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Conservation Prioritization of Ecologically Susceptible Zones at Disaggregated Levels

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Abstract

Ecologically susceptible zones (ESZs) are endowed with the distinct bio, geo, climatic, hydrological, and ecological integrity that sustain natural resources to support the livelihood of dependent populations. However, globalization and consequent anthropogenic activities have led to the erosion of the natural resource base and enhanced the levels of pollutants, triggering global environmental change, evident from changes in the climate. Alterations in the structure and the ecological integrity of ESZs may lead to permanent and irreparable loss of extant life forms or cause significant damage to the natural processes. This study analyses the spatiotemporal processes of ecosystems through insights into land-use dynamics and delineation of ESZs at a disaggregated level (5′ × 5′ grids or 9 km × 9 km). This is based on the grid-based NES (National environment survey) in Gadag district, Karnataka, India, for sustainable management of natural resources. The temporal land use (LU) analysis indicated a decline of 0.33% in the forest cover from 1989 to 2019, primarily due to mining, unauthorized conversion of natural forests to agriculture, commercial cultivation, etc. The built-up area was found to increase from 0.05% to 1.4% due to the expansion of linear corridors, infrastructure projects, and new layouts at the periphery of the town of Gadag. Spatial patterns of landscape dynamics through landscape metrics revealed an increase in the number of patches around Gadag, and Kappata Gudda of Shirahatti from 1989 to 2019, indicating fragmentation of forests with greater shape complexity. ESZ analysis at disaggregated levels (grids equivalent to one administrative unit—panchayat or local governance—with a cluster of villages for implementing biodiversity conservation measures as per the Biodiversity Act 2002, Government of India) indicated nine grids with higher ecological susceptibility (ESZ-1), 31 grids in ESZ-2 (high ecological susceptibility) with a potential to be ESZ-1, 13 grids were in ESZ-3 (moderate ecological susceptibility), and four grids in ESZ-4 (low ecological susceptibility). The implementation of the ESZ framework in decentralized governance would ensure sustainable development. The approach is tailored to take into account the agents of landscape dynamics and local ecosystem conditions to develop appropriate location-specific management strategies for fragile ecosystems. The systematic framework drafted in the current study would aid as a guiding tool for the sustainability of natural resources (water, medicine, food, etc.) by building a self-reliant and decentralized society and averting over-exploitation of natural resources.

Keywords

ESZs; biodiversity; conservation; cluster-based development; ecologically susceptible; ecosystem structure; natural environment survey

1. Introduction

Ecological susceptibility or fragility refers to the enduring and irreparable loss of extant life forms or the significant damage to the natural processes of evolution and speciation with alterations in the ecological integrity of a region. The comprehensive knowledge of the ecological susceptibility of a region is essential for developing conservation strategies and mitigating calamities. Ecologically susceptible zones (ESZs) are landscape elements or places vital to the long-term endurance of hydrologic regimes, biological diversity, soil, and other natural resources to sustain the livelihoods of dependent populations. Delineation of ESZs entails understanding the factors responsible for ecological susceptibility and visualizing future growth to overcome the issues of uncontrolled development. A landscape is a physical system of integrated features of biotic and abiotic elements, whose structures are either altered by natural processes or anthropogenic interventions and management. The health of a landscape is based on the bio-geoclimatic, hydrological, and ecological factors present in a specific geographical extent at disaggregated levels and their interactions.

Disaggregated-level analyses assess spatial patterns and their underlying trends by integrating data at a micro-scale and enhancing the quality of assessment, thereby aiding in decision-making processes through successful implementation and monitoring. Considering that anthropogenic activities are leading to pronounced changes in landscape structures globally while gradually decreasing natural habitats, maintaining landscape characteristics such as configuration and composition, habitat cover, continuity, patch density, and connectivity is crucial to sustaining ecological functions.

Changes that occur in the physical, biological, and cognitive assets are referred to as landscape dynamics. The knowledge of these changes is vital for sustainable management and conservation. Monitoring and understanding landscape dynamics provide insights into the complex relationships between the social, environmental, and geophysical processes [1]. Land cover (LC) comprises the physical features present on the earth's surface [2], including water, vegetation, land surface, and other features. Land use (LU), on the other hand, comprises the alteration, modification, and mismanagement of land cover with naturally available environmental resources into other land uses [2] in ecologically fragile regions. Assessing Land Use Land Cover (LULC) dynamics and predicting future transformation scenarios using the supervised classification of temporal remote sensing data paired with field and collateral data aids in the development of appropriate management strategies. LULC is the key variable used in evaluating the status of a landscape. LU changes are primarily attributed to anthropogenic activities for economic development, the need for shelter, the production of food grains, and the extraction and processing of raw materials. LC analysis provides a baseline status of the natural resources, while the analysis of LU change identifies the consumption rates and associated issues. Large-scale LULC changes lead to alterations in the ecosystem structure, therefore impacting ecosystem functioning. This is evident from microclimatic alterations and global warming [3, 4], loss of biodiversity, alterations in hydrologic regime [5], imbalances in air quality [6], enhanced soil erosion [7], and landscape degradation [8, 9]. A detailed investigation of the changes in LULC aids in understanding the causal factors of the decline in natural resources due to human interventions [10].

LULC changes in forested landscapes result in the fragmentation of natural forests, which successively divides the contiguous forests into fragments to form a mosaic of patches, varying in size, shape, and connectedness [11, 12]. The ecological imbalance of fragmentation can be defined in two aspects (i) overall habitat loss (the total amount of suitable habitat removed from the landscape) and (ii) change in habitat configuration (patch size, isolation). Edges result in an increased forest edge-to-area ratio among existing forest patches, thus, significantly impacting communities and their survival. Forest edges will have a marked effect on the biotic as well as abiotic factors and establish distinct communities compared to the forest core [13]. The edge effect often leads to the replacement of larger trees within 300 m of the forest edge with densely spaced short-lived pioneers [14], resulting in a decrease in forest biomass and carbon sequestration potential [15]. Increased fragmentation creates a steep gradient in the microclimatic conditions (varied temperature, humidity, light availability across the patches) due to the exposure to additional sunlight and wind velocities. The isolated and smaller forest patches are less likely to receive migrant species and pollinators. This results in the isolated forest patches having lower biodiversity and the populations being more prone to extinction due to the inability to (re)colonize and due to inbreeding, improper gene exchange, etc. [16]. Accounting for this phenomenon over a temporal scale aids in addressing the adverse effects.

Assessing LULC changes and their impacts is necessary to understand the various factors that influence the growth rate and their adverse effects on the landscape. Numerous techniques have been developed globally to capture past and present LULC changes and predict probable changes. Landscape metrics or spatial matrices are effective tools to understand landscape configuration and the extent of fragmentation [17]. These metrics were developed to capture spatial heterogeneity of the landscape (the number and quantity of different habitat types), the configuration (the spatial arrangement of various LU classes), and for drawing relationships between ecological processes and spatial patterns [18]. There are, however, several challenges (at different scale and extent of a landscape) associated with selecting the appropriate metrics required to understand landscape dynamics depending on the resolution of the data utilized [19, 20]. The need for comprehensive knowledge of LULC changes has become increasingly important in sustainable planning, judicious resource usage, and visualization of future growth to overcome the issues of unplanned development [21]. The increased intensity of anthropogenic disturbances [22] has necessitated a systematic conservation planning approach for environmental protection and restoration of degraded fragile ecosystems to ensure human well-being with the sustenance of natural resources.

Ecologically susceptible zones (ESZs) or Eco-sensitive Zones (ESZs) or Ecologically Fragile Areas (EFAs) are “distinct geographical regions with a higher assemblage of diverse species, rich natural resources, natural communities, and environmental conditions” [23, 24], prioritized for conservation and application of prudent management strategies to sustain the livelihood of local communities. The areas are graded or demarcated by integrating distinct spatial characteristics based on bio geo-climatic conditions and ecological and social factors. This may aid in decision-making at disaggregated levels to implement effective conservation measures [25]. In this context, the Ministry of Environment, Forest and Climate Change (MoEFCC), the Government of India, has taken the initiative to protect and maintain forests under Section 3 of the Environment (Protection) Act 1986 (EPA). The Central Government can prohibit or restrict the location of industries and carry out operations based on considerations like ecological sensitivity under Section 5 of the EPA 1986. An expert committee was set up by the MoEFCC in 2000 with a mandate to identify the parameters for designating ESZs in the country to counter the rapid deterioration of the environment, both nationally and internationally [26].

Temporal LULC analyses form a building block for modeling and assisting in identifying drivers. The projection of likely landscape changes requires the understanding and integration of previous LU trends, feedback, and the incorporation of credible assumptions or scenarios [1]. LULC models consider LU history and factors that alter LU, with a configuration that offers a new opportunity for interdisciplinary research. There are numerous validated models such as Cellular Automata Markov chain (MCA), SLEUTH, CLUE-S, fuzzy-analytical hierarchical process (AHP) models, agent-based models (ABM), artificial neural network (ANN), etc., which help simulate and predict future LULC trends. Researchers and planners have tested and recommended these sophisticated models to effectively capture the current trend, factors, ecological conditions, and likely change responses. A hybrid model such as fuzzy AHP MCA is advantageous compared to other models in integrating multi-criteria evaluation approaches (MCE) in the decision-making process. This is achieved by comparing a set of relative weights for a group of factors considered through the estimation of eigenvectors or priority vectors, assigning preferred weights to each alternative, and thereby determining the final score [27, 28]. An appropriate LULC change model is thus selected to simulate identified social, economic, and ecological processes and the dynamics and interactions that shape the landscape [29]. The current study aims to identify ecologically susceptible zones at disaggregated levels (at the micro-level of 81 km^2 spatial extent) through grid-based NES of the abiotic and biotic components of ecosystems.

2. Materials and Methods

2.1 Study Area

Gadag (gadag.nic.in) is a district (14°57’-15°52’ N to 75°16’-76°02’ E) located in the western part of northern Karnataka with an area of 4656 km^2 at an average altitude of 655 msl. The district has a population of 1.065 million, with a decadal growth rate of 9.54%. Gadag has five taluks or tehsils (administrative divisions for taxation purposes, consisting of several villages) with 337 villages (Figure 1). The town of Gadag (district headquarters) lies at the center of the district. The major agro-climatic zones in the area are hot moist semi-arid, and hot dry sub-humid (Northern Dry Zone, KA 3). The district has significant forest cover in the Kappata Gudda Reserve Forest. The majority of the water demand in the area is met from the Tungabhadra River (to the Gadag taluk) and the small streams of Malaprabha and Bennihalli (to the villages of Naragund and Sasavi in Rona taluk, respectively). The net irrigated area of the district is 160,143 ha, while the gross irrigated area is 188,965 ha. The area primarily irrigated through wells and tube wells accounts for 25,560 ha. The district substantially depends on the monsoon rains, with an average rainfall of 630 mm. The monthly variation in rainfall is presented in Figure 2, which indicates that a higher amount of rain is received in August, September, and October. Gadag district is prone to flash floods during heavy rainfall due to poor drainage systems. Significant damages were reported to the public infrastructure and private properties during the rainy season. The monthly temperature between < 20 to 30°C dynamics are presented in Figure 3, indicating that April and May are the hottest months.

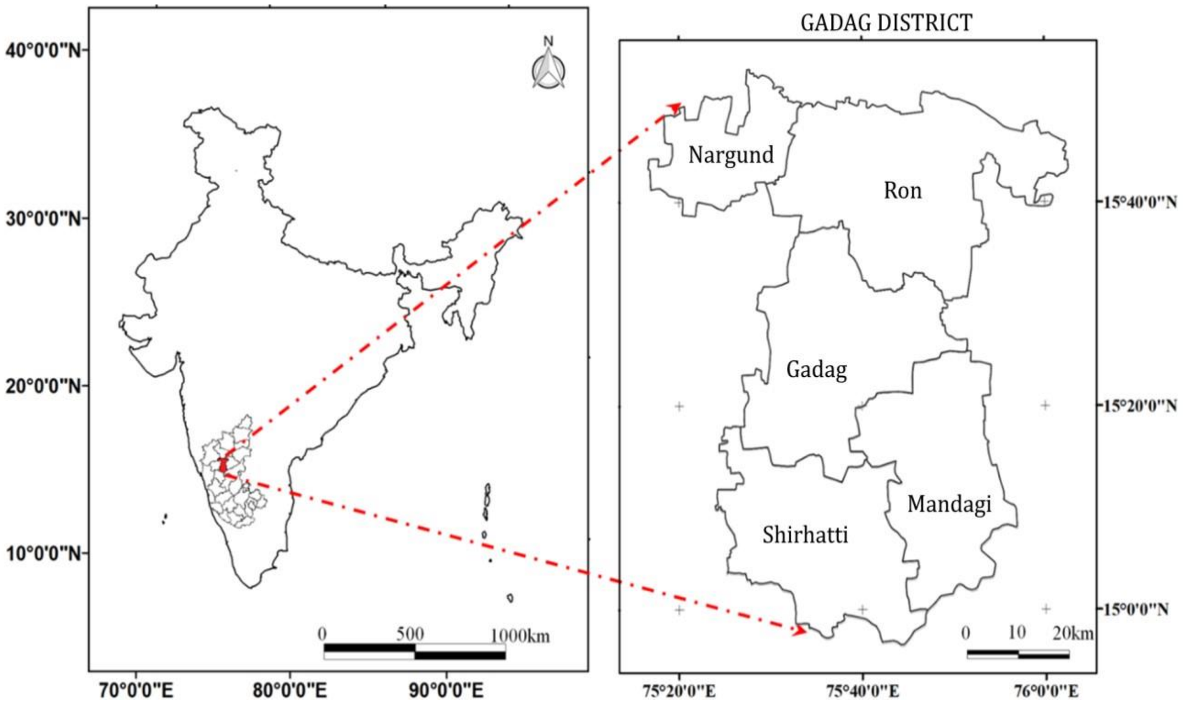

Figure 1 Study area–Gadag district, Karnataka, India.

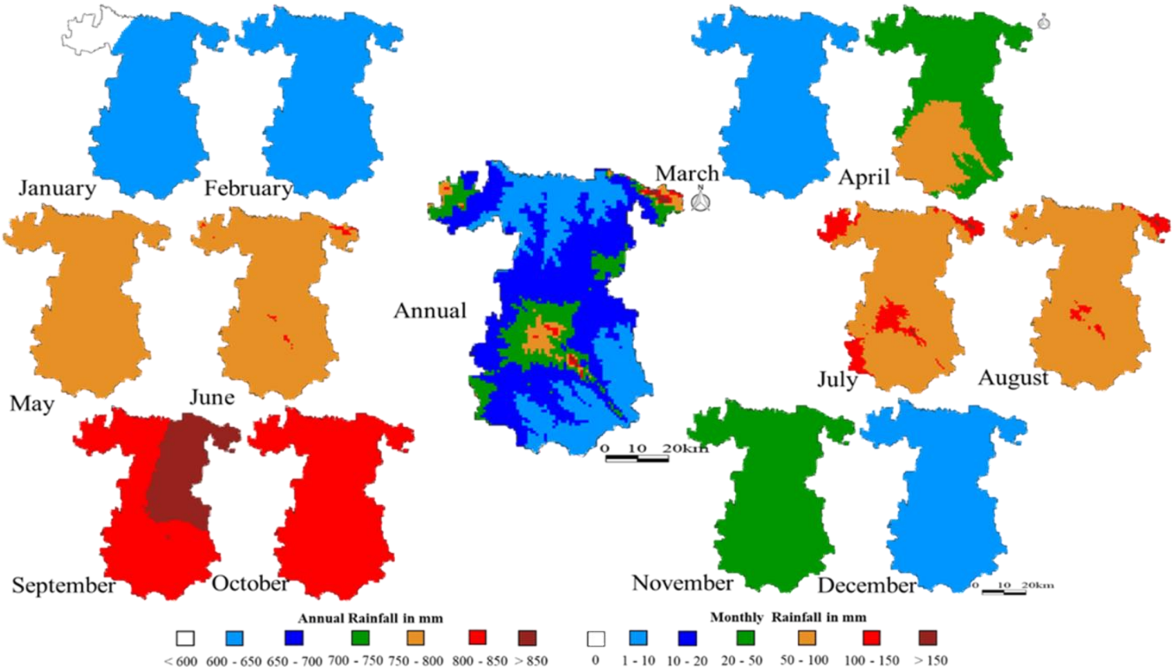

Figure 2 Monthly and annual precipitation in Gadag district.

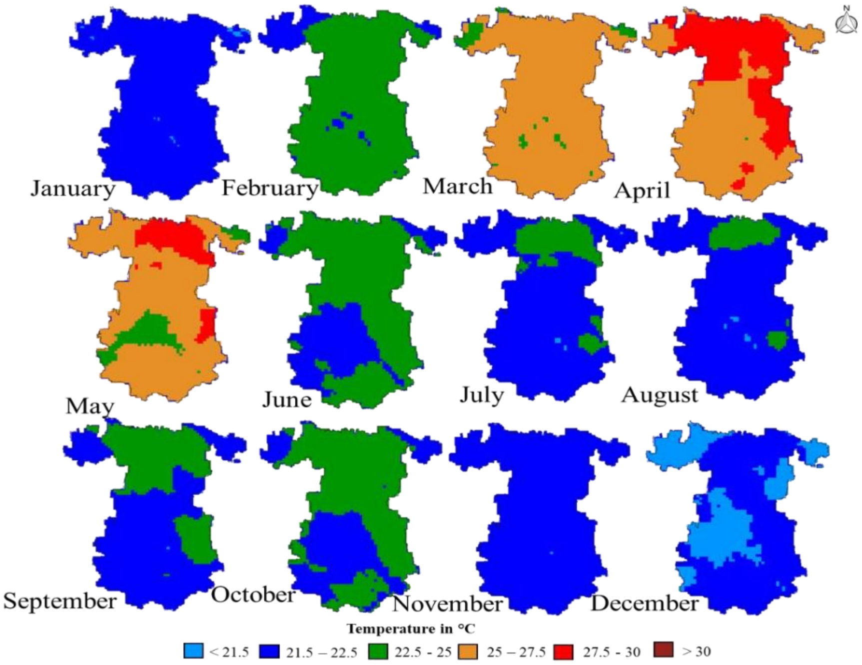

Figure 3 Monthly average temperature in Gadag district.

The district has rich tourist attractions such as Chalukya art, Trikuteshwara Temple, Veeranarayana Temple, and the Magadi Bird Sanctuary. The district is known for its industrial manufacturing units with 8088 small-scale industries, five medium-scale industries, six industrial estates, and a warehouse of 7000MT capacity with a large industrial set-up. Agriculture is the primary occupation in the Gadag district, with pulses and cotton being the major crops, followed by vegetables, jowar, oilseeds, and maize. The contribution of agriculture to the district is INR 35.64 billion from onion, green chilies, cotton, etc. The soils of the district comprise medium black soil

(27%), deep black soil (24%), red sandy soil (14%), and shallow black soil (12%). The district has a good transport and communication network, connected with one national highway, three state highways, and a railway line.

2.2 Method

2.2.1 Quantification of Landscape Dynamics and Evaluating Spatial Configuration of Landscape through Spatial Metrics

Temporal remote sensing data were acquired through space-borne sensors from 1989 to 2019. This was used to quantify landscape dynamics and evaluate landscape configuration through matrices. The method applied for the LU analysis and prioritization of ESZ is presented in Figure 4. Temporal Landsat data (Landsat 5 Thematic Mapper (TM), Landsat 8 Operational Land Imager (OLI), and Thermal Infrared Sensor (TIRS)) of 30 m spatial resolution was procured from the US Geological Survey with zero or minimal cloud cover from open data archives (https://earthexplorer.usgs.gov/). Pre-processing comprised geometric correction and image enhancement. The district boundary was used to crop the study area from the temporal satellite data.

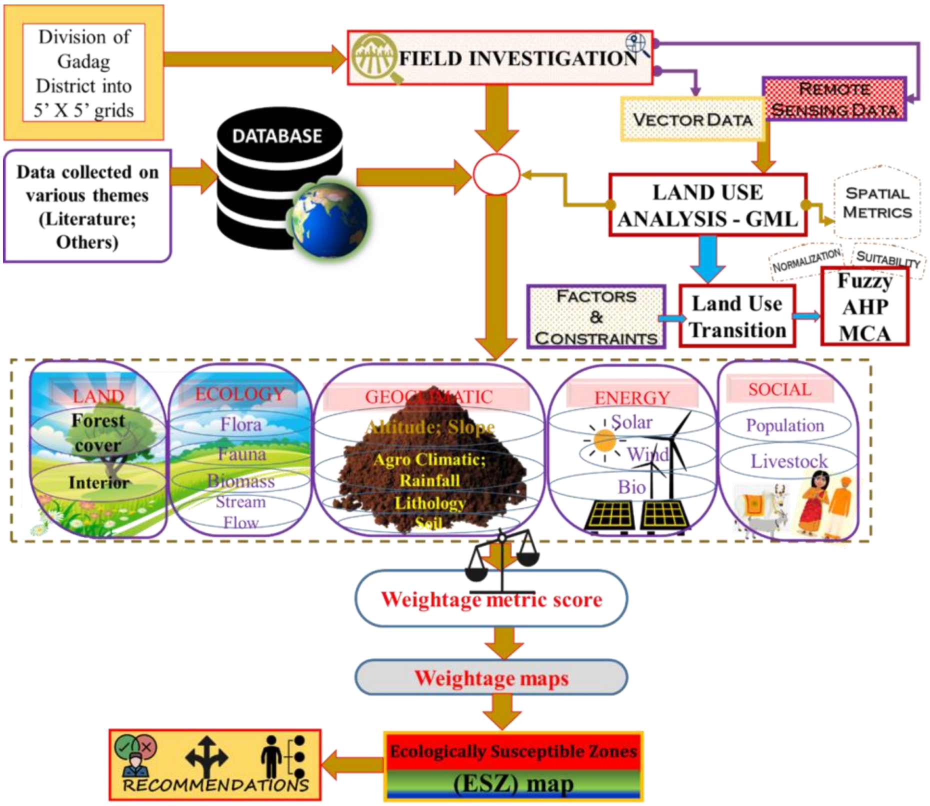

Figure 4 Protocol for the identification of Ecologically Susceptible Zones (ESZs) at disaggregated levels in the Gadag district.

Secondary data collection involved the collection of ancillary data such as vegetation maps from the French Institute of Puducherry [30], topographic maps of 1:50,000 from the Survey of India (SOI), flora and fauna data from the India Biodiversity Portal (IBP) (http://indiabiodiversity.org/), and virtual earth data from Google Earth (http://earth.google.com) and Bhuvan (http://bhuvan.nrsc.gov.in). This data provided additional input for data pre-processing and classification. A detailed field investigation was then carried out using a pre-calibrated global positioning system (GPS) to supplement the LU analysis.

The remote sensing data were classified with a supervised classifier based on a maximum likelihood classification algorithm using training data collected from the field. This quantitatively evaluates the variance and covariance of the category spectral response patterns while classifying an unknown pixel. An accuracy assessment was then performed to assess the efficacy of the LU classification by generating an error matrix. The error matrix was compared on a category-by category basis and assessed the relationship between reference data (ground truth) and the corresponding classification information. Reference signatures were additionally compiled from Google Earth for validating the classification. Kappa statistics, overall accuracy, category-wise producer accuracy, and user accuracy were calculated to evaluate the accuracy of the classified image. The kernel-based approach (of size 5 pixels × 5 pixels) was then implemented to assess the fragmentation of forests under five different categories through P_f and P_{ff} indices as presented in equations 1 and 2. The classification model identified five fragmentation categories: interior ($P_f = 1$), patch ($P_f < 0.4$), perforated ($P_f > 0.6$ and P_f-$P_{ff} > 0$), edge ($P_f > 0.6$ and P_f-$P_{ff} < 0$), and transitional ($0.4 < P_f < 0.6$). The study area was divided into 5′ × 5′ or 9 km × 9 km equal-area grids corresponding to the SOI toposheet divisions at a 1:50000 scale. This approximately covered a panchayat area in each division to account for changes at the disaggregated level. The spatial metrics at the grid level were computed to assess the landscape configuration through the software Fragstat. The details of the metrics calculated are presented in Table 1.

$$P_f = \text{Number of forest pixels/Total number of non} - \text{water pixels in the window} \quad (1)$$

$$P_{ff} = \text{Number of forest pixel pairs/Number of forest pixel pairs} \quad (2)$$

Table 1 Spatial metrics used in the analysis.

Indicators	Formula	Range	Significance/Description
Class Area	------	> 0	Total LU category area (in ha)
Number of Patches (NP)	NP = n NP equals the number of patches in the landscape.	NP > 0, without limit	It is a fragmentation Index. The higher the value, the more the fragmentation
Aggregation Index (AI)	$AI = \left[\sum_{i=1}^{m}\left(\frac{g_{ii}}{\max \rightarrow g_{ii}}\right)P_i\right](100)$ g_{ii} = number of like adjacencies (joins) between pixels of patch type (class) i based on the single count method. max-g_{ii} = maximum number of like adjacencies (joins) between pixels of	1 ≤ AI ≤ 100	AI equals 1 when the patches are maximally disaggregated and 100 when the patches are maximally aggregated into a single compact patch. Aggregation corresponds to the clustering of patches to form patches of a larger size.

	patch type class i based on single count method. P_i = proportion of landscape comprised of patch type (class) i.		
NLSI (Normalized Landscape Shape Index)	$NLSI = \frac{\sum_{i=1}^{i=N} \frac{p_i}{s_i}}{N}$ Where s_i and p_i are the area and perimeter of patch i, and N is the total number of patches.	$0 \le NLSI < 1$	NLSI = 0 when the landscape consists of a single square or maximally compact almost square, it increases when the patch types become increasingly disaggregated and is 1 when the patch type is maximally disaggregated

2.2.2 Modeling Landscape Dynamics through Fuzzy AHP MCA

The temporal LU analysis provided a spatial pattern on the temporal scale, which was used to analyze the LU transition probability and extent through the Markov process. The temporal land-use information was used to account for the stable and transformed LU classes which satisfy non-transition properties such as an urban class to water or vice versa. The transition probability spatial information is obtained based on the Markov process (equation 3). The factors such as built-up, road, slope, industries, educational institutions, city business district, bus and railway station (agents of LU transitions such as built-up, road, slope, industries, educational institutions, city business district, bus and railway station) were evaluated based on fuzzy normalization and distance influence of individual factors accounted through MCE. Weights were assigned based on the AHP. The consistency ratio and site suitability were estimated as per equations 3–5. The contributing factors-agents of transitions for different LUs were normalized between 0 and 255 through fuzzification, where 255 indicates the maximum probability of change and 0 indicates no change. The pairwise comparison matrices were generated across three agro-climatic regions. Their relative weights as eigenvectors were estimated using AHP [31] to measure the degree of importance between the criteria or criteria factors i and j. A response matrix R = [r_{ij}] was generated to measure the relative dominance of item i over item j. R is constructed with the assessment by decision-makers, r_{ij}, as pairwise comparisons that follow a uniform probability distribution.

$$r_{ij} = \frac{W_i}{W_j} * e_{ij} \tag{3}$$

where W_i and W_j are the priority weights belonging to vector W and $\sum W_j = 1$, e_{ij} is the inconsistency observed in the analysis. CA is used to simulate and predict future LU based on site suitability and transition potential. The net neighborhood influences were determined using a 5 × 5 contiguity filter explaining past LU changes and simulated future changes. The original transition probability matrix (denoted by E) of the LU type is obtained from two former LU maps.

$$E_{(N)} = E_{(N-1)} * E \tag{4}$$

where $E_{(N)}$ is the state probability of any times, and $E_{(N-1)}$ is the preliminary state probability.

T area matrix can be obtained by area based on site suitability

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ \vdots & \vdots & \vdots \\ r_{N1} & r_{N2} & r_{NN} \end{bmatrix} \tag{5}$$

where R is the transition area matrix; R_{ij} is the sum of areas from the ith LU class to the jth class during the years from start point to target simulation periods, and n is the number of LU types. The validity of the model results was evaluated by comparing the Kappa index of the agreement for each category, spatial patterns of the LU type, and the fractal parameter. The accuracy of the simulation is expressed through the calculation of the Kappa index for location and quantity. The Kappa index provided a summary statistics of agreement regarding the proportion of the total number of pixels, spatial patterns, and spatial distribution.

2.2.3 Delineation of Ecologically Susceptible Zones

Data on various themes (biogeoclimatic, ecological, environmental, and social) were compiled from published literature, unpublished datasets, and ground-based field surveys. Floral and faunal details were collected from the field using quadrat sampling. Five 10 m × 10 m quadrats were laid in the Kappata Gudda forest area to assess tree diversity, dominance, and per hectare basal area. In each quadrat, the girth at breast height (gbh) and the height (m) were enumerated for trees > 30 cm gbh. One plot of 5 m × 5 m was laid within the same quadrat, from where tree saplings and shrubs above 1 m were recorded. Two plots of 1 m × 1 m were laid at the opposite end of the 10 m quadrats to enumerate the seedlings. In addition to the quadrat-based vegetation sampling, opportunistic plant recording was carried out across the district. Additional details on plant-animal interaction, faunal habitat, human-wildlife conflict, etc., were noted along with vegetation data. A detailed literature review was conducted to compile floral and faunal data [32, 33]. The conservation status of the floral and faunal species was evaluated by referring to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, the Herbarium JCB maintained by the Indian Institute of Science [32], and the IBP [33].

Grid-based (disaggregated level) mapping is a standardized approach to spatial data collection that efficiently compiles large datasets, where the output can be consistently and efficiently comprehensible. Weights were assigned to each metric capturing relative priorities associated with the respective theme (based on spatial extent and condition). Developing a weight metric score was based on a wide array of disciplines [34] and a standard framework [35], where multiple data sets were combined to infer the significance of delineating ESZs through an objective and transparent system. The weight is defined in equation 6.

$$Weight = \sum_{i=1}^{n} W_i V_i \tag{6}$$

Where n is the number of data sets, V_i is the value associated with criterion i, and W_i is the weight associated with that criterion. An indicator describes each criterion mapped to a value normalized between 10 to 2. The value 10 corresponds to a higher conservation priority, and 2 corresponds to low conservation priority. Values 8, 6, and 4 correspond to high, moderate, and low levels of conservation. The weights are based on an individual proxy and assigned to respective grids. The final ESZs at disaggregated levels (9 km × 9 km) may aid decision-makers in the effective planning and management of natural resources.

3. Results and Discussion

3.1 Estimation of Spatiotemporal Changes in LU and Landscape Configuration

LU changes have been analyzed using temporal remote sensing data, revealing the level of degradation from 1989 to 2019 (Table 2). LU changes in the Gadag district were analyzed under various LU classes such as agriculture, built-up area, dry deciduous forests, water, horticulture, scrub open, and hills for each decade. Table 3 and Figure 5 present the spatial LU transition from 1989 to 2019 under each class. Forests occupy approximately seven percent of the total geographical area. The LU analysis depicted a decrease in forest cover by 509 ha from 1989 to 2019 due to the encroachment of forest land and the transition to agriculture in the peripheral area. Area under cotton cultivation has increased with the setting up of industries in the district. An increase in urbanization subsequently led to the conversion of agricultural land to built-up, as observed from 2009 to 2019. The transition from agriculture to built-up cover is noticed in the sub-urban regions of Gadag due to new residential layouts and small-scale industries. The primary causal factors of LU changes are the implementation of infrastructure projects like the road connecting Bagalkot and Gadag, the development of an agri-logistic hub, large-scale industries like the Gadag Co-operative Textile Mill, the Farmer's Co-operative Spinning Mills, oil mills, sugar factories, a 700MW gas-based power project, etc. The overall accuracy of the classification was 87.01% (1989), 87.75% (1999), 94.11% (2009), 91.88% (2019) with kappa value as 0.87, 0.88, 0.91 and 0.88, respectively.

Table 2 Spatiotemporal LU dynamics.

Year	**1989**		**1999**		**2009**		**2019**	
Category	**km²**	**%**	**km²**	**%**	**km²**	**%**	**km²**	**%**
Agriculture	4320.7	92.9	4323.56	92.95	4318.98	92.86	4265.91	91.73
Built-up	2.01	0.04	4.89	0.11	9.9	0.21	64.53	1.39
Dry deciduous	296.57	6.38	290.29	6.24	291.17	6.26	280.75	6.04
Water	22.28	0.48	23.61	0.51	22.28	0.48	21.71	0.47
Horticulture	0.05	0.01	0.07	0.01	0.07	0.01	1.29	0.03
Scrub	3.77	0.08	3.41	0.07	6.46	0.14	14.50	0.31
Open area	3.18	0.07	3.16	0.07	0.17	0	0.00	0.00
Hill	1.81	0.04	1.8	0.04	1.75	0.04	1.71	0.04

Table 3 LU transition from 1989 to 2019.

2005	**2019**								
LU Category (km^2)	**Agriculture**	**Built-up**	**Dry deciduous**	**Water**	**Horticulture**	**Scrub**	**Open area**	**Hill**	**Total**
Agriculture	4263.210	53.315	0.000	0.000	1.168	3.047	0.000	0.000	4320.74
Built-up	0.000	0.378	0.083	0.001	0.000	0.003	0.000	1.545	2.01
Dry deciduous	0.000	10.839	277.037	1.507	0.000	7.185	0.000	0.001	296.57
Water	0.002	0.000	1.866	20.039	0.093	0.280	0.000	0.000	22.28
Horticulture	0.011	0.000	0.004	0.033	0.001	0.000	0.000	0.000	0.05
Scrub	0.000	0.000	0.000	0.000	0.000	3.770	0.000	0.000	3.77
Open area	2.379	0.000	0.324	0.108	0.022	0.216	0.001	0.130	3.18
Hill	0.308	0.002	1.436	0.025	0.007	0.001	0.001	0.030	1.81
	4265.91	64.53	280.75	21.71	1.29	14.50	0.00	1.71	4650.41

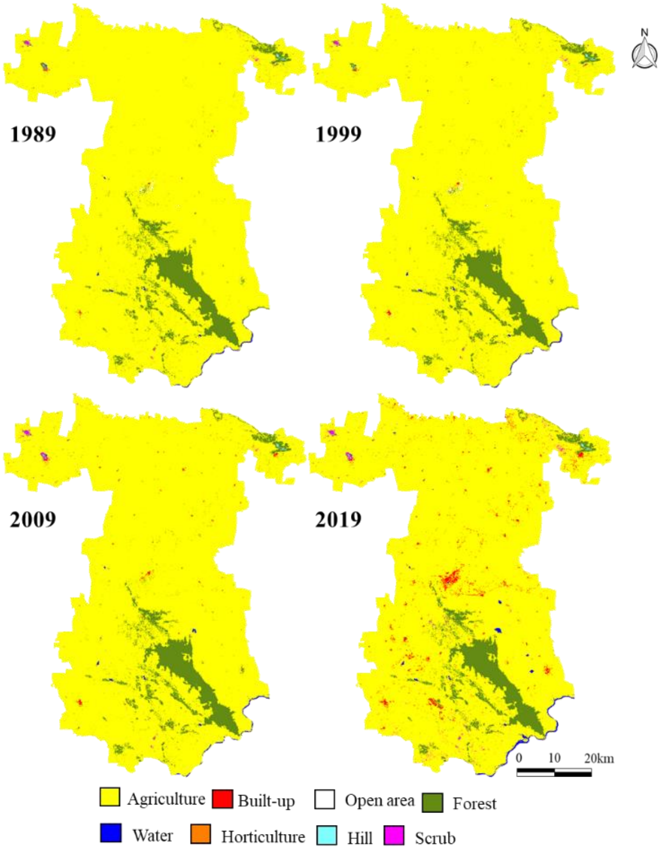

Figure 5 LU of Gadag from 1989 to 2019.

The assessment of spatiotemporal forest fragmentation, i.e., zone of forests prone to degradation, has been achieved through temporal LU information. Table 4 presents the spatial extent of various fragmentation types—interior, perforated, edge, transitional, patch, and non-forest. Figure 6 presents the spatial patterns of forest fragmentation, showing 4.06% of contiguous interior forests in 2019 as part of the Dharwar craton named Kappata Gudda. Edge forests (0.25%)

are located around non-forest areas, roads, rivers, etc., while perforated forests (1.08%) are the forest types formed between the interior and smaller perforations within each forest type (Figure 7). It was evident from the field visit that the cultivation practices at the edges of Mundargi and the implementation of windmill power projects (total power generation of 115.4 MW generation under various schemes) have contributed to the degradation of forests.

Table 4 Temporal changes in forest fragmentation from 1989 to 2019.

Year	**1989**		**1999**		**2009**		**2019**	
Fragmentation Type	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
Non-forest	4339.6	93.32	4346.1	93.45	4352.77	93.59	4355.77	93.66
Patch	26.5081	0.57	24.114	0.52	22.6505	0.49	21.1664	0.46
Transitional	26.3092	0.57	24.623	0.53	22.7558	0.49	23.1825	0.5
Edge	12.3054	0.26	12.163	0.26	11.9103	0.26	11.634	0.25
Perforated	53.3736	1.15	52.055	1.12	51.1703	1.1	50.1442	1.08
Interior	192.31	4.14	191.7	4.12	189.523	4.08	188.887	4.06

Figure 6 Temporal pattern of fragmentation between 1989 and 2019.

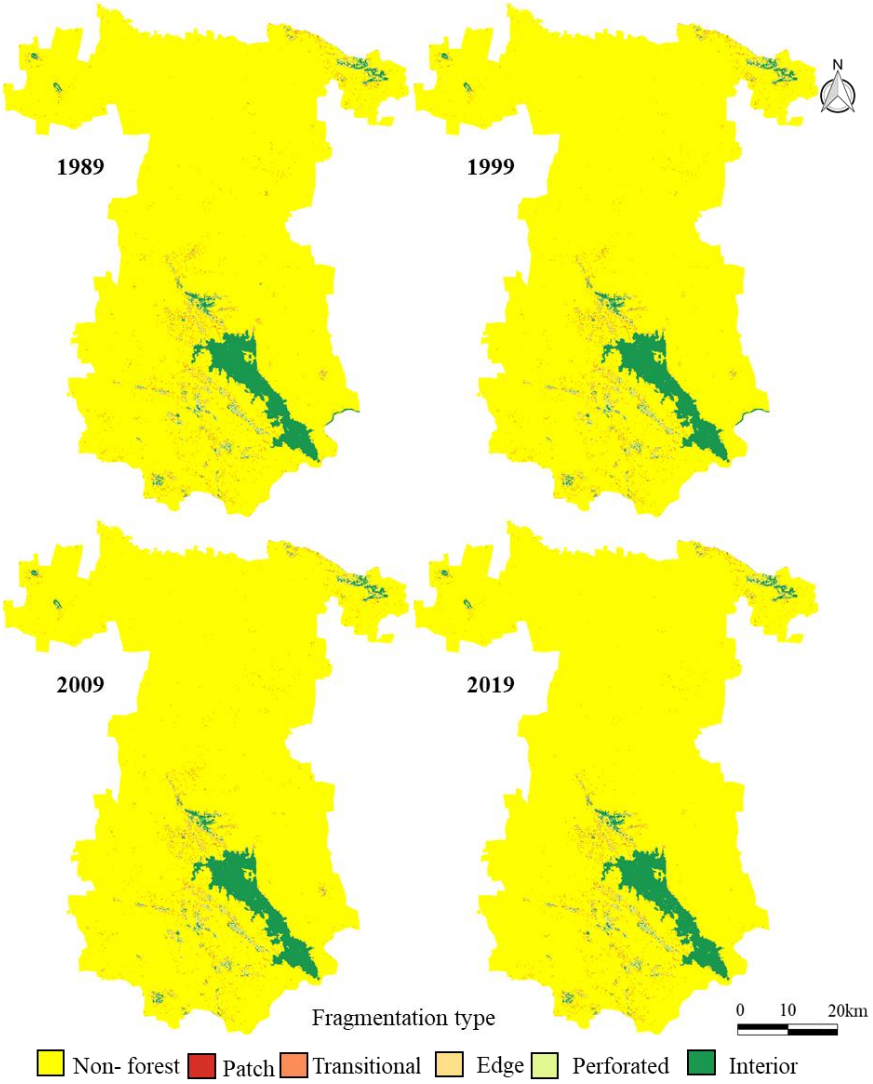

Figure 7 Forest fragmentation between 1989 and 2019.

The landscape metrics were assessed to understand the spatial patterns of the LU dynamics of built-up and forest classes across the grids based on the classified LU data of 1989, 1999, 2009, and 2019 (Figure 8 and Figure 9). Four prioritized spatial indices [17] were computed at the landscape level —class area, Normalized Landscape Shape Index (NLSI), Aggregation Index (AI), and Number of Patches (NP).

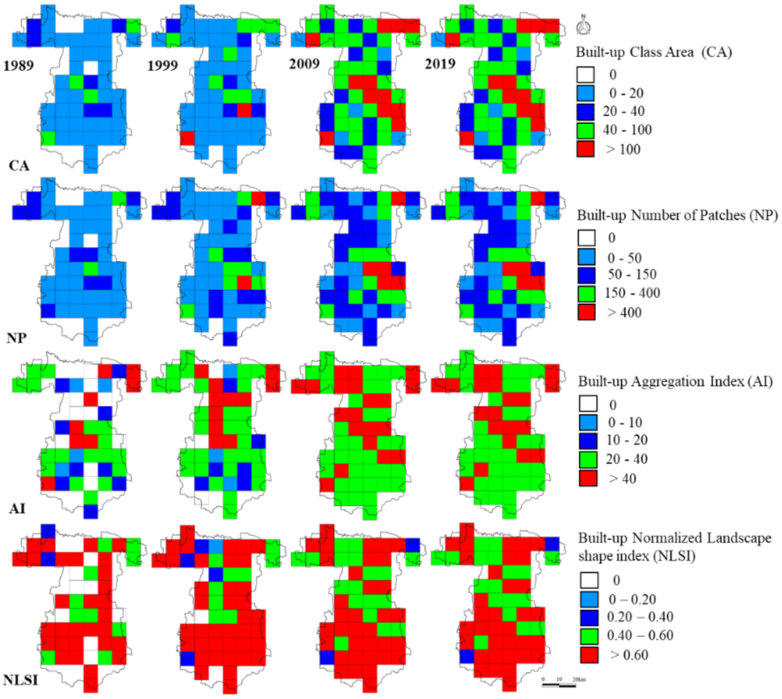

Figure 8 Spatial pattern analysis of built-up class over a temporal scale.

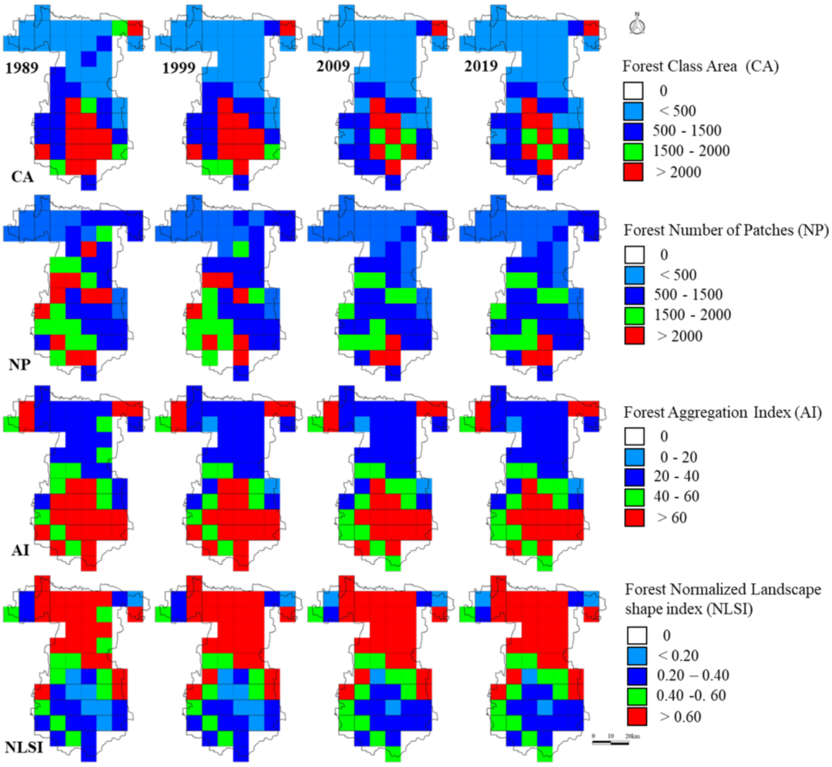

Figure 9 Spatial metrics concerning forest classes for 1989–2019.

3.1.1 Class Area

The class area comprises the area of the particular class type present in the particular grid, with the maximum area that can be occupied in a single cell being 81 sq km or 8100 hectares. The change in the built-up over time was evident, especially with the Gadag City Municipal Council and the town of Gajendragad experiencing significant urbanization. It is evident that the area under forests has decreased over time, particularly in the Mundargi and Shirahatti side of the Kappata Gudda range and in the Rona taluk of Gajendragad.

3.1.2 Number of Patches (NP)

NP is one of the fragmentation indices where a higher number indicates more fragmentation, while an NP closer to “0” indicates agglomerated or compact growth. Mundargi, Gajendragad, and Gadag were found to experience considerably higher scattered growth. Loss of forest patches was observed around the Gadag and Shirahatti sides of Kappata Gudda from 1989 to 2019, indicating an increase in fragmentation.

3.1.3 Aggregation Index (AI)

AI is equal to 100 when the patches form a single compacted cluster. On the other hand, the value is equal to 1 when the patches are disaggregated. The AI values were initially observed for built-up areas in some confined patches of Gadag, Gajendragad, and Shirahatti around 1989. There was then a rise in the increase of built-up cover across the district, indicating a compact cluster around Gajendragad and Gadag. The decline of the AI value in the Gadag and Shirahatti regions indicates forest fragmentation.

3.1.4 Normalized Landscape Shape Index (NLSI)

NLSI describes the shape of the landscape. The value 0 indicates the class compactness in a grid, while 1 indicates the most scattered class. Gadag district started experiencing considerable urban sprawl in 1999, evident from the higher NLSI values. The NLSI values declined post-2009 in Gadag, Gajendragad, and Naragund, indicating compacted growth. Similarly, the forest cover around the Mundargi side of Kappata Gudda declined, as evident from the increased shape complexity.

3.2 Modeling LU Dynamics

The prediction of the likely LU transitions is made through a hybrid fuzzy AHP MCA modeling approach considering 5 LU categories (Table 5)—natural vegetation (deciduous forest and scrub), monoculture plantations (forest plantations and horticulture), agriculture, built-up, and water. Based on the zone of influence and the growth trend of each agent with respect to built-up and classes of monoculture agriculture, weights were assigned with acceptable consistency, i.e., eigenvalues were generated such that the consistency of the weights < 0.1 for each agent (Table 6). Transitions from 2009–to 2019 were estimated and simulated using the LU of 2019, which was compared with the actual LU of 2019 for validation through accuracy assessment. The agreement of simulated LU with the actual LU was evaluated through a set of Kappa indices such as K_{no} (0.9), $K_{location}$ (0.94), $K_{standard}$ (0.89). Based on the consistency, the LU for 2029 was simulated by incorporating the influencing factors and constraints (Figure 10). The results indicated a likely increase of built-up of 4%, with the loss of agriculture and forest cover hindering the availability of natural resources and food. Supporting industrialization policies and water availability would aid as a major catalyst for large-scale LU transitions in the region.

Table 5 LU categories used for simulation and prediction.

Land Use	Categories
Forest	Dry Deciduous, Scrub
Monoculture	Forest plantation, Horticulture.
Agriculture	Agriculture
Built-up	Built-up
Water	Water

Table 6 Function type, range, and the weights assigned across the LU classes.

Built-up	Function	Range (m)	Weight
Road	J-Shaped Decreasing	100 – 2500	0.2935
Slope (%)	Linear Decreasing	1–30	Constraint
Industry	Sigmoidal Decreasing	2000 – 6000	0.0827
Education	Sigmoidal Decreasing	500–4500	0.1336
City center	Sigmoidal Decreasing	1000 – 20000	0.3022
Socio-culture	Sigmoidal Decreasing	1000–4000	0.0329
Bus & Railway Station	Symmetric	0 – 2500, 5500 – 8000	0.1551
Monoculture	**Function**	**Range (m)**	**Weight**
Road	J-shape Decreasing	100–25000	0.3239
Slope (%)	Linear Decreasing	1–55	Constraint
Industry	Symmetric	0 – 10000, 75000–85000	0.1201
Education	Symmetric	0 – 6000, 20000 – 35000	0.1813
City center	Linear Increasing	0 – 10000	0.0568
Socio-culture	Symmetric	0 – 10000, 30000–50000	0.0826
Bus & Railway Station	Symmetric	0 – 20000, 45000–65000	0.2353
Agriculture	**Function**	**Range (m)**	**Weight**
Road	Linear Decreasing	100–5500	0.3367
Slope (%)	Linear Decreasing	1–10	Constraint
Industry	Symmetric	0 – 5000, 17000–22000	0.1807
Education	Symmetric	0 – 1500, 3000–8000	0.0897
City center	Symmetric	0 – 5000, 17000 – 25000	0.0305
Socio-culture	Symmetric	0 – 2000, 6000–12000	0.0716
Bus & Railway Station	Symmetric	0 – 2500, 8000–24000	0.2908

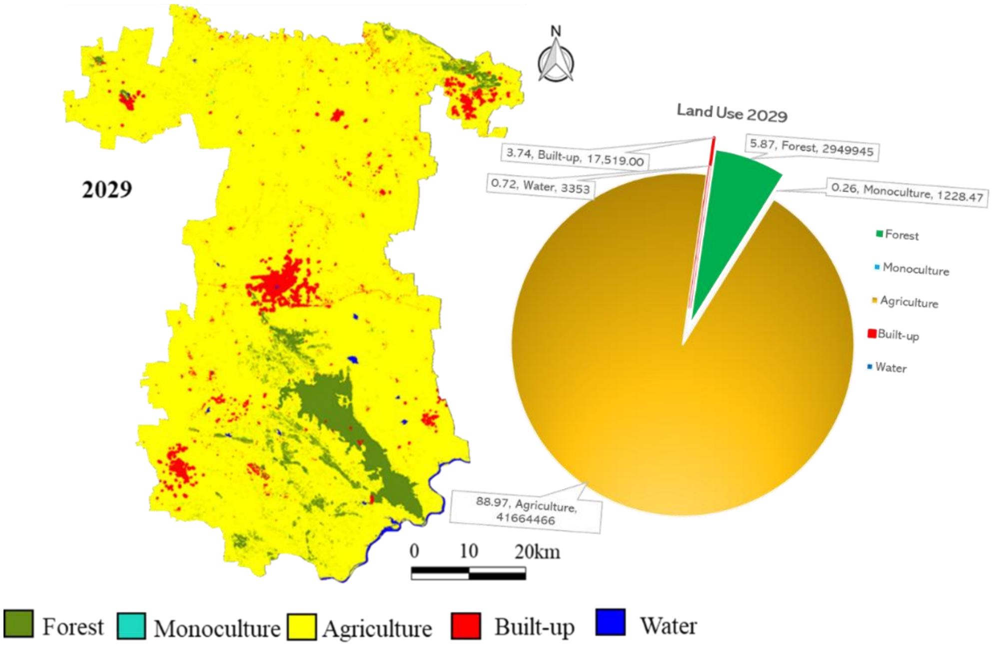

Figure 10 Projected LU of Gadag.

3.3 Prioritization of Ecologically Susceptible Zones (ESZ) at Disaggregated Levels

Prioritization of ESZs at disaggregated levels (grids) was achieved by integrating location-specific land, ecology, bio-geo-climatic, energy, and social variables. Weights were assigned to these variables at grid levels based on the conditions assessed through field investigations supplemented with literature review. Figure 11 depicts conditions of the forest and interior forest cover in the grids with their relative weights (based on the spatial extent and ecosystem conditions). This highlighted that the forest cover and the interior forest are intact and dense in the grids corresponding to the Kappata Gudda forest range and Gajendragad region. Figure 12 depicts forest biomass ranging less than 300 Gg and the corresponding weight.

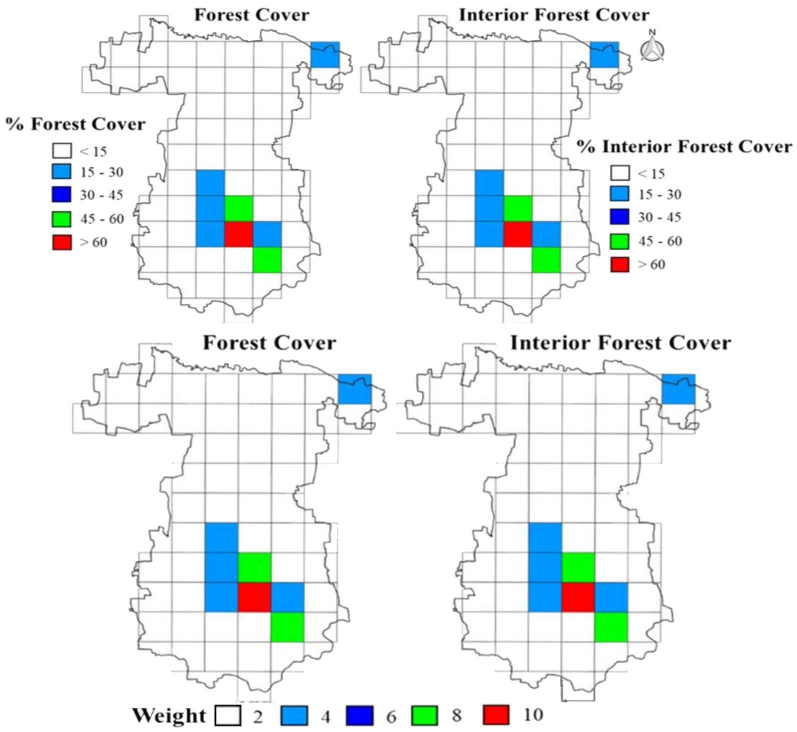

Figure 11 Percentage of forest cover, interior forest cover, and the corresponding weights.

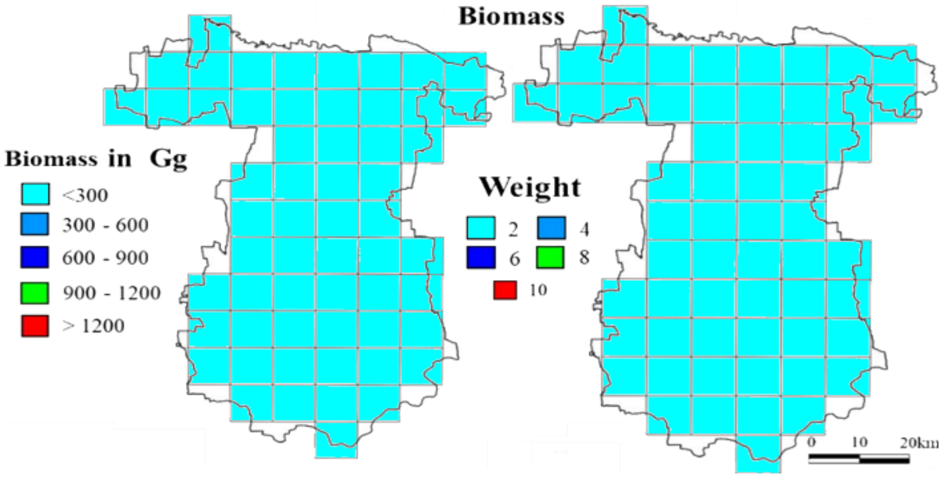

Figure 12 Biomass of the district and the corresponding weight.

The flora and fauna details (Figure 13) were compiled from the field and published literature [15, 23], and weights were assigned as per the occurrence of species based on their conservation status. The district has 435 species of flora under 106 families with vulnerable species such as *Chloroxylon swietenia, Santalum album,* and very rare species such as *Ehretia laevis.* The district has good faunal diversity with 23 mammal, 7 reptile, 338 bird, and 16 fish species with critically endangered (CR) species such as *Ardeotis nigriceps, Gyps bengalensis, Gyps indicus, Sarcogyps calvus*, vulnerable (VU) species such as *Aquila rapax, Cervus unicolor, Ciconia episcopus, Clanga clanga, Clanga hastata, Gallinago nemoricola, Leptoptilos javanicus, Semnopithecus hypoleucos*, endangered (EN) species such *as Aquila nipalensis, Coun alpinus, Neophron percnopterus, Sterna acuticauda* and the near threatened (NT) species like *Anhinga melanogaster, Anthracoceros coronatus, Antilope cervicapra,* *Aythya nyroca, Circus macrourus, Esacus recurvirostris, Falco jugger, Haliaeetus ichthyaetus, Limosa limosa, Mycteria leucocephala, Oreochromis mossambica, Pelecanus philippensis, Phylloscopus tytleri, Sterna auranta, Threskiornis melanocephalus,* and *Sypheotides indicus*. The water availability of the streams across the district was assessed, and the weight was assigned based on the duration of flow (Figure 14). Streams are perennial only in the catchments dominated by forest cover.

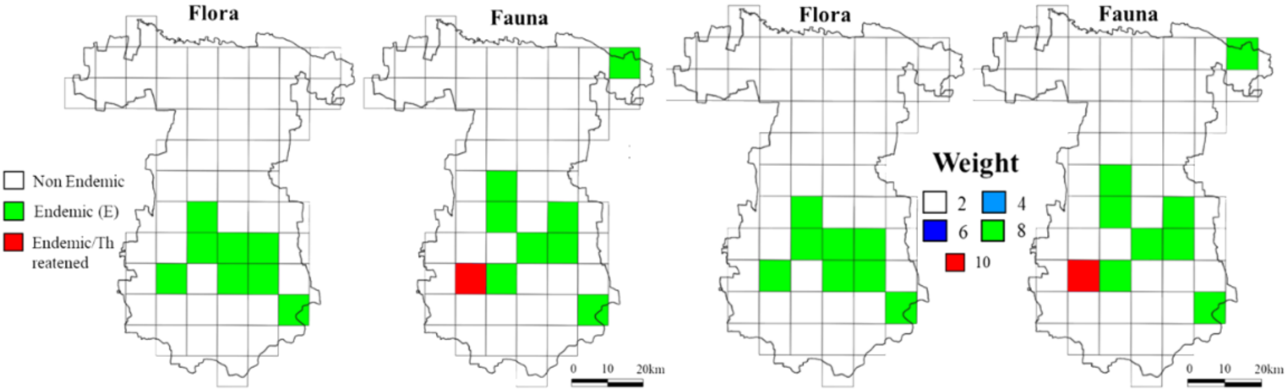

Figure 13 Floral and faunal distribution, and the corresponding weights.

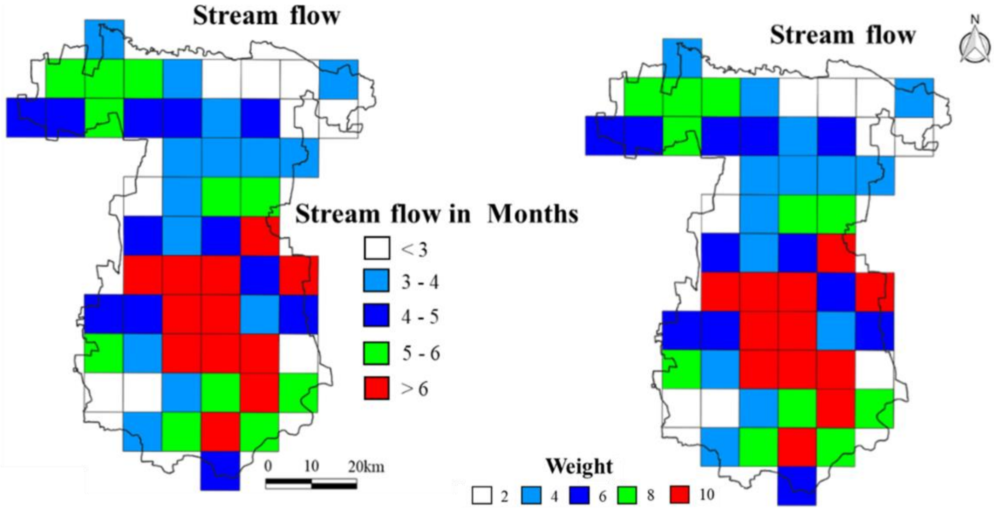

Figure 14 Streamflow and the corresponding weights.

Figure 15, Figure 16, and Figure 17 depict the variability of the selected geo-climatic parameters such as elevation, rainfall, slope, soil, and lithology. The soil type was clayey loamy around Gadag taluk and sandy skeletal in the southern rocky outcrops in the north of the district. The weights were assigned based on the water holding capacity of the soil. The slope was approximately 15% across the district, whereas it was greater than 15% in forested areas. The very gently sloping lands covered an area of 362,045 ha (78%), followed by gently sloping lands covering 66,371 ha (14%), and nearly level lands covering an area of 35,964 ha (8%). Gadag has good renewable energy potential across the district (Figure 18). The central government has therefore proposed the development of ultra-mega renewable energy power parks in the district of Gadag.

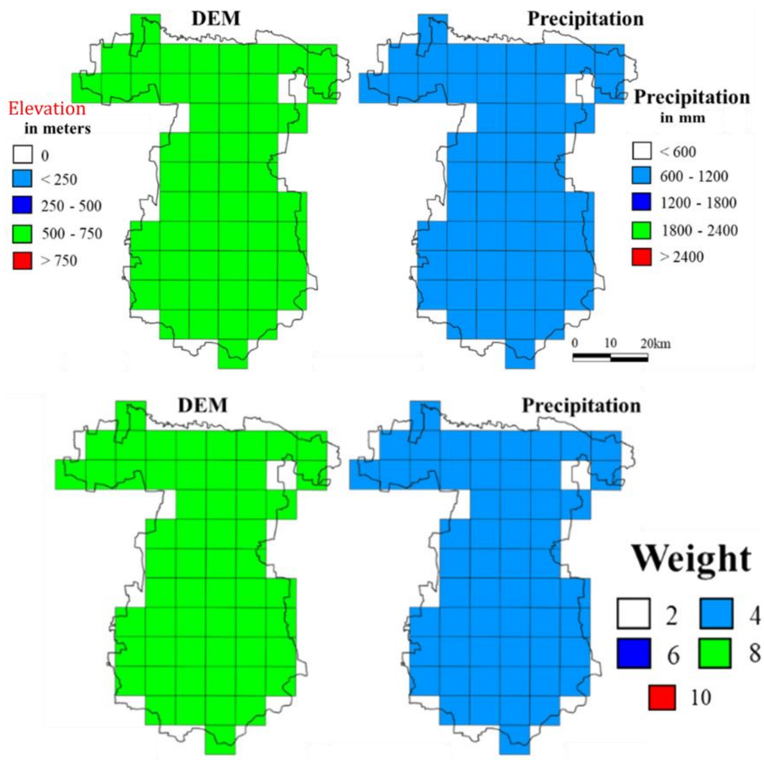

Figure 15 Elevation and rainfall, with their corresponding weights.

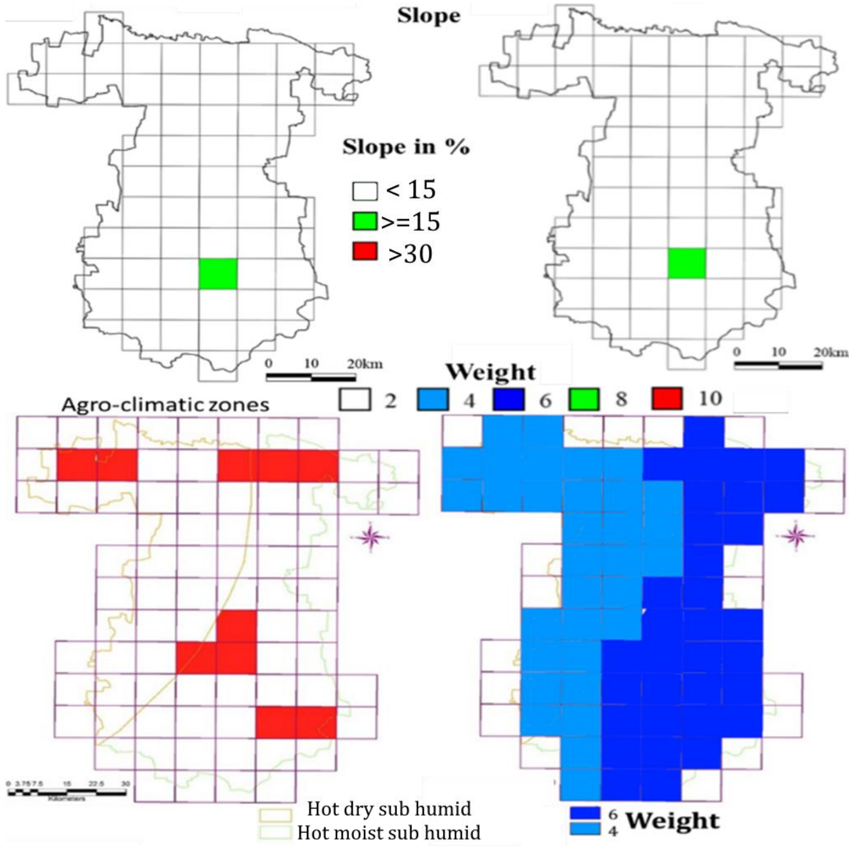

Figure 16 Slope in %, agro-climatic zones, and their corresponding weights.

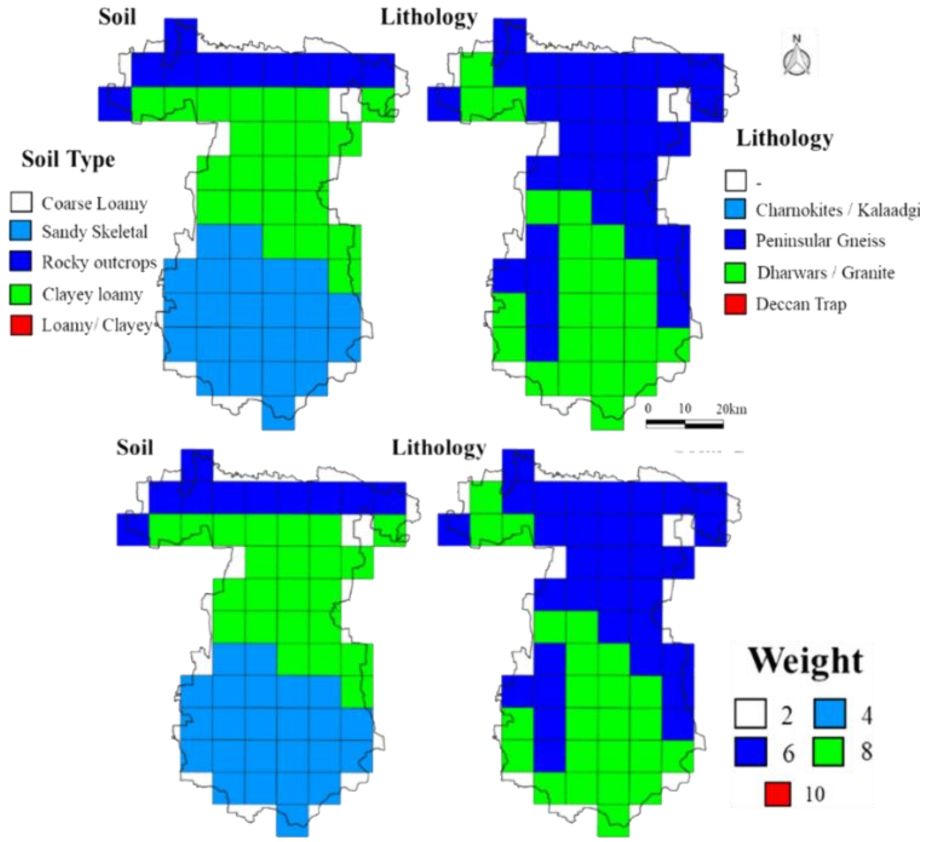

Figure 17 Soil and lithology details for Gadag region, and their corresponding weights.

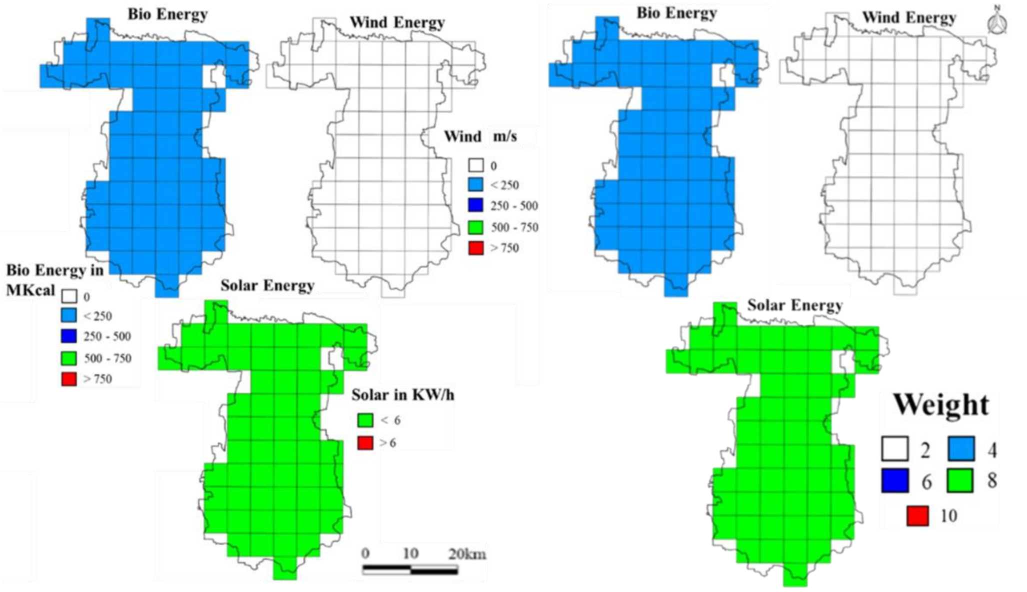

Figure 18 Energy prospects of Gadag and their corresponding weights.

Gadag ranks 26th in terms of population, with a population of 1,064,570, comprising 537,147 males and 527,423 females (2011 Census). As per the 2011 census, the rural and urban population of the district is 685,261 and 379,309, respectively. The population density was evaluated across the grid for the year 2011, which depicts that the majority of the district has a density of 100–250 persons per hectare. The population density was revealed to be high in the grids of Gadag city with

250–500 persons per hectare, while the rest of the grids have a range of 100–250 persons per hectare (Figure 19). The livestock density at the grid level is a social factor that provides alternative income for the rural population. The total cattle and buffalo population in the district is 203,644, where the population of cattle is 142,655 (70.9%), and that of buffalos is 60,989 (29.1%). The grids of the Ron taluk possessed the highest livestock density, followed by Gadag.

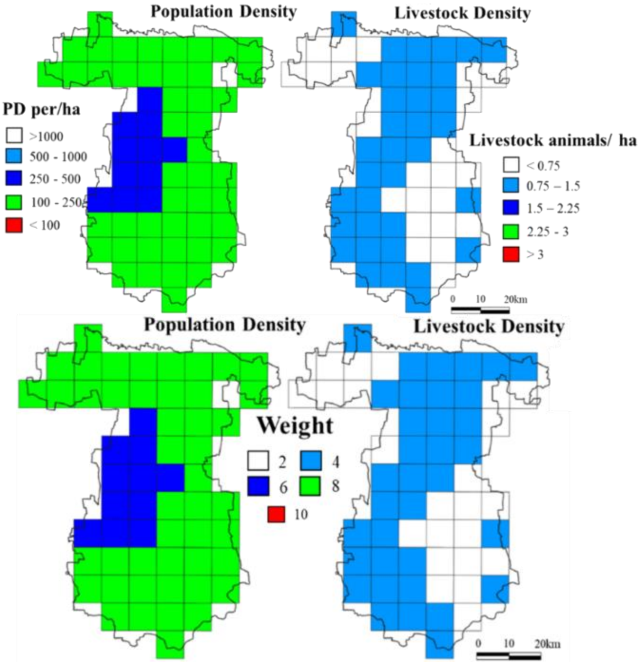

Figure 19 Population and livestock densities, and their corresponding weights.

The delineation of ESZs was conducted based on the regional characteristics and the various sensitivity levels described by the data considering distinct themes. The bio-geo-climatic, ecological, and social factors were aggregated, and the grids were grouped into four categories based on the frequency distribution of aggregate scores: ESZ1 (for grids with > μ ±2α weights, where μ: average, α: standard deviation), ESZ2 (for grids with weights between μ ±2α and μ ±α), ESZ3 (grids with weights between μ ±α and μ) and ESZ4 (grids with weights < μ). ESZ1 and ESZ2 are highly susceptible zones where any alteration to the ecological integrity is not permitted. These zones fall in the Kappata Gudda range Naragund and Gajendragad and should be devoid of large-scale development projects such as mining. ESZ3 is the region of moderate sensitivity where developmental activities may be allowed with stringent environmental norms through environmental impact assessments (EIA) and environmental management plans (EMP) to mitigate the impacts. Here, unauthorized land conversion will be regulated while permitting location-specific small-scale industries like the agro-based industries, garments industries, information technology (IT), etc., which would boost the rural economy. The rural youth and the women's self-help groups should therefore be provided incentives for setting up new agro-processing industries based on locally available natural resources. It was found that 9 grids (16% spatial extent) of the Gadag district fell under ESZ1, 31 grids (54% spatial extent) under ESZ2, 13 grids (23%) under ESZ3, and the rest under 4 grids (7%) representing ESZ4 (Figure 20). Village-wise ESZ demarcation showed that 36 villages fell under ESZ1, 201 villages under ESZ2, 74 villages underESZ3, and the rest 41 villages fell under ESZ4.

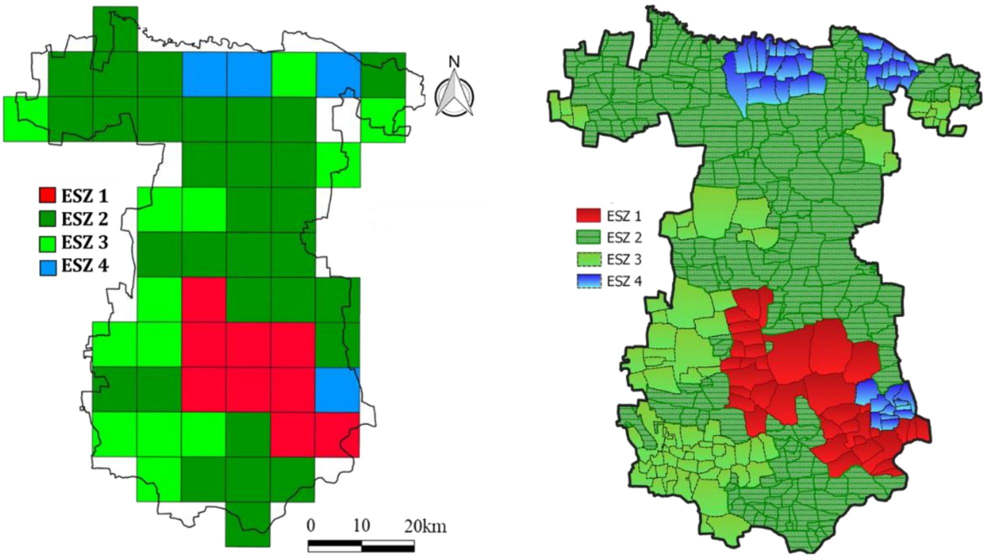

Figure 20 Grid and village-wise ESZ categories in Gadag.

ESZ4 is suitable for developmental activities. The assessment of the spatial extent and visualization of likely changes in the ecosystem shows that urban growth has occurred around the Gajendragad town of the Ron taluk. This study highlights the district's potential of setting up environmentally friendly or less-polluting industries, creating green jobs, and providing an opportunity to transition to a low carbon economy. This entails maintaining ecological integrity by protecting ESZ1 and ESZ2 to sustain water and other natural resources. The regulatory authorities should focus on investments in renewable technologies as an emerging economy in the context of low-carbon growth, including sustainable development. Overall, the state of Karnataka has the potential to create green jobs in the sectors of renewable energy, with 26,000 jobs in the wind energy sector, 14,000 jobs in the biomass-based energy sector, and 833,000 jobs in the solar energy sector [36]. Gadag district is the ideal location for aiming to Decentralized energy development, which reduce the migration problem and aid in socio-economic and environmental welfare gains. Monoculture plantations should be discouraged, and existing exotic plantations should be replaced with native species. Location-specific bio resource-based industries would enhance job opportunities and also the optimal utilization of resources. The activities should be regulated and should be subject to social audits. Those development projects should be adopted which will have the least environmental impact by involving all the stakeholders, including local community members, in decision making and environmental monitoring. Controlled activities should be permitted based on their socio-economic importance. Appropriate conservation and management measures should restrict activities like reclaiming wetlands, converting areas under natural forests, and activities leading to alien invasive species.

4. Discussion

4.1 Management of ESZs

The management of ESZs entails the protection of natural resources for improving the quality of life for both the present and future generations (stewardship or sustainability) through effective and prudent planning. This includes land use planning, management of water and other resources, and biodiversity conservation to protect natural landscapes and livelihoods. Preventing ESZ from further degradation will support the local communities through improved health and productivity. The management recommendations for the ESZ also focus on permissible activities by emphasizing the future sustainability of agriculture, tourism, fisheries, and forestry. There is a need to address unregulated resource use, unplanned urbanization, and other developmental activities to sustain the livelihoods of local people. ESZ4 and ESZ3 act as “shock absorbers”. Regulated activities in these regions may therefore enrich the ESZ1 and ESZ2 areas. They also act as a transition zone from areas of high protection to areas involving lesser protection. The policy measures required to sustain natural resources in the Gadag district are provided below:

- ESZ1 represents the zone requiring the highest conservation, with stringent norms to prevent further degradation. ESZ2 may be converted to ESZ1 if provided with strict regulations and with the improvement of forests and their environs by increased protection. A small change in ESZ2 will have significant adverse effects on ESZ1.
- No new major/expansion of roads or railway lines would be allowed in the ecologically susceptible ESZ1. The expansion, if crucial, should be subjected to an EIA (environmental impact assessment) with strict monitoring based on social audits.
- The Forest Rights Act, 2006 would need to be implemented in its true spirit by ensuring genuine stakeholders are not deprived of their rights
- Monoculture plantations of exotic species should be regulated in the ESZs, and existing species should be replaced with endemic species.
- Monoculture plantations of exotic species should be restricted in the plantations within ESZ1.
- Decentralized energy should be promoted through incentives for harvesting decentralized renewable energy sources (solar, wind, bioresources).
- Local bio resource-based industries should be promoted with strict regulations, subject to social audits.
- Development projects with the most negligible environmental impact should be adopted by involving local community members in decision-making and environmental monitoring.
- The tourism master plan should be as per the guidelines and regulations of the MoEFCC, Government of India (after considering social and environmental costs). Restrictions should be imposed on the construction of large hotels or resorts and new tourism establishments in ESZ1.
- Controlled activities should be permitted based on socio-economic importance. Activities that deprive wetlands and natural forests and introduce alien invasive species should not be permitted.

The activities (sector-wise) that should be allowed and regulated across various ESZ are as follows:

(i) Energy: Solar (rooftop) energy may be permitted in all zones and wind and bioenergy in all zones except ESZ1.

(ii) Forests: There should be strict regulations with LU changes (forest to other land uses), restrictions on monoculture plantations, permission to collect NTFP, and forest management by involving all stakeholders through VFCs (Village Forest Committees) in all zones. The extraction of medicinal plants may be permitted on a sustainable basis in ESZ3 and ESZ4. Grid-based mapping aids in identifying the spatial distribution [37] at disaggregated levels of biologically distinct, ecologically valuable, and potential habitats at higher risk [38]. This should be safeguarded under stringent regulations. The conservation and enrichment of the existing biodiversity of the region may be successfully achieved through ecological restoration approaches [39]. The degraded patches in the Kappata Gudda forest region and partly degraded habitats within the district should be enriched with the reforestation of native species, which will aid in habitat restoration, assisted establishment, or assisted colonization of suitable species. Regulating unauthorized LU changes and a complete ban on mining in the Kappata Gudda region will aid decision-makers and forest managers in recovering the land and restoring forest habitat. This also helps understand the risk of fragmentation and prevents decolonization. The protected forest lands would thus act as regeneration blocks and aid in conservation. Monitoring vegetation in such blocks, preferably by local volunteers, would enhance environmental awareness among the local communities.

(iii) Agriculture: Agroforestry, organic farming, and animal husbandry may be practiced in all the zones, with a complete ban on genetically modified crops.

(iv) Horticulture: The use of hazardous endosulfan should be banned in all zones, and the use of nitrogen (N) and phosphorous (P) should be prohibited. The use of N and P fertilizers, as well as pesticides, may only be permitted in ESZ4, provided the quantity is applied only after the assessment of soil quality. Crops such as watermelon, muskmelon, and ginger cultivation may be practiced only in ESZ3 and ESZ4.

(v) Industries (large scale): Agro-processing industries may be permitted in all zones, while green (non-polluting) industries, information technology (IT), and garment industries may be permitted in ESZ3 and ESZ4. The establishment of new industries may be permitted in ESZ4 (allowed only after critical review by local stakeholders and experts). Red category (polluting) industries should be banned in all zones.

(vi) Industries (small scale): Domestic industries (home-based industries such as for papad, mango processing, milk products and processing, dry fruits and spices, fruit processing, beekeeping and bee nurseries, vegetable dyes, fruits and vegetable preservation, medicinal plants cultivation and processing) may be permitted in all zones. Industries such as coir industries, Pongamia plantations for biofuel (in private lands), biopesticides manufacturing, poultry farms and powdered eggs, aromatic plants and essential oil distillation, flower harvesting industries, and garment industries may be permitted in ESZ2, ESZ3, and ESZ4.

(vii) Tourism: Promotion of activities such as organic villages and homestays, VFC managed tourism, arts, handicrafts, museum, and trade centers may be permitted in all zones, while ecotourism may be promoted in ESZ2, ESZ3, and ESZ4.

(viii) Mining and mineral extraction: Sand extraction (on a sustainable basis to meet the local demand with a ban on exporting) may be permitted in ESZ3 and ESZ4, while the extraction of quartz, limestone, etc., may be permitted in ESZ4. Large-scale extraction of iron ore, manganese, and bauxite should be banned in ESZ1 and ESZ2.

(ix) Waste disposal: Hazardous waste processing units should be banned in ESZ1, ESZ2, and ESZ3. Solid waste disposal, liquid waste discharge, and recycling and waste processing units may only be permitted in ESZ4.

(x) Transportation: Linear projects (roads and expressways), railway and freight corridors, and the up-gradation of existing infrastructure may be permitted in ESZ3 and ESZ4.

5. Conclusion

The information on LULC over a temporal scale has aided in understanding the landscape composition and configuration of the Gadag district. The built-up area increased from 2 to 65 km^2 at the cost of a forest cover loss of 16 km^2 from 1989 to 2019. LULC information is a base to model possible changes over geographic space and to observe the growth in built-up cover and loss in agriculture and forest area. Landscape metrics accounted for landscape patterns and the influence of patch adjacency. Ecologically susceptible regions in the Gadag district were assessed through composite metrics by integrating bio, geo, hydro, climatic, and ecological factors paired with social aspects. These were compiled at the micro-level through a grid-based NES for representative grids and through an extensive literature review for district-level information. The delineation of ESZ reveals ESZ1 and ESZ2 as the highly sensitive zones where largescale development activity should not be permitted. ESZ1 and ESZ2 fall within the Kappata Gudda range and Naragund and Gajendragad region. Mining activity is reported in the Kappata Gudda range. The grid-wise analysis shows that ESZ1 covers nine grids (16%), ESZ2 covers 31 grids (54%), ESZ3 13 grids (23%), and ESZ4 covers four grids (7%) in the study area. The community-engaged conservation approach, where local communities are involved in decision-making, will aid in the conservation of biological diversity and nourishment of natural resources. The identification of ESZ will assist in shaping effective policies to achieve the sustainable development goals through pattern analysis and all possible dimensions from various interdisciplinary themes.

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Author Contributions

Ramachandra T V: data analysis and interpretation of data; revising the article critically for important intellectual content; final editing. Bharath Setturu: field data collection, interpretation of data, writing. Karthik R Naik: field data collection, data analyses, interpretation of data, writing. Jagadeesha Pai: data analyses and interpretation.

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Competing Interests

The authors have no competing interests, either financial or non-financial.

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