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Blue space resilient urban planning to enhance severely distressed thermal environment

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ABSTRACT

Water resilience is a vital aspect of current smart city planning. Maintaining the quality and volume of urban blue spaces can benefit local ecology, environment, and social well-being. The application of geospatial techniques provides an opportunity to achieve such goals in a spatially and temporally effective manner. While researchers often highlight city-level environmental problems, location-based solutions are insufficient, particularly for the rapidly sprawling Asian cities—the current work aimed to examine the water-resilient urban planning scopes for an Indian tropical megacity. The work assessed a major environmental hazard, i.e., urban heat island, which appeared to cover 9.6 %–17.4 % of the area of the city region during the summer months. The importance of blue spaces in mitigating heat islands was quantified using data from nearly 150 waterbodies, including a river, a vast wetland, and multiple lakes and urban tanks. Linear and logarithmic models established how the cooling effect increases with larger water bodies. Blue space ranging between 1.8 km^2 and 2.3 km^2 was recommended as the smallest yet effective size for future recreational zones. Incorporating ambient wind patterns further aided in deciding the locations of blue wedges that can be key for heat island mitigation. Moreover, to substantially amplify the blue resource recharge rate in a cost-effective manner, a multi-parameter decision analysis was carried out. Overlay of five surface characteristics contributed to planning sites for surface infiltration systems. The entire framework of the work was built to achieve sustainable development goals.

1. Introduction

Urbanization has been the driving force behind regional climate change and a significant threat to sustainability, particularly in recent decades (Cheng and Hu, 2023; Han, 2020). The conversion of natural land into impervious built-up aided by concentrated anthropogenic activities occasionally leads to the local hazard of temperature surge over the city regions (Chapman et al., 2017; Nimish et al., 2020). This localized hike of intense temperature is known as the Urban Heat Island (UHI) effect (Kim and Brown, 2021). Intensification of UHI over the years and the rise of associated temperature raises heat-related stress and mortality rates (Santamouris and Fiorito, 2021; Wong et al., 2013). Such occurrences were observed in the case of both temperate cities (De Troeyer et al., 2020; Mitchell et al., 2016) and tropical cities (Azhar et al., 2014; Kumar et al., 2022; Singh et al., 2021; Gupta et al., 2024a). Particularly in densely populated tropical Asia, an increase in heat waves has emerged as a major threat to urban health and the liveability of city dwellers (Dimitrova et al., 2021; Dong et al., 2021). A densely populated country like Bangladesh reported very high UHI intensity above 8°C–10 °C in its major districts (Rahman et al., 2022). Thus, it has become necessary for city planners to develop climate-resilient urban designs (Climate Action). UHI also threatens sustainability by excess energy use, particularly in summer. In a tropical city like Delhi, India, UHI may increase electricity consumption by nearly 11% (Kumari et al., 2021). Depending on the location, UHI can raise the energy demand by 15%–200% (Palme et al., 2017). The effects of overheating by UHI on energy balance were quantified by Su et al. (2021), where they found that cooling energy needs hikes by 0.17–1.84 kWh/m^2 for every 0.5 K temperature rise. This problem of soaring energy use is profound in the city centre's commercial sections (Hirano and Fujita, 2012). Such commercial sections have a vital share of energy use in any metropolitan or megacity. Thus, to meet the Sustainable Development Goals (SDG), policies must incorporate city-specific UHI information like the spatial extent, intensity, or locations of critical thermal hotspots and possible UHI mitigation strategies.

UHI development is closely linked to surface characteristics (Derdouri et al., 2021; Liu et al., 2020). An increase in built-up cover and a decrease in vegetation, water bodies, and soil are generally the causes

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behind UHI intensification (Dutta et al., 2023). A study in the Delhi metropolitan observed a 4.6 °C rise in maximum UHI intensity in 27 years and linked it with the increase of 405.1 km^2 built-up cover during the same time period (Shahfahad et al., 2022). UHI mitigation thus focuses on enriching vegetated and water surfaces. Studies have depicted that water bodies can produce maximum cooling in urban climates, even more than vegetation cover (Dutta et al., 2021). Tan et al. (2021) also depicted that urban water bodies can reduce the Land Surface Temperature (LST) conditions at a greater rate than vegetation. Urban Blue Space (UBS) is becoming the fundamental tool for improving urban thermal climate (Ampatzidis and Kershaw, 2020; Völker et al., 2013; Yu et al., 2020). UBS refers to all the natural and man-made water surface environments in a city near city dwellers and act as public health resources (Mishra et al., 2020). Blue spaces can be freshwater-enclosed bodies like lakes, ponds, rivers, seas, artificial pools, recreational areas, etc. Since most major settlements have developed near waterbodies (Smith et al., 2021), applying UBS must be prioritized to maximize city-level cooling effects and provide sustainable urban solutions. Several global studies have highlighted how UBS can potentially augment physical and mental well-being (Hunter et al., 2023; Pasanen et al., 2019; Gupta and De, 2024a). Britton et al. (2020) evaluated thirty-three cases to conclude that blue spaces significantly positively impact urban health. A randomized crossover study on 59 adult office-goers in Barcelona, Spain, showed that short walks around blue spaces notably boost well-being (Vert et al., 2020). Another study in Plymouth, UK, outlined that positive well-being and life satisfaction were higher after improving the quality of local beaches (van den Bogerd et al., 2021). Promoting freshwater blue health should be a part of current city planning agendas (McDougall et al., 2020).

It is also necessary to plan water-resilient smart cities. Water-resilient cities can recover their blue space resources from ongoing environmental threats (Kaaviya and Devadas, 2021). A healthy water system also helps urban green spaces to thrive (Pitman et al., 2015). Water resilience can incorporate various aspects like urban surface and groundwater resource monitoring (Liu et al., 2023), identification of recharge potential zones to replenish blue resources (Shaban et al., 2006), optimizing the system of water supply and sanitation (Rausch et al., 2018), urban flood management to avoid environmental disaster (Motta et al., 2021; Pathak et al., 2020a), water resources risk mapping (Cordão et al., 2020), etc. An issue with most UBS studies is adding new UBSs within the city region (Ampatzidis and Kershaw, 2020). Blue or green wedge planning to improve thermal microclimate (Badach et al., 2022) is a likely option in highly planned cities. Still, in most densely built Asian cities, city-wide reconstruction of small lakes is unfeasible. Studies need to utilize the potential of current UBSs with minimal landscaping. Also, the cooling effect of UBS may vary considerably based on its location or size, time of the day, wind flow patterns, etc. Depending on the geographical setting, UBS at night can cause more warming in the local environment than the surrounding built-up due to concrete's quicker heat loss property. The benefits of UBS exposure may even vary with the type of freshwater bodies (McDougall et al., 2022). Thus, climate-responsive urban planning using present UBSs must be specific to a city and can only be achieved through empirical studies.

With the focus on these goals, the current work formulated a remote sensing-based methodology to achieve SDGs to enhance UBS resources and local UHI mitigation. The application of techniques like Geographic Information Systems (GIS), remote sensing, machine learning, and spatial data analysis in current research works rapidly enhances the potential of water-responsive sustainable city planning (Doorga et al., 2022; Gargiulo et al., 2023; Pathak et al., 2020b). This work broadly evaluated the significant aspects of urban climate resilience in a densely populated Indian metropolitan area while looking into both the problem and solutions, as follows: (a) The severity of UHI was evaluated using temporal satellite images. (b) The cooling effect of UBS was quantified at various scales. The wind flow pattern was incorporated with outdoor land management, which is crucial in elevating thermal comfort (Huang et al., 2024). (c) The paper laid out a thorough Multi-Criteria Decision Analysis (MCDA) to strengthen the conditions of available blue resources in a city. Since the study region already has various blue spaces, the work focused on maintaining the health of these spaces. Various layers like soil permeability, slope, elevation, proximity to the impervious urban surface, vegetated land cover, etc., were used to infer the most suitable recharge spots to restore the health of around 150 small, medium, and large water bodies considered in the study. Such GIS-oriented planning will effectively identify high-priority zones for optimal recharge with minimal reconstruction. The outputs of this study are likely to benefit sustainable urban management practices in fast-growing city regions.

2. Study area description

Kolkata city, the capital of the Indian state of West Bengal, was taken as the current study area. Kolkata is the largest commercial urban centre in East India. The city is situated beside the Ganga River and lies in the tropical zone. The study area covered nearly 530 km^2. The location and extent of the region are shown in Fig. 1. This city region provides an ideal case study opportunity for multiple reasons. Since the city has a hot and humid climate, it witnesses severe summer heat stress. The temperature rises beyond 40 °C in the warm summer months of Kolkata. Added to the humid environment (relative humidity in summer is around 70%–80%) (Banerjee et al., 2020), the local climate of Kolkata creates critical discomfort.

Kolkata is also densely populated, with a district population density of 24,306 people per sq. km (District Census HandbookKolkata, 2014). The demography causes more than 10 million urban-suburban populations to be vulnerable to heat stress-related illnesses (Gupta et al., 2024b). The rapid urbanization around Kolkata and subsequent development of suburbs is similar to the urban sprawl conditions of many developing countries. Thus, a study of this city will provide a framework for urban climate studies for other tropical metropolitans. Lastly, the presence of the Ganga River, a vast East Kolkata Wetland (EKW), and multiple small tanks in this city region allows the analysis of blue space cooling scopes from various aspects. The area considered for this study was thus extended beyond Kolkata city to incorporate the EKW and suburban satellite towns.

3. Datasets used

Landsat satellite images were used to extract the surface temperature and water information. The satellite images were obtained from the Earth Explorer site, with products from United States Geological Survey (USGS). Landsat Level-2 datasets were used, which include atmospherically corrected surface reflectance for further processing. While thermal Landsat bands were specifically used for the LST mapping, other band combinations provided supplementary surface characteristics. Since the work focused on a distressed summer environment, data was obtained for the months of April and May. Images with a cloud cover of less than 5% were only considered. As for the elevation profile, the Digital Elevation Model (DEM) of Shuttle Radar Topography Mission (SRTM) was collected. While multiple Landsat scenes were used to generate average summer LST patterns, a single DEM image was used for elevation. The details of the various satellite data are shown in Table 1.

Additionally, the soil data for the study area was procured from the European Digital Archive of Soil Maps (EuDASM). The data provided detailed soil taxonomy of the study area along with boundary maps for soil moisture regimes. Lastly, the wind flow data was used to thoroughly analyze the cooling effect patterns. This data was obtained from the National Centre for Medium Range Weather Forecasting (NCMRWF). The wind flow data is generated by a reanalysis model, primarily based on the station data of India Meteorological Department (IMD). This reanalysis wind data is provided at 12 km resolution as a point file, and in and around Kolkata, 12 such data points were available (Gupta et al.,

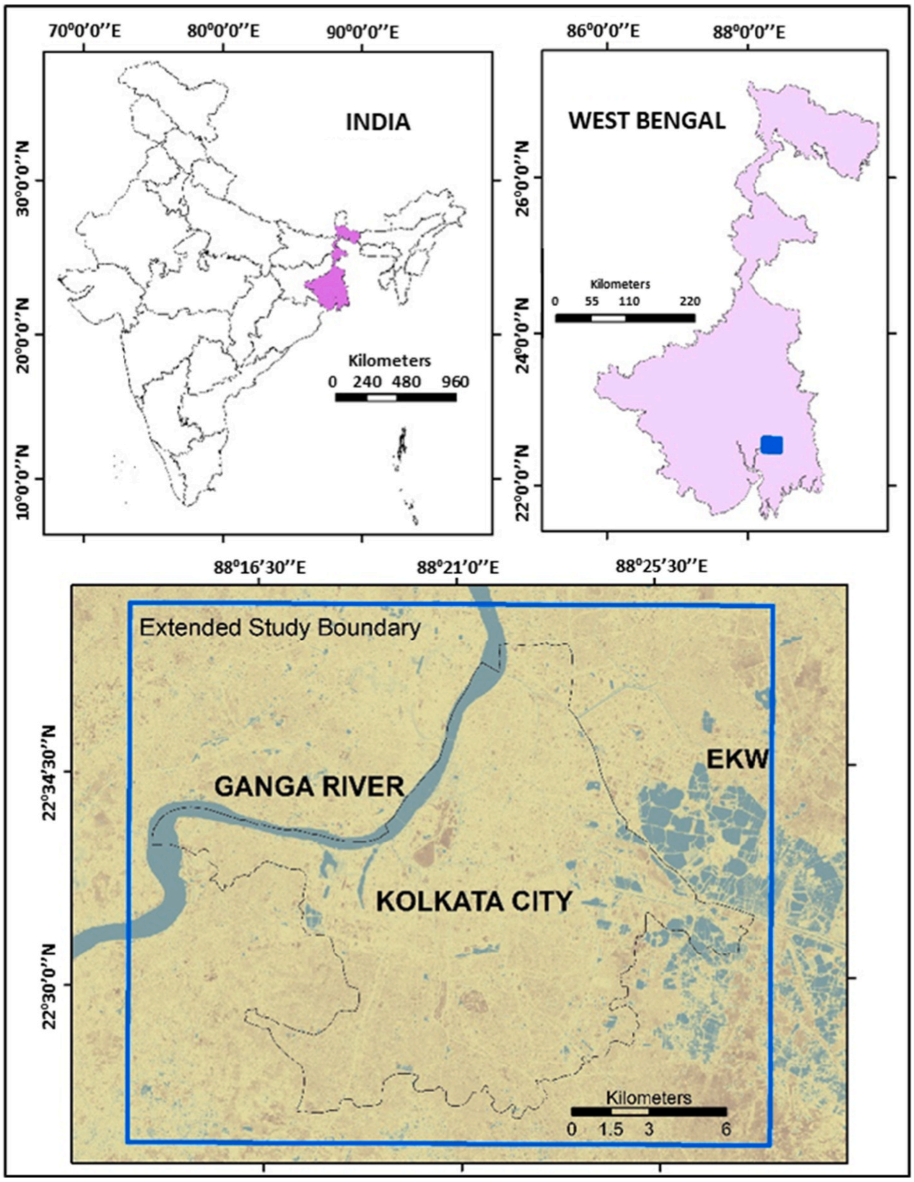

Fig. 1. Study area of Kolkata city region.

Table 1
Remote sensing data considered for the study.

Satellite	Sensor type	Date	Bands used	Spatial resolution
Landsat 8 Landsat 9	OLI/TIRS (Operational Land Imager/Thermal Infrared Sensor)	April 15, 2023 April 07, 2023 May 25, 2023	B3 B4 B5 B6 B10	30 *m*
SRTM	Imaging radars	February 22, 2000	DEM	30 *m*

2024b). Hourly 'u' component and 'v' component data were obtained for computing wind velocity and speed.

4. Methodology

As mentioned in the introduction section, the current work broadly focuses on three objectives. Based on these goals, the framework of the geospatial techniques was prepared. A brief overview of these objectives, framework, and methodology is shown in Fig. 2.

4.1. Critical summer UHI mapping

4.1.1. LST data extraction

Studies have noted tropical summers to be critical due to the presence of very high absolute temperatures. Hence, the study demarcated the current UHI characteristics for summer months using multiple LST patterns derived from thermal images. The processing of thermal band Digital Number (DN) to LST layers included a series of conversions (Landsat handbook). DNs were first converted to the top of atmosphere spectral radiance (L_{TOA}) as,

$$L_{TOA} = M_L \times DN + A_L \tag{1}$$

Where M_L is the multiplicative factor, and A_L is the additive factor for band 10.

The L_{TOA} was then converted to the brightness temperature in Kelvin (T_K) with the following formula,

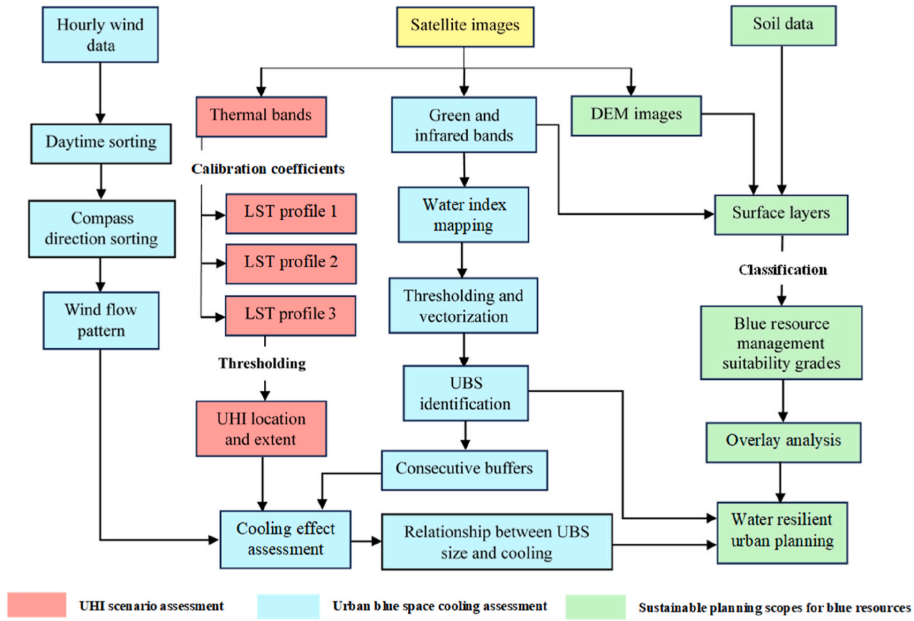

Fig. 2. Methodological flow followed in the work.

$$T_K = \frac{K_2}{\ln\left(1 + \frac{K_1}{L_{TOA}}\right)} \tag{2}$$

Where K_1 and K_2 are pre-launch calibration constants, the obtained LST were finally converted to degree Celsius values from Kelvin temperatures.

4.1.2. UHI extent identification

Each LST map was used to generate the summer daytime UHI boundary using the threshold temperature value of (Mean + Standard Deviation) for that LST scene (Dutta et al., 2021). As the threshold value separating UHI from the remaining LST profile is generated from the LST pattern itself, it provides a relative uniformity for UHI detection. The UHI patterns demarcated from each scene were then overlayed. Since the work used multiple summer LST scenarios, the UHI extent and pattern would vary slightly for each case. This aspect was used to delineate a common UHI boundary throughout the summer and also a maximum UHI extent. A common area cover was obtained as the intersection of all UHI profiles using overlay techniques. This was identified as the summertime average UHI condition. On the other hand, the union of all UHI profiles added certain areas that reflected UHI conditions only in specific scenes. This total area was demarcated as the maximum UHI extent for summer days.

4.2. Demarcation of blue space

The Modified Normalized Difference Water Index (MNDWI) was used to differentiate the water surfaces from the rest of the study area. MNDWI can successfully remove spectral noise caused by other land cover classes and thus enhances the ability to identify open water bodies (Xu, 2006). MNDWI was computed using the relative difference in reflectance of green and Mid Infrared (MIR) bands as,

$$MNDWI = \frac{Green - MIR}{Green + MIR} \tag{3}$$

Thresholding was applied to the generated MNDWI map to extract water surfaces solely within the study area (Dutta et al., 2018). In this case, the threshold was 0.5, which was determined by checking MNDWI values along with a reference base map (Google Earth Pro). Subsequently, an image was created representing only water bodies. This image was then vectorized into polygons to obtain the layers of UBSs. This demarcation of UBSs in and around Kolkata is shown by a sample area example in Fig. 3.

4.3. Cooling effect assessment

The potential of UBS in summer daytime cooling was thoroughly evaluated to aid sustainable city planning. The cooling effect of UBSs was analyzed for all UBSs present in the study area and also separately for the major UBSs.

4.3.1. Size vs. cooling effect for all UBS

It is expected that larger water bodies will cause more cooling of urban climate than smaller bodies. This was checked for the study region, and the relationship between UBS size and its cooling effect was quantified. Concentric buffers of 50 *m* and 50 *m*–100 *m* were created around all the UBS. LST values were extracted for the UBS and the surrounding buffer zones. The increase in LST was used to compute the cooling effect of that UBS. Two different regression models, linear and logarithmic, were used to see how increasing UBS size affects cooling potential. The obtained results are likely to help in planning future recreational areas. The accuracy of the models was checked using Root Mean Square Error (RMSE) as,

$$RMSE = \sqrt{\frac{\sum (x_i - \hat{x}_i)^2}{N}} \tag{4}$$

4.3.2. Distance wise cooling effect at major UBS

While all the urban water bodies were used to examine the change in cooling effect with size, the larger UBSs were specifically studied to see how far major water bodies can affect thermal patterns. The impact of major water bodies on a city-level climate was evaluated using similar 50 *m* buffer zones, but the distance was up to 250 *m*. A study in the same city showed that the cooling effect of green parks went up to 205 m (Dutta et al., 2021) and varied with varying park geometry (Gupta and De, 2024b), and for another Asian city, it was 240 m (Lee et al., 2009). Thus, in the current study, the cooling potential was checked up to 250 *m* from the UBS boundary.

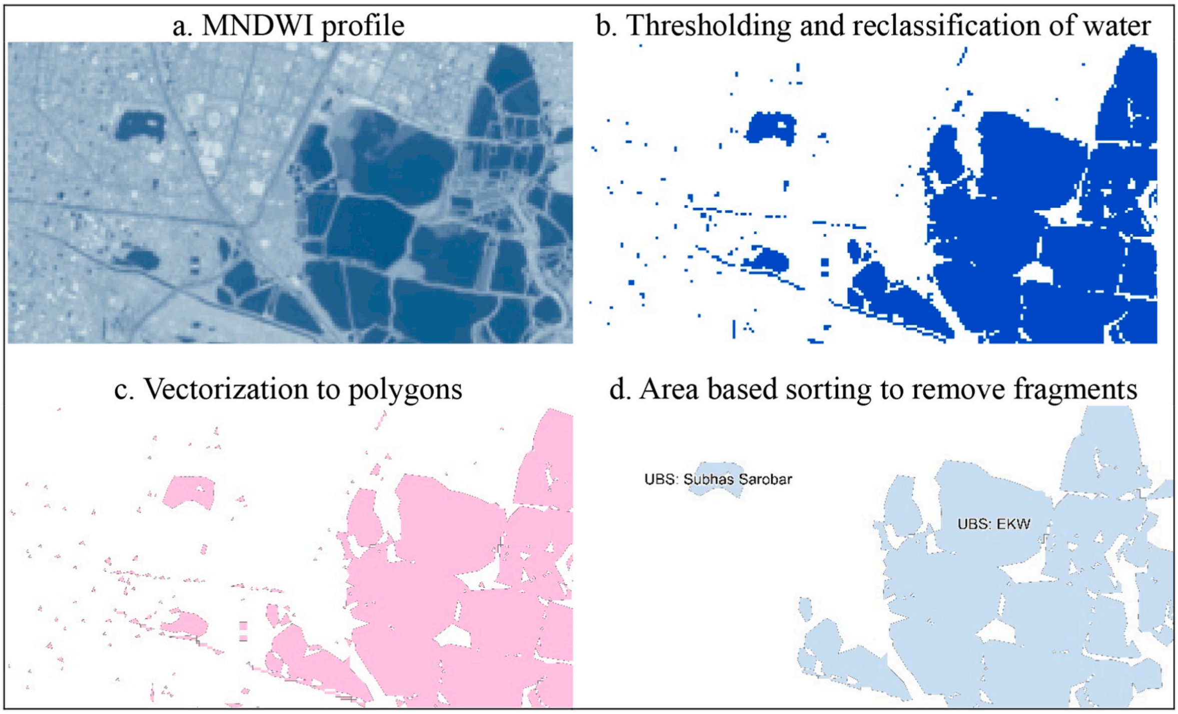

Fig. 3. Remote sensing and GIS based UBS extraction for Kolkata city.

4.3.3. Summer season wind patterns

Apart from the location and size of UBSs, the wind speed and direction would considerably affect the city-level thermal environment. The cooling effect is expected to be higher on the downwind side. Hence to plan new recreational areas or green landscaping on available city structures, wind direction data should be incorporated. The point-based wind data in and around the city was obtained following the work of (Gupta et al., 2024b). The overall wind direction data for summer daytime was sorted into 16 compass directions as N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, and NNW. Since the work aimed to check scopes of daytime cooling, the wind direction between 8 a.m. and 2 p.m. was only considered.

4.4. Water resilient city planning

Following the UHI problem analysis and establishing the positive influence of UBS on local climate, the goal was to provide water-resilient city planning suggestions. The approach followed in the work was to maintain the health of UBSs and prevent their drying. Blue space shrinkage and water bodies drying is a common problem in many cities globally (Barría et al., 2021; Isazade et al., 2021; Singh and Singh, 2019). Water bodies and groundwater recharge should be amplified using techniques like percolation tanks, recharge pits or shafts, dug wells, ditches, furrows, etc. (Muthuminal and Mohana, 2022). Induced recharge of UBS can maintain the quality and quantity of water bodies, which will eventually benefit the regional climate and environment. Identification of suitable sites for such artificial recharge must be based on multiple parameters. In this study, a number of relevant surface characteristics were chosen, such as soil permeability, slope and elevation, distance of impervious built-up, and nature of land cover depicted by the presence of vegetation. An MCDA approach was applied using all these layers to assist GIS-based planning.

4.4.1. Spatial profile of topography

The low-lying areas with inward aspects of slope will receive maximum water after rainfall. Planning recharge areas at such locations would be suitable. The SRTM DEM data was used to classify the region into low, moderate, and high elevations. Simultaneously, the slope and aspect patterns were also generated. The slope map was also classified into three zones based on suitability. The slope (θ) at each cell was computed in degree values as,

$$\theta = \tan^{-1}\frac{rise}{run} \tag{5}$$

4.4.2. Fractional vegetation cover (FVC)

The presence of vegetation reflects natural land cover, and such areas are expected to amplify the recharge process. To identify these areas, the FVC index was computed and mapped. FVC is a crucial phenotypic parameter for vegetation cover mapping in ecosystem studies (Chu, 2020; Gao et al., 2020). FVC is computed using the range of Normalized Difference Vegetation Index (NDVI) for the study area (Gutman and Ignatov, 1998) as,

$$FVC = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \tag{6}$$

The FVC map was also classified into three zones, where higher vegetation corresponded to higher suitability as a recharge zone.

4.4.3. Proximity to impervious surfaces

The presence of impervious built-up will obstruct recharge, and hence, zones in proximity to dense built-up will not provide an effective recharge amount. Impervious surface (IS) was simply identified as (Dutta et al., 2019),

$$IS = 1 - FVC \tag{7}$$

A proximity map was then prepared with three classes showing areas near dense built-up, at a moderate distance, and far away from built-up. Locations at or near dense built-up will witness high evaporation losses and hence are not suitable as recharge zones.

4.4.4. Soil characteristics

The study area depicted the presence of very deep fine soils and loamy soils apart from the impervious surfaces. The capacity of percolating water or causing flood varies with the type of soil (Umer et al., 2019). The surface properties of the soils in the study region varied from being clayey to loamy, poorly drained to imperfectly drained, etc. Chances of water stagnation would be higher above clayey surface soil. In contrast, a loamy surface is expected to percolate water more effectively. Thus, recharge zones will be suitable over deep loamy soils.

4.4.5. MCDA based suitable site selection for artificial recharge zones

Two layers of topography, two layers for surface cover and one for soil characteristics, were overlayed together to constructively map suitable recharge zones. This final stage of the work followed Multi Criteria Based Decision Making (MCDM), as water-resilient city planning is very much dependent on multiple parameters. MCDM has been proven to be the most effective site selection approach while dealing with diverse controlling factors (Armanuos et al., 2023; Farkas, 2009; Shao et al., 2023). In the current work, all five layers were categorized into three zones of suitability for artificial recharge sites. This categorization was performed using the Jenks Natural Breaks algorithm as it uses the inherent attributes of each dataset for the categorization.

Value 1 was assigned to the least suitable conditions and 3 to the most suitable areas. Finally, the layers were overlayed together with uniform weightage to produce an artificial recharge zone suitability map with a scale from 3 to 15. Zones with values 15 would meet all criteria of artificial recharge planning, while areas with values 3 would indicate the least suitable conditions. The MCDA overlay process to delineate artificial recharge sites is shown in Fig. 4.

5. Results

5.1. Characteristics of critical summer UHI

The extent of UHI was determined from summer LST patterns to improve the scope of temporal monitoring. The daytime UHI for Kolkata is shown below in Fig. 5. Results showed that a 50.5 km^2 area from central and northern Kolkata showed the presence of continuous heat island conditions on summer days. Additionally, the 40.6 km^2 area witnessed an occasional rise in relative temperature and acted as UHI zones. Statistical analysis presented a negative skewness value (−0.61) for the average summer temperature data (all statistical characteristics are added in Appendix section Table A1). This suggested that the overall dataset was showing a moderate shift towards higher values in summer, indicating a stronger UHI. Apart from the remarkable extent, the UHI condition in Kolkata was severe in terms of magnitude. Over the summer UHI cover, the maximum, average, and minimum LST values were 4.29 °C, 3.17 °C, and 7.12 °C higher than the maximum, average, and minimum LST values of the non-UHI remaining land cover, respectively.

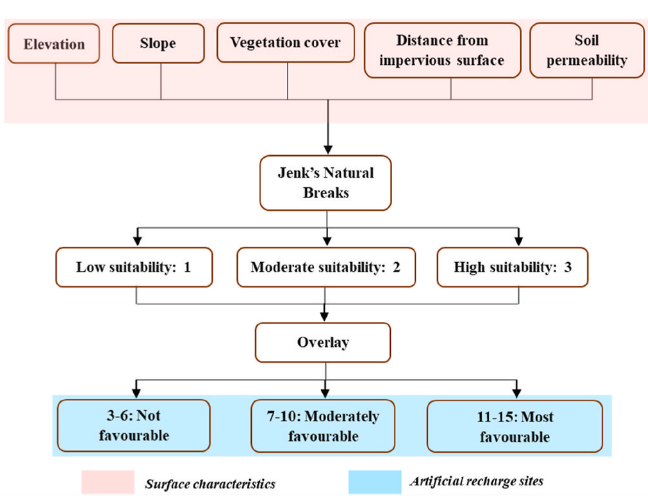

Fig. 4. MCDA process for blue space resource management. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5.2. Distribution and cooling effect of UBS

The UBS identified using MNDWI in the Kolkata city region is shown in Fig. 6. Overall, nearly 150 polygons of water bodies were extracted for the study area.

The cooling effect of UBS per 50 *m* distance from UBS boundaries was plotted against the size of the UBS. The rate of increase in cooling with larger UBS was checked using both linear and logarithmic relations. In both cases, results showed a strong positive influence of the size of the water body on the cooling effect. The correlation (r = +0.43) was significant at $\alpha_{0.01}$. However, by computing the RMSE for the two obtained equations, it was noted that the linear relation between these two parameters provided better estimations. The RMSE, respectively, for linear and logarithmic relations were 0.20 °C and 0.37 °C. Thus, it can be summarized that the cooling effect will steadily increase with larger water bodies, and they will act as critical units in the local thermal environment. The distribution of cooling effect values with respect to UBS size is plotted in Fig. 7 for both regression models.

5.3. LST variations around major UBS

Other than the overall cooling effect assessment, the major UBS of the city region was thoroughly analyzed for further empirical findings. In this regard, 7 prominent UBS of Kolkata were identified with varying shapes and extent. These were the Ganga River, EKW, Keshtopur Canal, and four major lakes, Subhas Sarobar, Rabindra Sarobar, Eco Park Lake, and New Town Lake (all are marked in Fig. 6). The detailed cooling per 50 *m* for these UBSs is shown in Fig. 8.

Results showed that blue spaces impart a very strong cooling effect on the surrounding city regions. The effect is strongly present till 150 *m*, and then gradually, the cooling rate reduces, but the effect is present even beyond 250 *m*. The Keshtopur Canal had the lowest cooling effect, while the Ganga River caused the highest cooling of surrounding built-up.

5.4. Wind flow pattern of Kolkata

The summer daytime hourly wind data was plotted as a wind rose and is shown in Fig. 9. During summer days, Kolkata experiences maximum wind flow from the WSW direction, followed by the SW direction. Wind flow from northern and north-eastern directions is nearly absent at this time. The observed wind speed was not very high. Only around 33% of the time, the speed was above 10 kmph. The speed mostly varied between 4 kmph and 9 kmph.

5.5. Artificial recharge site selection with MCDA

The final objective of the work was fulfilled by combining multi-parameter inputs to select recharge spots for blue resources. The various surface layers used for the overlay are shown in Fig. 10. The topography did not depict much variation for the study region as the area is flat and featureless. Within this, the central city region is comparatively higher than the surrounding rural and natural land cover. In terms of soil cover, the city region belongs to the Delta Plain. All around the impervious built-up, there is the presence of deep alluvium of loamy or clayey surfaces. As for the land cover, the FVC and impervious built-up cover showed exactly contrasting spatial patterns. The northern part of the city portrayed a maximum lack of natural land cover, which would be the cause behind intense UHI development in the same region.

All these layers were combined together to map the suitability of sites as artificial recharge zones. The final overlay map of all inputs is shown in Fig. 11. The higher values in this map represent better suitability. It is noticeable that the city fringes and rural counterparts

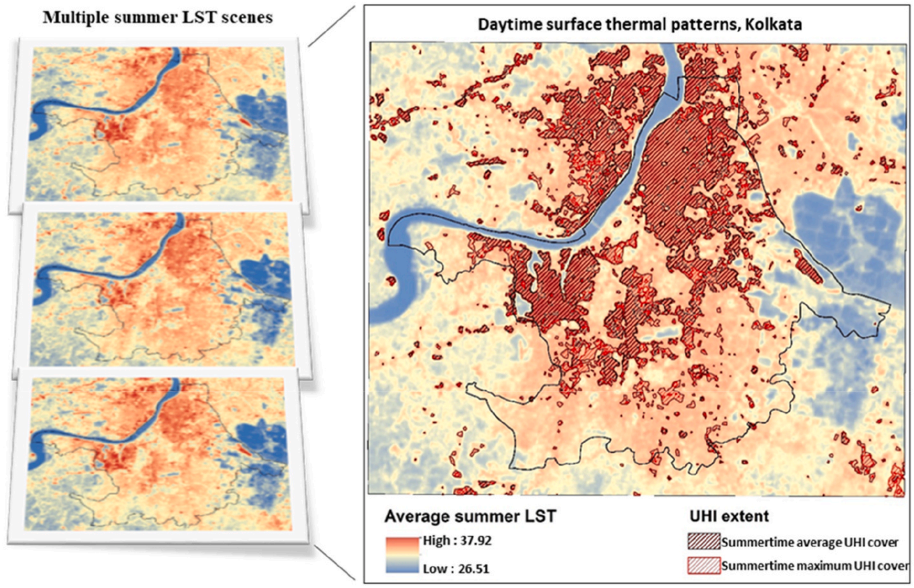

Fig. 5. Summer daytime UHI pattern of Kolkata city region.

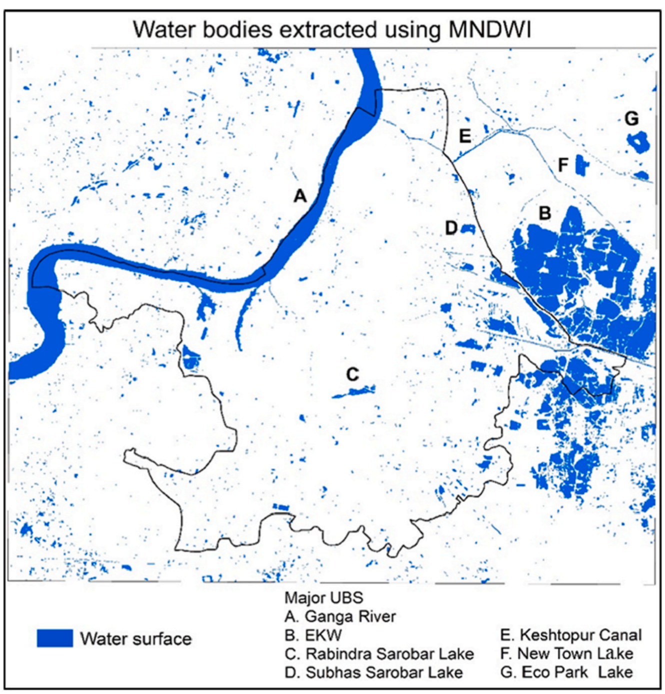

Fig. 6. Urban blue spaces of Kolkata city region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

showed high values, but for planning purposes, the higher values in and around the city would be more important. These locations will promptly recharge the blue spaces of Kolkata city and will eventually bring a cooling effect at the ambient level. Within the city, a few such locations were identified as places where immediate planning of recharge sites should be carried out (marked in Fig. 11). These locations were the land around Eden Gardens and Fort Williams (A), Behala Flying Club (B), Padmapukur Water Treatment Plant (C), Central Park (D), and Chowbaga Fields (E).

6. Discussion

6.1. Severity of UHI problem

The UHI problem of the Kolkata city region appears to be critical. A vast part of the study region, i.e., 9.62% of the total area, was under the UHI effect during summer days. Another 7.73% area occasionally reflected high relative LST values and the presence of intense heat island-like conditions. Thus, the maximum UHI in summer can extend to 17.35% of the city region. The UHI extent demarcation performed in the study laid an opportunity to uniformly monitor UHI growth over time. Summertime UHI of Kolkata appeared critical also in terms of the LST intensity. The minimum LST at UHI was more than 7 °C higher than the minimum LST in the remaining study area. The mean LST during summer days appeared to be around 30°C–32 °C in the study region. An additional rise due to high UHI magnitude would produce severe thermal discomfort at the regional level. The observed UHI values were comparable to a study carried out in a similar monocentric, densely populated, hot and humid Dhaka city, where city centres witnessed higher average temperatures by∼3 °C (Uddin et al., 2022). Such findings establish the ongoing problem of UHI growth and the urgent need to mitigate it.

6.2. UBS cooling potential

UBSs demonstrated a very high cooling potential. Compared to the immediate neighbouring urban area, UBSs showed an average cooling effect of 1.51 °C, which was only 0.94 °C for major green parks from the same city region (Dutta et al., 2021). Also, the extent of the cooling effect was beyond 250 *m*, which was higher than the reach of major green parks. The results established the significance of UBS in moderating extreme temperatures of the summer season and the necessity to focus on UBS resource monitoring and maintenance. Additionally, the variation among major UBSs showed that the canal had less potential for cooling than compact lakes like Subhas Sarobar or Eco Park Lake. The area of these water bodies is comparable, and even the average impervious surface area (ISA) around these three UBS was checked to rule out the influence of these parameters on cooling. Results showed that ISA values around Subhas Sarobar, Eco Park Lake, and the canal were 0.41, 0.44, and 0.57, respectively (the variation of ISA around all major UBS is added in the Appendix section Table A2). With higher built-up around the canal, the cooling effect should have been more effective, but the

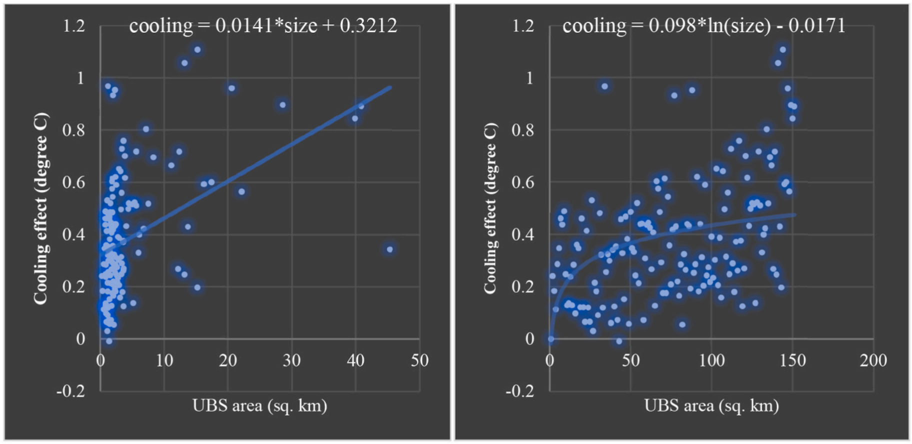

Fig. 7. Linear and logarithmic regression models showing increase in cooling effect with increase in UBS size.

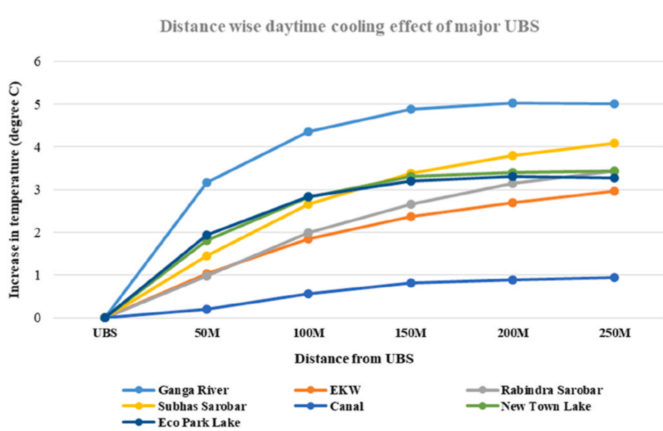

Fig. 8. Cooling of Kolkata city region by large water bodies.

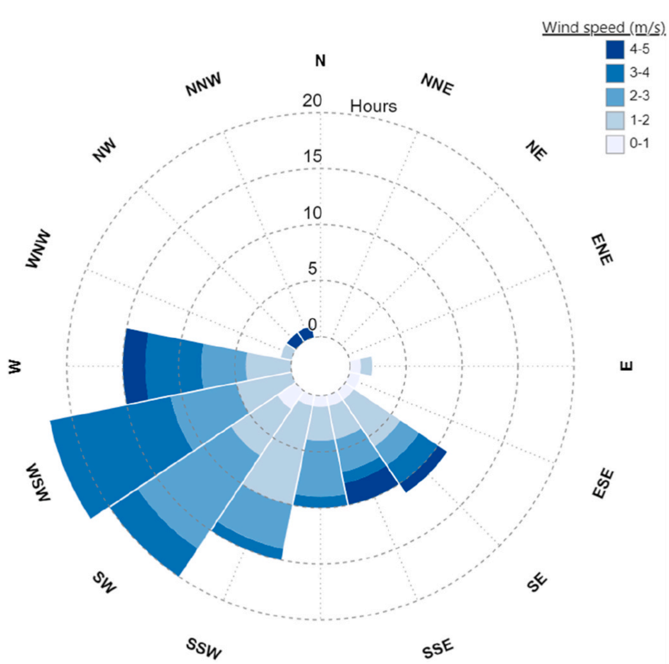

Fig. 9. Wind rose for Kolkata city region in summer.

canal depicted the lowest cooling potential. Hence, it can be inferred that narrow and linear UBS have less cooling scope than compact square or circle-shaped UBSs.

6.3. *Key inferences from the study*

The empirical observations from the study region provided quantitative guidelines for future urban planning. The results can be used in suburban smart city planning for Kolkata and similar tropical metropolitans.

6.3.1. *Future recreational areas*

The regression models helped to assess that UBSs of size around 1.8 km^2–2.3 km^2 have the most effective cooling potential. The cooling effect below this size reduces rapidly, and the size below 1 km^2 becomes nearly null. Though the cooling effect increases for larger UGS above the given size range, the rate of increase is much slower. Since building vast recreational areas in a densely populated city region is not possible, the size should be feasible in terms of planning and most effective in terms of cooling, which can be fulfilled at the above-mentioned range. As mentioned in the previous section, these UBSs should be of compact sizes to provide maximum cooling. Additionally, the flow pattern suggested that during summer days, maximum wind blows from WSW and SW directions. Thus, recreational areas with small water bodies should be located in the upwind south-west and west-south-west direction from the city. Such water bodies can then act as blue wedges and supply cooling wind to the heat island in the central city.

6.3.2. *Water resilience and maintenance of blue resources*

The MCDA process applied in the study effectively mapped the suitable zones for artificial recharge. The zones identified in the work with higher suitability as recharge sites and also in proximity to Kolkata city must be protected from future urban development. These areas already meet high percolation and recharge specifications, but artificially enhancing that rate would benefit the regional environment. Ditch and furrow lines should be planned in these areas. Uniformly distributed locations for percolation tanks and recharge pits should also be marked. Artificial infiltration planning would be cost-effective since these areas are far from building foundations. Planning a chain of surface infiltration systems at the identified locations will amplify the blue resource recharge rate for the Kolkata city region. This will eventually maintain the water quantity and quality of the multiple UBSs.

6.4. *Limitations and future directions of the current study*

The work provided one aspect of water resilience, focusing on maintaining major UBS systems to mitigate thermal health hazards in

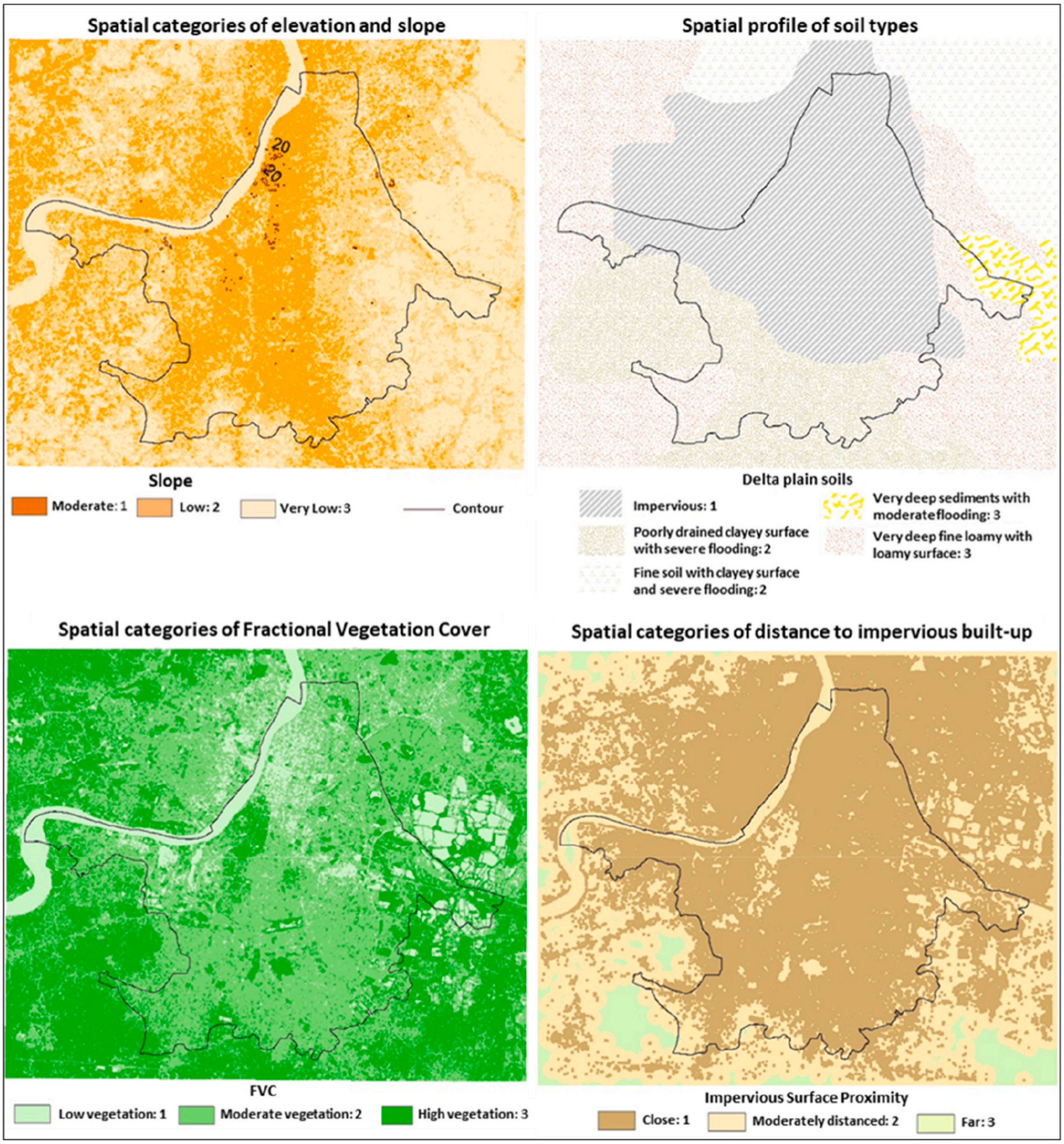

Fig. 10. Various surface layers for MCDA method.

tropical cities. The work can be applied to similar monocentric cities where UHI is more concentrated over central commercial districts. Such patterns will make UBS and wind direction-based planning more precise and less widespread. The UHI and UBS demarcation can be used in any city, and such studies can help develop inter-city comparative assessments. In comparison, contemporary works have looked into comparable strategies of artificial recharge (Fauzia et al., 2021; Vishwakarma et al., 2021), the inclusion of local wind flow to plan blue wedges and UHI mitigation is scarcely considered. The MCDA can also be applied in other cities to identify suitable recharge spots using similar input layers. In that case, the soil characteristics and elevation profile may change considerably, and the classes for these parameters must be determined accordingly. However, adding groundwater information regarding depth, quality, and quantity can significantly improve a similar study. The changes in water quality can be monitored by analyzing physical and inorganic chemical parameters at various UBS sites (Burgan et al., 2013). While the paper focuses on surface blue resources, a quantitative assessment of groundwater resources can be evaluated in a future case study.

7. Conclusions

The work highlighted the critical thermal environment conditions of the Kolkata city region on summer days. A comparison to neighbouring Dhaka city showed that such heat stress conditions are prevalent in hot humid tropical cities. This paper, hence, tried to draw policymakers' attention to this regional climate hazard so that necessary preventive measures are formulated. With the ongoing trend of rampant urbanization, Kolkata city and its suburban population may face severe heat stress related health issues in the near future as maximum UHI intensity reaches ~7 °C. With this concern, the effectiveness of urban blue spaces in cooling the surrounding environment was thoroughly established in this study. The results suggested that new recreational areas should include water bodies in them, not solely vegetation. The ideal size of

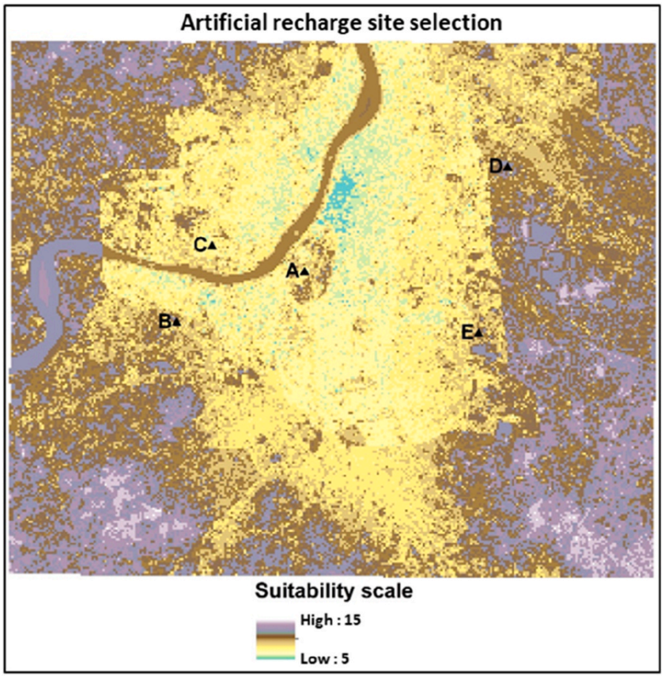

Fig. 11. Scope of water resilient city planning.

these blue spaces was derived to balance maximum cooling and land availability. Further, the location of those blue spaces was also provided in the paper to aid city planning. The scope of UBS in local environmental problem-solving is diverse. Hence, water-resilient city planning should be a key approach. The work outlines a framework that applies GIS and remote sensing to reach the sustainable goals of water resilience. Suitable sites for artificial recharge were found in different parts of Kolkata. These identified locations must be recognized and included in sustainable planning scopes. Spatial inputs are contributed by this study that may protect the blue resources and use them effectively for environmental problem-solving and mitigation of heat-related health hazards.

CRediT authorship contribution statement

Aman Gupta: Writing – review & editing, Writing – original draft, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **Bhaskar De:** Supervision, Resources, Conceptualization, Formal analysis, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX

Table A1
Statistical characteristics of the average summer LST profile over the study area

Parameter	Mean	SD	Coefficient of variation	Min	Max	Skewness
LST	31.82 °C	1.79 °C	5.6%	26.53 °C	37.74 °C	−0.61

Table A2
Variation in the average ISA values surrounding major UBS

UBS	Ganga	Subhas Sarobar	Eco Park lake	EKW	Canal	Rabindra Sarobar	New Town lake
Average ISA	0.52	0.41	0.44	0.37	0.57	0.38	0.52

*Mean = 0.46; SD = 0.07.

Data availability

Data will be made available on request.

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