat-stressed areas*).

Figure 9: Methodology and output: Spatial analysis of heat and identification of heat-stressed areas



Data source: [1] USGS earth explorer

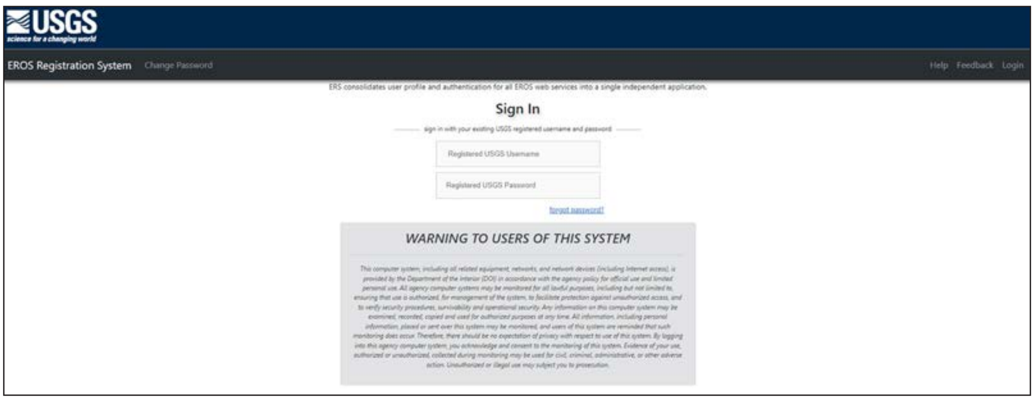
1) Estimation of land surface temperature

Land surface temperature (LST) measures how hot the earth's surface feels to the touch at a specific location. LST impacts ambient air temperature and wind patterns, and helps define the weather of a region. It serves as a vital parameter for understanding the urban heat island effect and residents' thermal comfort.

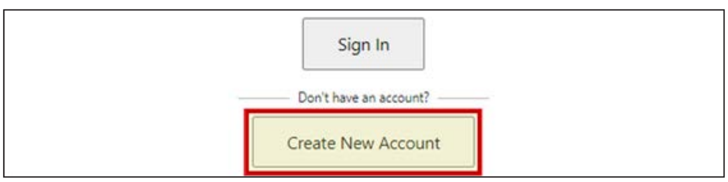
LST can be measured using remote sensing data, which is much faster and easier than collecting it on the ground. Landsat satellite provides 'Surface Temperature Science Products' at no cost for dates after August 1989. The steps to estimate LST are shown below:

Step 1: Create an account Earth Explorer

- Open the website https://earthexplorer.usgs.gov/



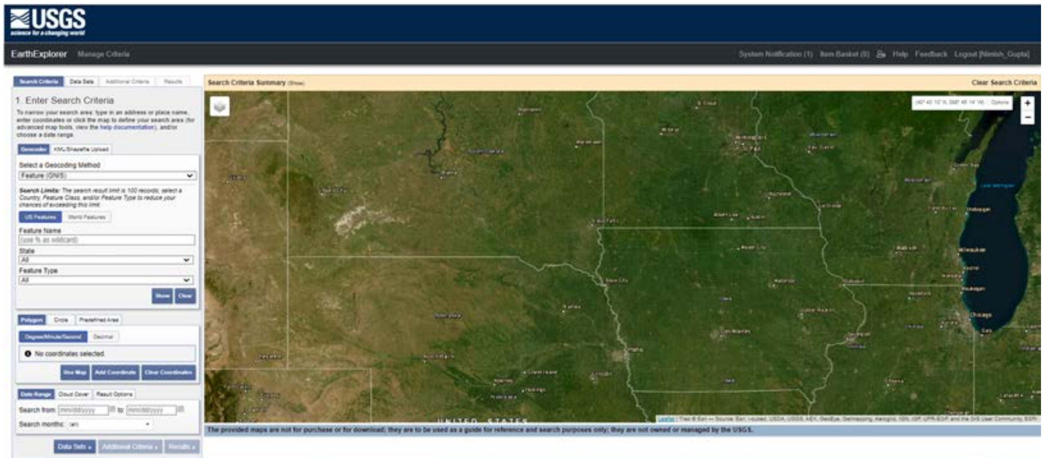
- Click on 'Create New Account'



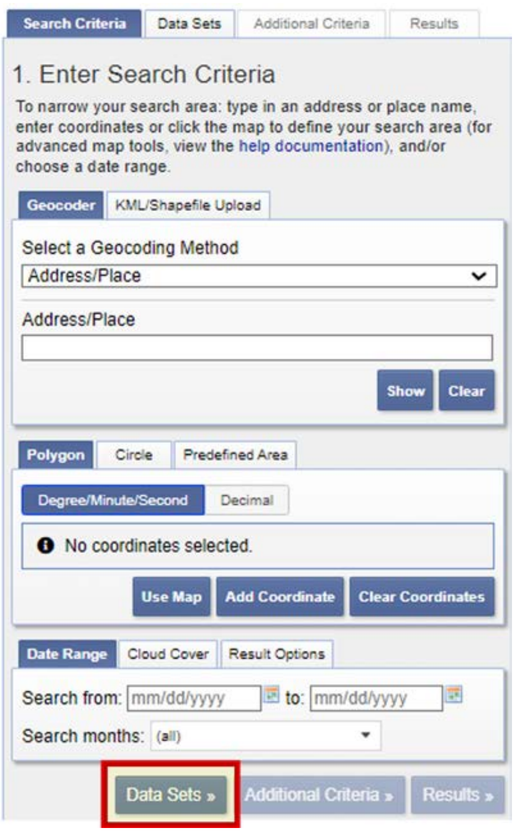
- Fill in the information and click 'continue'
- Verify the account and sign in

Step 2: Downloading remote sensing data

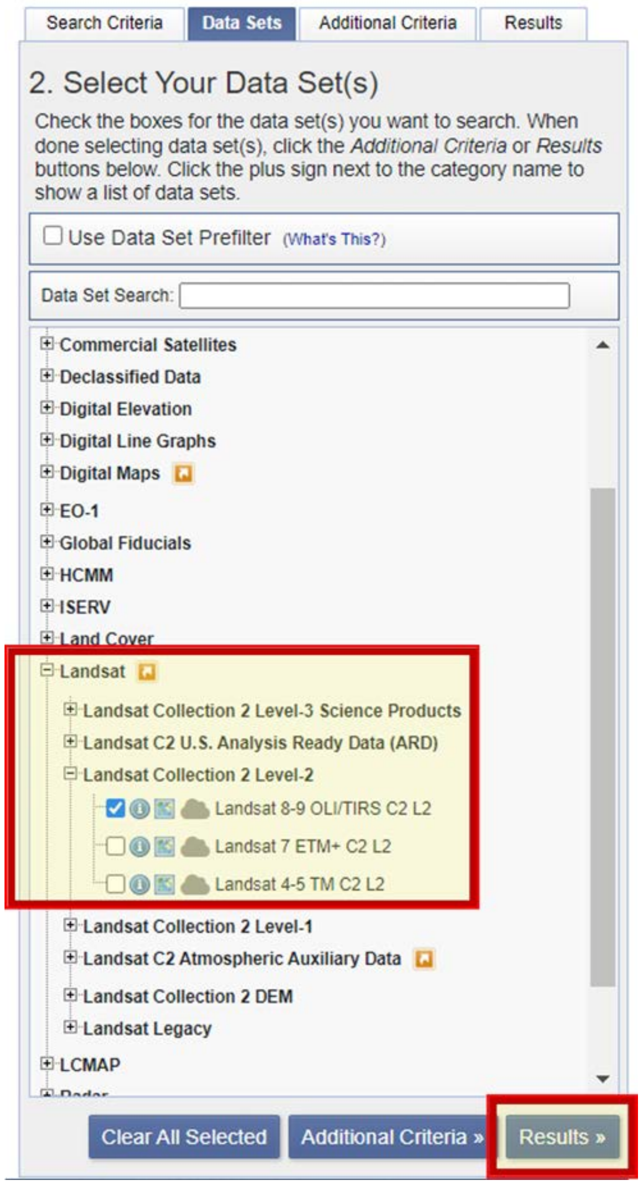
- Sign in to https://earthexplorer.usgs.gov/



- Provide inputs to ‘Search criteria’ and click on ‘Data sets’
  - » Under ‘Select a Geocoding method’ → choose ‘Address/Place’ → Type your ‘study area’ and click Show → Click on the hyperlink for your ‘study area’
  - » Under Date Range → type the range of dates for the data you need. Select the months from ‘Search Months’ for which the data is required.



- Provide inputs to 'Data Sets' and click on 'Results'
  - » Under Landsat Collection 2 Level 2 → Select 'Landsat 8/9 OLI/TIRS C2 L2'



- Download the image
  - » Choose the best image with no cloud cover over the study area—check from Metadata ( )
  - » Click on the download button ( )
  - » Choose the product option and download the product ending with '_ST_B10.TIF'

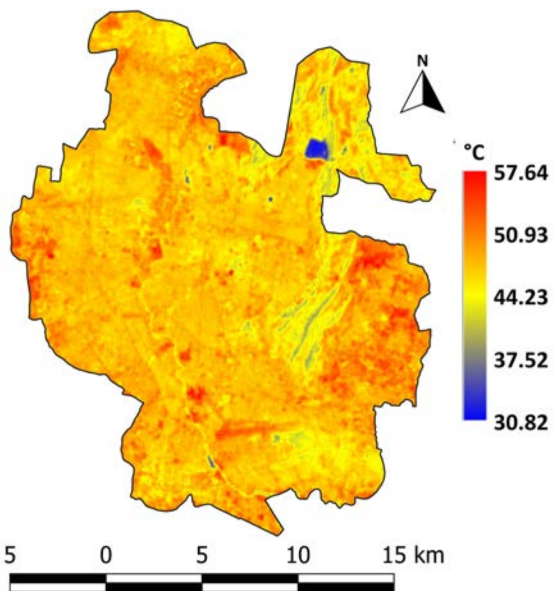
Step 3: Calculating land surface temperature

- Open QGIS (Quantum GIS) or any GIS software
- Add the downloaded satellite data and clip it to the study area
- Use Equation 1 to calculate land surface temperature

Equation 1:
LST (°C) = [(0.00341802 × *clipped satellite data*) + 149] – 273

The desired outcome obtained via 'Estimation of land surface temperature' is illustrated below (see *Map 1: Land surface temperature*)

Map 1: Land surface temperature



The average surface temperature of Jaipur city as recorded on May 8, 2023 was 47.63°C, with values ranging from 30.81°C to 57.64°C.

Data source: Landsat Series, USGS

2) Identification of heat-stressed areas

Areas with temperatures beyond a threshold, where people feel uncomfortable or stressed for a particular year, are called heat centres. In contrast, areas that consistently experience this discomfort over years are known as heat-stressed areas.

Determining this threshold is essential for identifying heat-affected regions. Thresholds can be established through in situ field surveys, statistical techniques, or the IMD-defined heatwave criteria.

DETERMINING THRESHOLDS

Thresholds are typically defined for representative indices of air temperatures; however, the values estimated spatially are land surface temperatures (LST). Therefore, a relationship must be established between them. This can be done by:

- Reviewing the literature. For example, Gallo et al. (2011)[28] suggest a mean difference of 2–7°C between LST and mean air temperature.
- Comparing LST values with the air temperatures obtained at meteorological stations.
- Setting up instruments to measure air temperature at representative locations across the study area and comparing them with LSTs obtained at the same locations (Ensure that the air temperature values correspond to the time at which the satellite captures thermal data).

a. In-situ field survey

This method involves using handheld instruments to measure air temperature, relative humidity, wind speed and globe temperature. A questionnaire survey should be conducted simultaneously to collect personal information and assess the thermal sensation of subjects. Personal information should include basic physical conditions such as gender, age, weight, height, state of activity, time spent outdoors, and clothing thermal resistance. The thermal sensation vote can be captured on a scale based on either the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Universal Thermal Climate Index (UTCI), National Oceanic and Atmospheric Administration Heat Index (NOAAHI), or user-defined ranges. These ranges should classify thermal sensations into categories such as extremely hot, very hot, moderately hot, slightly hot, and comfortable. The threshold can be determined based on responses from a representative sample size.

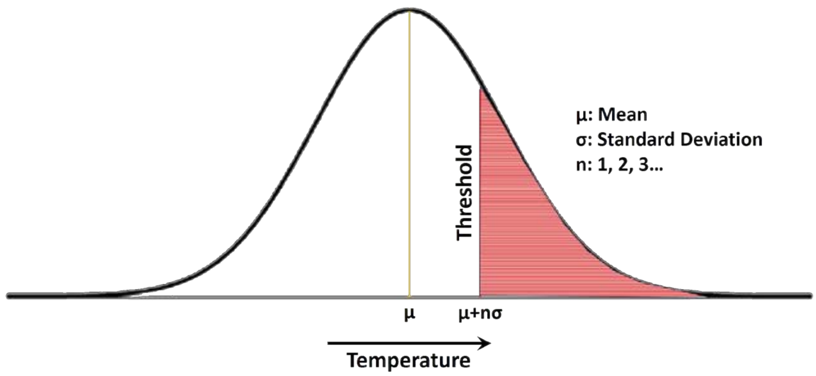
b. Statistical techniques

This method involves selecting a threshold based on a value that exceeds a specific multiplier of standard deviations from the mean temperatures (see *Figure 10: Selection of threshold using statistical technique*). The mean temperature should be based on long-term trends in the data to ensure unbiasedness, accuracy and precision.

c. IMD-defined heatwave

This method involves selecting threshold temperatures based on the criteria used by the India Meteorological Department (IMD) to categorize heatwave days. According to IMD,[29] a heatwave is considered if one or more of the following

Figure 10: Selection of threshold using statistical technique



Source: CSE

criteria are met at least in two stations within a meteorological sub-division for at least two consecutive days:

- The maximum temperature of a station reaches at least 40°C for plains, 30°C for hilly regions, and 37°C for coastal areas.
- The temperature exceeds 4.5°C above the normal temperatures. (Note: Normal temperature is calculated based on the 30-year average from a meteorological station.)
- The maximum temperature exceeds 45°C.

The desired outcome obtained via 'Identification of heat-stressed areas' is illustrated below (see *Map 2: Heat-stressed areas*)

Map 2: Heat-stressed areas

A decadal analysis (2014–23) shows that 79.23 per cent of Jaipur's geographical area experiences recurrent heat stress

Data source: Landsat Series, USGS

CASE EXAMPLE: SPATIAL ANALYSIS OF HEAT AND IDENTIFICATION OF HEAT-STRESSED AREAS

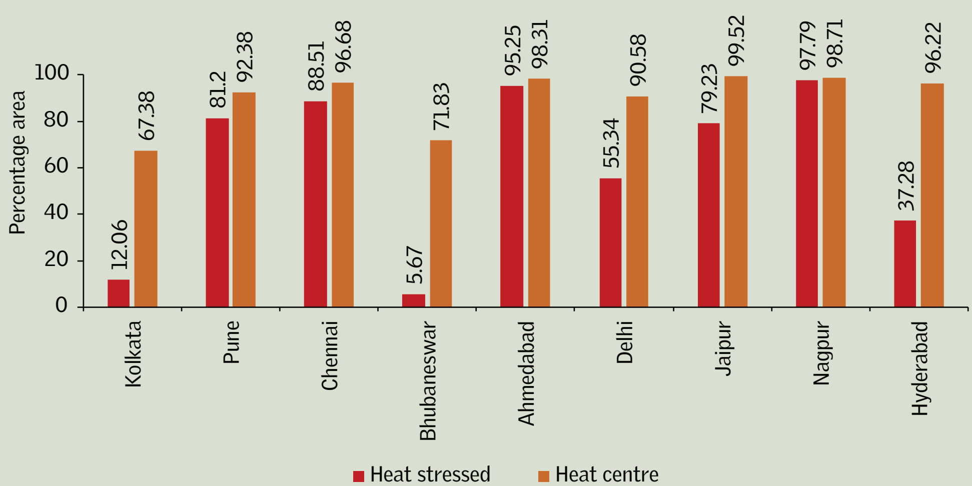
CSE conducted spatial analysis across nine cities: Kolkata, Pune, Chennai, Bhubaneswar, Delhi, Nagpur, Hyderabad, Jaipur and Ahmedabad, identifying heat-stressed areas. Satellite data for the summer months (March–July) was used to estimate LST and identify heat-stressed areas. The threshold was chosen based on 'IMD-defined heatwave criteria' (beyond 40°C for plains and 37°C for coasts). The relationship between air temperature and LST was considered as (LST = AT+5°C), based on Gallo j (2011).[30] (Note: Gallo et al. [2011] defined the relationship between air temperature and LST as ranging from 2–7 °C. A conservative estimate of 5°C was considered for the analysis).

If cloud-free images were not available for the historically hottest month, the month with the second-highest temperatures was considered. While the selected date may not always represent the highest heat-affected areas, it consistently identifies the most heat-stressed regions across a city. Heat-stressed areas were identified where heat centres have formed recurrently for six or more years during the decadal analysis (2014–23).

The analysis revealed that five out of the nine cities had approximately 80 per cent or more areas under heat stress (see *Figure 11: Identified heat-stressed areas across nine cities–land surface temperature more than threshold value for six or more years over decadal analysis*). Nagpur and Ahmedabad were identified as the worst-affected cities, with 97.79 per cent and 95.25 per cent of their regions classified as heat-stressed respectively. Chennai, Pune and Jaipur followed, with 88.51 per cent, 81.20 per cent, and 79.23 per cent of their areas associated with heat stress.

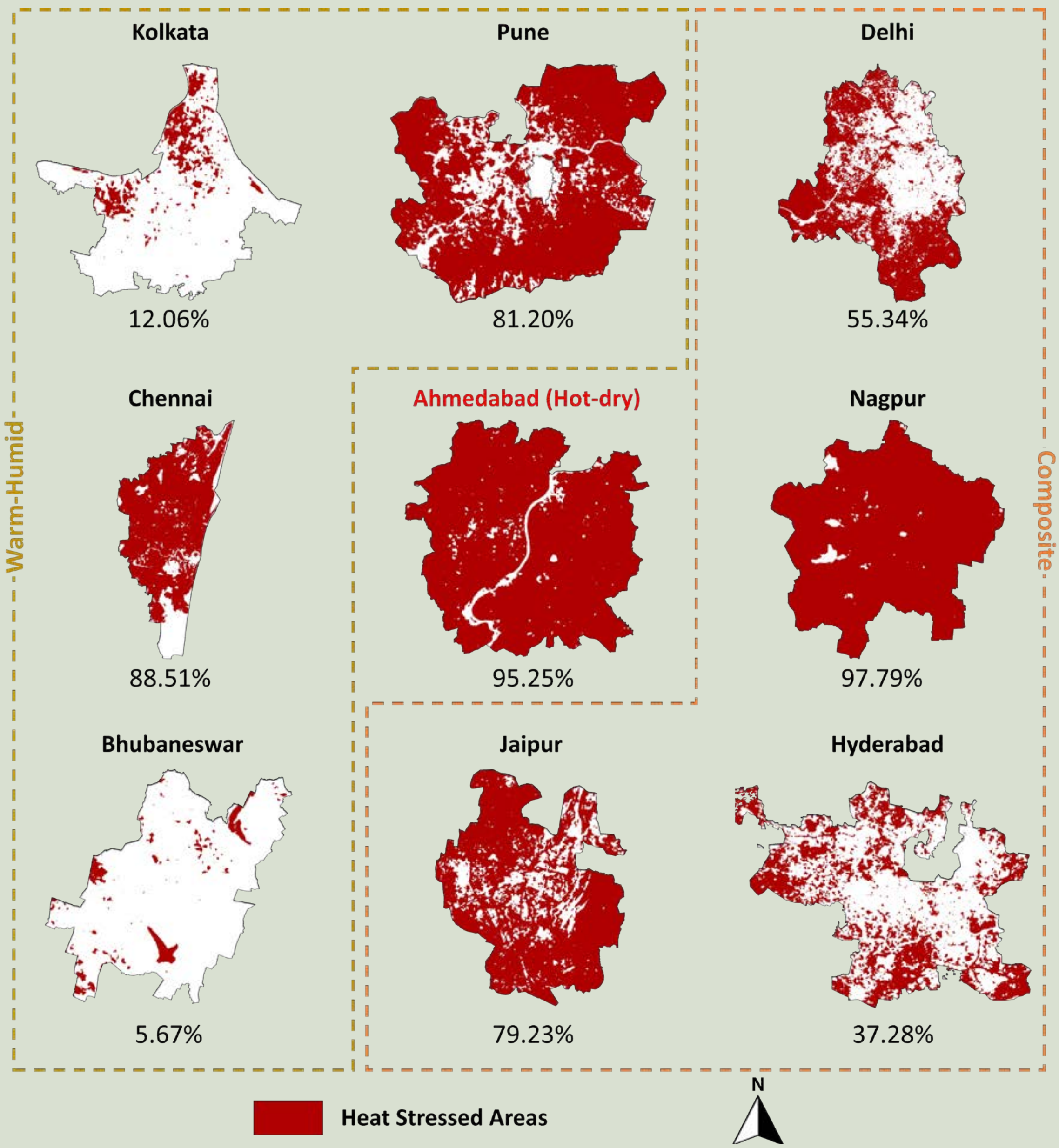
When individual years were analysed, the peak heat was even higher (see *Figure 12: Areas affected during peak heat [heat centres] in nine cities*). Most cities had more than two-thirds of their regions classified as heat centres. Except for Bhubaneswar and Kolkata, all other cities had over 90 per cent of their areas under heat centres (see *Graph 1: City-wise areas with heat centres and heat stress–recurrent heat centres*).

Graph 1: City-wise areas with heat centres and heat stress—recurrent heat centres



Data source: Landsat Series, USGS

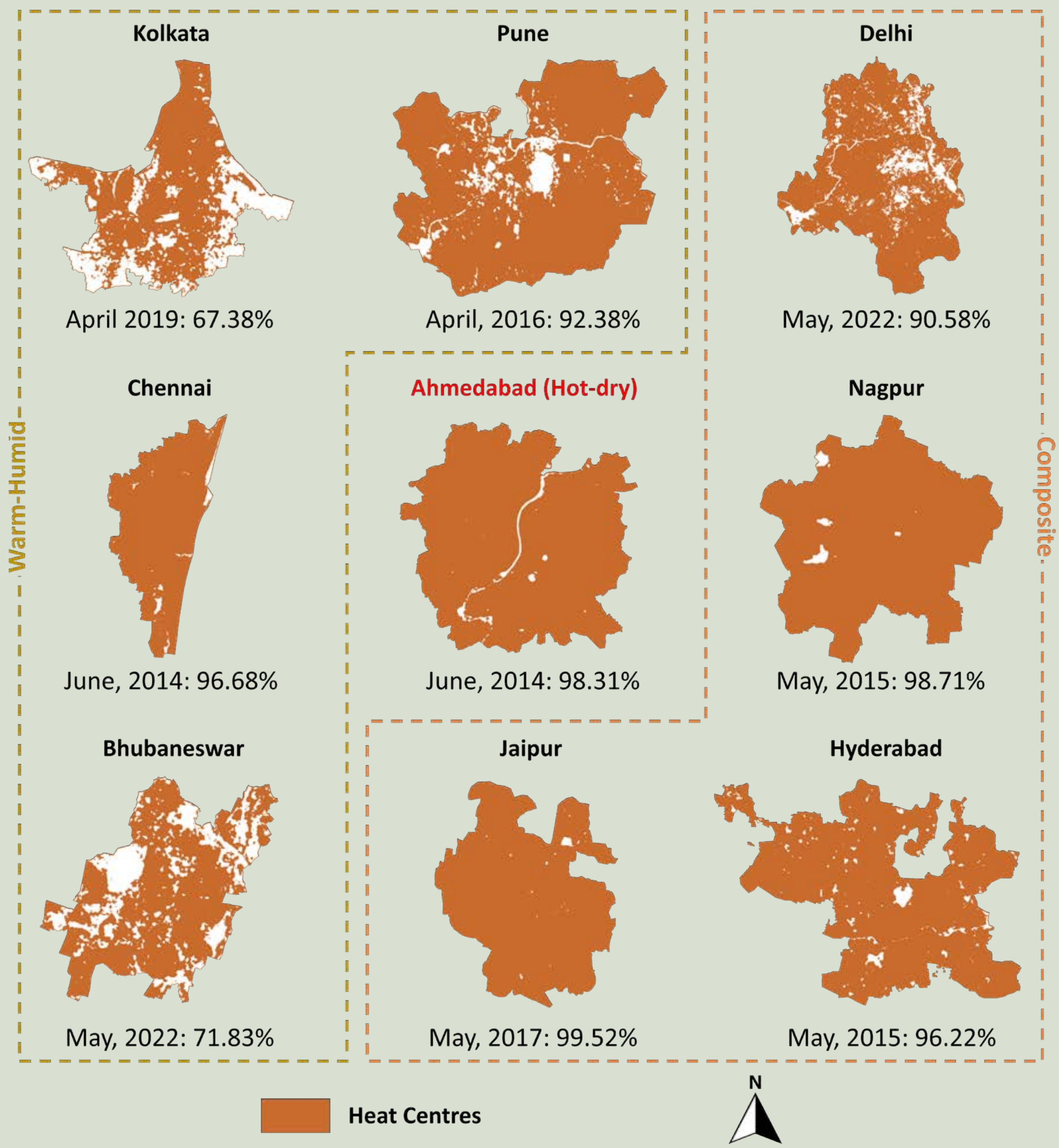
Figure 11: Identified heat-stressed areas across nine cities—land surface temperature more than threshold value for six or more years over decadal analysis



Note: The threshold chosen for all cities, except Chennai, is 45 °C. In the case of Chennai, being a coastal city, the threshold is set at 42°C.

Data source: Landsat Series, USGS

Figure 12: Areas affected during peak heat (heat centres) in nine cities



Note: Map not to scale

Data source: Landsat Series, USGS

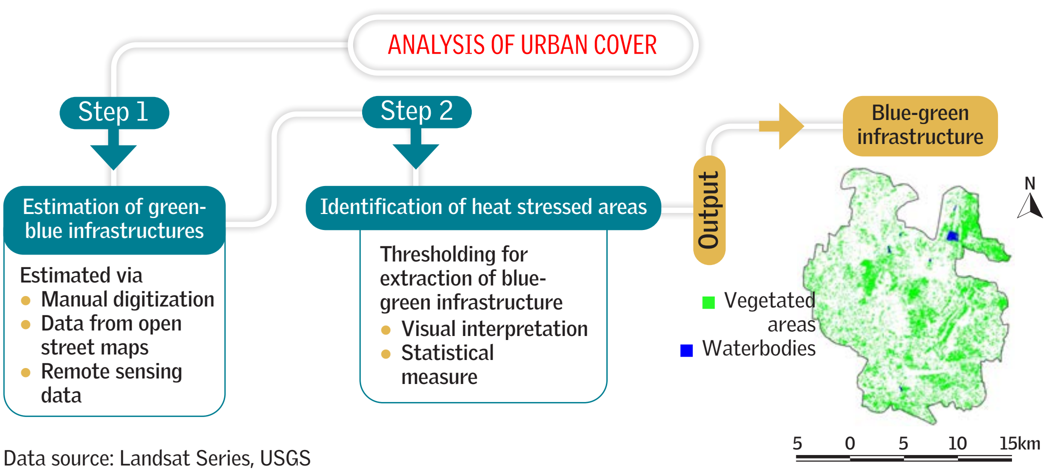
Influence of blue–green infrastructure on temperature

Blue-green infrastructure (BGI), comprising vegetation features such as parks, trees, gardens and waterbodies such as lakes, rivers and ponds, offers an effective way to reduce urban heat. Vegetation features absorb radiation and use it to convert water into vapour through evapotranspiration, preventing surface temperatures from rising. This process also cools the surrounding air by releasing moisture. Trees with dense foliage provide shade, reducing direct sunlight on surfaces and mitigating the urban heat island effect. Vegetation also sequesters carbon, helping to combat climate change and its related heat impacts. Waterbodies contribute to thermal regulation by absorbing and storing heat during the day, creating cooler microclimates.

Blue-green infrastructure improves air quality by trapping pollutants, which can otherwise contribute to heat. By lowering ambient temperatures, it reduces the need for energy-intensive cooling in buildings, cutting down energy use and heat emissions. BGI enhances outdoor thermal comfort, encouraging people to spend time outside and decreasing reliance on indoor cooling systems. It also manages storm-water runoff, limiting the heat release from impervious surfaces. The effectiveness of blue-green infrastructure in reducing heat depends on both its presence and quality.

This analysis involves two steps: a) Estimating blue-green infrastructures; b) Thresholding to extract blue-green infrastructure (see *Figure 13: Methodology and output: Influence of blue-green infrastructure on temperatures*).

Figure 13: Methodology and output—influence of blue-green infrastructure on temperatures



Data source: Landsat Series, USGS

1. Estimating blue-green infrastructure

Blue and green spaces in an urban area can be estimated using various methods. These include manual digitizing, downloading from OpenStreetMap, or classifying remote sensing data.

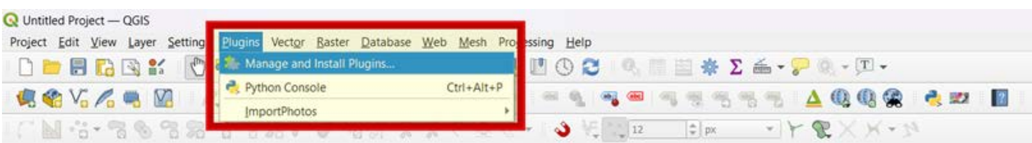
a. Manual digitization

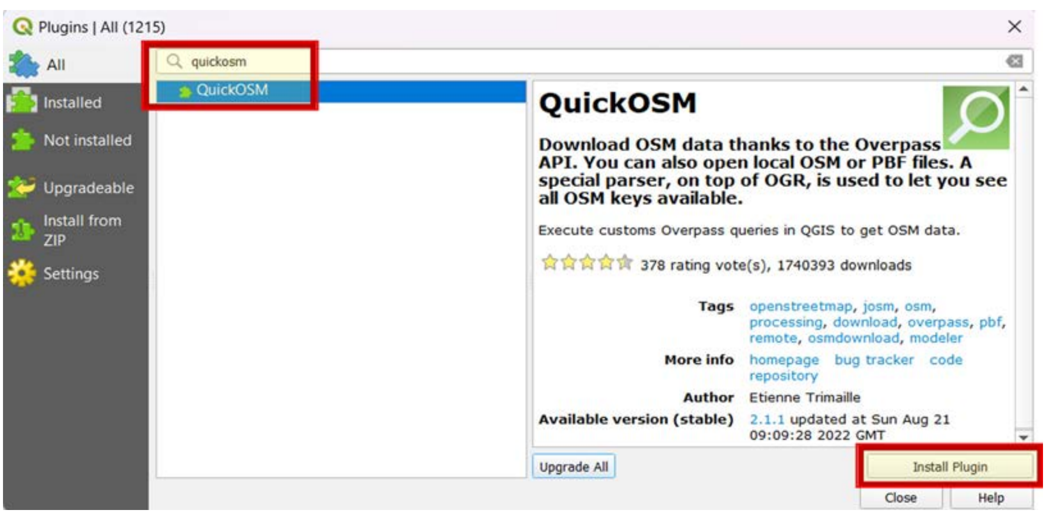
This method uses Master Plans (MP), Zonal Development Plans (ZDPs) or other plans that have the latest map of the city. The maps are assigned with location information via georeferencing, and blue-green areas are marked using GIS software. Google Earth can also be used to extract information on blue and green infrastructure.
Note: Refer to Module 14.2 and 14.3 of QGIS Training Manual for the procedure of georeferencing and digitizing (https://docs.qgis.org/3.34/en/docs/training_manual/).

b. Downloading from Open Street Maps

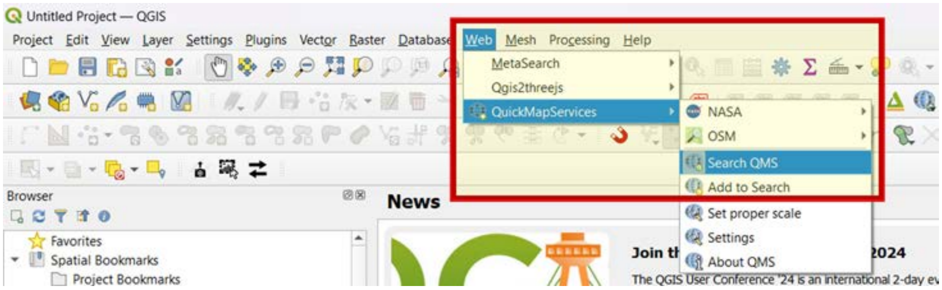
This method involves uses the data repository in OpenStreetMap. The steps are as follows:

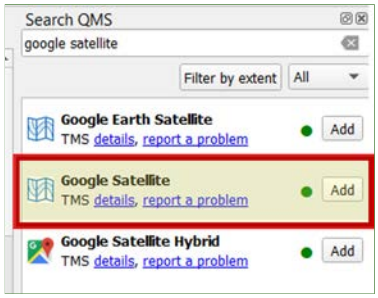
- Open QGIS
- Click on Plugins, select 'manage and install plugins'.
- In the search box, type 'QuickOSM', and click on install plugin.
- Similarly, install 'Quickmapservices' as well.



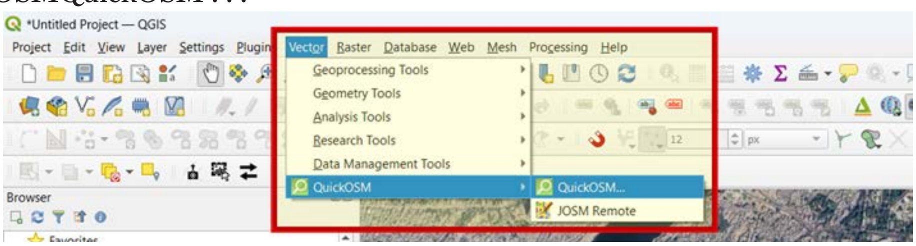


- Click on ‘Web’, select ‘QuickMapServices’, and choose ‘Search QMS’. Type ‘google satellite’ in Search QMS tab, select ‘Google Satellite’ and click on ‘Add’

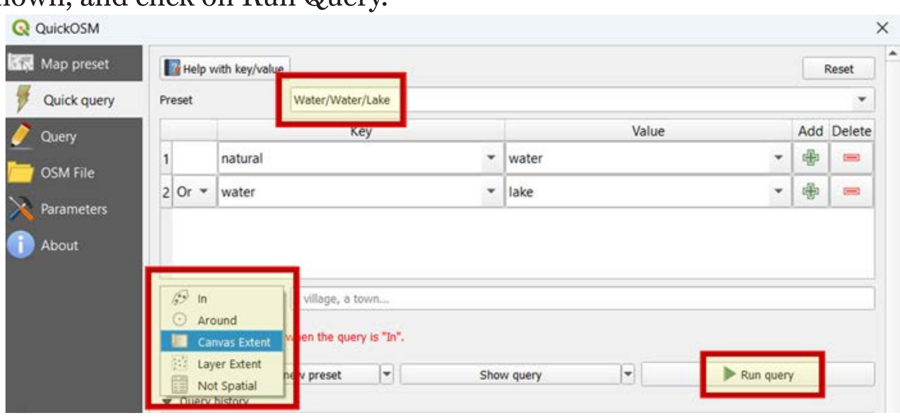




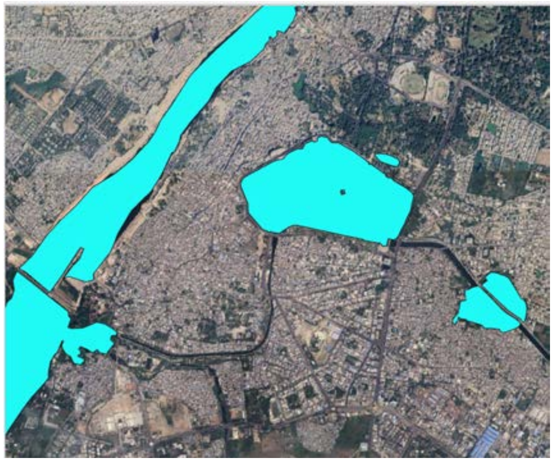
- Zoom in to your study area, and click on ‘Vector, select ‘QuickOSM’, and choose ‘OSMQuickOSM . . .’



- Type the desired dataset required in Preset (e.g., lake), select ‘Canvas Extent’ as shown, and click on Run Query.



- The desired dataset would be downloaded. Similarly repeat it for all other required classes (e.g.: ponds, rivers, parks, forests, etc.)



c. Classification via remote sensing data

This method uses remote sensing data to classify and extract blue and green infrastructures. Remote sensed data can be downloaded from https://earthexplorer.usgs.gov/, by selecting Landsat 8/9 OLI/TIRS C2 L1 (follow similar steps for downloading as shown in the section 'Downloading remote sensing data').

Various vegetation and water indices can be used to extract green spaces and water bodies. These indices and their formulas are shown below (see *Table 2: Vegetation and water indices for extraction of blue and green infrastructure*). The most widely used among these are Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI).

Table 2: Vegetation and water indices for extraction of blue and green infrastructure

S. no.	Land cover/index	Formulae
		Vegetation/Green areas
1.	Atmospherically Resistant Vegetation Index (ARVI)	$\frac{(NIR - RB)}{(NIR + RB)}$ Here, RB = RED – γ(BLUE – RED) γ = 1 is taken generally when the aerosol model is not available.
2.	Difference Vegetation Index (DVI)	NIR – RED
3.	Global Environment Monitoring Index (GEMI)	$\frac{n(1 \neq 0.25n) - (RED - 0.125)}{1 - RED}$ Here, n = $\frac{2(NIR^2 - RED^2) + 1.5NIR + 0.5RED}{NIR + RED + 0.5}$

S. no.	Land cover/index	Formulae
4.	Infrared Percentage Vegetation Index (IPVI)	$\frac{NIR}{NIR + RED}$
5.	Modified Soil-Adjusted Vegetation Index (MSAVI2)	$0.5 * [(2NIR + 1) – \sqrt{(2NIR + 1)2 – 8(NIR – RED)}]$
6.	Normalized Different Moisture Index (NDMI)	$\frac{NIR - SWIR_1}{NIR + SWIR_1}$
7.	Normalized Difference Tillage Index (NDTI)	$\frac{SWIR_1 - SWIR_2}{SWIR_1 + SWIR_2}$
8.	Normalized Difference Vegetation Index (NDVI)	$\frac{NIR - RED}{NIR + RED}$
9.	Optimized Soil-Adjusted Vegetation Index (OSAVI)	$\frac{NIR - RED}{NIR + RED + X}$ Here, X = 0.6
10.	Ratio Vegetation Index (RVI)	$\frac{RED}{NIR}$
11.	Soil Adjusted Vegetation Index (SAVI)	$\frac{(NIR - RED)(1 + L)}{NIR - RED + L}$ Here, L = 0.5 is considered as the default value for most of the surfaces
		Water
12.	Automated Water Extraction Index (AWEInsh)	$4(GREEN - SWIR_1) - (0.25 * NIR + 2.75 * SWIR_2)$
13.	Modified Normalized Difference Water Index (MNDWI)	$\frac{GREEN - SWIR_1}{GREEN + SWIR_1}$
14.	Normalized Difference Water Index (NDWI)	$\frac{GREEN - NIR}{GREEN + NIR}$
15.	Water Ratio Index (WRI)	$\frac{GREEN + RED}{NIR + SWIR_2}$

Here,

***The Land cover/index under Vegetation/Green areas (S. no. 1-11 in Table 2)** provides information about the vegetation.*

***The Land cover/index under Water (S. no. 12-15 in Table 2)** provides information about the water bodies.*

***Blue:** Digital number (DN) associated with blue band (0.45-0.52 µm); Band 2 for Landsat 8/9 and Band 1 for Landsat 4/5/7*

***Green:** Digital number (DN) associated with green band (0.52-0.60 µm); Band 3 for Landsat 8/9 and Band 2 for Landsat 4/5/7*

***Red:** Digital number (DN) associated with red band (0.63-0.69 µm); Band 4 for Landsat 8/9 and Band 3 for Landsat 4/5/7*

***NIR:** Digital number (DN) associated with near-infrared band (0.76-0.90 µm); Band 5 for Landsat 8/9 and Band 4 for Landsat 4/5/7*

$SWIR_1$: *Digital number (DN) associated with shortwave-infrared band (2.09-2.35 µm); Band 6 for Landsat 8/9 and Band 5 for Landsat 4/5/7*

$SWIR_2$: *Digital number (DN) associated with shortwave-infrared band (1.55-1.75 µm); Band 7 for Landsat 8/9 and Band 7 for Landsat 4/5/7*

2. Thresholding to extract blue-green infrastructures

This involves setting thresholds to classify regions into vegetated and non-vegetated areas using the vegetation index and into water and non-water areas using the water index. Threshold values can be determined through visual interpretation or statistical measures.

a. Visual interpretation

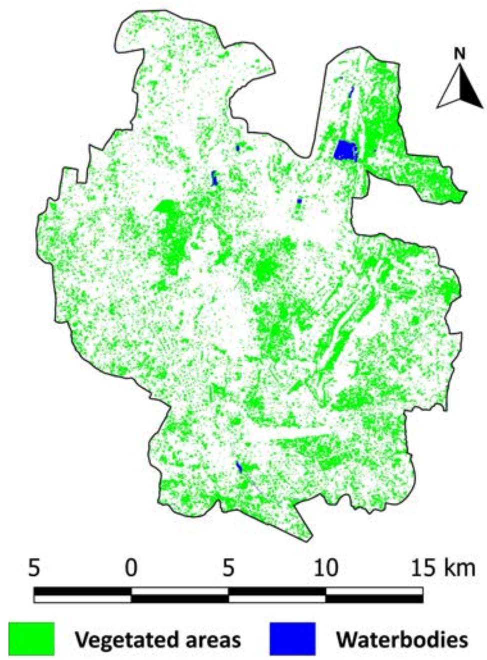
This involves choosing a random threshold value to distinguish vegetation/water from non-vegetation/non-water. The resulting classification is validated by overlaying it on Google Earth or satellite images. The thresholds are then adjusted until they accurately match the vegetation or water classes.

b. Statistical measure

This follows a similar approach to 'statistical techniques' under 'identification of heat stressed areas'. A threshold value is chosen based on a value that exceeds a specific multiplier of standard deviations from the mean values.

The desired outcome obtained via 'Estimating blue-green infrastructures' is illustrated in *Map 3: Blue-green infrastructure.*

Map 3: Blue-green infrastructure



The mean surface temperature of vegetated areas and waterbodies in Jaipur was found to be up to 9.01°C lower than areas without them

Source: CSE

CASE EXAMPLE: INFLUENCE OF BLUE-GREEN INFRASTRUCTURE ON TEMPERATURES

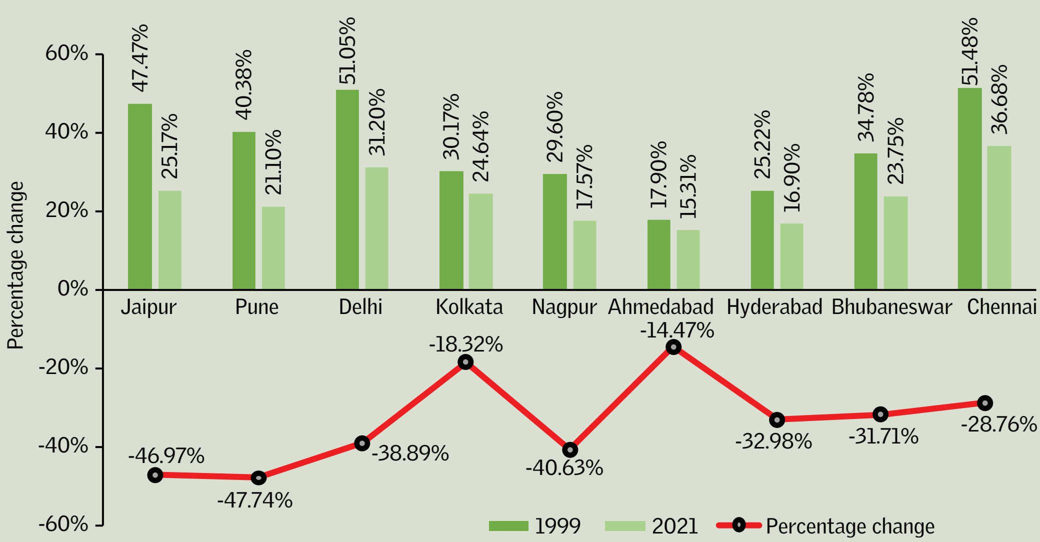
CSE analysed nine cities to study the changes in blue and green infrastructure from 1999 to 2021. The analysis used the 'classification via remote sensing' method to delineate blue-green spaces. NDVI was used for vegetation and NDWI was used for waterbodies, followed by observing the changes.

Note: NDVI includes all kinds of green areas, including agricultural fields, fallow lands with little vegetation, grass, shrubs, and trees, among others. As a result, the estimated green spaces might be slightly higher than the actual green cover. Similarly, NDWI identifies blue spaces that include different types of waterbodies such as ponds, lakes, wetlands and rivers. Each of these has a different potential to improve the local microclimate.

The analysis showed a decline in blue and green infrastructures in all cities (see *Graph 2: Changes in vegetated areas [green infrastructure] between 1999 and 2021* and *Graph 3: Changes in waterbodies [blue infrastructure] between 1999 and 2021*). This decline is one of the major reasons for rising surface temperatures. Pune experienced the highest reduction in greens, with a decline of 47.74 per cent. Jaipur and Nagpur followed, with declines of 46.97 per cent and 40.63 per cent, respectively. Kolkata, Delhi, and Bhubaneswar lost approximately 42.90 per cent, 33.09 per cent, and 24.69 per cent of their water bodies, respectively. Kolkata and Ahmedabad showed lower reductions in greens. However, Kolkata had a high overall reduction in blues, while Ahmedabad had a lower percentage of vegetation than other cities.

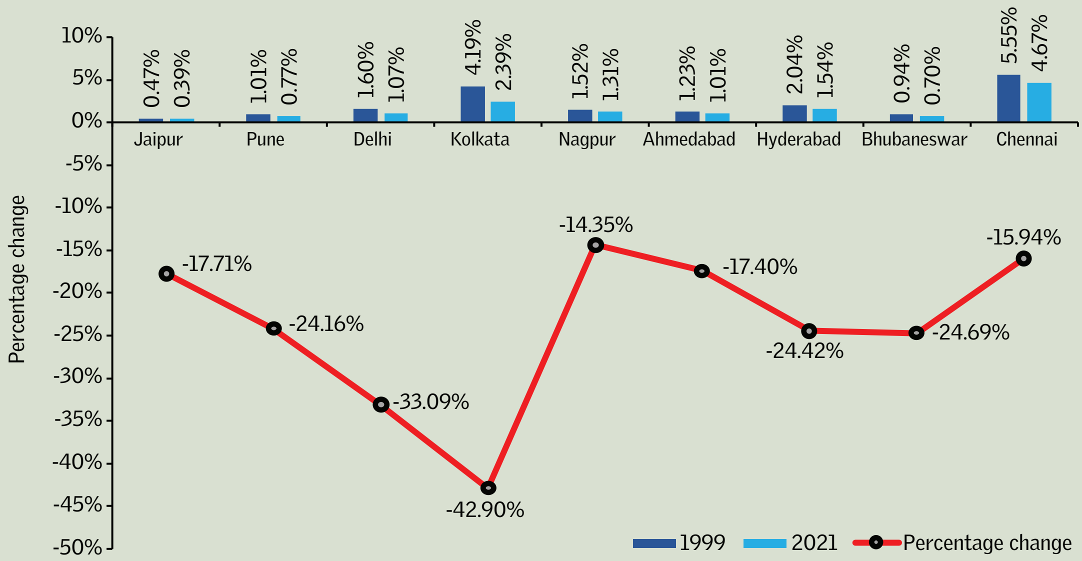
These parameters affect micro-climate, and a reduction in both of them can cause temperatures to rise. For instance, in Kolkata, the loss of these infrastructures led to increases in average, maximum, and minimum LST from 1999 to 2021 (see *Map 4: Temporal variation in LST, green, and blue infrastructure across Kolkata city between 1999 and 2021*). Minimum surface temperatures rose from 26.47°C in 1999 to 30.95°C in 2021, and maximum LST from 50.25°C in 1999 to 52.18°C in 2021. The mean surface temperature surged from 37.82°C to 42.65°C during this period.

Graph 2: Changes in vegetated areas (green infrastructure) between 1999 and 2021



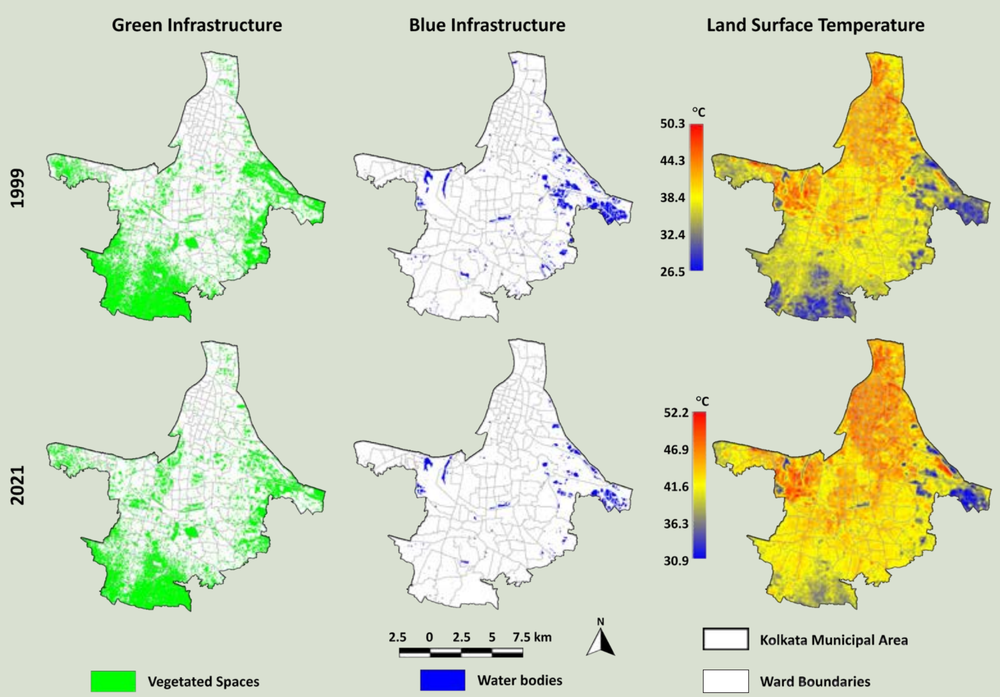
Source: CSE

Graph 3: Changes in waterbodies (blue infrastructure) between 1999 and 2021



Source: CSE

Map 4: Temporal variation in LST and green and blue infrastructure across Kolkata city between 1999 and 2021



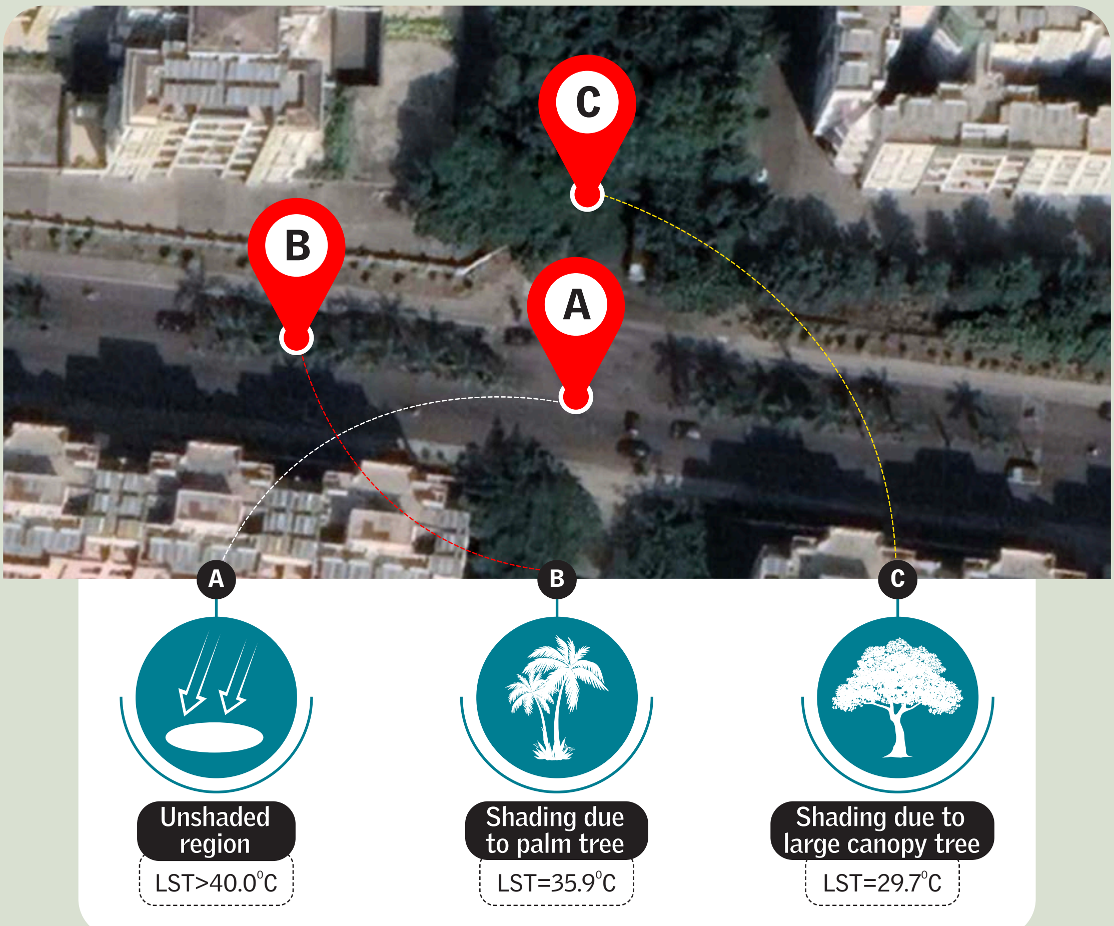
Data source: Landsat Series, USGS

Quality of blue-green infrastructure matters

The effectiveness of blue-green infrastructure in reducing heat depends on both their presence and quality. Key factors include vegetation height, shading, canopy cover, and the size and depth of waterbodies. Selecting blue-green infrastructure that suits local conditions is essential for maximizing heat reduction.

CSE conducted an analysis using ground measurements to compare surface temperatures in different settings. The areas include one with no shade, one shaded by palm trees, and one shaded by dense canopy cover (see *Figure 14: Variation in temperature with variation in canopy cover*). The results showed that the unshaded area had surface temperatures above 40°C. In contrast, the area with palm tree shade had a LST of 35.9°C, while one with dense canopy cover recorded an even lower LST of 29.7°C.

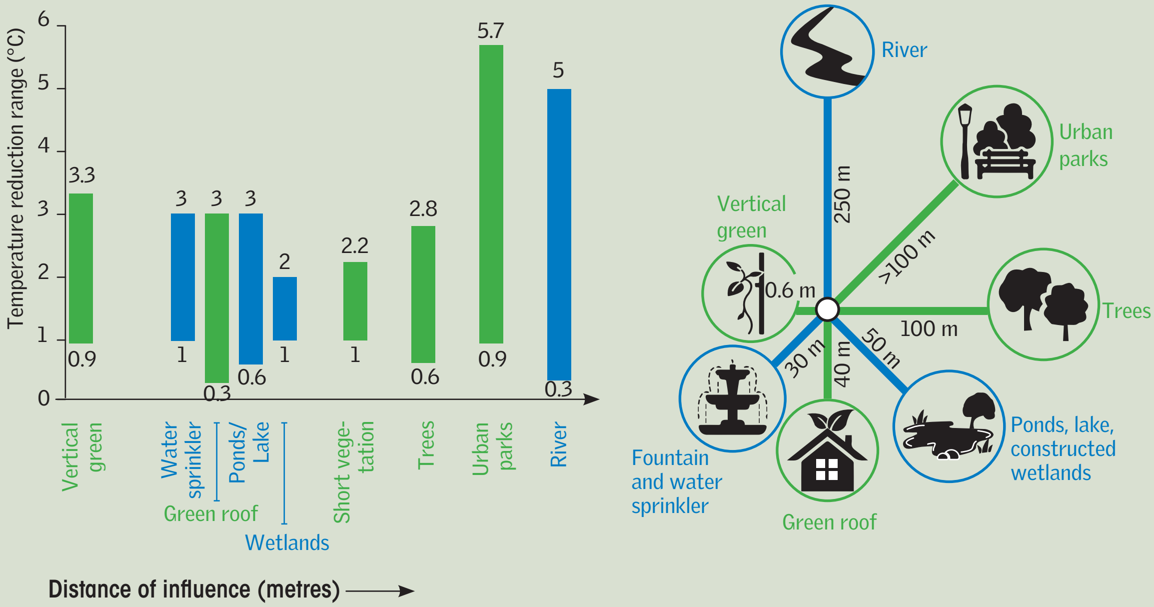
Figure 14: Variation in temperature with variation in canopy cover



Source: Google Earth and in situ data collection

Another analysis conducted by a team of researchers[31] estimated the temperature reductions and distance of influence of various blue-green infrastructures (see *Figure 15: Impact of blue-green infrastructure—temperature reduction and distance of influence*). Among these, rivers had the highest distance of influence, reaching up to 250 m, followed by urban parks (over 100 m), trees (100 m), ponds/lakes (50 m), green roofs (40 m), and fountains/water sprinklers (30 m) for air temperatures. Vertical greenery had the smallest effect, influencing air temperatures over just 0.6 m. Quantitatively, temperature reduction in green spaces ranged from 0.3–5.7°C, while for blues spaces, the reduction varied from 0.3–5°C.

Figure 15: Impact of blue-green infrastructure—temperature reduction and distance of influence



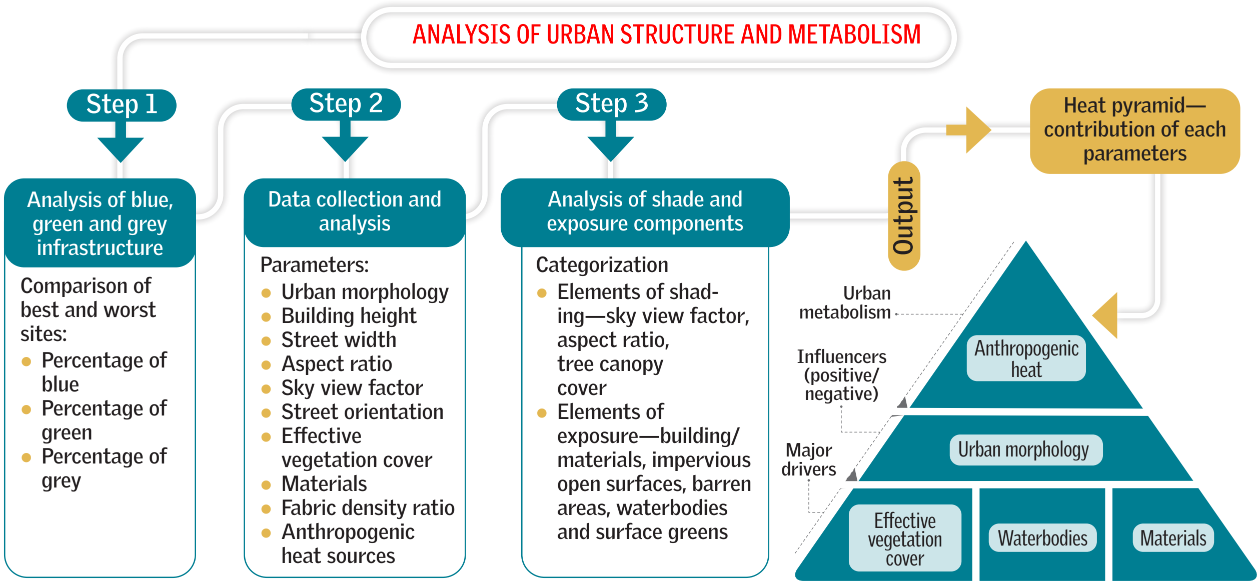
Source: https://iwaponline.com/bgs/article/4/2/348/92495/Blue-Green-Systems-for-urban-heat-mitigation

ANALYSIS OF URBAN STRUCTURE AND METABOLISM: IN-DEPTH ANALYSIS OF SHADE AND EXPOSURE ELEMENTS

With the identified heat-stressed areas in the city, this analysis goes deeper to understand what traps the heat or generates it. It looks at parameters at a neighbourhood level and explains how each one adds to or reduces heat.

This involves the following three steps: a) Analysis of blue-green-grey infrastructure, b) Data collection and analysis; and c) Analysis of shade and exposure components (see *Figure 16: Methodology and output: In-depth analysis of shade and exposure elements*).

Figure 16: Methodology and output—in-depth analysis of shade and exposure elements



Source: Created by CSE

Analysis of blue, green and grey infrastructure

Urbanization that lays stress on grey infrastructure and falls short of maintaining the green and blue infrastructure adversely affects urban heat dynamics. Blue and green infrastructure (BGI) helps regulate temperatures. In contrast, grey infrastructure, such as buildings and roads, raises temperatures because of their heat-absorbing and heat-retaining properties. As urban areas expand, grey infrastructure often replaces blue and green areas, increasing heat risks for residents.

The best and worst sites with similar morphology along with a 100–500 metres buffer should be selected for analysis. The best sites are those with lower land surface temperature (LST), while the worst refers to sites with higher LST. Blue, green and grey infrastructure on these sites can be assessed using Google Earth. The fraction of these infrastructures, along with the average surface temperatures at these sites, should be compared to see how differences in the proportion of these infrastructures influence surface temperatures.

Data collection and analysis

For the identified heat-stressed areas, various sites should be selected. Elements like street width, average building height, presence of blue and/or green infrastructure, morphology, anthropogenic sources of heat and other relevant factors should be recorded through spatial analysis or in situ data collection. This data should be used to estimate parameters such as aspect ratio, sky view factor, effective vegetation cover, etc. These parameters should be correlated with land surface tempoerature (LST) to determine how each one contributes to heat gain or loss. The parameters under urban structure and metabolism that need to be collected are listed below.

1. Urban structure

Analysis of urban structures advances beyond the top view to focus on details at the neighbourhood-level. Key parameters include urban morphology, construction materials, building heights, street width, sky view factor, and building orientation, among others. These can be measured directly on the ground or estimated through spatial analysis. By examining these parameters, it can be determined which ones contribute most to heat gain in specific local areas.

a. Urban morphology

Urban morphology can be captured individually or in combination using spatial (Google Earth images) and in situ (field observations) datasets. The sites in the study area should be classified based on their density (how close buildings are to each other) and height (number of storeys) (see *Figure 3: Urban morphologies [on page 20]*).

b. Aspect ratio

Aspect ratio (AR) can be calculated using the average building height and street width, as shown in Equation 2. Building height and street width can be obtained through direct field measurements,[32] remote sensing and GIS,[33, 34] digital elevation models (DEMs) and 3D modelling,[35] etc.

Equation 2:

$$AR = \frac{H_{avg}}{W}$$

Here,
Havg: Average building height (metres)
W: Street width (metres)

c. Sky view factor

Sky view factor (SVF) can be calculated by using the fish-eye photography method,[36] DEM and GIS,[37] mathematical models and algorithms,[38] mobile applications,[39] manual estimation,[40] or by using data collected from the field. Equation 3 can be used to estimate sky view factor (2D), as shown in the following.

Equation 3:

$$SVF = \cos\left(atan\left(\frac{2H_{avg}}{W}\right)\right)$$

d. Street orientation

Street orientation (SO) can be measured on the ground using a compass. It can also be captured using Google Earth images.

e. Effective vegetation cover

Effective vegetation cover (EVC) can be measured spatially. Singapore's Green Mark Criteria for Residential Buildings provides a way to calculate EVC. This framework assigns the highest weightage to green areas covered by trees, followed by shrubs and grass. This weight reflects how different types of vegetation vary in their ability to reduce heat. EVC is quantified as shown in Equation 4.

Equation 4:

$$EVC = [(0.15 \times V_G) + (0.30 \times V_S) + (1 \times V_T)] \times VC$$

Here,

V_G: *Fraction of grass (out of total vegetation cover)*

V_S: *Fraction of scrubs (out of total vegetation cover)*

V_T: *Fraction of trees (out of total vegetation cover)*

Note: The effectiveness of cooling for grass was considered as 15 per cent, for scrubs 30 per cent and for trees 100 per cent. Thus, the weightages assigned to them are 0.15, 0.3 and 1 respectively. These parameters can be altered as desired by the analyst.

For example:

Total green cover on the site = 27 per cent

Fraction of grass = 0.10; Fraction of scrubs = 0.20; Fraction of trees = 0.70

EVC = [(0.15 × 0.10) + (0.30 × 0.20) + (1 × 0.70)] × 0.27 = 0.20925
= 20.925 per cent

f. Construction material
The materials used for construction can be captured on the ground or through Google Earth images using visual interpretation.

g. Fabric density ratio
Fabric density ratio (FDR) can be estimated using Equation 5. The building perimeter and total analysis area can be measured on the ground or through Google Earth images.

Equation 5:

$$FDR = \frac{\text{Perimeter of buildings} \times \text{H}_{avg}}{Total\ analysis\ area}$$

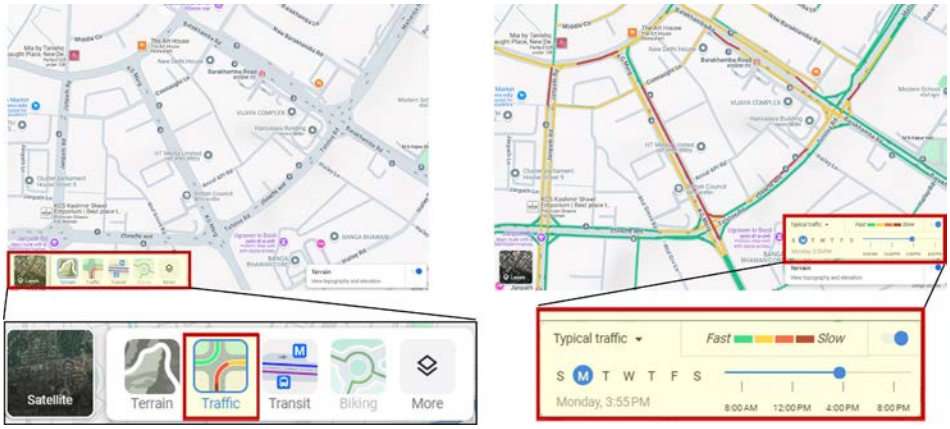
2. Urban metabolism
Certain areas, even when appearing optimized in terms of all the parameters, exhibit high temperatures. This indicates the presence of other heat sources, often linked to human activities. These activities not only contribute to greenhouse gas emissions but also increase local temperatures. This excess heat creates localized hotspots, exacerbating heat-related challenges. Identifying and addressing these heat sources is essential to manage urban heat.

a. Air conditioners
The number of air conditioning units at a site can be captured during field visits.

b. Vehicular density and traffic congestion
Traffic congestion points can be derived from Google Maps (see *Figure 17: Traffic congestion points*). Select the 'Traffic' option in the bottom left corner, and choose 'typical traffic'. Select the days (Monday, Tuesday, . . . Sunday) and the time. The map will display typical traffic conditions for that day and time. Analyse this data by changing the date and time to locate areas with heavy traffic congestion.

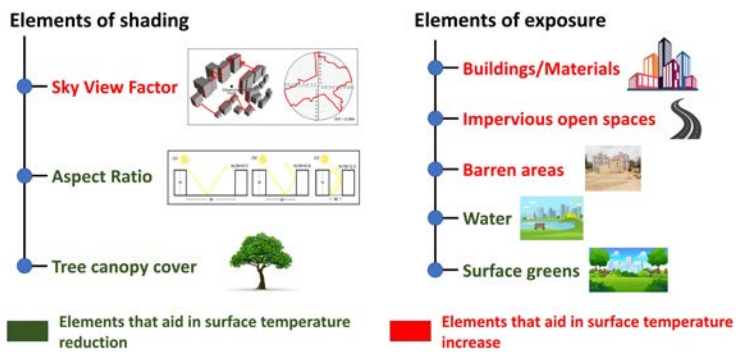
Analysis of shade and exposure components
To understand how various parameters collectively influence surface temperature across different urban morphologies, both underperforming and high-performing locations should be analysed. The parameters from spatial analysis and field visit, along with the landscape type, should be grouped into elements of shade and exposure (see *Figure 18: Elements of heat gain and reduction–shade and exposure*).

Figure 17: Traffic congestion points



Source: Google Maps

Figure 18: Elements of heat gain and reduction—shade and exposure



Source: CSE

Shade elements include sky view factor, aspect ratio, and tree canopy cover. Exposure elements include buildings, impervious open spaces (such as roads), barren areas (such as open areas or parking spaces without green cover), water bodies and surface greens (land with grass, shrubs, etc.). In the shade category, sky view factor, and in the exposure category, buildings, impervious open spaces, and barren areas increase surface temperatures. In contrast, all other parameters help in reducing the surface temperatures.

Sky view factor and aspect ratio can be calculated via ground measurements or other tools. Other parameters including tree canopy cover, buildings, impervious open spaces, barren areas, water bodies and surface greens can be demarcated using Google Earth. These parameters, along with surface temperatures, should be compared for similar morphologies to capture how they collectively and individually affect LST.

CASE EXAMPLE: ANALYSIS OF BLUE-GREEN-GREY INFRASTRUCTURE

The analysis compared the worst and best sites with similar urban morphology to assess the impact of green, blue, and grey infrastructure on surface temperatures. The analysis revealed that variations in the proportion of these infrastructures influenced LST.

Among the urban morphologies analysed (see *Figure 19: Analysis of blue-green-grey infrastructure across various urban morphologies [case of Pune])*, open low-rise and compact low-rise settings showed LST variation of 7.76°C and 6.23°C respectively across best and worst sites. In the best-performing open low-rise site, grey infrastructure covered 56.30 per cent of the area, while in the worst-performing site, it covered 99.51 per cent. Similarly, compact low-rise sites had grey infrastructure covering 81.61 per cent in the best site and 99.51 per cent in the worst site.

In contrast, surface temperature differences were 4.86°C and 1.22°C, respectively in open mid-rise and compact mid-rise settings. In these configurations, grey infrastructure covered 63.26–98.95 per cent in the open mid-rise site and 82.08–99.79 per cent in the compact mid-rise site. This analysis highlights how different proportions of blue, green and grey infrastructure impact LSTs across different urban morphologies and suggests the need for strategic planning and design interventions to reduce heat accumulation in urban areas.

CASE EXAMPLE: FIELD ANALYSIS

For the identified heat-stressed areas on impervious built surfaces, multiple sites within a 500-metre buffer were selected. The focus was on areas with a high concentration of heat-stressed zones. Several locations within this buffer were chosen for field visits to collect in situ data. Sites characterized by a single predominant factor driving heat gain (e.g., highways and barren areas) were excluded. Instead, sites characterized by multiple drivers of heat gain were chosen.

The obtained dataset was used to estimate parameters such as aspect ratio, sky view factor, effective vegetation cover, etc. These parameters were then compared with surface temperatures to understand how they affect heat gain or loss.

A total of 232 sites were visited across four cities: Delhi, Jaipur, Pune and Kolkata. Specifically, 48 sites were visited in Delhi, 44 in Jaipur, 48 in Pune, and 92 in Kolkata. In Pune, the number of sites was limited to 31, with the remaining sites surveyed in the neighbouring city of Pimpri-Chinchwad. In Kolkata, due to the comparatively smaller area under heat stress, only 14 of the 92 sites fell within the Kolkata Municipal Corporation (KMC) boundary. The remaining sites were visited in the Kolkata Metropolitan Area to understand the planned and unplanned urban morphologies.

Of the total 137 sites across four cities under heat stress, 70 per cent were compact low-rise, 16 per cent were compact mid-rise, and 4.37 per cent were open mid-rise and low-rise. The rest were lightweight and large low-rise (see *Graph 4: Number of sites (under heat stress) visited during field investigation*).

CASE EXAMPLE: ANALYSIS OF SHADE AND EXPOSURE COMPONENTS

Various influencing parameters across different sites with similar urban morphologies were compared to surface temperatures to understand their collective influence on land surface temperature (LST).

Comparison of sites

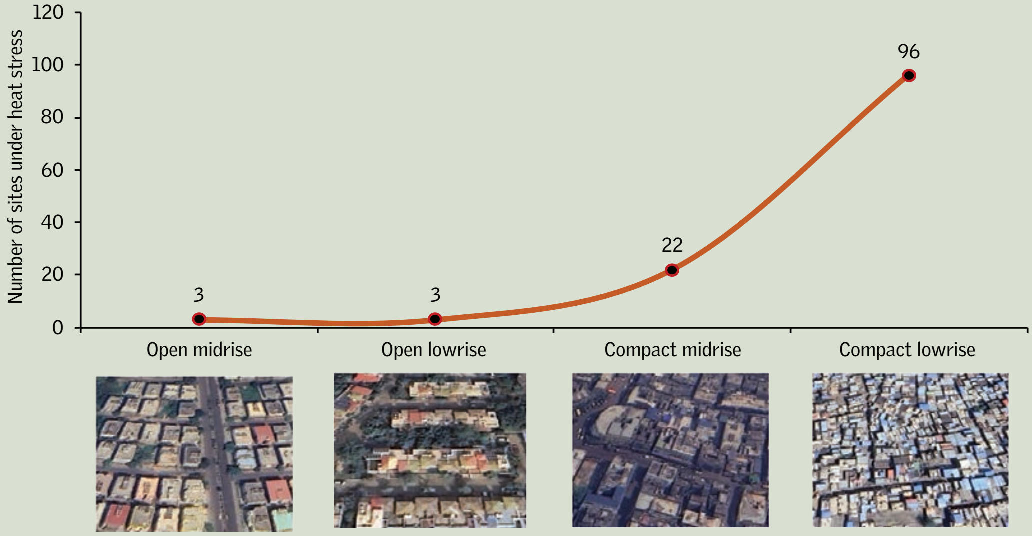
a. Open mid-rise development (Sasane Nagar vs Sutarwadi)

A difference of 2.87°C in LST was observed between the sites in Sasane Nagar and Sutarwadi (see *Figure 20: Comparative analysis of shade and exposure across sites under the open mid-rise category in Pune*). Both sites had

Figure 19: Analysis of blue-green-grey infrastructure across various urban morphologies (the case of Pune)

Source: Google Earth

Graph 4: Number of sites (under heat stress) visited during field investigation



Source: Google Earth; created by CSE

similar grey component coverage, but Sutarwadi showed higher temperatures. This indicates that factors related to shade and exposure may play a key role in the temperature difference.

Detailed analysis showed that while shading elements were almost the same, exposure elements differed largely. The higher temperatures in Sutarwadi were due to its large pervious open space (21.28 per cent), mainly used as a bus parking lot. The buses, with their metal roofs, trapped heat, raising surface temperatures around the area. This indicates how land utilization can affect the local microclimate.

b. Compact mid-rise development (Akurdi vs Kausar Baugh)

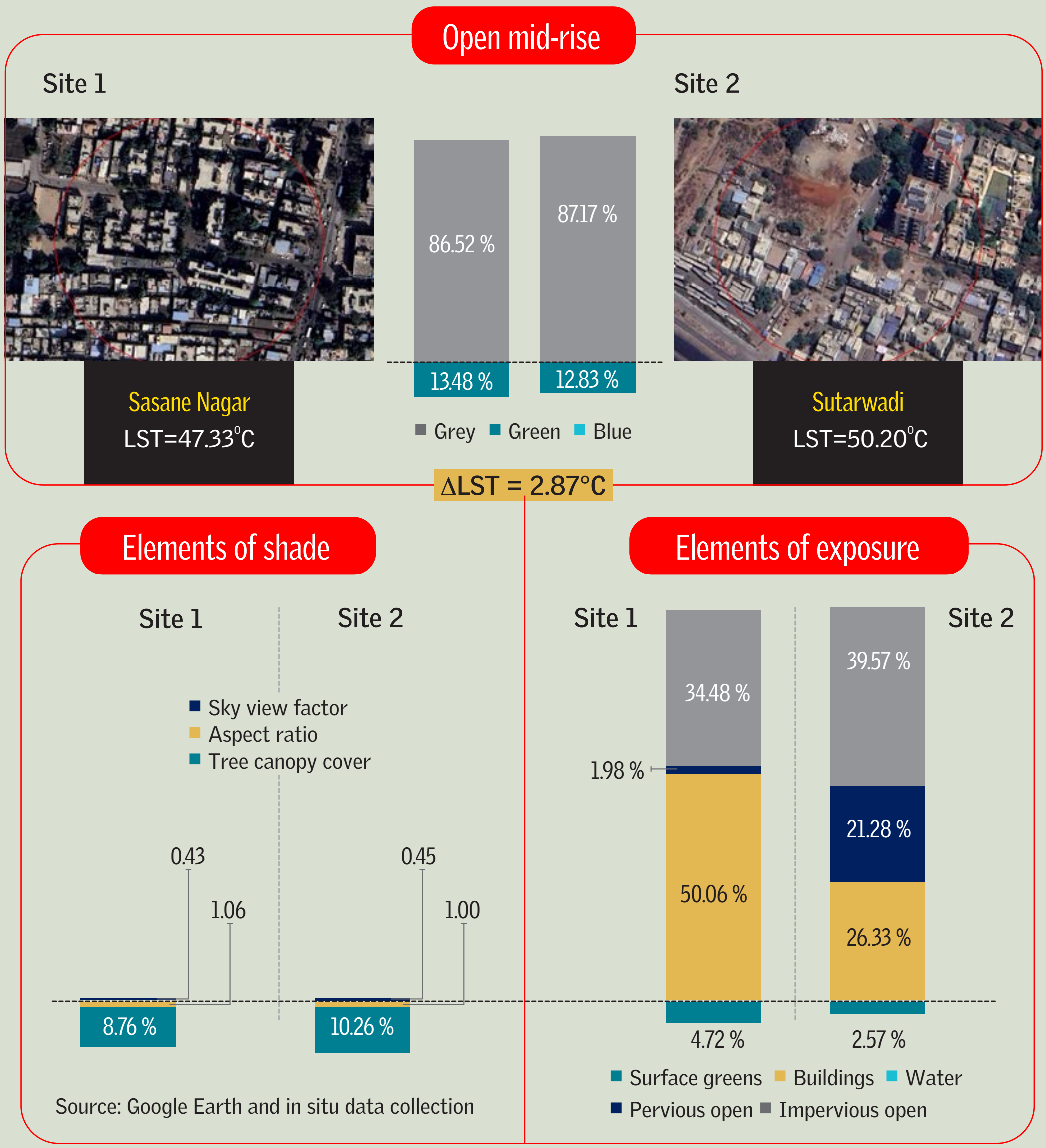
A comparison of the sites in Akurdi and Kausar Baugh showed that the Akurdi site had a lower LST of 47.09°C compared to Kausar Baugh's 48.83°C (see *Figure 21: Comparative analysis of shade and exposure across sites under the compact mid-rise category in Pune*). The Akurdi site had less grey infrastructure (73.93 per cent) and more green space (21.51 per cent) compared to Kausar Baugh, which had 94.53 per cent grey space and only 5.47 per cent green space. Akurdi also had a waterbody (4.56 per cent blue space), while Kausar Bagh had none.

The analysis of shade and exposure showed that Akurdi had a higher aspect ratio, lower sky view factor, more surface greens, and greater tree canopy cover. These factors provided more shade and reduced direct sun exposure, resulting in lower temperatures. Additionally, the presence of green spaces and waterbodies improved the local microclimate. This highlights the importance of incorporating soft landscaping and careful planning in urban development.

c. Open low-rise development (Sasane Nagar vs Maharshi Nagar)

A LST difference of 5.21°C was observed between the sites in Sasane Nagar and Maharshi Nagar (see *Figure 22: Comparative analysis of shade and exposure across sites under the open low-rise category in Pune*). The Sasane Nagar site had less grey space coverage (79.29 per cent) compared to Maharshi Nagar (87.31 per cent), with the remaining areas in both sites consisting of green spaces. The higher green space in Sasane Nagar was linked to lower LSTs.

Figure 20: Comparative analysis of shade and exposure across sites under open mid-rise category in Pune



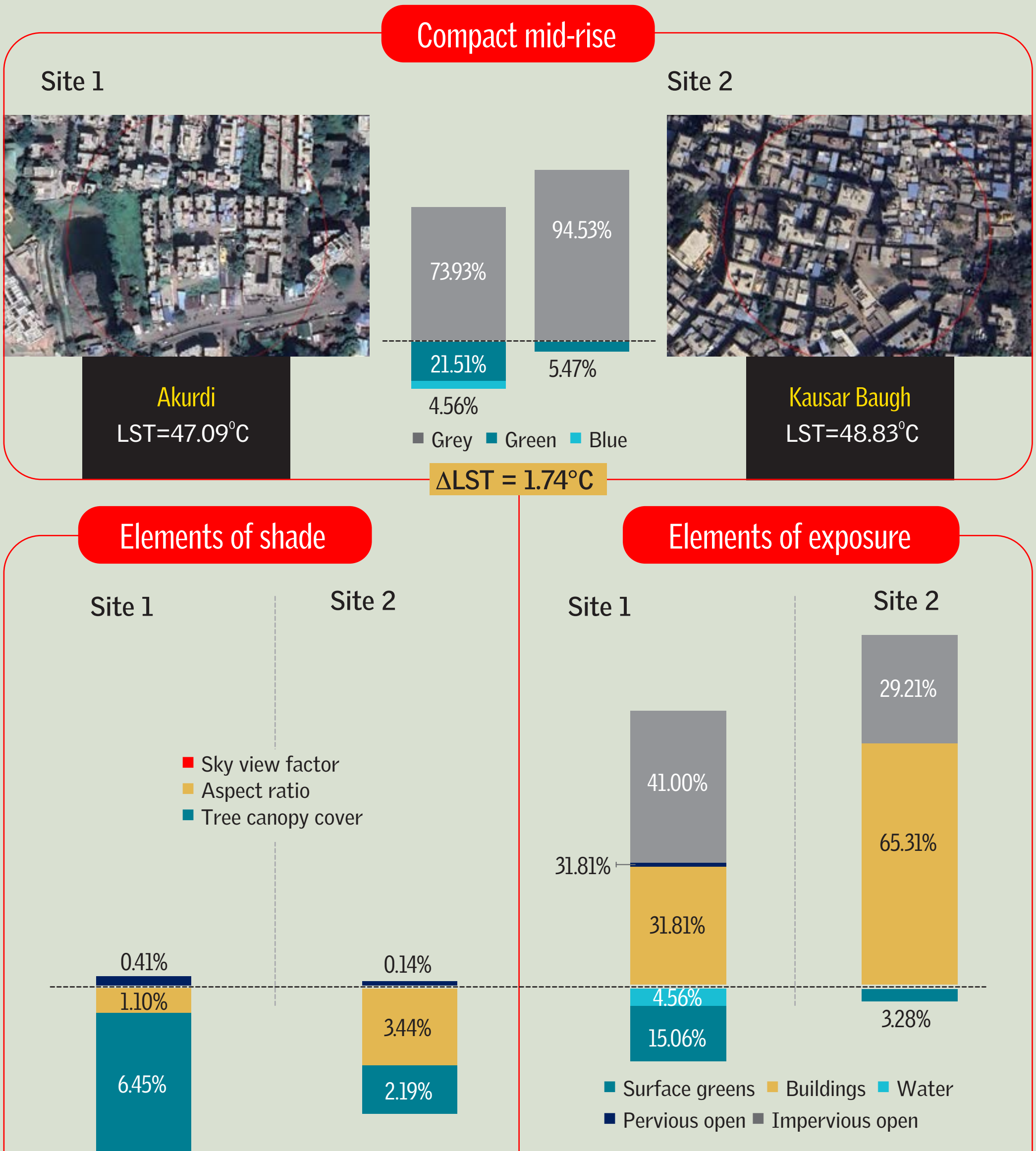
Source: Google Earth and in situ data collection

The analysis revealed that despite having a better aspect ratio and lower sky view factor, the Maharshi Nagar site, which is a marketplace, experienced higher temperatures. This was due to less tree canopy cover and use of heat-retaining roofing materials such as corrugated metal sheets, asbestos sheets, plastic sheets and galvanized iron sheets, among others. These materials trap and retain heat, causing the overall land surface temperature (LST) to rise across the site. This highlights how the choice of materials can affect LSTs in urban areas.

d. Compact low-rise development (Thite Nagar vs Chikhali)

Thite Nagar and Chikhali sites showed an LST difference of 7.33°C, with Thite Nagar being cooler (see *Figure 23: Comparative analysis of shade and exposure across sites under the compact low-rise category in*

Figure 21: Comparative analysis of shade and exposure across sites under compact mid-rise category in Pune

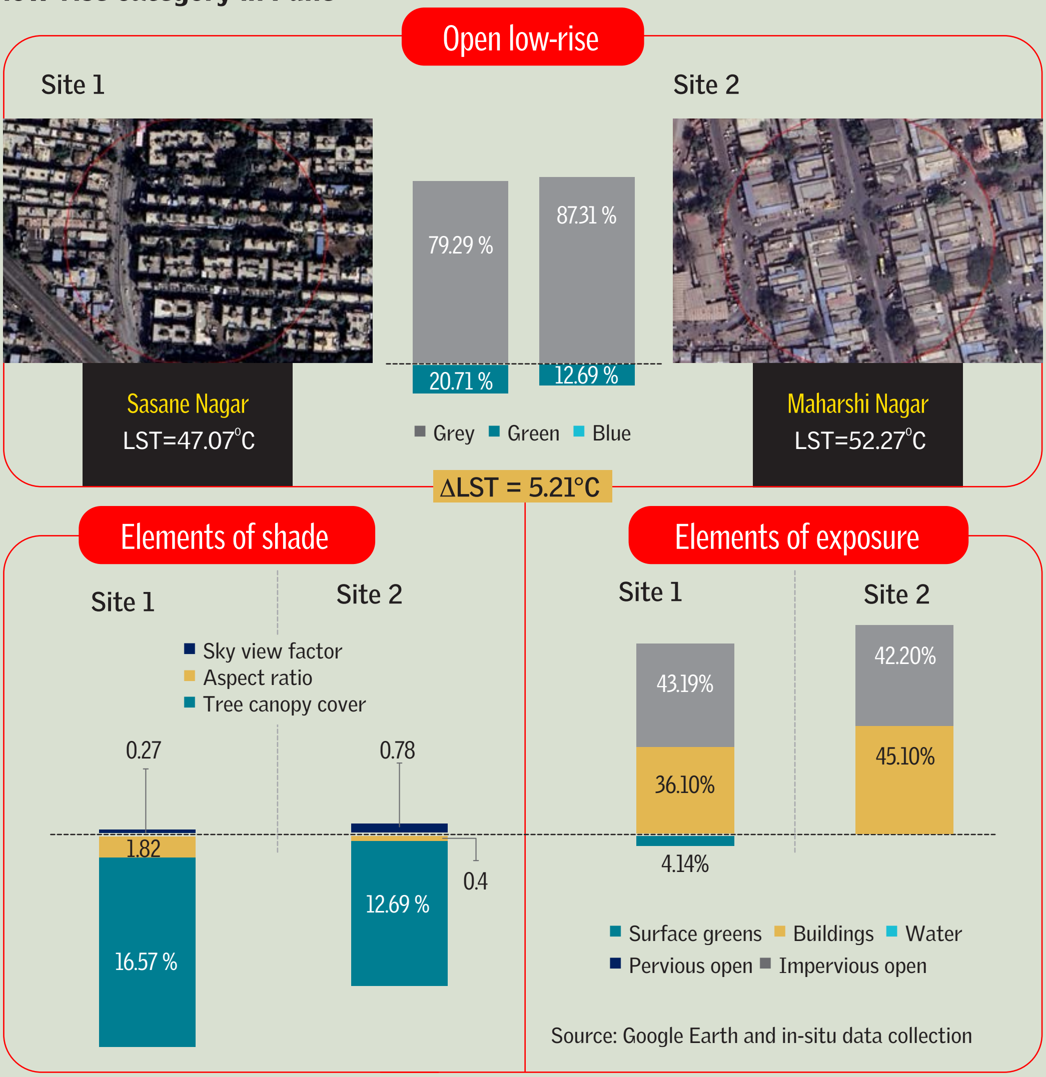


Source: Google Earth and in-situ data collection

Pune). Both sites had similar grey space coverage (Thite Nagar at 94.15 per cent and Chikhali at 97.78 per cent). However, Thite Nagar had slightly more green space, contributing to its lower LST.

The analysis revealed that similar to the site analysed in Maharshi Nagar, Chikhali had higher temperatures due to less tree canopy cover and the use of heat-retaining roofing materials in commercial and industrial areas. The surface temperature in Chikhali reached 55.31°C, making it the hottest site compared to others.

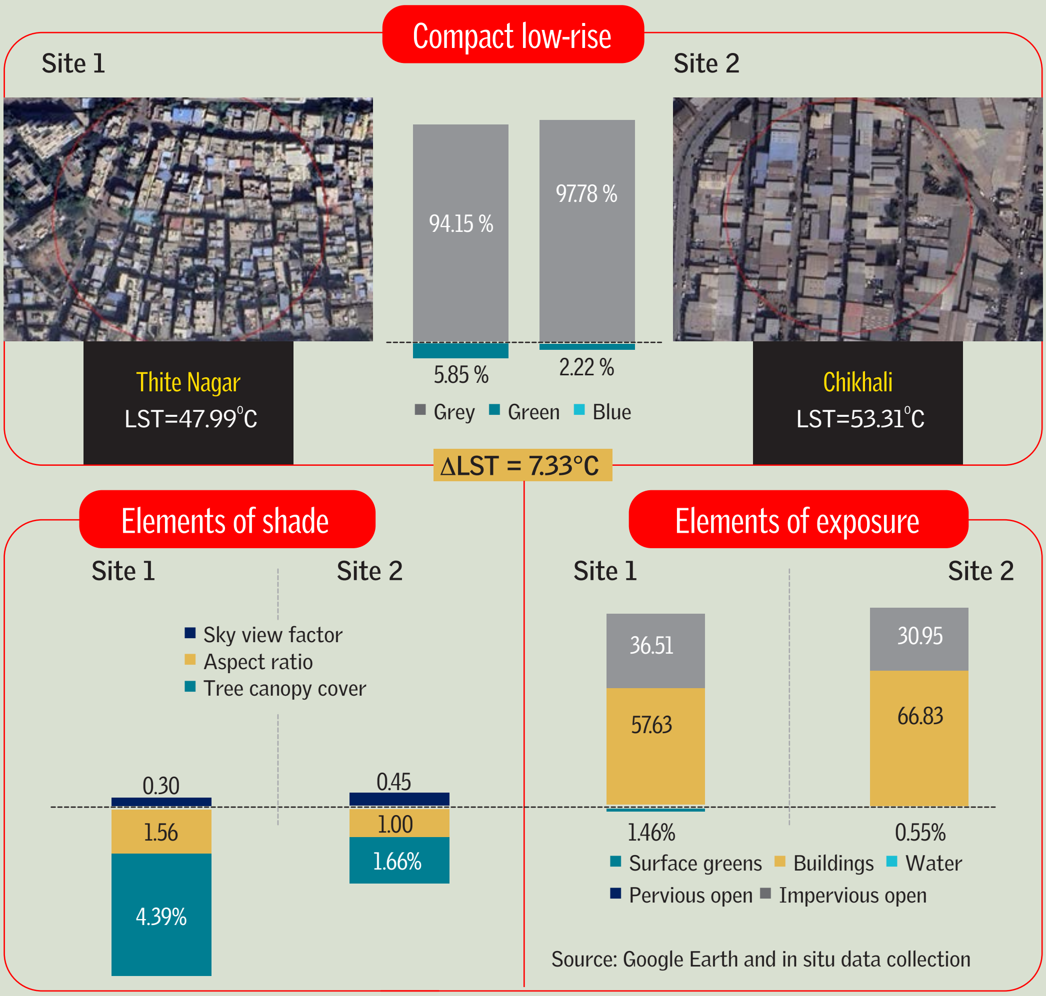
Figure 22: Comparative analysis of shade and exposure across sites under open low-rise category in Pune



The worst sites in Pune were identified to be in large low-rise and lightweight low-rise urban morphologies (see Figure 24: Sites with urban morphology—large low-rise and lightweight low-rise). All these sites had LSTs exceeding 50°C. The areas included industrial sheds or slum areas. These sites often used heat-trapping roofing materials like asbestos, galvanized iron sheets, and plastic sheets. The people living and working in these areas are mainly from low-income backgrounds. They often lack access to electricity, water, sanitation and healthcare. This makes them highly vulnerable to heat-related illnesses.

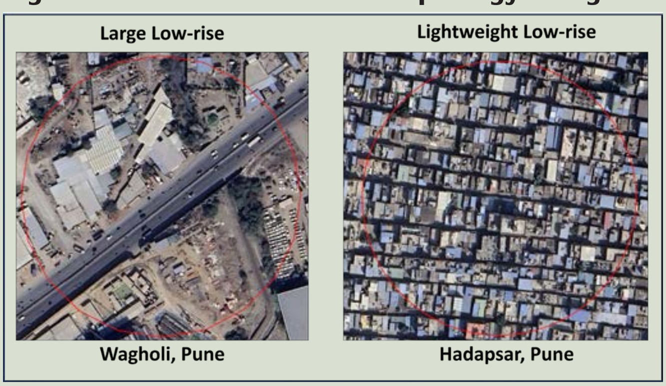
This analysis provides evidence of the fact that green spaces, tree canopy cover and type of roofing material greatly influence land surface temperature. Sites with higher green coverage and fewer heat-retaining materials tend to have lower temperatures. These findings highlight the need for urban planning strategies that integrate green spaces, waterbodies and suitable building designs and materials to reduce heat and create cooler urban environments.

Figure 23: Comparative analysis of shade and exposure across sites under compact low-rise category in Pune



Source: Google Earth and in situ data collection

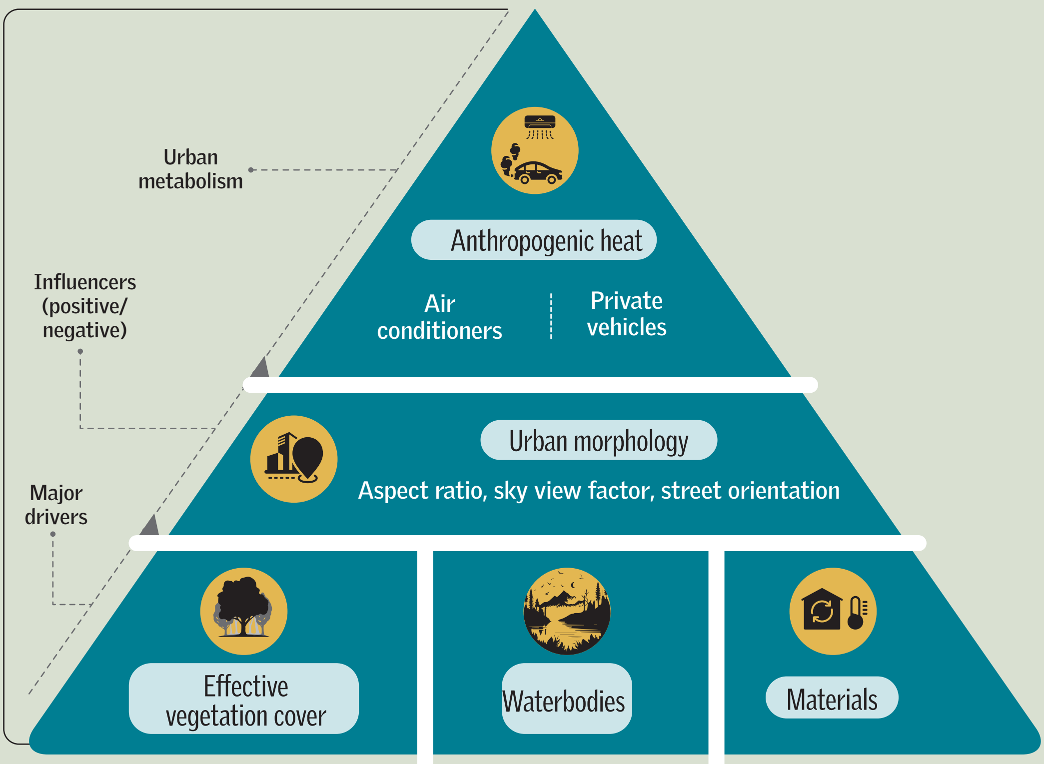
Figure 24: Sites with urban morphology—large low-rise and lightweight low-rise



Source: Google Earth

The analysis led to the development of a heat mitigation pyramid that identifies key parameters affecting heat (see *Figure 25: Heat mitigation pyramid—contribution of each parameter*). The major drivers of heat gain or reduction include effective vegetation cover, waterbodies and material choice. Urban morphology serves as an influencer that can improve the microclimate if planned and optimized. Additionally, human-generated heat from air-conditioner exhausts, vehicles and household appliances should also be considered as contributing factors. Prominent parameters, however, may differ across cities and various climatic zones.

Figure 25: Heat mitigation pyramid—contribution of each parameter

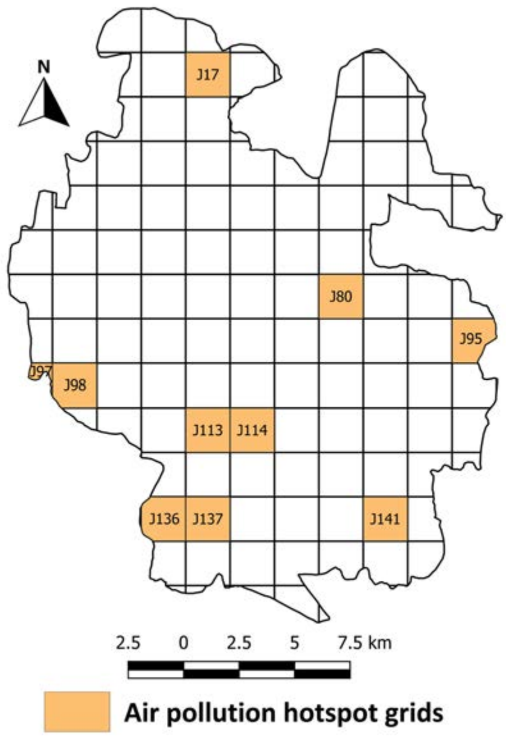


Created by: CSE

Air pollution and land surface temperatuires—an existing correlation

CSE conducted a grid-based analysis of Jaipur city, dividing the entire city into 2x2 km grids to identify air pollution hotspots. These hotspots include Vishwakarma Industrial Area (J17); Transport Nagar (J80); Saraswati Colony, Chander Nagar (J95); Nirman Nagar, Geetanjali Colony and Bank Colony (J97, J98); Gayatri Nagar, Mansarovar RIICO (J113); Jawahar Circle, Mata Colony, Jagatpura Road (J114); Pratap Nagar, Dada Gurudev Nagar and Ramnagar Colony (J136, J137); Ram Nagariya: Housing Board Colony (J141) (see *Map 5: Identified air-pollution hotspot grids in Jaipur city*). Land surface temperature (LST) data for 2023 and heat-stressed areas were overlaid onto these same grids.

Map 5: Identified air-pollution hotspot grids in Jaipur city

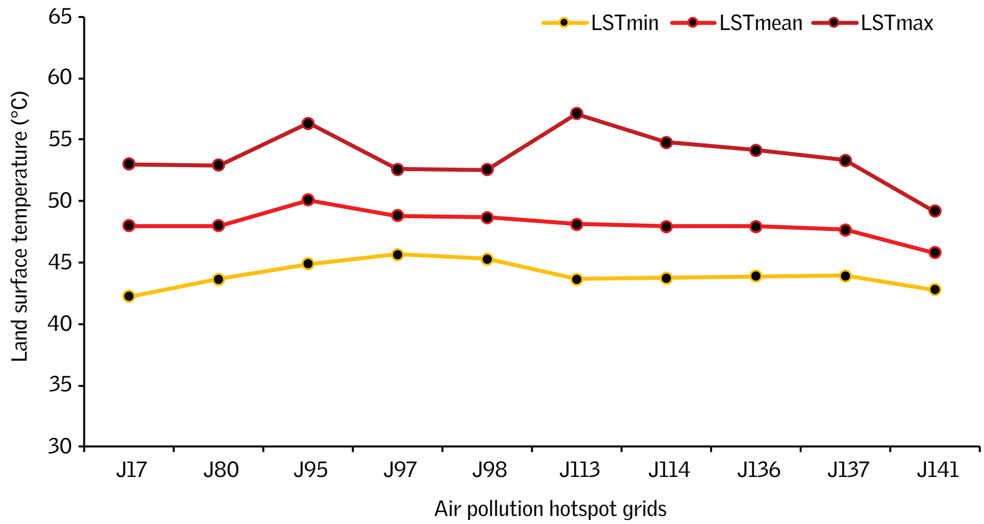


Data source: Landsat Series, USGS

It was observed that the mean surface temperatures in the selected grids were higher than the city's overall mean. Significant highs were noted in the minimum surface temperatures across these grids, which ranged from 42.25°C to 45.64°C (see *Graph 5: Mean, minimum and maximum land surface temperature [2023] for the hotspot grids*). The highest mean surface temperatures were recorded in Saraswati Colony, Chander Nagar (J95); Nirman Nagar, Geetanjali Colony and Bank Colony (J97, J98), with temperatures of 50.09°C, 48.81°C and 48.67°C, respectively.

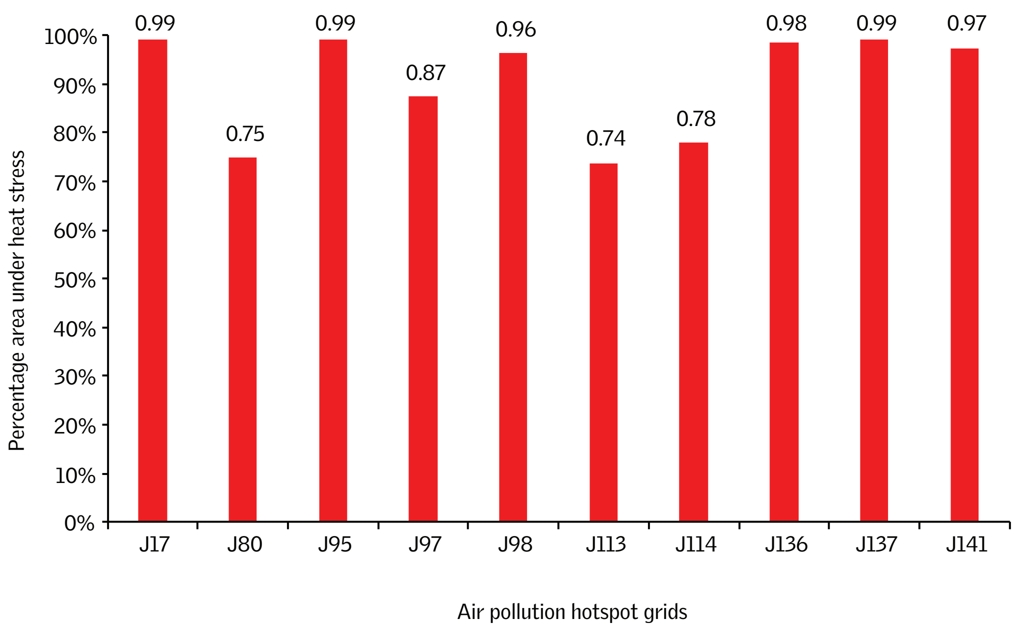
Further analysis of heat-stressed areas within these grids showed that around three-quarters or more of the area was heat-stressed (see *Graph 6: Air pollution hotspot grids associated with heat-stressed areas*). Six out of ten grids had over 96 per cent of their area classified as heat-stressed. Specifically, Vishwakarma Industrial Area (J17); Saraswati Colony, Chander Nagar (J95); and part of Pratap Nagar, Dada Gurudev Nagar and Ramnagar Colony (J136, J137) had nearly their entire area under heat stress.

Graph 5: Mean, minimum and maximum land surface temperature (2023) for the hotspot grids



Created by: CSE

Graph 6: Air pollution hotspot grids associated with heat-stressed areas



Source: CSE

HEAT STRESS AND INFORMAL SETTLEMENTS

The roofs of informal settlements are often made from materials like corrugated metal sheets, plastic or tarpaulin sheets which do not insulate well. They absorb and retain a lot of heat, raising the temperature inside and outside the structure. The roofs lack proper insulation, so the heat is directly transmitted into the living space, leading to higher indoor temperatures. Most structures in informal settlements lack proper ventilation, which prevents heat dissipation, and traps hot air, making it even hotter. According to CSE's analysis, 70 per cent of slums in Kolkata coincided with the heat-stressed areas (see *Map 6: Slums in heat centres in Kolkata*).

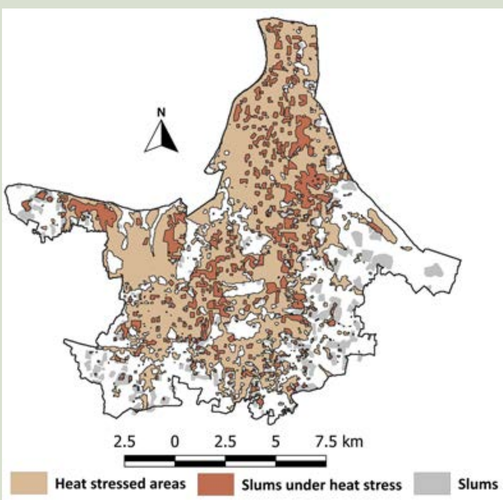
Industrial and manufacturing areas under heat stress

Industrial and manufacturing areas generate heat from heavy machinery and equipment that use a lot of energy. The roofs in these industries, often made of concrete and metal sheets, have high thermal mass and retain heat. Additionally, the absence of green spaces and the presence of extensive paved surfaces contribute to heat accumulation in these regions.

Parking lots as heat-stressed

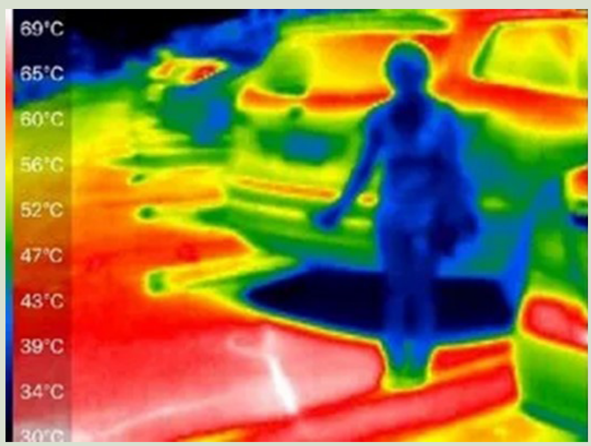
Parking lots are often made from heat-trapping materials such as asphalt or concrete, which increases local temperatures. The dark colour and high thermal mass absorb heat during the day. If parking lots are not covered, the roofs of parked cars absorb and radiate heat, much like a metal roof. This combination of heat-retentive surfaces and exposed cars increases heat in and around parking lots. According to a study published in Advanced Materials Research, the surface temperature in a parking lot can reach 65°C (see *Figure 26: Uncovered parking lots record high temperatures*).[41]

Map 6: Slums in heat centres in Kolkata



Created by: CSE

Figure 26: Uncovered parking lots record high temperatures



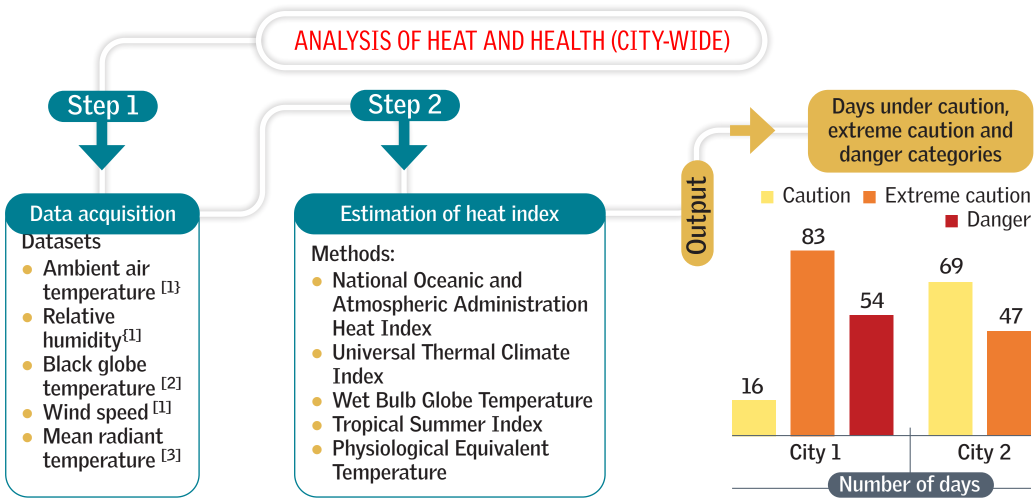
Source: Improving microclimate in Los Angeles' heat-vulnerable communities, Institute of the Environment and Sustainability, University of California, Los Angeles, USA

Urban heat and health: an interface

ANALYSIS OF HEAT AND HEALTH (CITY-WIDE)

With an understanding of the factors that cause heat gain, the next step is to assess their impact on people's health. Heat impacts individual health in different ways. It can cause discomfort, leading to heat exhaustion, heatstroke and cramps. Higher temperatures can also extend allergy seasons resulting in more people suffering from pulmonary diseases and respiratory issues. A city-level analysis of heat and health would help quantify the number of days classified under heat risk, offering preliminary insights into the impacts on residents (see *Figure 27: Illustration of methodology and output: heat index analysis—a measure of real feel*).

Figure 27: Methodology and output: heat index analysis—a measure of real feel



Data sources: [1]India Meteorological Department (IMD) | [2] In situ | [3] Empirical formula or simulations

Heat index analysis—a measure of real feel

The heat index (HI) or Humidex measures how the human body perceives temperature when both ambient air temperature and humidity are factored together. It is directly associated with thermal comfort. When our bodies heat up, we sweat, and the evaporation of sweat helps regulate our body temperature. However, during high heat and humidity, this self-cooling process slows down because the air is already saturated with moisture. As a result, the body struggles to regulate its temperature, leading to discomfort.[42]

High temperatures combined with high humidity create sultry weather that hinders both mental and physical work. Prolonged exposure to such conditions can decrease productivity and efficiency, resulting in loss of work hours.[43]

According to research published in the Proceedings of the National Academy of Sciences, a global temperature rise of 1.5°C above pre-industrial levels will expose billions of people to extreme heat and humidity. This will make natural cooling mechanisms ineffective. If the temperature rises by 2°C, approximately 2.2 billion residents of the Indus River Valley, one billion people in eastern China, and 800 million people in sub-Saharan Africa will experience several hours of heat beyond human tolerance each year.[44]

Several indices assess the thermal comfort of residents. These include the National Oceanic and Atmospheric Administration Heat Index (NOAAHI), Universal Thermal Climate Index (UTCI), Wet Bulb Globe Temperature (WBGT), Tropical Summer Index (TSI), and Physiological Equivalent Temperature (PET). NOAAHI and UTCI are particularly popular for their ease of use and accurate estimations. However, the choice of thermal comfort index can depend on available data and user preference.

1. National Oceanic and Atmospheric Administration Heat Index (NOAAHI)

NOAAHI is calculated using a mathematical formula developed by the National Oceanic and Atmospheric Administration (NOAA). This formula uses a second-order polynomial function that takes into account ambient air temperature and relative humidity as shown in Equation 6.[45]

Equation 6:

$$HI = -42.38 + 2.05\times T + 10.14\times RH - 0.22\times T\times RH - 0.006\times T^2 - 0.05\times RH^2 + 0.001\times T^2\times RH + 0.0008\times T\times RH^2 - 0.000002\times T^2\times RH^2$$

Here,
HI: (°C)
T: Ambient air temperature (°F)
RH: Relative humidity (%)

Note: Ambient air temperature and relative humidity datasets can be sourced from the India Meteorological Department.

The NOAAHI chart (see *Figure 28: NOAAHI chart*) categorizes levels of heat disorders. Heat index in the range of 26.67–32°C falls under the caution category, while 32– 38°C is classified as extreme caution. Danger is denoted by temperatures of 38– 52°C, while anything exceeding 52°C falls into the category of extreme danger. The associated effects of each category on humans are illustrated below (see *Table 3: Heat stress categories under NOAAHI and their effect on humans*). The methodological flowchart showing estimation and categorisation of heat index is shown below (see *Figure 29: Methodological chart: Estimation and categorisation of Heat Index*)

Figure 28: NOAAHI chart

Relative Humidity (%)	Ambient Air Temperature (°C)													
	26.67	27.78	28.89	30.00	31.11	32.22	33.33	34.44	35.56	36.67	37.78	38.89	40.00	41.11
40	26.67	27.22	28.33	29.44	31.11	32.78	34.44	36.11	38.33	40.56	42.78	45.56	48.33	51.11
45	26.67	27.78	28.89	30.56	31.67	33.89	35.56	37.78	40.00	42.78	45.56	48.33	51.11	54.44
50	27.22	28.33	29.44	31.11	32.78	35.00	37.22	39.44	42.22	45.00	47.78	51.11	55.00	58.33
55	27.22	28.89	30.00	31.67	33.89	36.11	38.33	41.11	44.44	47.22	51.11	54.44	58.33	
60	27.78	28.89	31.11	32.78	35.00	37.78	40.56	43.33	46.67	50.56	53.89	58.33		
65	27.78	29.44	31.67	33.89	36.67	39.44	42.22	45.56	49.44	53.33	57.78			
70	28.33	30.00	32.22	35.00	37.78	40.56	44.44	48.33	52.22	56.67				
75	28.89	31.11	33.33	36.11	39.44	42.78	46.67	51.11	55.56					
80	28.89	31.67	34.44	37.78	41.11	45.00	49.44	53.89						
85	29.44	32.22	35.56	38.89	43.33	47.22	52.22	57.22						
90	30.00	32.78	36.67	40.56	45.00	50.00	55.00							
95	30.00	33.89	37.78	42.22	47.22	52.78								
100	30.56	35.00	39.44	44.44	49.44	55.56								

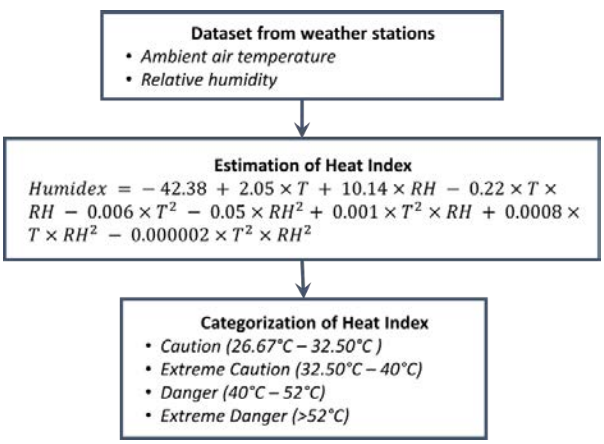
Source: National Oceanic and Atmospheric Administration

Table 3: Heat stress categories under NOAAHI and their effect on humans

Categories	Temperature range	Effect on humans
Caution	(26.67–32°C)	Fatigue possible with prolonged exposure and/or physical activity
Extreme caution	(32–38°C)	Heatstroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity
Danger	(38–52°C)	Heat cramps or heat exhaustion likely, and heatstroke possible with prolonged exposure and/or physical activity
Extreme danger	(> 52°C)	Heatstroke highly likely

Source: National Oceanic and Atmospheric Administration

Figure 29: Methodological chart: Estimation and categorisation of Heat Index



2. Universal Thermal Climate Index (UTCI)

Universal Thermal Climate Index (UTCI) takes into consideration the clothing adaptation of the population in response to actual environmental temperature. Four variables are required to calculate the UTCI: 2 m air temperature, 2 m dew point temperature (or relative humidity), wind speed at 10 m above ground level, and mean radiant temperature (MRT).

Note:

- Air temperature, dew point temperature, and wind speed datasets can be sourced from either the India Meteorological Department or the ECMWF ERA5 reanalysis.[46]
- The mean radiant temperature can be obtained either by using building simulation models (such as ENVI-met) or by available literature. One of the methods to quantify MRT is by using Equation 7.

Equation 7:

$$MRT = t_g + \left[(2.42 \times v_{air}) \times (t_g - t_a)\right.$$

Here,

T_g: Globe temperature (°C)
V_{air}: Air velocity (m/s)
T_a: Ambient air temperature (°C)

Note: To measure globe temperature, use a globe thermometer, which has a thermometer sensor inside a hollow, 6-inch diameter copper sphere coated with a matte black finish or similar material. Ensure the globe thermometer is not shielded from direct radiant heat during measurement. The globe temperature should be measured at various locations across the study area.

The obtained UTCI values should be categorized into various heat stress categories (see *Table 4: Heat stress categorization based on UTCI*) to comprehend heat stress levels.

Table 4: Heat stress categorization based on UTCI

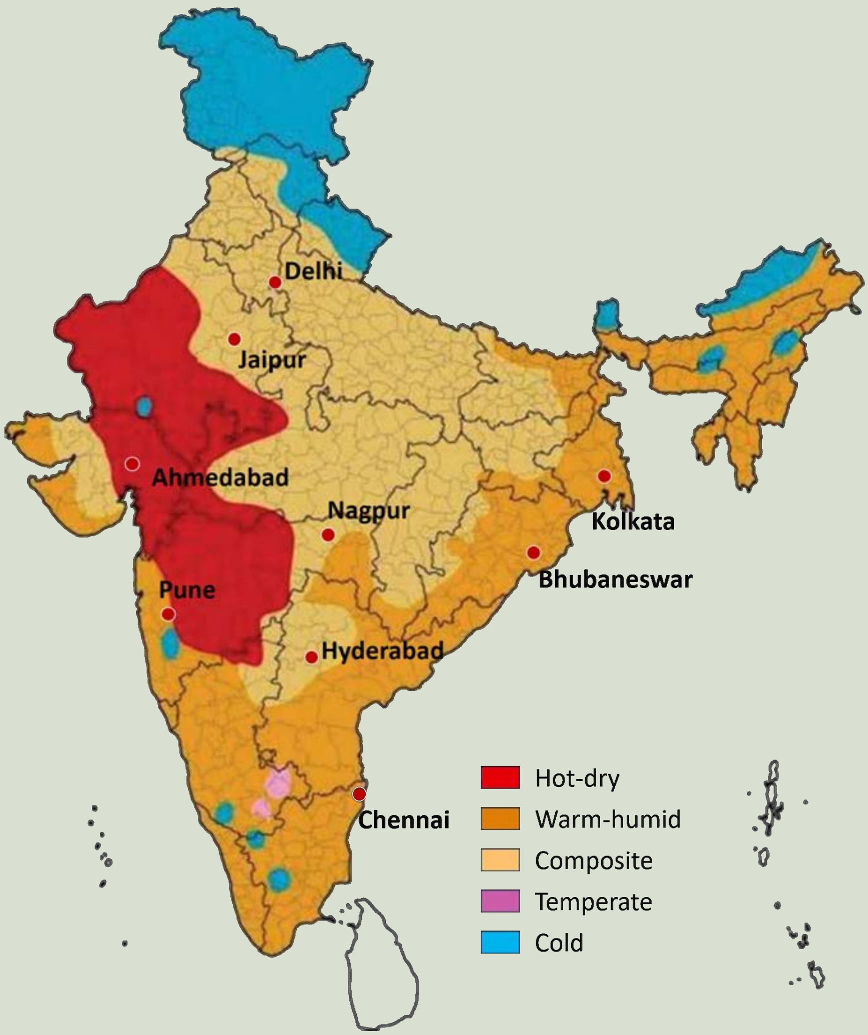
Categories	Temperature range
Extreme heat stress	> 46°C
Very strong heat stress	38–46°C
Strong heat stress	32–38°C
Moderate heat stress	26–32°C
No thermal stress	9–26°C

Source: Huang et al.., 2016[47]

CASE EXAMPLE: HEAT INDEX ANALYSIS—A MEASURE OF REAL FEEL

CSE calculated the NOAA Heat Index over the summer months of 2023 (March–July) for nine Indian cities selected based on population, occurrences of heat stress, and incidents of heat-related mortalities and casualties. This analysis provided insights into the number of days residents experienced thermal discomfort. The chosen cities span a range of climates: Kolkata, Pune, Chennai and Bhubaneswar fall within warm and humid zones; Delhi, Nagpur, Hyderabad and Jaipur are situated in composite climatic regions; while Ahmedabad lies within a hot and dry zone (see *Map 7: Cities analysed across various climatic zones*).

Map 7: Cities analysed across various climatic zones

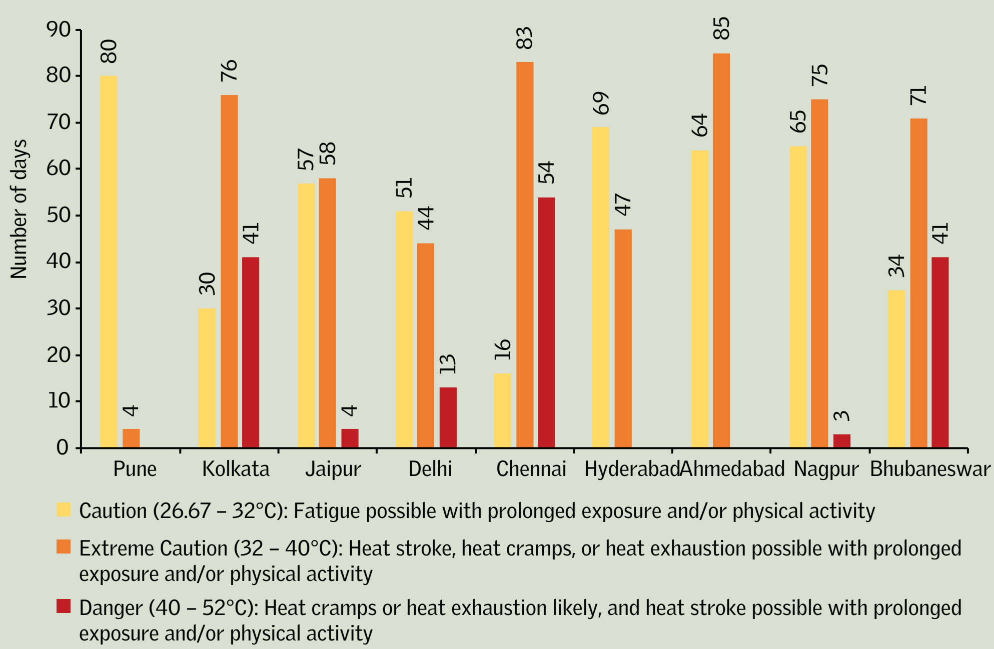


Source: Country Report on Building Energy Codes in India

In hot-dry and composite climatic zones, specific levels of relative humidity help lower the heat index. In contrast, warm-humid zones see higher heat indices due to increased humidity, negatively affecting residents' thermal wellbeing. Cities such as Chennai, Bhubaneswar and Kolkata, which have higher moisture levels, recorded the highest heat index values during summer months (March–July). Following closely were Ahmedabad, Nagpur, Jaipur and Delhi, situated in hot-humid and composite climatic zones. Most cities reached their highest heat index values in May and June, except for Jaipur and Delhi, which peaked in July. As summer transitions to monsoon, humidity levels rise, making it feel hotter, even in hot-dry and composite climatic zones. Thus, in addition to temperature, high humidity also influences the thermal comfort of residents.

The heat index values for nine cities were classified according to the classifications outlined in *Table 3* (see *Graph 7: Classification based on heat disorders due to Heat Index*). Chennai experienced 54 out of 153 days classified under the danger category, followed by 41 days each for Kolkata and Bhubaneswar. Delhi and Jaipur had 13 and four days in this category, respectively. This category indicates a high risk of heat exhaustion, cramps, and heat stroke with prolonged exposure. Additionally, cities experienced varying days under extreme caution: 85 days for Ahmedabad, 83 for Chennai, 76 for Kolkata, 75 for Nagpur, 71 for Bhubaneswar, 58 for Jaipur, 47 for Hyderabad, and 44 for Delhi. This indicates a possible risk of heatstroke and heat cramps/exhaustion with prolonged exposures. Overall, the city most affected by discomfort was Chennai, experiencing discomfort for all 153 days, followed by Ahmedabad with 149 days, Kolkata with 147 days, Bhubaneswar with 146 days, Nagpur with 143 days, Jaipur with 119 days, Hyderabad with 116 days, Delhi with 108 days, and Pune with 84 days.

Graph 7: Classification based on heat disorders due to Heat Index

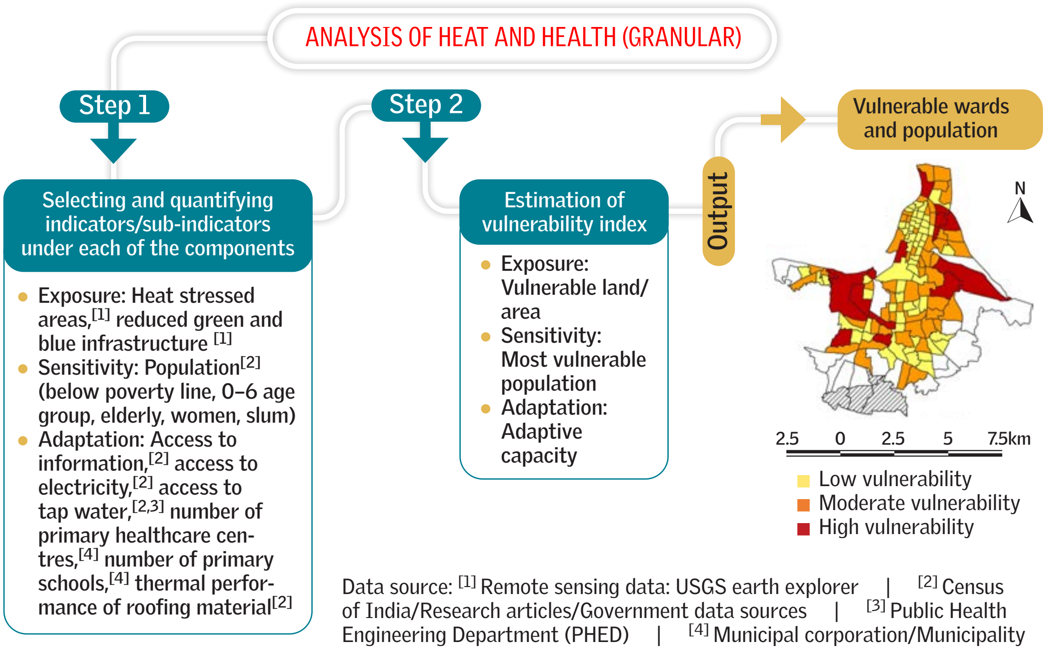


Source: CSE analysis based on National Oceanic and Atmospheric Administration classification

ANALYSIS OF HEAT AND HEALTH (GRANULAR)

After conducting a preliminary analysis of heat risk days, a more detailed assessment of the population at risk is crucial for designing targeted interventions. This involves a vulnerability assessment (see *Figure 30: Methodology and output: heat vulnerability assessment—ward level*) at the zonal or ward level to identify populations most affected by heat. The assessment should consider three key factors: exposure to heat, sensitivity of the exposed population, and their ability to adapt to extreme heat. By analysing these factors, the assessment can highlight the most vulnerable areas in the city. This outcome is vital for prioritizing interventions in high-risk localities, allowing authorities to allocate resources effectively and reduce negative effects on public health.

Figure 30: Methodology and output: heat vulnerability assessment—ward level



Data source: [1] Remote sensing data: USGS earth explorer | [2] Census of India/Research articles/Government data sources | [3] Public Health Engineering Department (PHED) | [4] Municipal corporation/Municipality

Source: CSE

Heat vulnerability assessment—ward level

Heat affects different groups in society differently. Vulnerable populations, such as the elderly, children and low-income communities, often bear the brunt of heat-related health risks. Understanding how various factors contribute to heat vulnerability is essential for creating effective mitigation strategies and improving resilience, especially with climate change intensifying these risks.

DEFINITION OF KEY TERMS—IPCC ASSESSMENT REPORT 6[48]

Exposure: Exposure refers to the presence of people, livelihoods, species or ecosystems, environmental functions, services and resources, infrastructure, or economic, social and cultural assets in places and settings that could be affected.

Sensitivity: Sensitivity is the degree to which a system or species is affected (either adversely or beneficially). The effect may be direct (e.g., increased energy demand for cooling in response to a change in the mean, range or variability of heat) or indirect (e.g., damages caused by an increase in the frequency of heatwaves).

Adaptive capacity: Adaptive capacity is the ability of systems, institutions, humans and other organisms to adjust, take advantage of opportunities, or cope with the consequences.

Vulnerability: Vulnerability is the propensity or predisposition to be affected. It encompasses sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

As outlined by the Intergovernmental Panel on Climate Change (IPCC), vulnerability is assessed through three main components: exposure, sensitivity and adaptive capacity. These components, each with specific indicators, collectively estimate the vulnerability index (see *Box: Definition of key terms*).

In this analysis, exposure pertains to heat; sensitivity relates to wards affected by heat with the highest vulnerable population concentrations; and adaptive capacity refers to the infrastructure available to reduce the impact of heat. Together, these components form the basis for estimating heat vulnerability across different wards (see *Table 5: Indicators and sub-indicators for estimation of heat vulnerability*). To conduct the analysis, the datasets required and their sources are mentioned below (see *Table 6: Parameters and their sources*).

Steps to calculate Vulnerability Index

Step 1: Exposure: Vulnerable land/area

a. Identification of heat-stresses areas (land vulnerable to heat)

- Identify heat-stressed areas (see '*Identification of heat-stressed areas*') and estimate blue and green infrastructure (see '*Estimation of blue-green infrastructure*') across the study area.
- Superimpose heat-stressed areas with blue and green infrastructure, and eliminate regions where they overlap since these areas have the potential to improve the local micro-climate. The presence of such infrastructure can lower temperatures by up to 6°C, with cooling effects extending to 250 metres.[49]

Table 5: Indicators and sub-indicators for estimation of heat vulnerability

Component	Input		Output
	Indicator	Sub-indicators	
Exposure	Vulnerable land/area	Heat-stressed areas Reduced blue and green infrastructure	Areas affected by high temperatures
Sensitivity	Most vulnerable population	Vulnerable population: • Below poverty line • 0–6 age group • Elderly population (60-plus age group) • Women population • Slum population	Demographic profile with heat-related status
Adaptation	Adaptive capacity	Available infrastructure: • Access to information • Access to electricity • Access to tap water • Number of primary healthcare centres • Number of primary schools • Thermal performance of roofing material	Overall adaptive capacity of the sensitive population

Note: The chosen parameters may vary depending on the availability of the dataset. The higher the number of parameters considered, the more precise the assessment will be.

Table 6: Parameters and their sources

Parameter	Source(s)
Heat-stressed areas and blue-green infrastructure	Remote sensing data (Landsat imagery)
• Population • Below poverty line • 0–6 age group • Elderly population (60-plus age group) • Women population • Slum population	Census of India, research articles, government data sources
Access to information	Census of India
Access to electricity	Census of India
Thermal performance of roofing material	Census of India
Access to tap water	Census of India
Number of primary healthcare centres	Municipal corporation/municipality
Number of primary schools	Municipal corporation/municipality

Note: The population parameters might overlap (persons residing in slums may be women who fall in the below poverty line as well) making percentage of vulnerable populations higher, so they need to be chosen with care and the data should be optimized.

b. Selection of the most vulnerable wards

- Select the wards with a high (x) percentage of area under heat stress. (Note: The value of ‘x’ can be user-defined. Eliminate those with percentage lower than X. Wards above the threshold should be considered for further analysis.)

Step 2: Sensitivity: Most vulnerable population

- Calculate the percentage of vulnerable populations (considering various sub-indicators) within the selected wards.
- Classify each sub-indicator based on the percentage of vulnerable population and assign values accordingly (assign higher values to the wards with a higher percentage of vulnerable population) (see *Table 7: Classification: Vulnerable population*).

Table 7: Classification: Vulnerable population

Percentage of vulnerable population at ward level	Value (1, 2, 3 . . . n)
Low	Lowest value (1)
Medium	(2)
..	.
..	.
High	Highest value (n)

Step 3: Adaptation: Adaptive capacity

- Estimate/quantify each sub-indicator for the selected wards.
- Categorize the sub-indicators into classes based on user-defined thresholds and assign values (assign higher values to the wards with a higher percentage/value of the sub-indicator) (see *Table 8: Classification: Parameters of adaptive capacity*).

Table 8: Classification: Parameters of adaptive capacity

Value/percentage of sub-indicator	Class (1, 2, 3. . . n)
Low	Lowest value (1)
Medium	(2)
. . .	. . .
. . .	. . .
High	Highest value (n)

- Sum up all the assigned class values of sub-indicators for each ward (see Equation 8).

Equation 8:

$$\textit{Indicator value}_i = \sum_{i=1}^{n} \textit{Value}\ (\textit{Sub-indicator}_1, \textit{Sub-indicator}_2 \cdots \textit{Sub-indicator}_n)$$

- Assign values based on the indicator value (obtained by the sum of class assigned to sub-indicators) (assign higher values to the wards with a high total of sub-indicators, i.e., high adaptive capacity) (see *Table 9: Classification: Cumulative adaptive capacity*).

HOW CAN INFRASTRUCTURE IMPROVE ADAPTIVE CAPACITY FOR HEAT-RELATED ISSUES?

Access to information

Gadgets like radios, televisions and mobile phones help people receive early warnings and heat-related preparedness information. These devices provide access to news, weather forecasts, and awareness campaigns. They also deliver timely alerts, such as heat advisories and safety instructions, helping people act early and respond effectively. More people can be reached before and during heat events, allowing communities and authorities to prepare efficiently. This improves their ability to cope with heat and reduces their vulnerability to heat-related disasters.

Access to electricity

Access to electricity improves the ability to cope during heat-related disasters by powering cooling systems. It also provides essential resources and keeps communication channels open. This allows individuals and communities to stay informed and connected, respond proactively, and access critical services, reducing their vulnerability during extreme heat events.

Access to tap water

During heatwaves, families without reliable access to tap water are at higher risk of heat-related health issues. Water is critical for staying hydrated, and shortages make it difficult for households to cope with heat. When water supplies are cut off, families may not be able to afford alternatives like water tankers, leaving them more vulnerable to heat-related problems.

Number of primary healthcare centres

The presence of primary healthcare centres is crucial for reducing the health impacts of heatwaves. These facilities provide access to medical professionals, timely treatment, and education on how to prevent heat-related illnesses. They also monitor vulnerable populations, which helps lower the number of heat-related deaths and illnesses. In areas with limited healthcare services, people face higher risks during heatwaves. The National Health Mission (NHM) specifies that one primary healthcare centre (PHC) should serve 30,000 people.

Number of primary schools

Schools are important for building resilience in communities, especially among children. They help spread awareness about heat safety and prepare children for heat-related risks. Schools can integrate heat safety into the curriculum, providing vital information that enhances the community's ability to adapt to extreme heat. The Urban and Regional Development Plans Formulation and Implementation (URDPFI) guidelines suggest that there should be one primary school for every 5,000 people.

Thermal performance of roof materials

Roofing materials that reflect less heat and offer better insulation can reduce indoor temperatures during heatwaves. This helps lower energy consumption for cooling and improves thermal comfort inside buildings. By making homes and workplaces more resistant to heat, communities can better withstand extreme heat events, reducing their vulnerability.

Table 9: Classification: Cumulative adaptive capacity

Indicator value	Class (1, 2, 3 . . . n)
Low	Lowest value (1)
Medium	(2)
. . .	. . .
. . .	. . .
High	Highest value (n)

Step 4: Vulnerability Index

- A ward-wise cumulative score of sensitivity and adaptive capacity will give the vulnerability index (use Equation 9).

Equation 9:

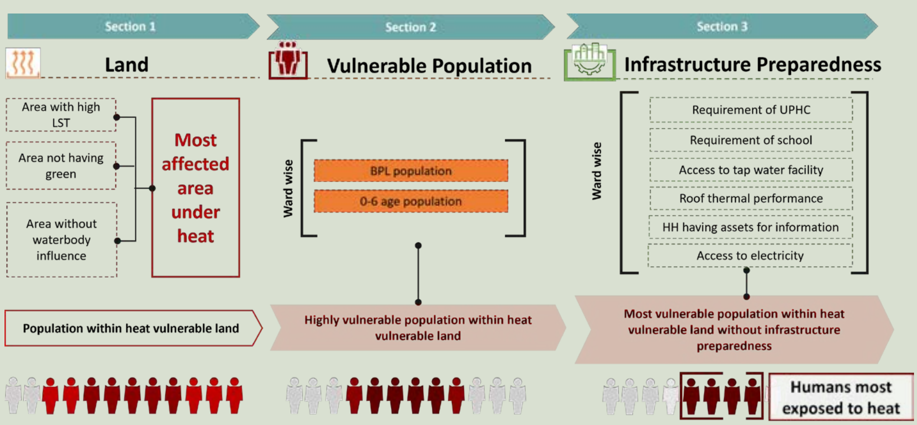
$$VI_i = I_{VP_i} - I_{AC_i}$$

Here,
VI: Vulnerability Index
I_{VP}: Final indicator class of vulnerable population for ward 'i'
I_{AC}: Final indicator class of adaptive capacity for ward 'i'
i = Ward number (1, 2, 3 … n)

CASE EXAMPLE: HEAT VULNERABILITY ASSESSMENT—WARD LEVEL

CSE conducted a ward-wise heat vulnerability assessment over Kolkata city. The methodology used for the analysis is illustrated below (see *Figure 31: Methodology for estimation of heat vulnerability*).

Figure 31: Methodology for estimation of heat vulnerability



Created by: CSE

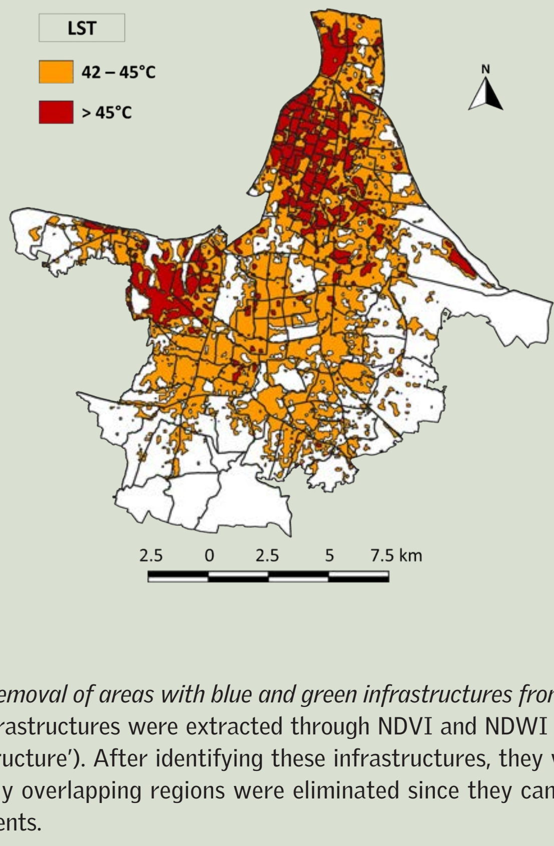
Step 1: Exposure: Vulnerable land/area

a. Identifying the heat-stresses areas

Based on IMD's criteria for heatwaves and high humidity levels in Kolkata, thresholds of 42°C and 45°C were selected to classify areas into severe (42–45 °C) and very severe (>45 °C) heat categories. A decadal analysis was conducted to assess heat stress across the city.

The analysis identified heat-stressed areas within Kolkata, marked by ward boundaries (see *Map 8: Identified heat-stressed areas in KMC region*). Findings indicated that approximately 58 per cent of the municipal area is susceptible to heat. Of this, 21.44 per cent was classified as very severe heat zones, while the remaining 78.56 per cent fell under severe heat zones. It was observed that almost half (70 out of 144) of the wards had over 90 per cent of their areas categorized as experiencing severe and very severe heat stress. Among these, the entire areas of 26 wards (ward numbers 10, 11, 16, 17, 18, 23, 24, 25, 28, 29, 37, 38, 39, 41, 42, 43, 47, 48, 49, 50, 51, 52, 53, 54, 83 and 84) were found to be affected by heat.

Map 8: Identified heat-stressed areas in KMC region



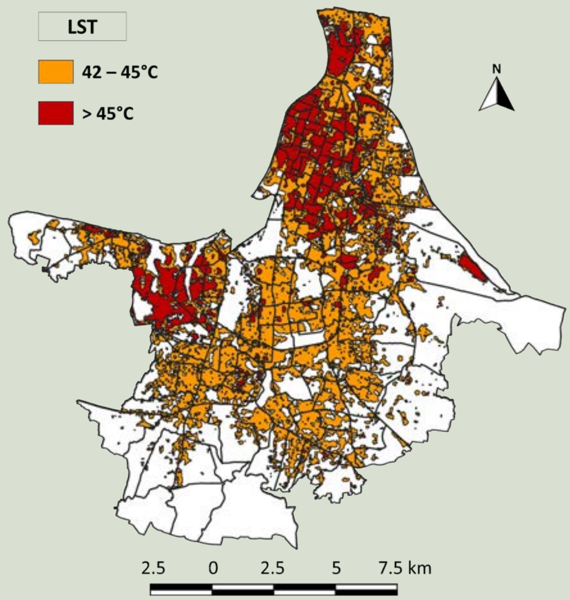
Source: CSE

b. Extraction and removal of areas with blue and green infrastructures from heat-stressed areas

Blue and green infrastructures were extracted through NDVI and NDWI (as shown in 'Estimating blue-green infrastructure'). After identifying these infrastructures, they were overlaid with heat-stressed areas. Any overlapping regions were eliminated since they can positively affect micro-climatic improvements.

The integration of blue-green infrastructure within the wards has led to a reduction in heat-stressed areas to about 50 per cent of the total municipal area (see *Map 9: Heat-stressed areas in KMC region with areas under blue-green infrastructures omitted*). Among these, very severe and severe heat zones account for 11.82 per cent and 38.25 per cent of the total municipal area, respectively.

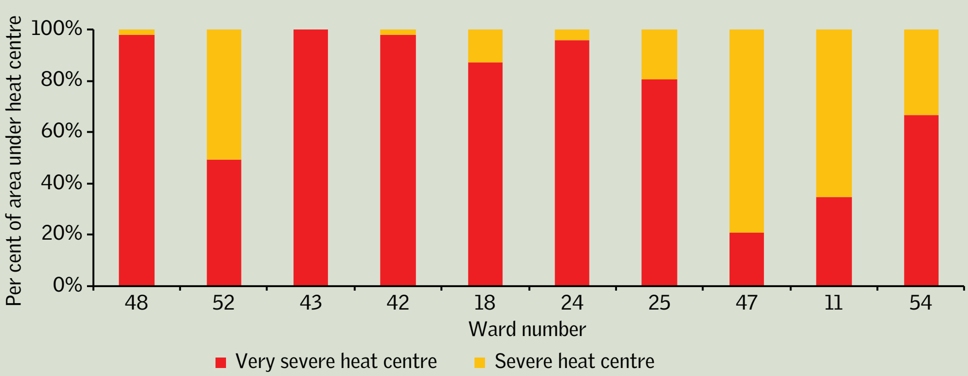
Map 9: Heat-stressed areas in KMC region with areas under blue-green infrastructures omitted



Source: CSE

Seventy-five per cent of the city's wards (109 out of 144) experience significant heat issues, with over half of their municipal areas affected. Specifically, ward numbers 48, 52, 43, 42, 18, 24, 25, 47, 11 and 54, which house approximately 220,000 residents, face heat stress across nearly their entire areas (see *Graph 8: Wards with >95 per cent of area under heat centres*). Among these, wards 43, 42, 48 and 24, have a combined population of around 80,000 and witnessed over 95 per cent of their areas classified as very severe heat zones. This situation underscores the extensive impact of heat stress in these densely populated regions.

Graph 8: Wards with >95 per cent of area under heat centres

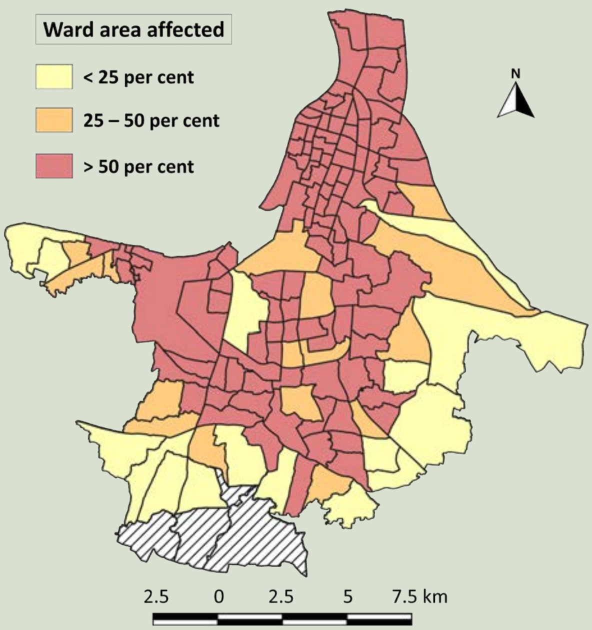


Source: CSE

Regardless of the extent of heat-affected areas, the significance of heat in wards 23, 39, 135, 24, 54, 29 and 41 is pronounced due to their high population density, exceeding 950 people per hectare. In Kolkata, these wards grapple with extensive heat stress, with percentages of affected areas reaching 98.93 per cent, 91.08 per cent, 89.22 per cent, 99.84 per cent, 99.35 per cent, 93.20 per cent and 87.39 per cent, respectively. This underscores the profound impact of heat stress on densely populated areas increasing the residents' susceptibility to heat.

To understand vulnerability, wards with heat-stressed areas contributing to less than 25 per cent were eliminated, as they might exhibit a degree of resilience. The remaining wards with more than 25 per cent of the region under heat stress (125 out of 144) were identified and utilized for further analysis (see *Map 10: Heat-stressed areas in KMC region categorized on the basis of percentage of ward area affected*).

Map 10: Heat-stressed areas in KMC region categorized on the basis of percentage of ward area affected

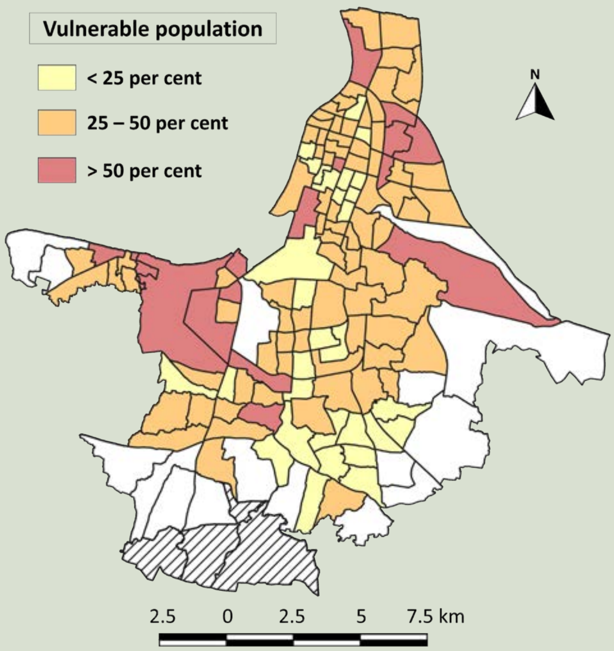


Source: CSE

Step 2: Sensitivity: Most vulnerable population

Vulnerability to heat has a large disparity, which revolves around age, gender, socioeconomic status, housing conditions and working environments. People with lower incomes often live and work in settings with high heat exposure, such as construction sites, street vending areas and industrial sheds. These environments use materials that trap heat and lack adequate ventilation. Children are also at risk due to their limited ability to regulate body temperature, slower adaptation rates and reliance on adults for hydration.

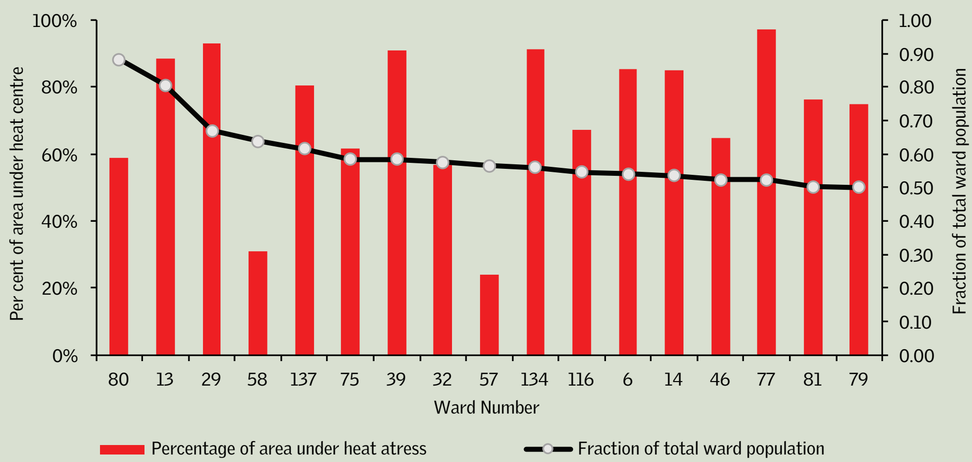
Map 11: Categories of wards based on most vulnerable population (BPL and children—0–6 years)



Note: Population datasets can be sourced from the Census of India.

Source: CSE

Graph 9: Wards with a high fraction of vulnerable population and percentage of area under stress



Source: CSE

Vulnerable wards were further categorized on the basis of presence of population—below poverty line and young children aged 0–6 years. The proportion of these groups in each vulnerable ward was calculated in relation to the total ward population and classified into three categories (see *Map 11: Categories of wards based on most vulnerable population [BPL and children—0–6 years]*). Seventeen wards—80, 13, 29, 58, 137, 75, 39, 32, 57, 134, 116, 6, 14, 46, 77, 81 and 79—had over 50 per cent of their population in high-risk areas (see *Graph 9: Wards with a high fraction of vulnerable populations and percentage of area under stress*). This shows where communities with limited resources are hit hardest by heat stress.

Step 3: Adaptive capacity

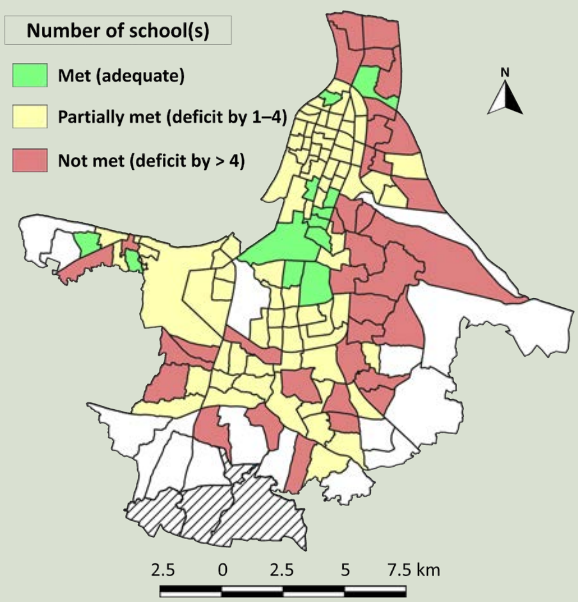
Availability of infrastructure plays a key role in reducing vulnerability and strengthening coping mechanisms. Assessing preparedness involves looking at how ready different wards are to handle heat-related issues. Six heat-related infrastructural parameters, including number of healthcare centres and schools; access to tap water, electricity and information; and the thermal characteristics of roofing materials were examined. These factors were analysed for the 125 wards where more than 25 per cent of the area is affected by heat stress.

Note: These datasets can be sourced from various entities, including the Census of India, municipal corporations, Public Health Engineering Departments (PHEDs) and urban local bodies.

a. Number of primary schools

On the basis of Urban and Regional Development Plans Formulation and Implementation (URDPFI) guidelines, which recommend at least one primary school for every 5,000 people, the existing number of schools in each ward was compared to the ideal count. The gaps were then divided into three categories: met, partially met and not met (see *Map 12: Infrastructure preparedness: availability of schools*).

Map 12: Infrastructure preparedness: availability of schools

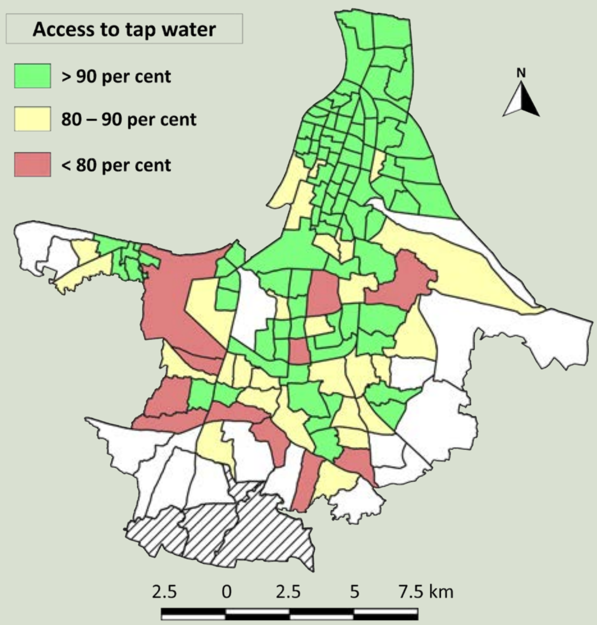


Source: CSE

Only twelve wards (63, 61, 47, 8, 138, 5, 69, 50, 53, 62, 70 and 133) had a sufficient number of schools, meeting the criteria. In 77 wards, the number of schools fell short by one to four, so they were classified as partially met. The remaining wards had a deficit of more than four schools and were categorized as not meeting the requirements. The situation was concerning in certain wards: wards 3, 14 and 58 had a deficit of 10 schools each, while ward 66 lacked 14 schools.

b. Access to tap water
An analysis was conducted to evaluate access to treated tap water across the wards. The findings were categorized into three groups: wards with less than 80 per cent access, those with 80 per cent to 90 per cent access, and wards where 90 per cent or more households had treated tap water connections (see *Map 13: Infrastructure preparedness: access to tap water*).

Map 13: Infrastructure preparedness: access to tap water



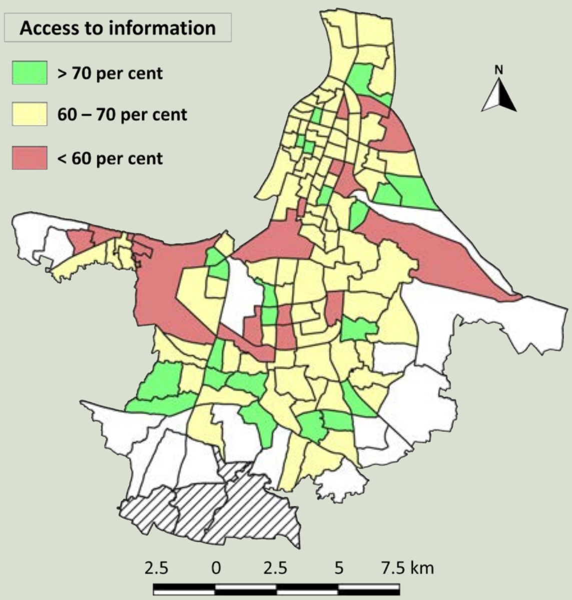
Source: CSE

The analysis revealed that 68.80 per cent of the wards had more than 90 per cent of households with treated tap-water connections, indicating string access. Additionally, 22.40 per cent of wards fell into the 80 per cent to 90 per cent range, showcasing moderate access. Meanwhile, 8.8 per cent of the wards had less than 80 per cent of households connected to treated tap water, indicating a gap in accessibility.

Certain wards—5, 18, 20, 19, 17, 8, 40, 4, 104, 2, 83, 35, 28, 68, 36, 42, 38, 7, 88 and 103—performed exceptionally well, with over 98 per cent of households connected to treated tap water. However, wards 129, 115, 100 and 132 faced serious challenges, with fewer than two-thirds of households having access, highlighting the need for improvement in these areas (see *Map 13: Infrastructure preparedness: access to tap water*).

c. Access to information
An analysis was conducted to evaluate information accessibility in different wards. The findings were categorized into three distinct categories, i.e. wards with less than 60 per cent access, those with 60 to 70 per cent access, and wards where more than 70 per cent of households had access (see *Map 14: Infrastructure preparedness: access to information*).

Map 14: Infrastructure preparedness: access to information



Source: CSE

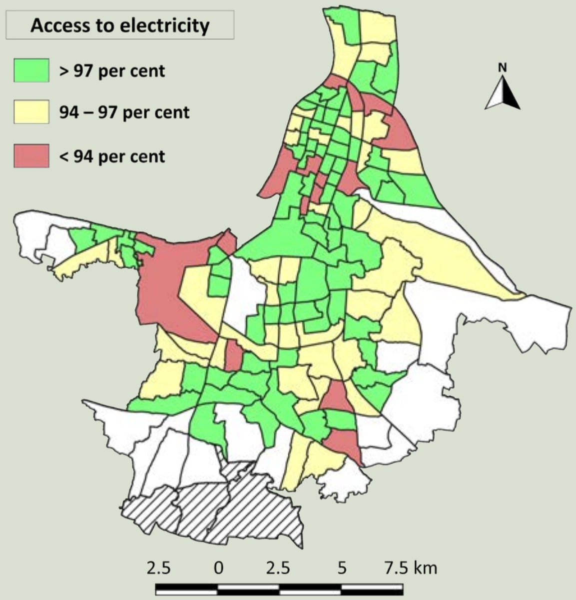
The analysis showed that 21 out of 125 wards had over 70 per cent of households with access to information, reflecting strong accessibility. Another 87 wards fell within the 60–70 per cent range, showing moderate accessibility. However, 17 wards had less than 60 per cent of households connected to information sources, indicating a gap.

Three wards—18, 23 and 34—excelled, with more than 75 per cent of households having access to information, indicating positive progress. In contrast, ward 80 had the lowest access, with only 44.80 per cent of households connected to information sources, pointing to the need for improvements in this ward.

d. Access to electricity
An analysis was conducted to evaluate electricity accessibility in different wards, and the results were divided into three categories: wards with less than 94 per cent access, those with 94–97 per cent access, and wards with 97 per cent or more households having access to electricity (see *Map 15: Infrastructure preparedness: access to electricity*).

The study revealed that 56 per cent of the wards had more than 97 per cent of households with electricity, indicating good accessibility. Another 32 per cent of the wards fell within the 94–97 per cent range, showcasing moderate accessibility. However, 12 per cent of the wards had less than 94 per cent of households with electricity, highlighting a gap in accessibility.

Map 15: Infrastructure preparedness: access to electricity



Source: CSE

Wards 18, 40, 50, 19, 23, 5, 55, 135, 68, 77 and 30 stood out, with 99 per cent or more households connected to electricity, showcasing successful electricity distribution. In contrast, wards 96, 52, 80 and 45 had less than 89 per cent access to electricity, emphasizing a need for improvement in these areas.

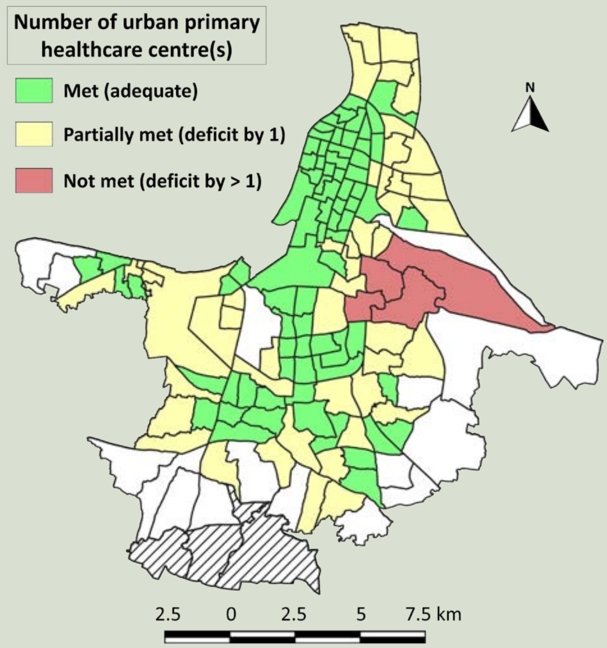
e. Number of primary healthcare centres

According to the NHM framework, a standard primary healthcare centre (PHC) should serve 30,000 people. Based on this standard, the number of ideal PHCs was compared with the existing ones in each ward. The disparities were categorized into three groups: met, partially met, and not met (see *Map 16: Infrastructure preparedness: access to urban primary healthcare centres*).

Out of 125 wards, 75 were found to meet the PHC requirements. However, 46 wards had a shortage of one PHC each, falling into the partially met category. Four wards showed the most significant gaps: wards 65, 59 and 58 lacked two PHCs each, while ward 66 had a shortfall of three, placing them in the not-met category.

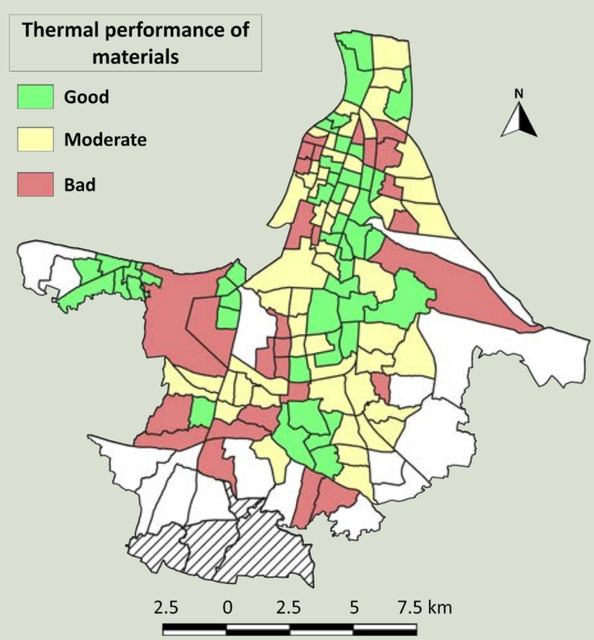
Healthcare infrastructure in slums of Kolkata: The number of urban primary healthcare centres (UPHCs) needed depends on the layout of slum areas. In cities where slums are spread out, each UPHC serves about 50,000 people, while it can serve 75,000 in densely packed slum areas. Typically, UPHCs are designed to support around 25,000–30,000 people in slums, ensuring that healthcare is tailored to the specific needs of urban areas, considering the density of slum settlements. According to Kolkata Municipal Corporation, approximately 1.5 million people in Kolkata live in slums. Based on the NUHM guidelines, the city would ideally need 30 UPHCs, each serving 50,000 residents. However, Kolkata currently has approximately 144 PHCs, far exceeding the recommended number. This shows the city's strong commitment to healthcare infrastructure, going well beyond the standard NUHM recommendations.

Map 16: Infrastructure preparedness: access to primary healthcare centres



Source: CSE

Map 17: Infrastructure preparedness: thermal performance of materials



Source: CSE

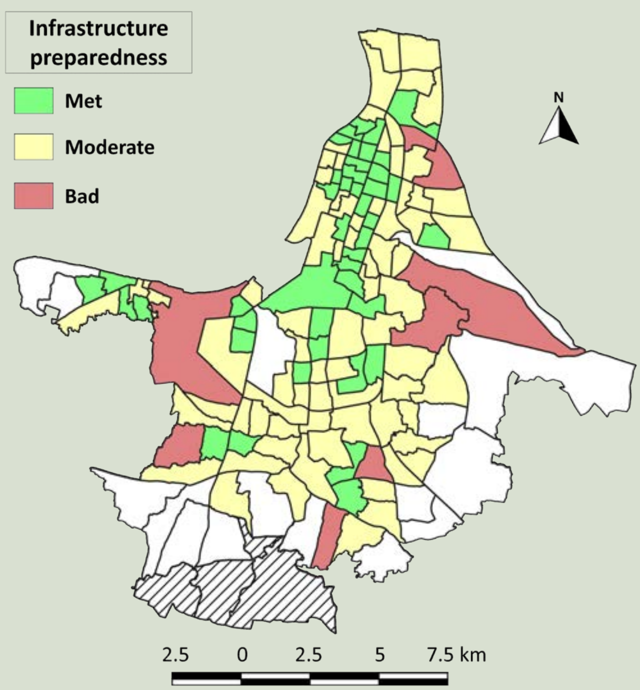
f. Thermal performance of roof materials
A ward-level assessment of the thermal performance of roofing materials was conducted, based on the percentage of roof material types and their U-values to create a thermal performance index. Lower index values represent better thermal efficiency, meaning the material transfers less heat. The index was divided into three categories: good, moderate and poor (see *Map 17: Infrastructure preparedness: Thermal performance of materials*).

Out of the 125 wards analysed, 44 showed excellent thermal efficiency, with index values below 6. Another 53 wards were classified as moderate, having index values between 6 and 12. The remaining wards performed poorly in thermal efficiency. Wards 137, 135, 138, 139, 87, 38, 60, 29 and 75 had strong thermal resilience, with index values under 3. In contrast, wards 89, 15, 79, 112 and 113 had the worst thermal performance, with index values exceeding 20.

Cumulative infrastructure preparedness
The infrastructure preparedness of wards with high heat and vulnerable populations was evaluated using six parameters. Based on the cumulative scores, the wards were classified into three categories: met, partially met and not met.

A total of 43 wards achieved the 'met' status, indicating strong preparedness. Another 74 wards were in partially met category, highlighting moderate preparedness. Wards 32, 129, 66, 96, 13, 113, 80 and 58, however, were identified as needing substantial adaptation (see *Map 18: Ward-wise infrastructure preparedness in heat centres*).

Map 18: Ward-wise infrastructure preparedness in heat centres

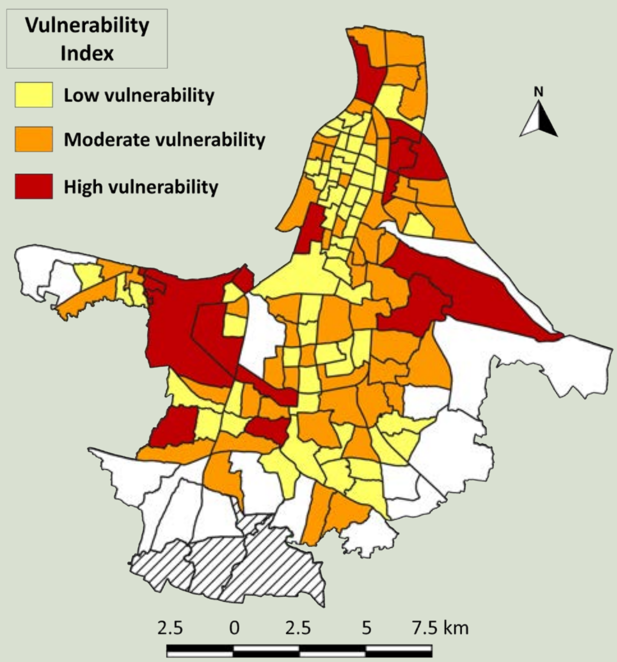


Source: CSE

Step 4: Vulnerability Index

A cumulative assessment of heat vulnerability (estimated using Equation 9) considering both the size of vulnerable population and infrastructure preparedness showed that 57 wards have low vulnerability as they house fewer vulnerable residents and have strong infrastructure preparedness. Fifty-three wards fall into the moderate vulnerability category, with a moderately vulnerable population and infrastructure readiness. In contrast, 15 wards face high heat vulnerability, due to a significant vulnerable population and limited infrastructure preparedness. The highly vulnerable wards—75, 134, 116, 6, 46, 29, 14, 81, 79, 129, 66, 32, 13, 80 and 58—collectively accommodate 675,080 people and need priority action to mitigate the risk (see *Map 19: Ward-wise vulnerability map of area under Kolkata Municipal Corporation*).

Map 19: Ward-wise vulnerability map of area under Kolkata Municipal Corporation



Source: CSE

4 MITIGATIVE MEASURES AND WAY FORWARD

Cities need a new approach to urban planning by integrating climate action and resilience.

Prioritize blue-green infrastructure.

Retrofit or `heatproof' existing development.

Conduct city vulnerability assessments.

Institutionalize heat management and secure fiscal support.

Reduce cooling load in buildings through climate-appropriate building design and low-carbon cooling technologies.

Innovate building materials.

Establish accountability instruments and disclosure systems.

Mitigative measures for improving micro-climatic conditions

Currently, nearly every major city struggles to cope with the warming climate and requires retrofits to its existing infrastructure to bring safeguards. Meanwhile, smaller cities stand on the brink of explosive growth and urgently need to pursue 'heatproof' development.

To mitigate rising heat and ensure thermally comfortable urban areas, a comprehensive approach addressing multiple aspects of urban planning and design is essential. The following mitigative measures can help cities adapt to and mitigate the adverse impacts of rising temperatures:

ENHANCEMENT OF BLUE-GREEN INFRASTRUCTURE

Enhancing blue and green spaces is the most effective solution for cooling cities, serving as the first line of defence due to their high potential to improve the microclimate.

Green infrastructure: Urban mini forests, street trees, parks and green spaces play a crucial role in improving microclimatic conditions. They release moisture via transpiration, which reduces air and surface temperatures, creating cool spaces. Additionally, these green areas enhance social wellbeing and provide recreational spaces, benefiting public health.

Blue infrastructure: Waterbodies such as lakes, rivers, ponds and constructed wetlands help cool urban areas and regulate the microclimate through evaporative cooling. During this process, the water absorbs heat, which is used to convert water into vapour, preventing actual temperatures from rising. The presence of waterbodies also enhances the aesthetic appeal of urban landscapes.

Integrated blue-green infrastructure (BGI) benefits: Storm-water management systems, such as rain gardens, bioswales and sustainable urban drainage systems, play a crucial role in cooling the environment. As an added benefit, these systems manage storm-water runoff, reduce flooding and enhance water infiltration through permeable surfaces. This infiltration not only cools the ground surface but also replenishes the groundwater table.

IMPROVEMENT IN PARAMETERS OF URBAN STRUCTURE

Urban morphology, aspect ratio, sky view factor and street orientation play a crucial role in improving microclimatic conditions when planned and designed according to native climate. These factors influence the amount of solar heat absorbed, trapped and released within an urban area. Optimizing aspect ratios and sky view factors enhances natural ventilation and cooling, reducing heat reaching the ground and facilitating its dissipation. Proper street orientation, aligned with prevailing wind directions and sun paths, could optimize shading and airflow, creating cooler microclimates within the city.

STREETSCAPING—DESIGNING AND RETROFITTING STREETS

According to the Institute for Transportation and Development Policy, streets account for about one-fifth of a city's area.[50] They can serve as crucial areas of intervention to achieve thermal comfort. Designing heat-resilient streetscapes with shading elements and improved microclimates can reduce heat exposure.

Shading through natural elements like trees and vertical plantations, combined with innovative design elements, can make streets pleasant and cool. This approach enhances thermal comfort and promotes public use. It enables pedestrians to move comfortably, helps street vendors set up shops without overheating, and provides cooler journeys for motorized transport users.

Installing water elements such as swales, rain gardens, ponds and fountains at intersections and wide streets, especially on the windward side, can cool the environment and improve a city's aesthetics. Plantation and swales can be designed together for improved thermal condition of a street (see *Figure 32: Streetscaping—tree plantation and vertical plantation on the median and swales of sidewalks*).

Figure 32: Streetscaping—tree plantation and vertical plantation on the median and swales of sidewalks

Source: CSE

Replacing sidewalks, parking lots and other paved surfaces with hollow grass pavers can reduce heat trapping. Integrating these solutions into planning regulations is essential for effective implementation and sustainability.

RETROFITTING OLD CONSTRUCTIONS

The current urban heat-stressed areas identified in the analysis included compact residential constructions, commercial markets, slums and industrial zones. These areas are dense and have limited opportunities for improving layout or increasing blue and green spaces. Therefore, using appropriate construction materials and implementing retrofits is crucial.

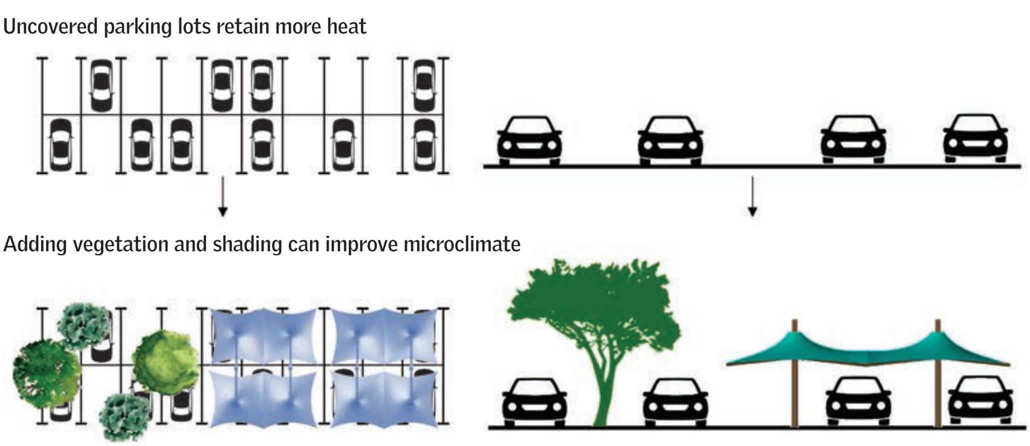
Retrofitting includes installing shading devices, adding insulation, and using reflective materials, such as cool roofs and green roofs. For example, cool roofs can lower indoor temperatures by up to 5°C. Telangana has released a cool roof policy aiming for 300 km^2 of cool roofs by 2028 to combat the urban heat island effect.[51] Additionally, an addendum to the URDPFI Guidelines recommends mandatory cool roofs as a city planning strategy.[52]

Retrofitting the existing open parking lots with covering can also aid in reducing temperatures in the nearby areas (see *Figure 33: Shading parking lots could reduce temperatures*).

POLICY INTERVENTIONS, GOVERNANCE AND FINANCES

Urban local bodies (ULBs) hold the potential to facilitate necessary heat action, as recognized by the Union government. The emerging needs for clean air, climate action and energy conservation are directly linked to the functions of ULBs.

Figure 33: Shading parking lots could reduce temperatures



Source: CSE

For instance, the 15th Finance Commission has allocated Rs 1,21,055 crore for ULBs, including Rs 38,196 crore for million-plus cities.[53] This grant for million-plus cities is tied to their performance in improving ambient air quality and meeting service-level benchmarks for urban drinking water supply, sanitation and solid waste management. This makes the grant and its execution one of the most crucial tools for implementing and monitoring city-level initiatives.

The guidelines established by the 15th Finance Commission have the potential to immediately integrate measures to prevent and mitigate heat stress in cities. India's Long-Term Low Emission Development Strategy, submitted to the United Nations Framework Convention on Climate Change (UNFCCC) during the 27th Conference of the Parties (COP 27) in November 2022, outlines several localized climate measures. These include the preparation of city climate action plans integrated with respective master plans and building bylaws. The strategy also recommends forming a climate change cell at the ULB level to coordinate climate action across various schemes, conduct vulnerability assessments, map heat sinks and develop heat action plans.

Current heat action plans primarily focus on disaster response. However, the framework provided by the 15th Finance Commission can guide cities to prioritize and effectively implement heat action measures. Simultaneously, voluntary initiatives like the Green Climate Fund (GCF), established within the UNFCCC framework to assist developing countries in climate adaptation and mitigation, can be leveraged by Union ministries. This involves a year-long procedure led by a national designated authority to prepare or collect funding proposals for heat action in cities, which are then approved by a technical advisory panel and the GCF Board overseeing the fund.

ULBs can also explore other voluntary tools such as green bonds specifically earmarked for climate and heat-related projects. This requires governance bodies to establish defined criteria that focus on measurable outcomes. Currently, green bonds cover areas such as renewable energy, energy efficiency, clean transportation, green buildings, natural resources and land use, water and waste management, and pollution prevention and control. These areas align with the nature of actions required for heat mitigation.

Globally, while the first green bond was issued by the World Bank in 2008, according to a 2022 report by Swiss carbon finance consultancy South Pole, green municipal bonds have been issued by several Indian cities, including Ghaziabad, Ahmedabad, Surat, Visakhapatnam, Amravati, Indore, Bhopal, Pune, Hyderabad, Lucknow and Vadodara.[54]

The way forward

Cities need a new approach to urban planning: Master plans and building bylaws should integrate climate action and resilience. This new approach must focus on compact urban forms, layouts with appropriate ventilation, adequate blue-green infrastructure (increasing per capita greens in cities), water-sensitive urban design and planning, passive design, and renewable energy.

Prioritize blue-green infrastructure: Master plans should emphasize a system of blue-green infrastructure in new developments, providing several co-benefits such as improved air quality, heat sinks, carbon sequestration, water resource augmentation and flood control.

Retrofit existing developments: Enhance microclimates by focusing on nature-based solutions, increased shading, cool roofs, cool materials, and water elements such as fountains, swales and rain gardens.

Conduct city vulnerability assessments: Prioritize action for vulnerable population groups and localities to ensure targeted interventions.

Institutionalize heat management and secure fiscal support: Establish city climate change/heat management cells, develop climate action plans and create state-level regulatory bodies. Channelize existing statutory funds, schemes and international (bilateral and multilateral) adaptation and mitigation support.

Reduce cooling load in buildings: Implement climate-appropriate designs and low-carbon cooling technologies. Focus on thermally efficient envelopes (e.g., wall thickness, insulated roofs, shading devices, reflective coatings, window size and glazing), building orientation and clustering. Further, adoption of energy conservation building codes is crucial.

Innovate building materials: Explore and promote local and traditional skills. Evaluate new materials for thermal comfort and efficiency, and implement regulatory interventions to balance cost and performance.

Establish accountability instruments and disclosure systems: Create mechanisms for availing incentives such as PAT schemes and carbon trading to ensure transparency and accountability in climate action initiatives.

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Increasing heat sources—and reducing heat sinks—in cities in India entrap both heat from the sun and their own waste heat. This places a huge public health threat as temperatures soar beyond adaptive capacity. While the built environment is a big contributor to the urban heat crisis, it also holds the key to reduce its ill effects. The Centre for Science and Environment found that appropriate planning and design techniques can bring ambient temperatures down by more than 7°C.

This toolkit presents a methodology to evaluate heat stress at the city, neighbourhood and local scales. It also touches upon the impact of land-use intensity (private vehicles, air conditioners, industries, etc.) and anthropogenic activities that intensify urban heat. By using several geo-spatial, spatio-temporal, climatological and socioeconomic datasets and indicators with remote sensing, it helps understand the rounded impact of heat and strategies to mitigate it. This assessment can empower city managers and policymakers to prioritize action and prevent damage in most vulnerable areas and communities.

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