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Living in the Heights: Mapping Urban Livability in a High-Altitude Himalayan Town in India Using Geographically Weighted Analysis

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Abstract

Urban livability is a multidimensional concern for sustainable urban planning, particularly in topographically constrained Himalayan towns. This study assesses urban livability in Darjeeling, a high-altitude Himalayan town in India, also known as the "*Queen of the Himalayas*," using a spatially explicit RS-GIS framework. A *Sustainable Urban Livability Index (SULI)* was developed from 44 indicators across nine domains using robust Geographically Weighted Principal Component Analysis (GWPCA), followed by Moran's I and Local Indicators of Spatial Association (LISA) to examine spatial clustering. The results reveal substantial spatial variation: 10 of 32 wards (31%) exhibit good livability, while 11 wards each (34.38%) fall within the fair and poor categories. SULI shows significant positive spatial autocorrelation (Moran's I = 0.266, $p = 0.009$), with high–high clusters indicating relatively favourable livability and low–low clusters identifying concentrations of less favourable conditions. Sensitivity analysis further demonstrates strong rank stability across alternative GWPCA specifications, with Spearman's $\rho = 0.974$ for the one-component specification and $\rho = 0.960$ under an alternative MCD support fraction. The findings highlight pronounced centre–periphery differences and demonstrate the value of spatially differentiated assessment for identifying neighbourhoods requiring targeted attention. The SULI provides a spatially explicit framework to support context-sensitive urban planning in topographically constrained Himalayan towns.

Keywords: urban livability; GWPCA; spatial analysis; sustainable cities; GIS

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1. Introduction

Urban livability is an important dimension of quality of life and sustainable urban planning, yet its conceptualisation and measurement remain complex and context-dependent [1,2]. As urbanisation reshapes human settlements, assessing livability is increasingly important for understanding how urban environments support residents' well-being and access to essential services [3,4]. More than half of the world's population lived in urban areas by 2018, and this proportion is projected to increase substantially by 2050 [5,6]. Livable cities therefore require attention not only to infrastructure, transportation, healthcare, education, and housing, but also to environmental quality, social inclusion, and equitable access to urban opportunities [7–11]. Urban livability is inherently multidimensional,

encompassing the physical, environmental, socioeconomic, cultural, and psychological conditions that shape everyday urban life, including housing, infrastructure and public services, environmental quality, safety, mobility, social interaction, and opportunities for participation and empowerment [3,12–14]. However, no universally accepted framework exists for measuring livability, as its dimensions and relative importance vary across geographical and socioeconomic contexts [13,15–17]. Existing approaches variously emphasise socioeconomic and cultural conditions, urban amenities and accessibility, ecological quality, and neighbourhood-level well-being [18–22]. These perspectives highlight the need for multidimensional assessment frameworks that remain sensitive to the geographical characteristics of individual urban settings.

This need is particularly relevant in Himalayan hill towns, where steep terrain, uneven infrastructure, environmental constraints, and accessibility differences can create marked spatial variations in living conditions. In such settings, the proximity of essential services, built-environment configuration, and local physical conditions may contribute to differentiated patterns of livability. Darjeeling, a prominent Himalayan town in India, provides a relevant context for examining these spatial variations. Its mountainous terrain and uneven urban development make geographically explicit assessment important for understanding differences in amenity access and the distribution of favourable and unfavourable living conditions. Although urban livability has been examined using multidimensional indicators and composite indices, citywide measures may conceal local variations in livability and its constituent domains. This limitation underscores the importance of integrating spatially differentiated assessment with local spatial analysis, particularly in topographically constrained urban environments.

Livability represents an interface between objectively measurable characteristics of places and the subjective experiences of their residents [23]. Objective indicators capture conditions such as housing, infrastructure, environmental quality, and access to services, whereas subjective assessments reflect perceptions, satisfaction, and well-being; these dimensions are related but not necessarily equivalent [24–26]. Spatial accessibility is an important link between them, while their relationships may also vary according to the spatial scale at which environmental conditions are measured and experienced [27]. This issue is particularly relevant in mountainous small towns, where topography, settlement morphology, and constrained transport networks can produce pronounced differences in accessibility and service provision over relatively short distances [28]. Therefore, city-wide or aggregated assessments may conceal important intra-urban variations. Addressing this gap, the present study examines livability at the ward level in Darjeeling by integrating multiple environmental, infrastructural, accessibility, and service-related indicators through a geographically weighted approach, thereby providing a context-sensitive assessment of fine-scale spatial differentiation in a Himalayan small-town setting.

Geospatial techniques enable the integration of environmental, infrastructural, and socioeconomic indicators to examine the spatial organisation of urban livability. Remote sensing and GIS support the preparation and integration of spatial datasets, while composite indices provide a systematic framework for synthesising multiple indicators. However, conventional global PCA captures the overall covariance structure and may not adequately reflect local variation in multivariate relationships. Geographically Weighted Principal Component Analysis (GWPCA) addresses this limitation by incorporating geographical proximity, enabling examination of local variations in the underlying data structure [29–31]. Combined with spatial autocorrelation techniques such as Moran's I and Local Indicators of Spatial Association (LISA), it can identify spatial clustering and local concentrations of relatively high or low livability, supporting neighbourhood-level assessment beyond a single aggregate score [32,33].

Despite these advances, important gaps remain. Existing livability studies largely rely on conventional composite indices that may not adequately capture spatially varying livability conditions in topographically constrained towns. Although PCA and GWPCA have been increasingly applied to spatially explicit index construction, their application to mountainous small towns remains limited, particularly in contexts shaped by uneven terrain, accessibility constraints, and unequal service provision. Moreover, spatial autocorrelation is often applied after index construction rather than integrated with locally weighted dimensional reduction. This approach moves beyond the repeated application of existing indicator systems by combining local dimensional structure and spatial clustering to identify intra-urban and centre–periphery variations in livability within a topographically constrained Himalayan town. Against this background, the present study develops and applies a spatially explicit framework to assess sustainable urban livability in Darjeeling, India, integrating remote sensing, GIS, and geographically weighted analysis. Specifically, it aims to (i) construct a composite Sustainable Urban Livability Index (SULI) using 44 indicators across nine domains; (ii) examine spatial variation in the overall index and its constituent domains across the 32 wards of Darjeeling Municipality; and (iii) identify local spatial clusters and patterns of spatial association using Moran's I and LISA. The study addresses three research questions:

- **RQ1:** How can multiple environmental, built-environment, infrastructural, and amenity-related indicators be integrated to assess sustainable urban livability across Darjeeling's municipal wards?
- **RQ2:** How does urban livability vary spatially across the 32 wards, and which domains exhibit comparatively favourable or unfavourable conditions?
- **RQ3:** What spatial clustering patterns characterise the distribution of urban livability, and how can the identification of localised disparities inform context-sensitive planning in a Himalayan hill town?

By addressing these questions, the study contributes a multidimensional and spatially explicit assessment of urban livability in a topographically constrained Himalayan settlement. Its principal contribution lies in integrating locally weighted multivariate analysis with spatial autocorrelation to examine both the composite pattern of livability and its geographical clustering. In this study, urban livability is assessed through objective, spatially measurable conditions, including environmental quality, housing, infrastructure, accessibility, and essential services and amenities. The SULI therefore captures the spatial conditions of urban living rather than subjective perceptions, social participation, or psychological well-being, which remain beyond its scope. The resulting assessment can help identify areas requiring closer planning attention and provide an analytical framework for examining neighbourhood-level inequalities in comparable hill towns. The study therefore seeks to support more geographically informed approaches to urban planning and sustainable development without assuming that the same interventions will be appropriate across all neighbourhoods.

2. Data and Methodology

2.1. Study Area Setting and Rationale

Darjeeling, known as the "*Queen of the Himalayas*", is the principal urban centre and administrative headquarters of the district (Figure 1). Its distinctive mountainous setting, cultural significance, tea plantations, and role as a tourist and educational centre contribute to its diverse urban character [34,35]. Established in 1850, Darjeeling Municipality is among India's oldest municipalities and comprises 32 wards and two cantonments, Lebong in the north and Jalapahar in the south. The town occupies 'Y'-shaped spurs extending northeast-

ward and northwestward from Ghoom Mountain [36], with residential, commercial, and institutional development distributed across steep and spatially constrained terrain.

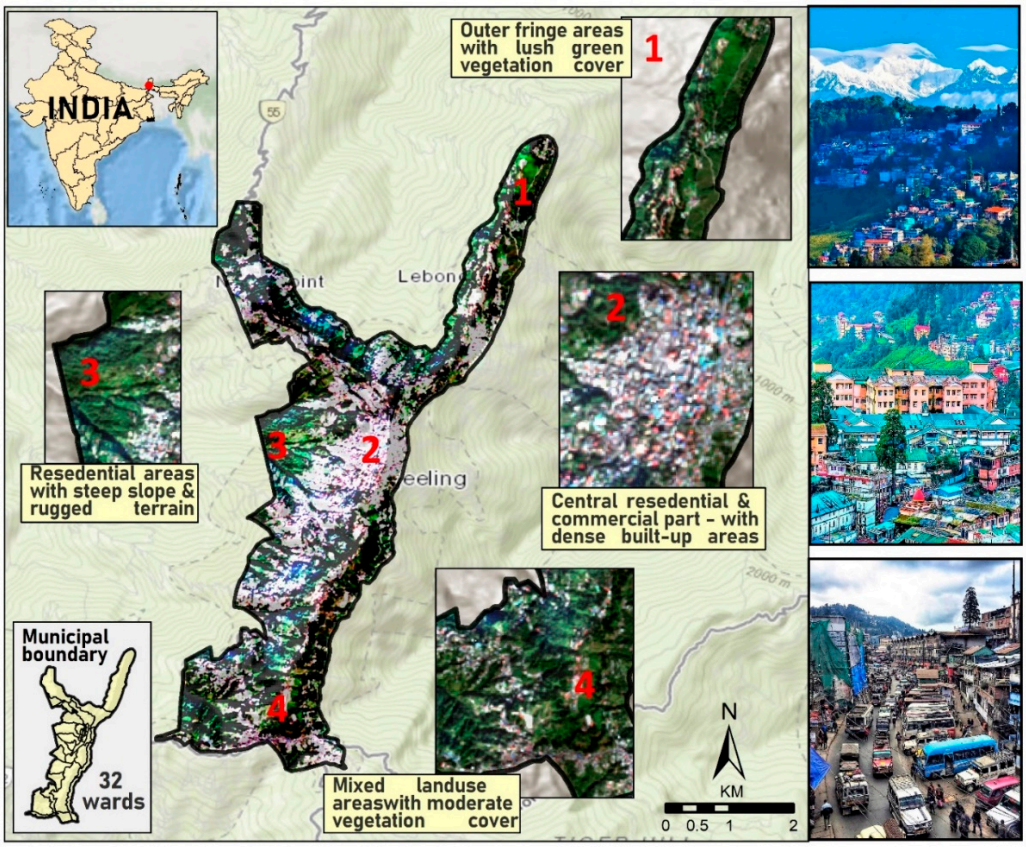


Figure 1. Location map of the Darjeeling town—"*the Queen of Himalayas*" in reference to India. True colour composite (TCC) of Darjeeling town using Sentinel-2A (10 m). The map also shows a few glimpses of field images.

Darjeeling covers approximately 10.57 km^2 and lies at an elevation of around 2050 m (6710 ft). According to the Census of India, its population increased from 73,062 in 1991 to 107,197 in 2001 (46.72% increase) and further to 118,805 in 2011 (10.83% increase), representing an overall population growth of 62.61% between 1991 and 2011, with a population density of approximately 11,238 persons km^{-2} in 2011. Population growth in Darjeeling reflects both natural increase and in-migration, with historical settlement shaped by migration from neighbouring Nepal, Sikkim, and Bhutan. More recently, seasonal migrants from West Bengal, Bihar, and Nepal have contributed to the town's population pressure, particularly through tourism, construction, plantation, and informal-sector activities [37,38]. Darjeeling's urbanization has largely occurred through incremental densification and peripheral expansion of the established hill town, including informal development in physically constrained areas, rather than through the development of entirely new planned urban districts. The town's ridge setting and surrounding tea gardens, forests, and restricted lands have substantially constrained conventional outward expansion [39,40]. This combination of demographic concentration, steep terrain, and constrained urban space creates challenges for housing, infrastructure, accessibility, public services, and environmental management [41–44].

The 32 municipal wards constitute the basic spatial units of analysis and provide a consistent framework for assessing intra-urban variations in livability. They vary considerably in population size, with 2011 populations ranging from approximately 1355 to

6428 residents, as well as in built-up conditions, infrastructure, service provision, accessibility, and environmental characteristics. As a major tourist and educational centre, the town also accommodates substantial transient populations, including tourists and students, potentially increasing demand for urban services. These demographic, topographic, and spatial variations make Darjeeling an appropriate setting for assessing spatially differentiated objective urban livability in a topographically constrained Himalayan town.

2.2. Framework of Sustainable Urban Livability Index (SULI) Dimensions and Associated Indicators Selection

Urban sustainable livability is a complex, multidimensional concept requiring interconnected, citizen-centred indicators [18,45–47]. Its assessment therefore requires a multidimensional and context-sensitive indicator framework [48,49], with greater emphasis on local environmental and socioeconomic conditions [50,51]. Accordingly, this study adopts a holistic, objective framework for assessing sustainable urban livability (SUL) in the vulnerable Himalayan town of Darjeeling, incorporating natural environment, built-up and housing conditions, infrastructure and public services, health, safety, culture and spirituality, recreation, and food and dining facilities [49,52].

The proposed framework comprises 44 indicators across nine dimensions (Table 1 and Figures S2–S10). A healthy natural environment and scenic landscape contribute to physical and mental well-being [45,53,54]; accordingly, five indicators capture Darjeeling's natural environmental conditions. Here, elevation is considered a positive indicator for its potential environmental and scenic advantages, whereas terrain-related constraints on accessibility and development are represented separately through slope and accessibility indicators. The built-up and housing dimension, represented by eight indicators, assesses built-up density and housing quality, reflecting urban spatial quality, land pressure, and citizen well-being [18,48,55–57]. Accessible infrastructure and public services are central to livability, particularly the proximity of roads, transport facilities, banks and ATMs, markets, health services, and educational facilities [58–62]. The health dimension also includes four indicators.

Table 1. Indicator selection, rationale, and its relation to sustainable urban livability.

Domains	Variables	Relation	Description
Physical environment	Average elevation	+	Elevation influences weather, water management, transportation, scenic views, and resilience, while elevated locations enhance livability through scenic and natural-resource advantages.
	Average slope	-	Slope negatively affects SUL by constraining land use, stability, accessibility, and water supply while increasing natural-hazard risks.
	Dist. from natural water source (Jhora)	+	Urban livability depends on residents' access to safe, reliable, and nearby drinking water.
	Dist. from open dumping place	+	Proximity to such sites can lead to environmental pollution, health hazards, and degradation of quality of life.
	NDVI	+	SUL is positively associated with NDVI, as the quality and extent of green spaces enhance urban aesthetics and support a healthy, livable environment.

Table 1. *Cont.*

Domains	Variables	Relation	Description
Built-up and housing environment	Household density	-	Overcrowding of households can put a burden on infrastructure and decrease livability conditions.
	NDBI	-	Higher NDBI indicates built-up expansion and urban sprawl, reducing green-space access and increasing congestion, commuting time, and livability pressures.
	Mean noise level	-	Noise levels affect sustainable urban livability by influencing health, well-being, residential choices, and neighbourhood disturbance, particularly among vulnerable populations.
	Liveable House condition	+	Poor housing conditions increase disease risk, mental distress, and insecurity, thereby reducing urban livability.
	Dwelling rooms < 2	-	In overcrowded urban areas, limited room availability increases health risks by reducing space, ventilation, and comfort.
	Household having latrine facility	+	Greater latrine availability indicates better sanitation, hygiene, and public health, enhancing urban livability, while inadequate drainage causes pollution, odour, and health risks.
	No drainage	-	
	Drinking water within premises	+	Access to safe, clean water and shorter water-collection times enhances living conditions and supports a sustainable urban environment.
Public Infrastructural convenience Services	Dist. from major road	+	Greater distance from major roads increases travel time and may require additional transport, raising travel costs.
	Road density	+	It signifies an improved pattern of the road network across the urban area
	Dist. from major transport facilities	+	Greater distance from major transport facilities increases travel time and may require additional transport, raising travel costs.
	Dist. from bank and ATM	+	Access to financial services promotes economic inclusion, financial security, and emergency preparedness, enhancing urban livability.
	Dist. from supermarket	+	Close proximity to supermarkets ensures easy access to fresh food and other necessary items, promoting livability.
	Dist. from public toilet	+	Access to clean, well-maintained public toilets improves sanitation, public health, and overall urban livability.
	Dist. from municipal office	+	Proximity to municipal offices facilitates access to public services, reduces travel time, and supports citizen participation and administrative engagement.
Cultural and spiritual facilities	Dist. from art memorial	+	These cultural attributes foster community engagement, social cohesion, cultural diversity, artistic expression, education, and overall well-being.
	Dist. from botanical garden	+	
	Dist. from museum	+	
	Dist. from theatres	+	
	Dist. from place of worship		Proximity to places of worship reduces travel time and promotes social interaction and spiritual well-being, enhancing urban livability.

Table 1. *Cont.*

Domains	Variables	Relation	Description
Recreational facilities	Dist. from major attractions and viewpoints	+	Proximity to attractions and viewpoints enhances visual appeal, tourism, and recreation, while improving public engagement and highlighting cultural diversity.
	Dist. from Zoo	+	
	Dist. from parks and playgrounds	+	Proximity to parks, playgrounds, gyms, and sports centres supports physical health, emotional well-being, and community interaction, fostering a healthy, sustainable, and livable urban environment.
	Dist. from gym and sports centres	+	
	Dist. from malls	+	Close proximity to malls ensures economic activity and provides convenience, offers diverse amenities, and promotes walkability.
Fooding and dining services	Dist. from restaurants and takeaway counters of fast foods	+	Proximity to food and dining facilities supports leisure and social interaction, enhancing mental well-being and community cohesion, while access to diverse and sustainable food options promotes health and overall well-being.
	Dist. from bar		
	Dist. from cafeteria	+	
	Dist. from bakery	+	
Educational facilities	Dist. from school	+	Quality and accessible educational facilities are crucial to sustainable urban livability, promoting individual growth, knowledge, socioeconomic development, and employment opportunities that strengthen urban livelihoods.
	Dist. from college	+	
	Dist. library	+	
Healthcare services	Dist. from hospitals	+	An improved healthcare facility is a key component of urban sustainability. Close proximity to hospitals and other health services is paramount during emergencies.
	Dist. from private clinics/nursing homes	+	
	Dist. from pharmacy	+	
	Dist. from blood bank	+	
Safety service	Dist. from fire service	+	Access to police and fire protection ensures residents' safety and well-being, fostering social cohesion, reducing illicit activity, and protecting public spaces.
	Dist. from police station	+	
	Dist. from fuel stations	-	Close proximity to fuel station might increase the potential risk of live threats leak of dangerous materials, occurrence of explosion.

Culture, spirituality, and recreation also contribute to quality of life, social interaction, and community cohesion [59,63,64]. Accordingly, the cultural and spiritual dimension comprises five indicators, while five indicators represent recreational facilities. Food and dining facilities constitute an additional dimension, reflecting their relevance to urban livability and everyday accessibility [48,65], and are represented by four indicators. Finally, safety and emergency services are important components of sustainable urban livability, as greater accessibility to such facilities enhances residents' situational security [48,61,66,67]. Three indicators were therefore incorporated to assess the safety dimension in Darjeeling.

Indicators were selected based on five criteria: conceptual relevance to the respective livability domain, measurability and spatial comparability, non-redundancy, consistent directional interpretation, and contextual relevance to the study area. These criteria follow established principles for composite-indicator construction, which emphasise analytical soundness, measurability, relevance, comparability, and appropriate relationships among indicators [68,69]. Indicators that are unavailable or unsuitable in another context may therefore be replaced by conceptually equivalent measures within the same domain. The ward was adopted as the analytical unit in Darjeeling because it provided a consistent spatial framework for integrating the available indicators. For application elsewhere, the framework can be adapted to the smallest spatial unit at which the required indicators are consistently available, while maintaining a common spatial scale and standardisation procedure. Thus, the nine domains constitute the transferable conceptual structure, whereas individual indicators may be modified according to local environmental, infrastructural, service, and socioeconomic conditions. Potential redundancy was also considered by examining the conceptual overlap and spatial representation of indicators. Substantially overlapping indicators were avoided where appropriate, while conceptually distinct indicators were retained even when they exhibited similar spatial patterns. Such spatial similarity may reflect the underlying organisation of urban services rather than indicator redundancy. GWPCA further accounts for covariance among correlated indicators through locally weighted dimensional reduction.

Before index construction, the indicators were examined to determine their expected relationship with urban livability. Indicators representing beneficial conditions were treated as positive, whereas indicators representing adverse conditions were treated as negative, based on their conceptual relevance. The indicators were then standardized according to their direction to ensure consistent interpretation, with higher standardized values representing more favourable livability conditions. The direction assigned to each indicator was checked against its definition and role within the corresponding domain.

2.3. Data Source, Extraction and Its Processing Technique

Table 1 presents the assessment framework for the SULI in Darjeeling, comprising 44 indicators across nine domains: (i) housing and built environment, (ii) natural and physical environment, (iii) accessibility of public infrastructure and services, (iv) cultural and religious amenities, (v) recreational facilities, (vi) food and dining services, (vii) healthcare facilities, (viii) educational services, and (ix) safety services. The indicators were selected based on the conceptual framework, data availability, literature, and the specific physical, cultural, and historical context of the Darjeeling Himalaya. The study integrates spatial and non-spatial datasets from six sources: (1) GIS databases, (2) Landsat satellite imagery, (3) Digital Elevation Model (DEM), (4) Census data, (5) municipal records, and (6) primary field surveys. Of the 44 indicators, 70% were derived from GIS databases, including OpenStreetMap and Google Earth, 11% from the Census of India, 6% from municipal records, 5% from satellite imagery, and the remainder from the other two sources.

The GIS database includes roads, natural water sources, landfill sites, major bus and taxi stands, municipal offices, parks, playgrounds, hospitals, libraries, bars, restaurants, fuel stations, banks and ATMs, and police stations, extracted as point and polygon data in KML and shapefile formats and pre-processed in a GIS environment. Field observations at more than 135 locations were conducted to verify Google Earth and OSM-derived data. Google Earth imagery was used to manually capture relevant point, line, and polygon features, which were exported in KML format and subsequently converted to raster format where required for GIS-based analysis. Similarly, OSM data were obtained from the Geofabrik regional extract and subsequently processed for the required GIS-based analysis. Landsat-

8 OLI imagery acquired on 24 November 2022 at 30 m spatial resolution was obtained from the USGS Earth Explorer. The imagery was subsequently subjected to geometric and radiometric corrections using ArcMap 10.8, following the procedure described by Roy et al. [18]. NDVI and NDBI were subsequently derived in GIS. A 30 m SRTM DEM obtained from NASA Earthdata was used to derive elevation and slope, which are particularly relevant to livability given Darjeeling's hilly terrain and steep slopes. Ward-level data on livable housing conditions, dwelling rooms, sanitation, drainage, and drinking-water availability were obtained from the Office of the Registrar General & Census Commissioner, Government of India, 2011. Municipal records provided household density and the locations of schools and colleges. In addition, noise levels were measured through a primary survey at ten significant nodes in 2022 at weekly intervals using an HTC Instrument SL-1352 Professional Sound Level Meter, and the observations were interpolated using Inverse Distance Weighting (IDW) in GIS, following Roy et al. [18]. Given the varying spatial resolutions of the datasets, all SULI indicators were projected to UTM WGS-84 Zone 45 N and standardised to a 30 m cell size, consistent with the Landsat imagery. Euclidean Distance was subsequently applied to all point and polygon datasets to ensure spatial comparability and minimise potential inconsistencies in the final spatial outputs. Euclidean distance was used to provide a consistent and comparable measure of spatial proximity to facility locations. However, it represents straight-line distance and does not account for road-network configuration, terrain, physical barriers, or actual travel routes. Thus, these indicators are interpreted as measures of spatial proximity rather than network-based travel accessibility. Following this, the prepared and converted data layers were extracted using the 'Zonal Statistics as Table' tool. Subsequently, all of the ward-specific information obtained was transferred to Microsoft Excel for additional analysis. All spatial data processing and analysis, including NDVI and NDBI calculation, IDW interpolation, Euclidean distance raster generation, and zonal statistics, were performed using ArcMap 10.8. Moreover, the entire methodological flowchart was presented in Figure 2. Further correlation assessment has been done in order to verify any potential correlations within the dataset (Figure S1).

2.4. Indicators Standardization

For the synthetic index construction, several variables involved with different directions must be normalized [68]. The normalization enables removing the diverse nature of measurement units for each indicator [70]. For this research, 'homogenization' and 'non-dimensionalization' techniques were applied to normalize the entire dataset and exclude the dimensionality among the indicators [70,71].

Two different systems are utilized to normalize the indicators based on their direction of influence. The first one is applied to the indicators that positively influence the final outcomes (here, urban livability). In contrast, some indicators are inversely related to urban livability, which means increasing the value of the indicators lessens livability. The min–max transformation scales indicator values to a 0–1 range, with higher values representing more favourable livability conditions. Here, the positively related indicators were normalized using Equation (1), while Equation (2) was employed when the indicators were assumed to be negatively linked with livability.

$$Z_{ij}^{POS} = \frac{X_{ij} - Min\left(X_{ij}\right)}{Max\left(X_{ij}\right) - Min\left(X_{ij}\right)} \ (directed\ towards\ positive\ relation\ \uparrow) \quad (1)$$

$$Z_{ij}^{NEG} = \frac{Max\left(X_{ij}\right) - X_{ij}}{Max\left(X_{ij}\right) - Min\left(X_{ij}\right)} \ (directed\ towards\ negative\ relation\ \downarrow) \quad (2)$$

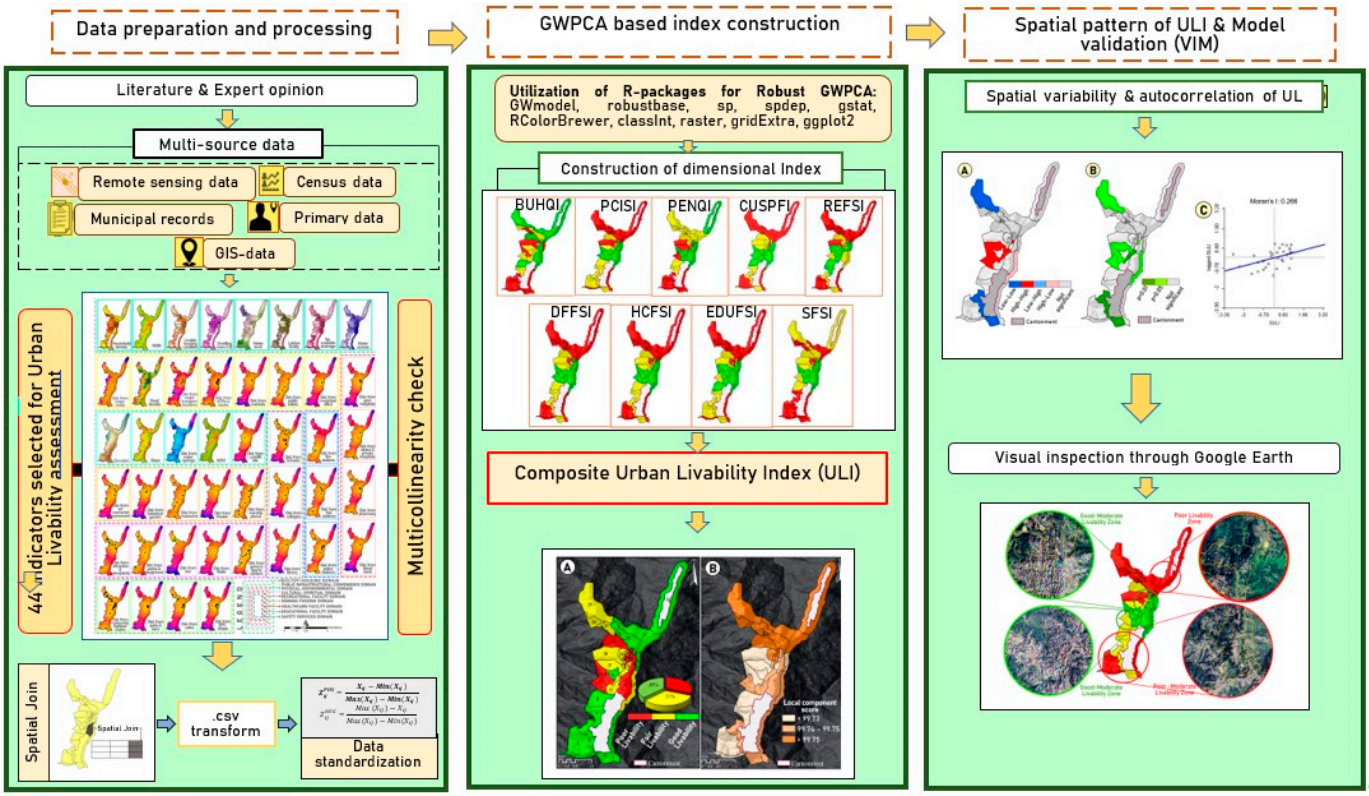


Figure 2. Methodological flowchart adopted for the present study.

2.5. Geographically Weighted Principle Component Analysis (GWPCA) and Sensitivity Assessment

GWPCA extends global principal component analysis (PCA) by incorporating geographical variability to capture spatial heterogeneity at the local scale [72,73]. Unlike global PCA, which assumes a global data structure and does not account for spatial non-stationarity, GWPCA is designed to capture spatially varying relationships and patterns in multivariate datasets [29,31,72,74]. Accordingly, PCA is performed locally within defined spatial regions rather than across the entire dataset, using appropriate algorithms implemented in R [75]. Here, all the calculation is related to each location of *i*th comprising the coordinates of (u,v).

Mathematically, the locally weighted variance-covariance matrix is obtained as [31].

$$\sum(u,v) = X^T W(u,v) X \tag{3}$$

where $W(u,v)$ represent the diagonal local spatial weight matrix of distance generated from locational coordinates of (u,v). The weight matrix is generated using adaptive kernel weighting function. X indicates the matrix generated from observations and covariates of the assigned data. Then, the local eigen-structure of GWPCA of each spatial location of (u,v) is calculated using the following formula:

$$L(u_i,v_i)V(u_i,v_i)L^T(u_i,v_i) = \sum(u_i,v_i) \tag{4}$$

The matrix of eigenvectors denoted by $L(u_i,v_i)$ portrays the loadings of every variable on each principal component (PC), whereas $V(u_i,v_i)$ represents the diagonal matrix of eigenvalues signifying the variances associated with the corresponding principal component. Then, the score of the retained component of GWPCA is obtained by:

$$Z(u_i,v_i) = X(u_i,v_i)L(u_i,v_i) \tag{5}$$

For the research, the optimal bandwidth selection for the optimum number of PC is done using Gaussian kernel weight function for robust GWPCA. The Gaussian weights are depicted as follows:

$$w_{ij} = exp\left[-1/2\left(d_{ij}/b\right)^2\right] \quad (6)$$

Here, the robust GWPCA utilized an adaptive Gaussian kernel, with the bandwidth defined by the number of neighbouring observations [76]. To achieve a robust GWPCA framework, the local covariance matrix at each location was estimated using the robust Minimum Covariance Determinant (MCD) estimator [31,77]. This approach reduces the influence of locally atypical observations and provides a robust estimation of the local covariance structure. The robustness of the MCD estimation was further examined by varying the MCD support fraction in the sensitivity analysis.

To assess the robustness of the SULI, an adaptive Gaussian kernel was used for the geographically weighted calculations, with bandwidth defined by the number of nearest neighbouring wards. Alternative neighbourhood sizes were evaluated using leave-one-out cross-validation (LOOCV) based on local reconstruction error. Principal components were retained according to the Kaiser criterion, with eigenvalues >1 considered eligible for retention; the global PCA identified two such components. Robust local covariance structures were estimated using the Minimum Covariance Determinant (MCD) estimator to reduce the influence of locally atypical observations. Sensitivity tests varied the adaptive bandwidth, kernel function, number of retained components, and MCD support fraction. The resulting indices were compared using Pearson's correlation, Spearman's rank correlation, RMSE, MAE, and changes in ward-level rankings.

2.6. Application of Robust GWPCA and Construction of Synthetic Suli

Several studies have applied GWPCA to construct composite indices and capture spatially varying influences [31,59]. In this study, GWPCA was applied to derive the dimensional indices and overall SULI for the 32 wards of Darjeeling Municipality, following the approaches of Mishra [72], OECD [68], and Nardo et al. [56]. The geographically weighted analyses, including GWPCA, were performed using the GWmodel package in R, which provides the required geographically weighted statistical procedures for the present analysis. The SULI integrates local principal component scores and local component variance at each location and was constructed in three steps: (i) computing dimensional indices (DIs) from the respective indicators using GWPCA-derived weights; (ii) standardizing the DIs; and (iii) aggregating the standardized DIs to derive the final SULI.

$$DI_{ik} = \sum_{i=32}^{n=N} LCV_{PCn} LCS_{PCn} \quad (7)$$

Also DI_{ik} mathematically represented as:

$$DI_{ik} = (LCV_{PC1i} \times LCS_{PC1i}) + (LCV_{PC2i} \times LCS_{PC2i}) + (LCV_{PC3i} \times LCS_{PC3i}) + \cdots + (LCV_{PCni} \times LCS_{PCni}) \quad (8)$$

where (I) is the dimensional index of the selected (k) domains ((k = 9)) for each location (i). Here, (k) represents the Built-up and Housing Quality Index (BUHQI), Physio-Environmental Quality Index (PENQI), Public Convenience and Infrastructural Status Index (PCISI), Healthcare Facility Status Index (HCFSI), Educational Facility Status Index (EDUFSI), Culture and Spirituality Status Index (CUSPFI), Recreational Facility Status Index (REFSI), Dining and Food Facility Status Index (DFFSI), and Safety Service Index (SFSI). LCV denotes the robust local component variance for location (i), while LCS represents the robust local principal component scores obtained from the retained PCs in GWPCA for each (k) dimension. *PC1 ... PCn* denotes the principal components obtained from robust GWPCA. The global PCA identified two components with eigenvalues > 1,

and these two components were therefore retained consistently for each of the nine SULI domains in the subsequent GWPCA. All 44 indicators across the nine domains are presented in Figure 3.

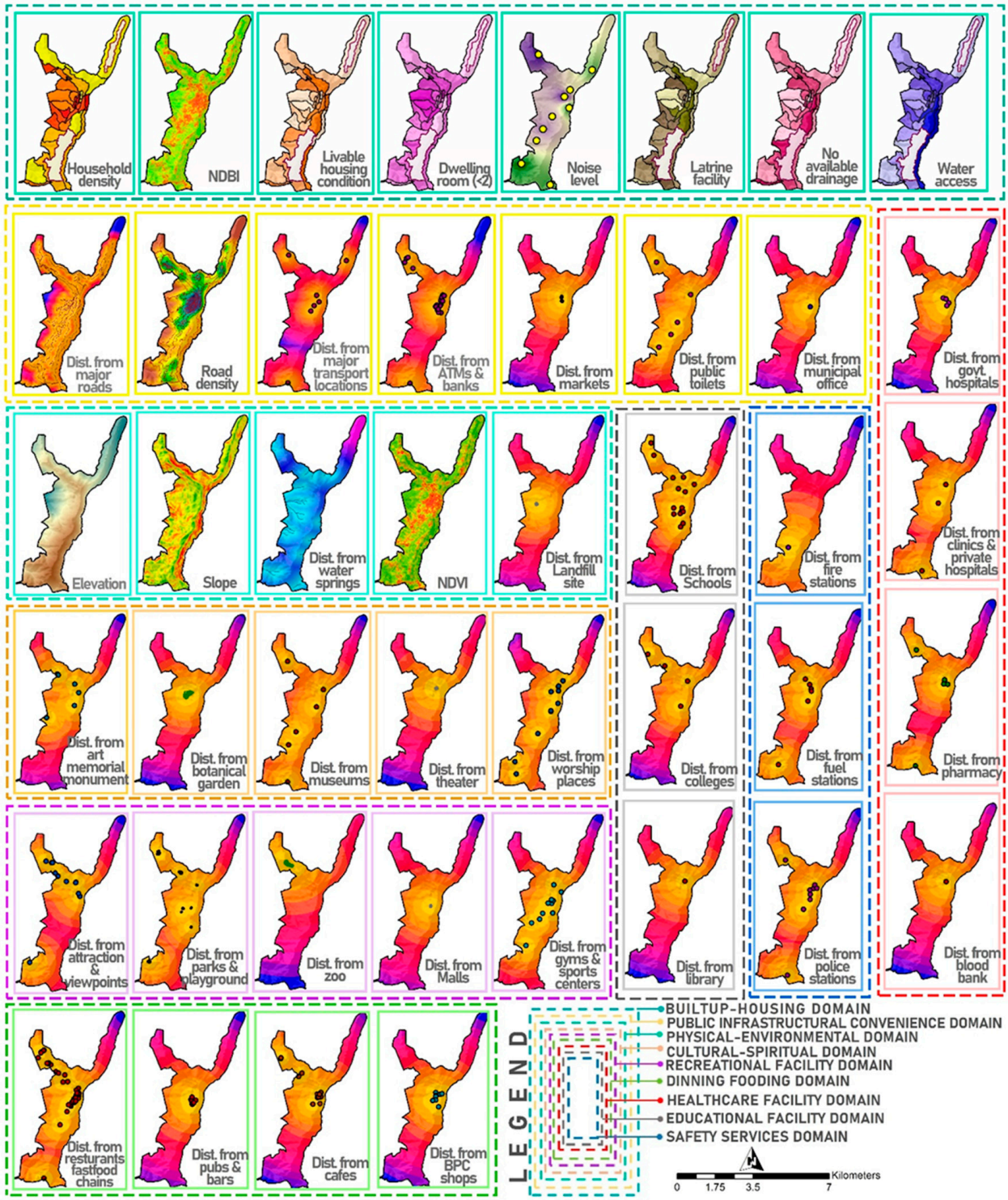


Figure 3. Selected 44 indicators and nine respective domains for SUL assessment.

In the next step, each dimensional index (DIik) value of SUL for each location needs to be standardized for better interpretation and visualization. The standardized score of DI ranges from 0 to 1, where 0 indicates low livability, and 1 indicates good livability. The

greater composite value indicates better livable conditions for the urban citizens of Darjeeling town. The dimensional index values are standardized using the following expression:

$$STD_{DIik} = \frac{DI_{ik} - Minimum_{DI_{ik}}}{Maximum_{DI_{ik}} - Minimum_{DI_{ik}}} \quad (9)$$

The number of principal components was determined using the Kaiser criterion, retaining components with eigenvalues greater than 1. The global PCA identified two components satisfying this criterion, which were therefore retained for the subsequent GWPCA-based construction of the SULI. The robustness of this two-component solution was further examined by comparing it with a one-component specification in the sensitivity analysis.

Finally, the standardized value of each DI is used as an input to robust GWPCA for the SULI. The global PCA suggests two major components received values greater than 1 eigenvalue, which were also retained during GWPCA. The formula of SULI is expressed as:

$$SULI_i = (DILCV_{PC1i} \times DILCS_{PC1i}) + (DILCV_{PC2i} \times DILCS_{PC2i}) \quad (10)$$

where SULIi is the sustainable urban livability index for each location (municipality wards) of I and is the local component variance and component score obtained from the GWPCA of the nine-dimensional index, i.e., BUHQI, PENQI, PCISI, HCFSI, EDUFSI, CUSPFI, REFSI, DFFSI, and SFSI. The raw value of SULI is further standardized using the above-mentioned equation, where a greater value indicates better urban livability towards sustainability.

2.7. Determination of Spatial Clusters of SULI

Spatial clustering is a technique of exploratory spatial data analysis (ESDA) that enables the researchers to segregate the statistically significant high and low-value pockets and visualize the spatial pattern on the surface of the study region. In this research, univariate LISA was utilized to analyze the spatial pattern of the final computed SULI of Darjeeling town. This univariate LISA analysis helps to determine the potential high livable pockets with potential bottleneck areas concerning the geographical weighting and local-level spatial influence. The univariate Moran's I is expressed as:

$$Univariate\ Moran's\ I\ = \frac{n}{S_O} \times \frac{\Sigma_i \Sigma_j W_{ij}\left(x_i - \overline{X}\right)\left[x_j - \overline{X}\right]}{\Sigma_i \left[x_i - \overline{X}\right]^2} \quad (11)$$

After computing Moran's I, LISA was utilized to detect the high-high (HH), low–low (LL) clusters and associated outliers of SULI using the following equation:

$$Univariate\ LISA:\ I_i = \frac{n \cdot \left[x_i - \overline{X}\right]}{\Sigma_i \left[x_i - \overline{X}\right]^2} \Sigma_j w_{ij}\left[x_j - \overline{X}\right] \quad (12)$$

In which x represents the input variable, specifically SULI, and $\overline{X}$ denotes its corresponding mean; *n* signifies the count of spatial units (wards); W_{ij} pertains to the standardized weight matrix linking observation *i* with *j*, characterized by zeroes on the diagonal (queen contiguity weight matrix); and S_o corresponds to the summation of all spatial weights, that is $S_o = \Sigma_i \Sigma_j W_{ij}$.

3. Results

3.1. Variability of Domains and Their Contributing Factors

The nine-dimensional index (Figure 4A–I) quantifies key components of urban livability and enables their spatial visualisation to support targeted planning and policy interventions. Figure 4A shows the ward-wise Built-up and Housing Quality Index (BUHQI),

revealing diverse livability patterns across Darjeeling's 32 wards. Good BUHQI is concentrated in the core and adjacent wards, extending towards the northern parts, and covers 34.37% of wards. This pattern is associated with a higher concentration of livable housing, improved drainage and sanitation, and greater dwelling-room availability (Figure 3). In contrast, poor BUHQI dominates parts of the central area and most of the southern town, influenced by low built-up conditions, moderate-to-poor drainage and sanitation, higher noise levels, and housing density (Figures 4A and 5). Moderate BUHQI generally occurs around the better-quality central wards.

The highest PCISI score was recorded in Ward 11 and the lowest in Ward 1. Figure 4B shows that good PCISI, indicating better accessibility to public services and infrastructure, occurs in approximately 34% of wards, mainly in the central area. The town centre benefits from better road and transport accessibility and a concentration of banks, ATMs, supermarkets, and municipal services. In contrast, low PCISI scores (0–0.496) dominate the northern part and two southern wards, indicating limited access to public services and infrastructure (Figures 4B and 5). Figure 4C illustrates the Physio-Environmental Quality Index (PENQI), with good conditions concentrated in the central and northern margins. These areas combine tolerable elevation, lower slopes, greater green cover, favourable proximity to landfill sites, and better access to natural water sources (Figure 3). Conversely, low PENQI dominates the southern and parts of the central town, where greater elevation and steeper slopes, limited natural water availability, and proximity to landfill sites jointly constrain environmental quality and urban livability (Figures 4C and 5).

Figure 4D shows that only 34% (11 wards) have a good Cultural and Spiritual Facilities Index (CUSPFI), primarily concentrated in the central area. Cultural and spiritual facilities, including memorials, botanical gardens, museums, theatres, temples, churches, and monasteries, are clustered in the core and adjacent neighbourhoods, resulting in progressively poorer accessibility towards the northern and southern sections (Figures 3 and 4D). Figure 4E,F present the spatial distribution of the Recreational Facilities Index (REFSI) and Dining and Food Facilities Index (DFFSI), respectively. High REFSI is concentrated in the core and surrounding areas, particularly the south-central part (Figure 5). Accessibility to parks, playgrounds, malls, and sports facilities declines towards the outer periphery, producing poor recreational conditions in the northern and southern parts, encompassing 11 of the 32 wards (Figures 3 and 4E).

Additionally, Figure 4F shows that good Dining and Food Services Index (DFFSI) scores are concentrated in the urban core, while approximately 34% of wards in the outer areas record poor scores. This core–periphery disparity reflects the uneven distribution and accessibility of food and dining facilities, which support better livability in the central area but decline towards the town's periphery. Moreover, Figure 4G illustrates the Healthcare Facilities and Services Index (HCFSI), with high scores concentrated in the central area due to the greater concentration and accessibility of hospitals, clinics, pharmacies, and blood banks. Residents of the core therefore benefit from better healthcare accessibility. In contrast, the northern and southern peripheries face greater accessibility constraints associated with longer distances, higher elevation and slope, and limited transport facilities. Poor HCFSI is observed in six northern wards, three southern wards, and one central ward.

Figure 4H shows that only 34% (11 wards) have a good Educational Facilities Index (EDUFSI), primarily concentrated in the central area. Schools, colleges, and libraries are clustered around the core, while most northern, central, and southern wards fall within the poor EDUFSI zone. Moderate educational conditions generally occur in wards adjacent to the better-served central area (Figure 3). Finally, Figure 4I presents the Safety Facilities and Services Index (SFSI), with high scores concentrated in the core and surrounding areas. The good SFSI zone reflects better accessibility to police stations, fire services, and fuel

stations in central Darjeeling (Figure 5). Accessibility declines towards the outer periphery as distances to these emergency facilities increase, resulting in poor SFSI across the lower northern, central, and southern sections, encompassing 10 of the 32 wards (Figure 4I).

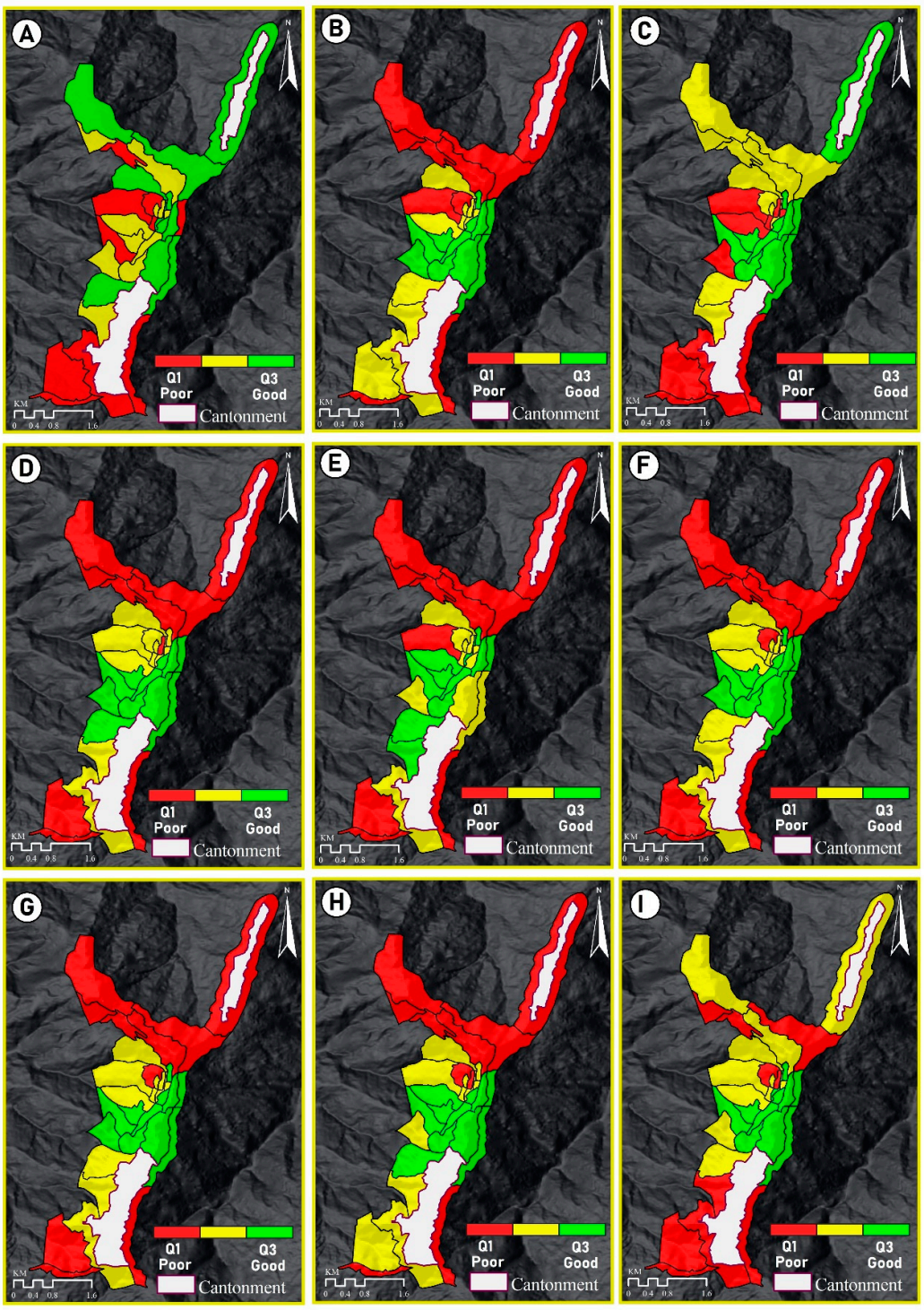


Figure 4. Spatial distribution of nine domains of SUL of Darjeeling town. (**A**) Built-up and housing domain; (**B**) public infrastructural convenience domain; (**C**) physical and natural environment domain; (**D**) cultural–spiritual domain; (**E**) recreational facilities domain; (**F**) dining and food domain; (**G**) healthcare facilities domain; (**H**) educational domain; (**I**) safety services domain.

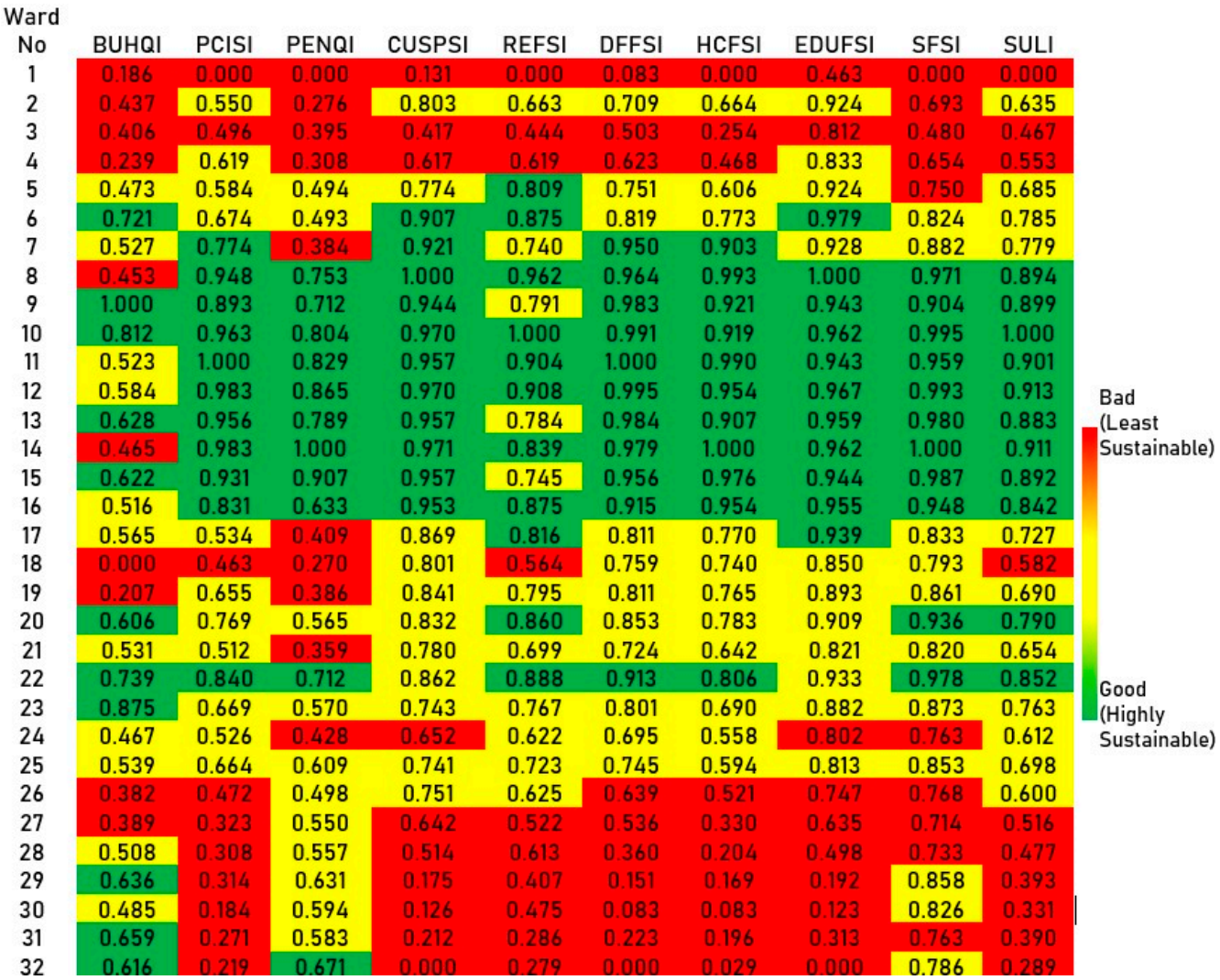


Figure 5. Heatmap showing the status of livability domains, including SULI for each spatial ward of Darjeeling.

3.2. Spatiality of Sustainable Urban Livability (SUL) and Visual Inspection

To formulate a unified synthetic index, all nine domains were integrated to capture the multidimensional nature of Sustainable Urban Livability (SUL) in Darjeeling. The local component score map (Figure 6A,B) indicates considerable spatial variation, with only 31% (10 wards) exhibiting good livability, while 34.38% (11 wards) each fall within the fair and poor categories. Good livability is concentrated in the central part of Darjeeling, where the strategic location and concentration of essential services enhance residents' access and overall living conditions. Major roads, transport facilities (bus and taxi stands), ATMs and banks, markets, and administrative offices provide greater convenience, while theatres, museums, botanical gardens, parks, malls, gyms, sports facilities, and cultural centres strengthen cultural and recreational opportunities. The central area also benefits from better housing and built-up conditions, including sanitation, drainage, livable housing, and drinking-water access. Diverse restaurants and catering facilities further enhance everyday accessibility, while hospitals, clinics, and healthcare centres provide better medical services. The presence of renowned educational institutions and safety facilities, including police stations and emergency services, further contributes to overall livability. Key areas with good livability include Chauk Bazar, Mall Road, Chowrasta, Tungsung Basti, Rajbari, Ganeshgram, and the upper part of Jalapahar.

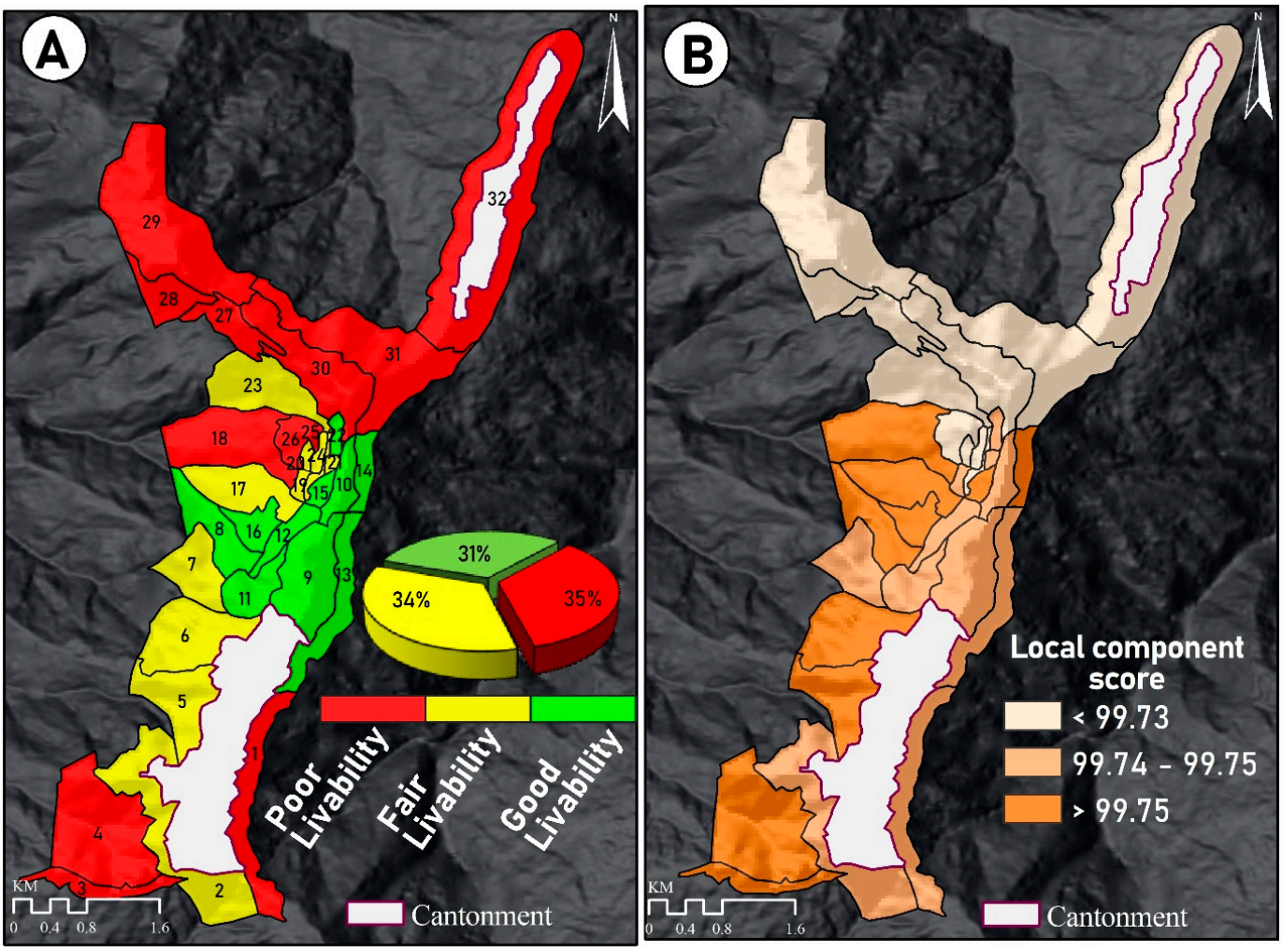


Figure 6. Composite SULI prepared using GWPCA (**A**) Spatial distributions and categorization of SUL zones, (**B**) Local component scores.

In contrast, the northern and southern fringe areas—including Lebong, Katapahar, Jalapahar, Singamari, 3-Mile Area, Naya Basti, Upper Bhutia Basti, Nalbangaon, Kothi Gaon, Limbugaon, Ghoom, Jorelhaṭṭa, and parts of Jorebungalow—exhibit poor livability conditions (Figure 6). These peripheral areas have limited access to public amenities, housing and built-up facilities, cultural and recreational opportunities, healthcare, education, and safety services. Steep slopes and elevated terrain further constrain infrastructure development, road accessibility, and everyday mobility. Although the peripheral landscape contributes to Darjeeling's distinctive character, inadequate access to essential services and challenging topography outweigh these advantages, resulting in poorer overall livability.

Furthermore, the model's efficacy in accurately depicting geographical variations in urban livability within the study region is assessed using the visual inspection method (VIM) by comparing the SULI map with corresponding satellite images procured from Google Earth (Figure 7). The outcomes of this visual observation method validate the correlation between livability and access to essential services and facilities. The results indicated that areas with good livability conditions exhibited better access to vital services, amenities, and facilities. These regions showcased a well-connected network of roads, indicating easier mobility and transportation options. They also demonstrated higher-density public amenities such as schools, hospitals, parks, recreational facilities, and other community resources, providing residents convenient access to comprehensive services that enhance livability (Figure 7). In contrast, the fringe areas exhibiting poor livability conditions were observed

to have inadequate access to essential facilities. Such peripheral zones displayed the limited or scattered distribution of public amenities, fewer educational institutions, inadequate healthcare services, and a lack of recreational spaces. The observations highlighted the challenges inhabitants face in these regions, including longer travel distances for necessities and lack of proximity to community resources. Visual observations using Google Earth provide supplementary visual support for the observed spatial patterns by confirming the spatial distribution of essential service provision. It offers a holistic perspective on the accessibility and availability of facilities in different locations, shedding light on factors contributing to overall livability standards at each location.

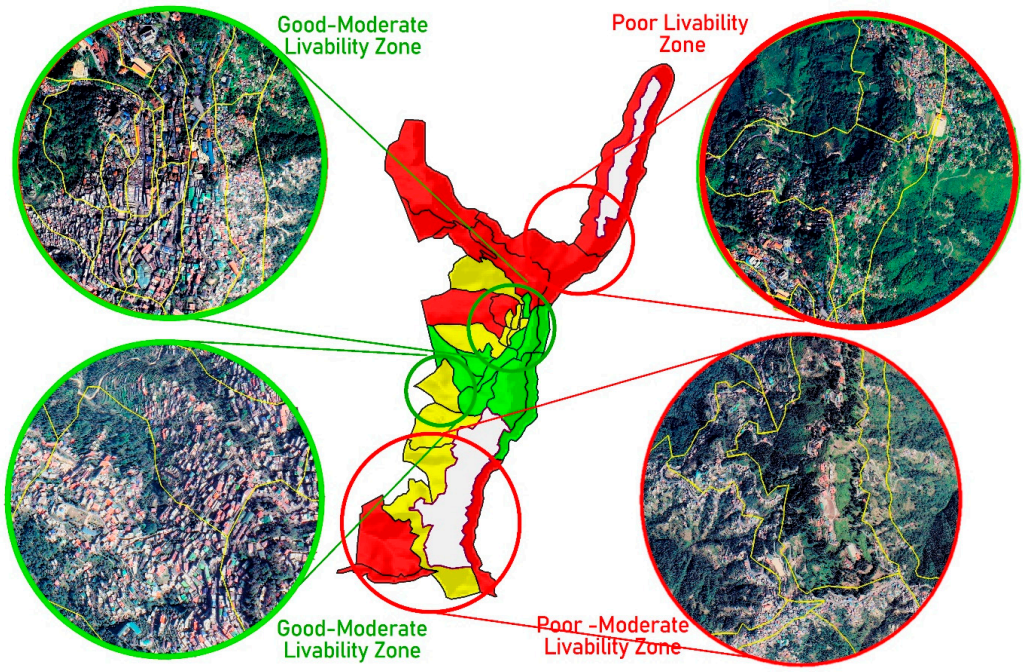


Figure 7. Visual inspection of SUL using Google Earth.

3.3. Clustering Pattern and Spatial Autocorrelation Analysis of Sul: Moran's I and Lisa

A visual illustration of the univariate spatial autocorrelation of the computed SULI can be seen here in Figure 8A–C. Figure 8C depicts Moran's scatter plot indicating local spatial association, and the Figure represents the univariate LISA map to showcase the geographic pattern and associated significance based on SULI as a single input variable. Statistical significance for Global Moran's I and LISA was assessed using 999 random permutations, with results considered statistically significant at $p < 0.05$. The univariate ESDA indicates that the SULI had a high Moran value ($I = 0.266$, $Z\ score = 2.623$, $Sig. = 0.009$), suggesting the presence of a spatial cluster. This clustering pattern corresponds with the presence of HH (hotspots) and LL (coldspots) clusters with HL and LH outliers. Figure 8A,B shows that the univariate visualization indicates that the part of the core in Darjeeling Town (wards no. 11, 19, 21, 22, and 26) corresponds with geographically significant HH clusters (hotspots), indicating that the high-value SULI wards are surrounded by neighbouring wards with similarly high values, and the neighbourhood influence is highly noticeable on the central part of the town (Figure 8A). In contrast, two wards located at the outer margin of the town (one in the south, another in the north) emerged as cold spots, suggesting that the low value of SULI corresponds with the low value of the adjoining neighbourhood (Figure 8A). The findings indicate that urban residents residing in the central part of Darjeeling have higher levels of livable conditions, as they benefit from the presence of various facilities necessary for their daily lives to function smoothly. Conversely, the peripheral wards exhibit

significantly lower livable conditions, with residents facing numerous challenges sustaining a decent livelihood.

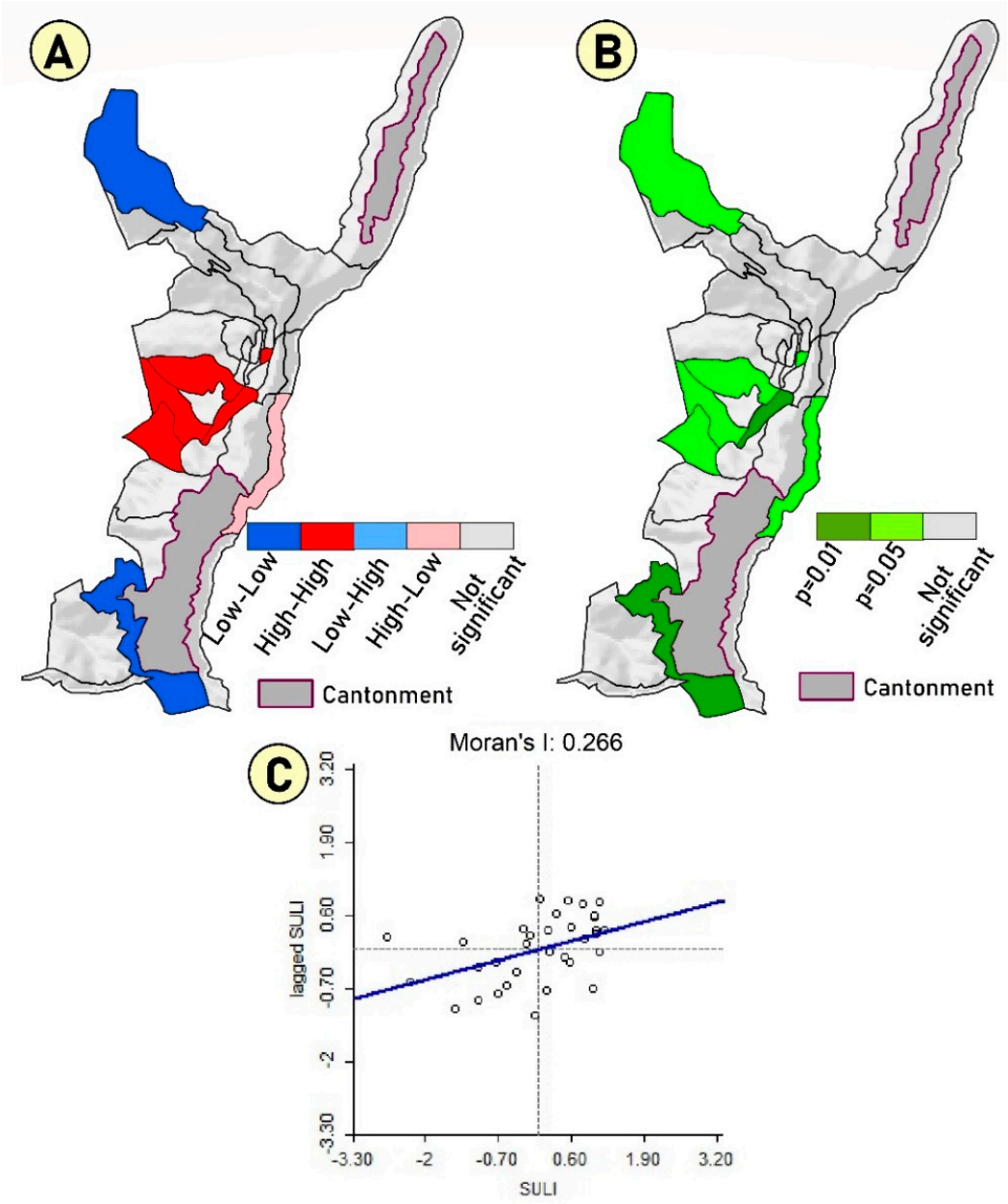


Figure 8. LISA map: (**A**) clustering pattern of SULI; (**B**) its significance level; (**C**) Moran scatter plot.

3.4. Dimensional Interdependencies with SULI

Figure 9 shows that all nine domain indices have moderate-to-strong positive correlations with SULI. The strongest associations are observed for PCISI ($r = 0.967$), HCFSI ($r = 0.964$), DFFSI ($r = 0.960$), and CUSPFI ($r = 0.937$), while BUHQI shows a comparatively moderate relationship with SULI. These correlations indicate the strong interconnection of the domains within the composite livability framework. However, because SULI is constructed from the nine domain indices, such strong associations are partly expected and should not be interpreted as independent evidence that these domains exert causal influence on overall livability. Rather, the correlation structure demonstrates how different dimensions collectively contribute to the spatial differentiation captured by the SULI. The substantial positive correlations among several domains also suggest that favourable

conditions in one dimension may spatially coincide with favourable conditions in others, particularly across areas with greater concentrations of urban services and amenities.

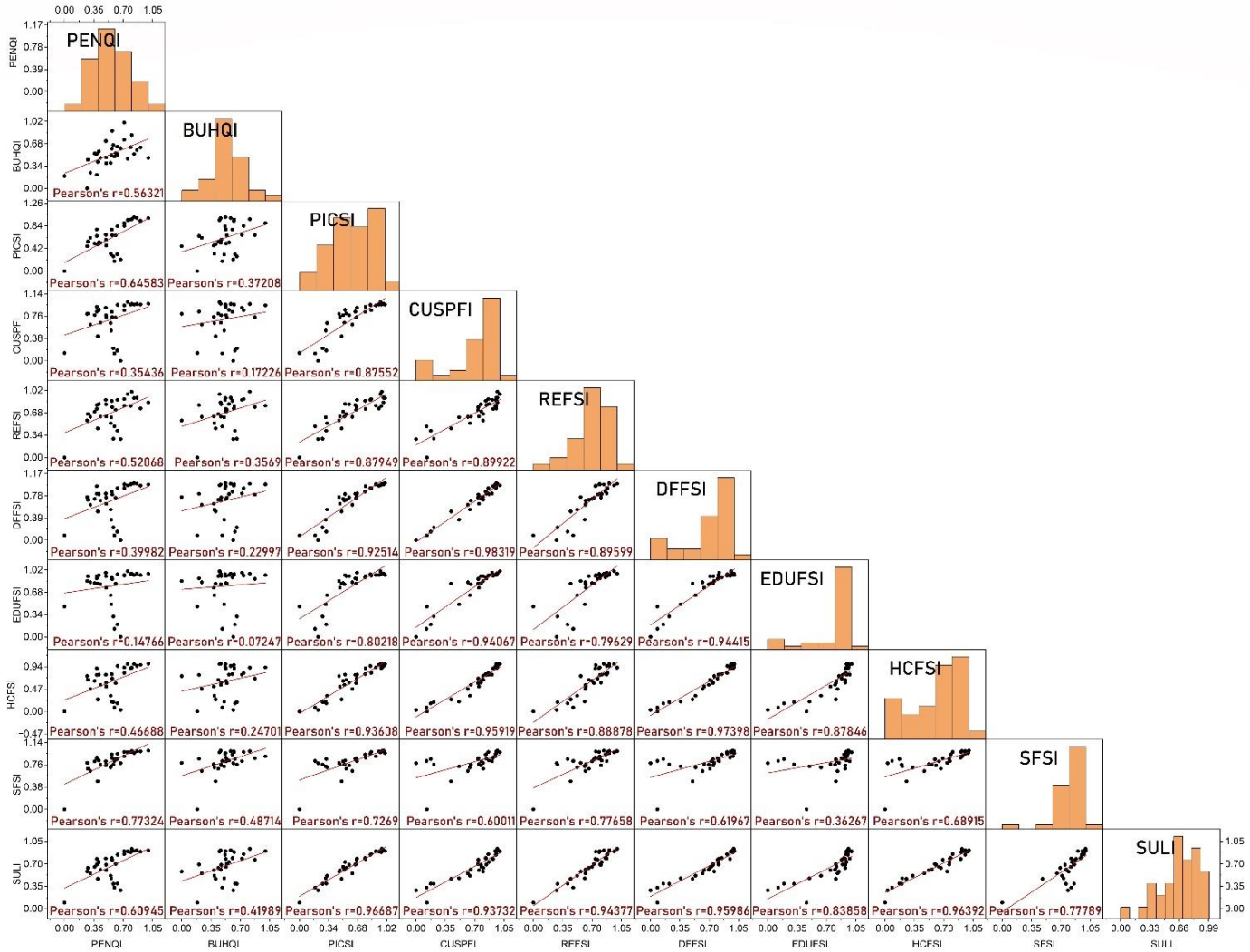


Figure 9. Scatter matrix showing relationship between SULI and associated nine domains.

3.5. Sensitivity and Robustness Analysis of SULI

To evaluate the structural stability and spatial sensitivity of the Sustainable Urban Livability Index (SULI), the baseline index was assessed against alternative specifications involving principal-component retention, robust covariance estimation, adaptive bandwidth, and kernel function. Overall, the SULI demonstrated high rank stability across most structural perturbations. Retaining one rather than two principal components produced the strongest agreement with the baseline solution (Pearson's $r = 0.991$); Spearman's $p = 0.974$), with a low RMSE of 0.052 and MAE of 0.040. Similarly, alternative MCD support fractions of 85% and 90% maintained high rank correlations ($p = 0.960$) and 0.947, respectively), with relatively low RMSE values of 0.105 and 0.084. These results indicate that the composite index is not unduly sensitive to the specification of robust local covariance estimation (Table 2).

Alternative Gaussian bandwidths also preserved the broad spatial ordering of wards, with Spearman's p ranging from 0.892 to 0.942 and mean absolute rank changes of approximately 2–3 positions. Among the tested Gaussian specifications, the 18-neighbour bandwidth provided a strong balance between rank stability ($p = 0.942$) and reconstruction error (RMSE = 0.109; MAE = 0.081), whereas smaller bandwidths produced greater local

variation. Bi-square and tri-cube kernels generated comparatively greater deviations from the baseline ($p = 0.725$) and 0.701, respectively), indicating greater sensitivity to more restrictive distance-decay functions. Nevertheless, the broad spatial ordering remained positively associated with the baseline solution. Collectively, the sensitivity analysis demonstrates that the principal spatial pattern of the SULI is reasonably robust to alternative choices of dimensionality, robust estimation, bandwidth, and spatial weighting, supporting its use for comparative assessment of ward-level urban livability.

Table 2. Sensitivity Analysis of the SULI to Alternative GWPCA Specifications.

Specification	Spearman's *p*	RMSE	MAE	Mean Absolute Rank Change
Gaussian, 10 neighbours	0.892	0.229	0.171	2.75
Gaussian, 12 neighbours	0.941	0.238	0.186	2.25
Gaussian, 18 neighbours	0.942	0.109	0.081	2.25
Gaussian, 20 neighbours	0.908	0.136	0.103	2.81
Gaussian, 25 neighbours	0.901	0.127	0.096	3.13
Bi-square kernel	0.725	0.16	0.128	4.06
Tri-cube kernel	0.701	0.166	0.132	4.38
1 PC retained	0.974	0.052	0.04	1.38
MCD support 85%	0.96	0.105	0.081	1.69
MCD support 90%	0.947	0.084	0.065	2

Note: Spearman's *p* indicates rank association with the baseline SULI; RMSE and MAE indicate the magnitude of index deviation; mean absolute rank change represents the average change in ward position.

4. Discussion

The findings demonstrate that urban livability in Darjeeling is spatially differentiated rather than uniformly distributed. The Sustainable Urban Livability Index (SULI), based on 44 indicators across nine domains, indicates that approximately 31% of municipal wards exhibit good livability, while the remaining 69% fall within the fair or poor categories. This distribution highlights the importance of examining neighbourhood-level disparities rather than relying solely on citywide assessments. Relatively favourable conditions in central Darjeeling reflect better access to public infrastructure, healthcare, education, cultural and recreational facilities, and safety services. These findings align with previous research highlighting the importance of accessibility, transportation, and neighbourhood amenities in shaping urban livability [17,33,65,78]. Cultural and recreational facilities may further support social interaction and community engagement [79,80]. In contrast, many peripheral wards exhibit fair or poor livability, reflecting uneven access to infrastructure and essential services, including housing, sanitation, drainage, healthcare, education, recreation, and emergency facilities. Limited local provision may increase the distance and effort required to access everyday necessities. These patterns highlight that livability depends not only on the availability of amenities but also on their geographical distribution and accessibility.

Darjeeling's steep slopes, elevation differences, and constrained terrain may further complicate infrastructure development, housing provision, and mobility. The less favourable conditions observed in several peripheral areas suggest that physical constraints may intersect with uneven service provision to produce differentiated livability outcomes, consistent with research on hill settlements [17,81]. However, these associations should not be interpreted as evidence that topography directly causes lower livability. Spatial autocorrelation analysis provides further evidence of geographical differentiation. The global Moran's I value of 0.266 ($Z = 2.623$, $p = 0.009$) indicates statistically significant positive spatial autocorrelation, suggesting that neighbouring wards tend to exhibit similar livability values. Local analysis identifies high–high clusters in central wards 11, 19, 21, 22, and 26, alongside

low–low clusters in peripheral areas. These patterns demonstrate the value of combining SULI with local spatial analysis: the composite index summarises multidimensional conditions, while spatial autocorrelation identifies their geographical concentration. GWPCA further contributes to this assessment by incorporating geographical proximity into the analysis of multidimensional indicator data. Combined with domain-level assessment and spatial clustering, it provides a more locally differentiated understanding of livability than an aggregate citywide measure alone. Its principal value lies in identifying spatial variations that might otherwise remain obscured, rather than establishing causal relationships. The SULI framework can be applied to other Himalayan towns facing topographic constraints, uneven urban development, tourism, and seasonal or temporary population mobility. Its nine-domain structure can be retained while adapting individual indicators to local conditions and data availability. For tourism-oriented or seasonally fluctuating towns, greater emphasis may be placed on accommodation, dining, recreation, cultural facilities, accessibility, infrastructure demand, temporary population pressure, and service demand. Such contextual adaptation preserves the framework's conceptual comparability while capturing local urban conditions.

Further, the pronounced centre–periphery differentiation may reflect both the historical development of Darjeeling and the contemporary concentration of urban services and infrastructure in the established core. The central area has long functioned as the principal urban and institutional centre, with greater concentration of public facilities, commercial activities, healthcare, education, cultural amenities, and transport services. Peripheral areas, in contrast, have developed under greater topographic and spatial constraints, which may complicate infrastructure provision, accessibility, and urban expansion. These factors may jointly contribute to the observed differences in livability. However, the present analysis cannot establish the historical or causal mechanisms underlying this pattern; such explanations would require dedicated historical and longitudinal investigation.

From a planning perspective, the findings support targeted interventions in less-favoured wards, guided by domain-level deficiencies and the distribution of low SULI values. Priorities may include essential infrastructure, housing and sanitation, healthcare and educational access, recreational facilities, and emergency services where shortcomings are identified. Improving access for peripheral neighbourhoods requires ward-specific strategies that account for both service distribution and local physical conditions rather than uniform interventions across the municipality. These findings should be interpreted in light of the assessment's limitations. SULI reflects the selected indicators, their assigned directions, available datasets, and methodological choices; it does not fully capture residents' subjective experiences or quality of life. Similarly, visual inspection provides a supplementary assessment of spatial outputs rather than comprehensive independent validation. Future research could strengthen the assessment by incorporating residents' perceptions, additional temporal observations, and further validation. Overall, the study demonstrates the value of integrating multidimensional measurement with geographically explicit analysis to identify neighbourhood-level livability inequalities in a Himalayan hill town.

5. Limitations and Future Research

Despite its multidimensional framework and robust spatial analysis, this study has some limitations. First, the SULI is designed to assess and compare spatial variations in objective urban livability rather than estimate the causal or relative contribution of individual factors. Thus, the observed centre–periphery patterns should not be interpreted as causal effects, and the index does not explicitly quantify the independent contribution of factors such as topographic constraints, service density, accessibility, or distance decay. Future research could complement the SULI with factor-specific approaches, such as geographically

weighted regression or variance decomposition, to examine the spatially varying influence of individual determinants. Second, the SULI primarily captures objectively observable conditions, including the availability and spatial distribution of infrastructure, services, facilities, and environmental attributes, rather than residents' subjective perceptions, experiences, or satisfaction. It should therefore not be interpreted as a direct measure of perceived livability. Additional shortcomings include the relatively small number of spatial units for GWPCA, and potential temporal inconsistencies among datasets. Moreover, the concentration of several facilities in central Darjeeling may partly reinforce the observed centre–periphery pattern through the structure of the indicator framework itself. Future studies could integrate resident perception surveys or other subjective measures with the objective SULI to examine the relationship between observed urban conditions and lived experiences, while also incorporating public health indicators (e.g., morbidity rates), emergency incidents (e.g., fires and traffic accidents), and crime statistics to provide a more comprehensive assessment of urban livability and safety. Despite these limitations, the study provides a novel spatially explicit and multidimensional framework for assessing urban livability in a topographically constrained Himalayan town, integrating diverse urban conditions through robust GWPCA and providing a reproducible basis for ward-level comparison and planning.

6. Conclusions

This study developed a spatially explicit framework for assessing sustainable urban livability in Darjeeling, India, integrating remote sensing, GIS, and spatial statistics, including Geographically Weighted Principal Component Analysis (GWPCA) and spatial autocorrelation analysis, across 44 indicators and nine domains. The findings reveal pronounced spatial inequalities, with comparatively favourable conditions concentrated in central wards and less favourable conditions in several peripheral areas. Significant positive spatial autocorrelation further demonstrates the geographical clustering of similar livability conditions. Sensitivity analysis indicates that the SULI retains a broadly consistent spatial ordering across alternative specifications of bandwidth, kernel function, component retention, and robust covariance estimation, supporting the overall robustness of the assessment. The study highlights the value of combining multidimensional measurement with geographically explicit analysis to identify neighbourhood-level disparities and inform context-sensitive planning. Nevertheless, the index remains constrained by its selected indicators, data sources, spatial scale, and methodological assumptions and does not capture residents' subjective experiences or establish causal relationships. Future research integrating perception-based, temporal, and network-based measures could provide a more comprehensive assessment of urban livability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/geographies6040127/s1. Figure S1: Showing correlation among the selected variables. The dark red showing strong positive correlation and the dark blue showing negative correlation. Figure S2: Built-up and Housing environment. Figure S3: Public convenience & infrastructure. Figure S4: Physical environment. Figure S5: Cultural & Spiritual facilities. Figure S6: Recreational facilities. Figure S7: Dinning & Fooding services. Figure S8: Healthcare facilities. Figure S9: Educational facilities. Figure S10: Safety services.

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