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Geospatial Multi-Criteria Evaluation of Ecotourism Suitability in Bankura District, India Using AHP-PROMETHEE-GIS Integration

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Abstract:

This study develops a comprehensive AHP-PROMETHEE-GIS framework to evaluate the suitability of ecotourism activities in Bankura district, West Bengal, India, a region characterized by ecologically sensitive and culturally rich landscapes. The methodology integrated multi-criteria decision-making and geospatial analysis over 2,531 delineated landscape units, encompassing geomorphological, ecological, and infrastructural variables. The PROMETHEE method implemented in Python enabled hierarchical suitability rankings visualized in ArcGIS, revealing significant spatial heterogeneity. Approximately 69.8% of the highly suitable zones are concentrated in the western uplands, including the Jhilimili-Ranibandh-Mukutmanipur belt, supporting activities such as cross-country adventure, trekking, forest recreation, and environmental research. Secondary suitability zones cover about 45.0%, whereas moderate and marginal suitability units account for 35.6% and 33.8% respectively. This spatial framework balances ecological protection with economic and social benefits, providing operational guidelines for zonation and sustainable ecotourism planning. It advances landscape unitdriven strategies to optimize ecotourism layouts, mitigate landscape fragmentation, and foster synergies between biodiversity conservation and community livelihoods in alignment with the UN Sustainable Development Goals.

Keywords: *Ecotourism Suitability, AHP-PROMETHEE-GIS, Spatial Analysis, Sustainable Planning, Bankura District.*

1.0 Introduction

Since the mid-twentieth century, the accelerated pace of global economic growth has intensified the exploitation of natural resources, resulting in significant ecological imbalance and environmental degradation(1). Industrial expansion, urban sprawl, and unsustainable agricultural practices have disrupted the intricate equilibrium of ecosystems and weakened biodiversity resilience(2). Scholars worldwide have emphasized the necessity of transitioning toward sustainable development pathways that integrate economic advancement with environmental conservation and social equity (3). Ecotourism has emerged as a critical approach to sustainable development, integrating environmental conservation with socio-economic benefits for local communities. It promotes responsible travel to natural areas that conserve biodiversity, supports cultural heritage, and fosters equitable economic opportunities(4, 5). This study leverages a geospatial multi-criteria evaluation framework to identify ecotourism suitability zones that balance ecological protection with community livelihoods, aligned with sustainable development goals (6, 7). This paradigm marked the genesis of scientific exploration into sustainability-oriented tourism, particularly the domain of ecotourism, which promotes environmentally responsible travel to natural areas, supports local livelihoods, and fosters ecological awareness (8).

The theoretical foundations of ecotourism evolved as a constructive response to the observed tensions between developmental imperatives and ecological vulnerability, especially in biodiversity-rich regions of the Global South(9). Through the lens of environmental economics and conservation geography, ecotourism is perceived not merely as a recreational practice but as an environmental management tool capable of achieving a symbiotic relationship between nature conservation and socioeconomic enrichment (10). Modern frameworks of ecotourism emphasize carrying capacity analysis, stakeholder participation, and environmental impact mitigation to ensure the long-term integrity of natural assets (11). Within this context, ecotourism has become a critical element of regional sustainable development strategies, particularly in ecologically sensitive landscapes like the Bankura district of West Bengal, India.However, the intensification of unregulated tourism and associated land-use transformations has begun to threaten the ecological stability of Bankura's forested ecosystems. Anthropogenic pressures especially deforestation, illegal mining, and landscape fragmentation have disrupted native habitats and reduced ecological resilience (12). These environmental stresses highlight the urgent need for developing an ecotourism suitability assessment framework that integrates spatial, environmental, and socio-economic variables. The application of Geographic Information System (GIS) and multi-criteria decision-making (MCDM) techniques offers robust tools for systematically evaluating landscape suitability for ecotourism development(13).

The Analytic Hierarchy Process (AHP), as established by Saaty (1980), is widely acknowledged for its structured approach to quantifying qualitative factors through pairwise comparison matrices and assigning priority weights based on expert judgments. It facilitates the systematic hierarchization of decision criteria such as terrain, vegetation, slope, land use, proximity to water sources, and accessibility to assess spatial suitability (14). Nevertheless, while AHP is effective in structuring decision problems, it often exhibits subjectivity arising from expert-dependent weighting processes(15). To mitigate this limitation, the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) provides a complementary decision framework that enhances objectivity ranking alternatives pairwise using preference functions (16). The integration of AHP and PROMETHEE within a GIS spatial environment allows for both quantitative and qualitative dimensions of ecotourism suitability to be represented effectively(17).

In the context of Bankura, such a hybrid analytical approach can guide the zoning and planning of ecotourism sites that harmonize tourism promotion with environmental protection. The process typically involves the acquisition and analysis of spatial datasetsincluding topographic maps, vegetation indices derived from remote sensing imagery, and elevation models derived from Digital Elevation Models (DEMs)to delineate the landscape's ecological and recreational features. Hydrological and geomorphological attributes, such as slope gradient, drainage density, distance from water bodies, and soil erosion potential, are incorporated to assess the ecological vulnerability and environmental carrying capacity of the region (18).

Developing an evaluation index system for ecotourism suitability in Bankura necessitates integrating sustainability-oriented indicators such as biodiversity richness, soil stability, geohazard susceptibility, cultural heritage resources, and accessibility to infrastructure. Quantitative analysis using GIS-based modelling enhances the precision of spatial decision-making and ensures that ecotourism development aligns with ecological conservation principles(19). Moreover, this methodological design aligns with the objectives of India's sustainable tourism development policies, which emphasize harmony between ecological function and community welfare (Ministry of Tourism, Government of India, 2023).

The spatial differentiation of ecotourism suitability zones will facilitate the delineation of core conservation zones, buffer areas, and recreation-intensive zones, mirroring international best practices in national park management. Such zoning promotes the rational distribution of recreational activities and minimizes human disturbances within ecologically fragile landscapes. The insights derived from the Bankura study can thus contribute to broader regional planning initiatives and serve as a prototype for sustainable ecotourism strategies across eastern India.

The proposed research, therefore, has three primary objectives:

1. To develop a multi-dimensional evaluation index framework that captures the environmental, cultural, and infrastructural determinants affecting ecotourism suitability in Bankura.
2. To spatially classify and prioritize suitable ecotourism zones using an integrated AHP–PROMETHEE–GIS model.
3. To provide evidence-based recommendations for local authorities and policy makers to enhance the ecological, cultural, and economic potential of Bankura through sustainable ecotourism planning.

By employing a scientifically rigorous, multi-criteria spatial modelling framework, the study aims to bridge the gap between environmental conservation and economic viability in the Bankura district. The outcomes are expected to yield operational guidelines for ecotourism zoning, capacity optimization, and community engagement toward achieving a resilient and inclusive model of regional eco-development. The methodological paradigm described herein has potential replicability in other lateritic and semi-arid landscapes of India and may contribute meaningfully to achieving the commitments of the 2030 Agenda for Sustainable Development Goals (SDGs 8, 11, 13, and 15) through sustainable tourism integration at the district level.

2.0 Materials and Methods

2.1 Study Area

Bankura district, located in West Bengal, is bounded by Purba Bardhaman and Paschim Bardhaman districts to the north, Purulia district to the west, Jhargram and Paschim Medinipur districts to the south, and Hugli district to the east (23.1645° N, 87.0624° E)(20-22). Administratively, Bankura is divided into three sub-divisions: Bankura Sadar, Khatra, and Bishnupur. The Bankura Sadar sub-division encompasses the community development (C.D.) blocks of Bankura-I, Bankura-II, Barjora, Chhatna, Gangajalghati, Mejhia, Onda, and Saltora. Khatra sub-division comprises the blocks of Khatra, Indpur, Hirbandh, Ranibandh, Raipur, Sarenga, Simlipal, and Taldangra, while Bishnupur sub-division includes Bishnupur, Indas, Jaypur, Patrasayar, Kotulpur, and Sonamukhi C.D. blocks. As an extension of the Chotanagpur Plateau, Bankura’s rugged terrain and dense forest cover have limited road accessibility, thereby preserving its diverse natural landscape(23). The district is defined by rolling red-soil hills and groves of lush Sal trees and is home to varied ethnic communities, including the Santhali, Bhumij, Munda, Oraon, Birhor, Mal, Pharia, Kharia, and Ho, who collectively comprise 18.45% of the total population. Known for its cultural richness, Bankura hosts traditional fairs and festivals across the district, with Bishnupur revered as the cultural capital and renowned as the "Temple Town" for its historic temples(24-27). The Biharinath (448 meters) and Susunia (440 meters) Hills serve as primary hubs for adventure tourism, particularly during the winter season, when the rugged topography attracts rock-climbing enthusiasts (28-30). Prominent ecotourism sites include Jhilimili, Sutan, and Joypur, celebrated for their scenic forest cover and biodiversity. Chenchuria further distinguishes itself with its temple-centered cultural attractions (31, 32). Another notable site, the Mukutmanipur Dam, stretches along the confluence of the Kangshabati and Kumari rivers, forming India’s second-longest earthen dam at 11.27 kilometres, surpassed only by the Sri Ram Sagar Project in Telangana.

This monumental structure significantly enhances the district's scenic and ecological value, underscoring Bankura's diverse potential as a hub for both cultural and ecological tourism(33-35)as depicted in Fig. 1.

2.2 Collection and Processing of Data

The data collection procedure in this study were organized into five key stages:

1. Preliminary Data Acquisition: This stage involved the systematic collection of all relevant datasets required for the analysis.
2. Identification and Evaluation Framework Development: Ecotourism activities were identified, followed by the construction of an evaluation index system and the determination of the relative weights of each indicator.
3. Landscape Unit Delineation: Geographic Information System (GIS) techniques were employed to delineate landscape units and process spatial data, resulting in the generation of a zoning map representing the influencing factors.
4. Suitability Ranking: The PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) method, integrated with GIS, was applied to assess and rank the suitability of ecotourism activities and produce ecological suitability maps.
5. Spatial Optimization: Based on the results, the spatial layout of potential ecotourism activities was determined to ensure sustainable and balanced regional development.

The ecotourism suitability evaluation process adopted a comprehensive approach, incorporating both environmental and anthropogenic dimensions. The datasets utilized included DEM data, vegetation distribution, Enhanced Difference Vegetation Index (EVI), soil erosion intensity, geological hazard sites, and wildlife activity ranges. Elevation data were obtained from the Geospatial Data Cloud with a spatial resolution of 30 m × 30 m. The remaining datasets and their corresponding sources are presented in Table 1, and all selected resolutions were deemed appropriate for the characteristics of the study area and the research objectives.Most data sources used in this study, such as ArcGIS Living Atlas, EarthExplorer, and OpenStreetMap, represent secondary geospatial data with varying temporal resolutions and acquisition years. To address potential biases from temporal discrepancies and resolution differences across datasets, the study employed the most recent available data (e.g., Sentinel-2 imagery from 2023 with 30 m spatial resolution) and harmonized spatial layers with appropriate geoprocessing techniques to ensure compatibility. Additionally, to enhance local relevance and ground validation, certain datasets were supplemented by manually digitized local features, such as geo-sites, cultural sites, tourism infrastructure, and security centers, using Google Earth Pro, reflecting district-level specificities. Expert consultations with local ecologists and planners further integrated indigenous ecological knowledge and local biodiversity insights, although no official district tourism department or biodiversity records were directly incorporated. Table 1 present the sources of data for various factors utilized in ecotourism site suitability modelling.

Table1 Sources of data of various factors utilized in ecotourism site suitability modelling

Variable	Abbv.	Source of Data
Forest Coverage	(FST)	(https://livingatlas.arcgis.com/landcover/)
Elevation	(ELV)	(https://earthexplorer.usgs.gov/)
Slope	(SLP)	https://earthexplorer.usgs.gov/)
Topographic Roughness	(TGR)	https://earthexplorer.usgs.gov/)

Distance from Geo-Sites	(GES)	Digitization Google Earth Pro
Distance from Surface Water Body	(WTB)	(https://livingatlas.arcgis.com/landcover/)
Distance from tribal village	(TBV)	(https://livingatlas.arcgis.com/landcover/)
Distance from cultural sites	(CST)	Digitization in Google Earth Pro
Distance from tourism infrastructure	(TIF)	Digitization in Google Earth Pro
Distance from Security Centre	(SEQ)	Digitization in Google Earth Pro
Distance from transport network	(TRN)	(https://www.openstreetmap.org/#map=9/23.201/86.363)
Distance from river	(RVD)	(https://www.hydrosheds.org/).

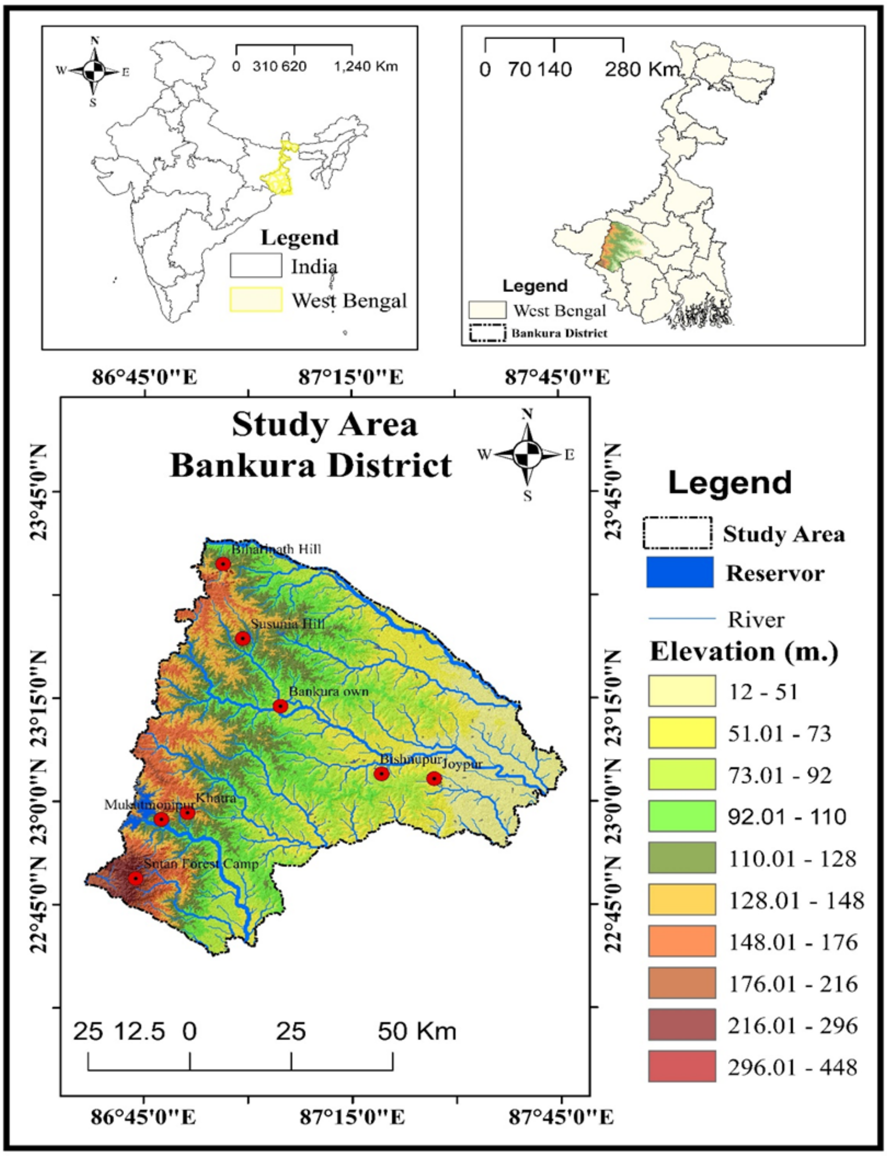

Fig. 1: Geo-spatial Mapping of Bankura District (West Bengal, India): Terrain, Hydrology and Cultural–Natural Landmarks. The maps were generated using ArcGIS software version 10.8 (https://www.arcgis.com/index.html).

2.3 Ecotourism Activity Selection

The classification of ecotourism activities in Bankura district was developed through an integrated assessment of its geomorphological, ecological, and socio-cultural characteristics(36). Guided by the principles of environmental sustainability and community participation, the study identified five major ecotourism categories aligned with the district's natural and cultural fabric: environmental research and education, geological and hydrological landscape interpretation, adventure-based exploration, recreational and wellness tourism, and ethno-cultural engagement(37). This classification was shaped by the interrelation between the region's functional ecosystems including lateritic uplands, forested ridges, riverine systems, and agro-cultural zones and visitor interaction patterns(38). Key examples include Susunia and Biharinath Hills, which are suitable for trekking and environmental learning; the Shilabati and Gandheswari river corridors, ideal for eco-interpretation and kayaking; and tribal villages around Mukutmanipur and Khatra, which provide immersive community-based cultural experiences. The activities were synchronized with existing tourism infrastructure and conservation programs to balance ecological protection and visitor satisfaction(39). The resulting classification was further structured into three functional clusters: educational-scientific, adventure sportive, and recreational-cultural each encompassing specific sub-modalities designed to promote sustainable resource use, environmental stewardship, and socio-economic inclusivity throughout the district, as given in Table 2.

2.4 PROMETHEE

The PROMETHEE technique represents an advanced framework within the domain of multi-criteria decision-making (MCDM)(40). In the present investigation, an objective assignment procedure was implemented, followed by a structured preference ordering analysis to evaluate the suitability of various ecotourism alternatives(41). The methodology operates through a pairwise comparison of the identified evaluation schemes, wherein the preference differentials between alternatives are calculated to generate hierarchical rankings of each criterion(42). These partial preference scores are subsequently aggregated into composite indices, yielding either a partially ordered ranking (PROMETHEE I) or a completely ordered hierarchy (PROMETHEE II)(43). The final ranking in PROMETHEE II is determined from the computed net flow values, typically ranging between −1 and +1, with higher positive values indicating greater suitability for ecotourism development(44).

Conceptually, the PROMETHEE model was originally developed following Brans' formulation, which introduced six principal preference function types: the Usual(45), U-shaped(46), V-shaped(46), Level(45), Linear(45), and Gaussian functions(47). Together, these variants encompass a broad spectrum of decision-making scenarios. However, because the latter five functions often require complex parameterization that may introduce uncertainty or interpretational ambiguity, the study adopted the Usual preference criterion(48).The methodology has been illustrated in Fig. 2

Table 2: Integrated Typology and Classification Framework of Ecotourism Activities in Bankura District

Functional Cluster	Category	Sub-Modal Type	Representative Locations	Core Ecological Features	Visitor Engagement	Sustainability Integration
Educational–Scientific Experiences	Environmental Research & Education	Biodiversity Study, Environmental Learning, Field Ecology	Susunia Hill, Biharinath Hill	Lateritic uplands, Forest biodiversity	Guided study tours, field workshops	Promotes awareness and conservation ethics
	Geological & Hydrological Interpretation	Geo-heritage Trail, Fluvial Exploration	Shilabati River, Gandheswari Basin	River morphology, sedimentary formations	River walks, kayaking, eco-	Enhances geomorphological understanding

					interpretation	
Adventure Sportive Pursuits	Nature Exploration & Trekking	Hill Trekking, Forest Trails	Biharinath, Jhilimili	Mixed deciduous forest, rugged terrain	Trekking, wildlife photography	Encourages low-impact outdoor recreation
	Adventure Water-based Activities	Kayaking, River Camping	Shilabati, Kangsabati Reservoir	Aquatic biodiversity, riparian vegetation	Kayaking, camping	Promotes eco-adventure ethics
Recreational–Cultural Interactions	Wellness & Leisure Tourism	Nature Retreat, Yoga, Birdwatching	Mukutmanipur, Talberia Dam	Forest–water interface, scenic landscapes	Yoga, relaxation, eco-resorts	Supports mental and physical well-being
	Ethno-Cultural Engagement	Tribal Art, Handicrafts, Folk Traditions	Mukutmanipur, Khatra Villages	Indigenous settlements, cultural landscapes	Cultural exchange, craft workshops	Fosters community-based tourism
	Agro-Cultural Experience	Farm Tourism, Rural Homestay	Sonamukhi, Onda Region	Agro-ecosystem diversity	Farm visits, participatory agriculture	Enhances livelihood diversification

This basic yet robust variant simplifies model calibration, reduces the cognitive burden on decision makers, and ensures analytical transparencymaking it particularly suitable for spatially explicit ecotourism suitability evaluation in the Bankura district(49).

Let B_x and B_y be the specific evaluation programmes in the set of evaluation programmes B ($B_x, B_y \in B$), and j be the specific evaluation index of each evaluation programme ($j = 1,2,\ldots,n$), then the specific steps of the PROMETHEE evaluation method are as follows

1. Calculation of the difference in evaluation programme values based on the two-by-two comparison method $D_j(B_x, B_y)$: $$D_j(B_x, B_y) = D_j(B_x) - D_j(B_y) \quad (1)$$

where: $D_j(B_x)$ and $D_j(B_y)$ are the values of the evaluation programmes B_x and B_y at indicator j, respectively; $D_j(B_x, B_y)$ is the difference between the two

2. Calculation of the preference of evaluation programmes based on the difference in their indicator values $P_j(B_x, B_y)$: $$P_j(B_x, B_y) = F_j[D_j(B_x, B_y)] \quad (2)$$

where: $P_j(B_x, B_y)$ is the degree of preference of the evaluation programme B_x and B_y with respect to the evaluation indicator j; F_j is the preference function of PROMETHEE II, capable of transforming the range of values of $D_j(B_x, B_y)$ between 0 and 1.

3. Calculation of an overall preference index based on indicator weights and preferences $\Pi(B_x, B_y)$ and $\Pi(B_y, B_x)$: $$\Pi(B_x, B_y) = \sum_{j=1}^{n} W_j P_j(B_x, B_y) \quad (3)$$

$$\Pi(B_y, B_x) = \sum_{j=1}^{n} W_j P_j(B_y, B_x) \quad (4)$$

where: $\Pi(B_x, B_y)$ and $\Pi(B_y, B_x)$ denote the preference of an evaluating programme x over y and the preference of an evaluating programme y over x when all evaluation indicators are considered; W_j is the weight of the evaluation indicators.

4. The positive flow rate $\phi^+(B_x)$ and the negative flow rate $\phi^-(B_x)$ are calculated as follows:

$$\phi^+(B_x) = \frac{1}{n-1} \sum_{B_y \in B} \Pi(B_x, B_y) \quad (5)$$

$$\phi^-(B_x) = \frac{1}{n-1} \sum_{B_y \in B} \Pi(B_y, B_x) \quad (6)$$

The criteria for decision-making (PROMETHEE I partial ranking) are as follows:

- When $\phi^+(B_x) \geq \phi^+(B_y)$ and $\phi^-(B_x) \leq \phi^-(B_y)$ (with at least one inequality being strict), the evaluation scheme x is preferred to y.

- When $\phi^+(B_x) = \phi^+(B_y)$ and $\phi^-(B_x) = \phi^-(B_y)$, the evaluation scheme x is indifferent (equivalent) to y.

- In all other situations, the schemes x and y cannot be determined (are incomparable).

5. The calculation of net flows $\phi(B_x)$ is as follows:

$$\phi(B_x) = \phi^+(B_x) - \phi^-(B_x) \quad (7)$$

The net flow is the PROMETHEE II measure (full ranking), where a larger value of $\phi(B_x)$ is preferred.

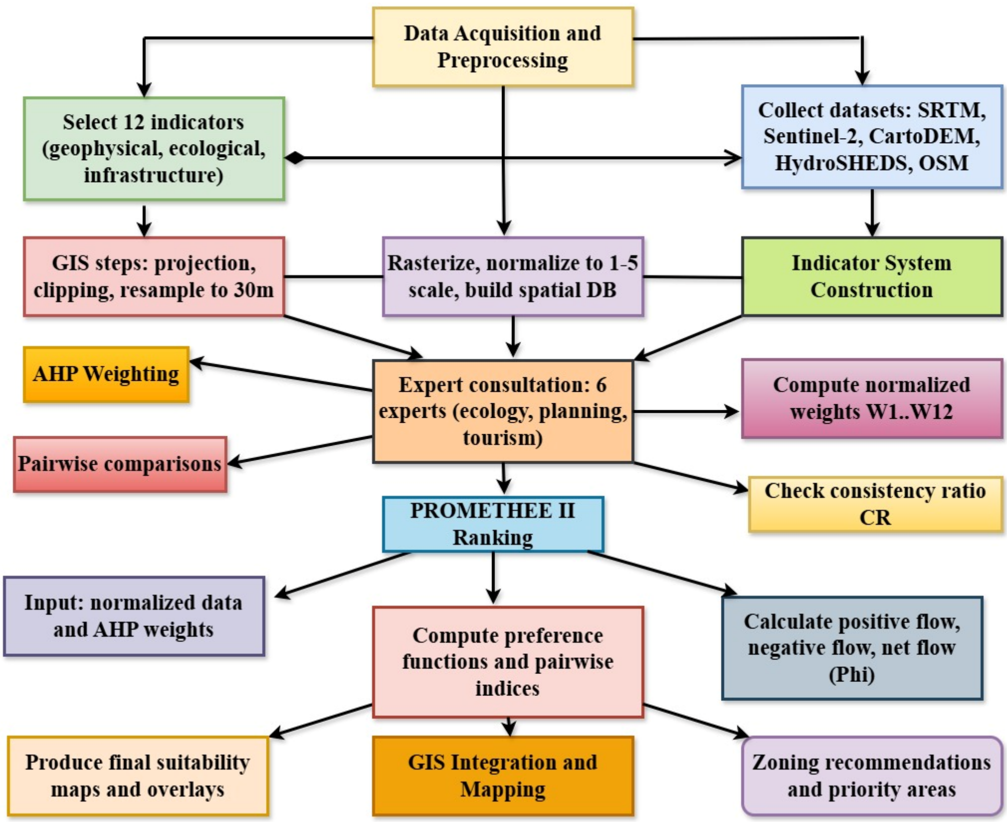

Fig. 2 : Integrated Analytical Workflow of the AHP–PROMETHEE–GIS Framework for Ecotourism Suitability Assessment in Bankura District, India

3.0 Results

3.1 Eco-Spatial Zonation for Ecotourism Suitability in Bankura

In the context of Bankura district, the concept of evaluation units forms the foundational spatial framework for ecotourism suitability assessment. Each evaluation unit represents the smallest and most homogenous landscape segment within which physical, ecological, and cultural attributes are systematically analysed, processed, and mapped. Serving as the operational basis for integrating environmental parameters into spatial modelling, these units allow for a precise representation of the natural heterogeneity inherent in Bankura's lateritic and undulating terrain(50). Unlike traditional tourism site identification that often relies on individual attraction points, the landscape unit approach delineates spatial polygons defined by distinct physiographic and ecological characteristics(51). This method helps address the limitations of unclear spatial boundaries that frequently hinder tourism planning, providing a continuous and quantifiable mapping framework for sustainable ecotourism development.

In Bankura's context, geomorphological variability is primarily governed by altitudinal gradients, slope configuration, and vegetation structureall of which reflect the dynamic balance between erosional and depositional forces shaping the region's lateritic plateaus and residual hills(52). Landscape differentiation also arises from distinct vegetation assemblages such as dry deciduous forests, scrublands, and agricultural mosaics, which collectively determine the ecological sensitivity and aesthetic value of each zone(53).

Accordingly, parameters including elevation, slope classes, and vegetation types were selected as the principal criteria for spatial segmentation. These datasets were analyzed through GIS-based overlay techniques, integrating multiple raster and vector layers to delineate ecologically coherent zones across the district(54). The process resulted in the identification of 2,531 discrete landscape units (as per the latest DEM and EVI datasets), each representing a unique synthesis of topographic, biological, and land-use attributes(55). These classified units served as the foundational framework for evaluating the suitability of ecotourism activities, ensuring spatial accuracy and ecological realism in the analysis of Bankura's diverse environmental landscape(56).

3.2 Weights of an Evaluation Indicator Framework

The construction of an evaluation indicator system for ecotourism suitability in Bankura district is grounded in the premise that sustainable tourism planning requires identifying and quantifying the multiple environmental and human factors influencing spatial suitability(57). Based on an extensive review of national and international research on ecotourism and geospatial sustainability assessment, as well as expert consultations with local ecologists, tourism managers, and planners, the study developed a comprehensive framework integrating geological, ecological, and socio-economic parameters(58). The approach combines both scientific objectivity and contextual relevance to local landscapes.

In developing this system, three primary dimensions were considered: geological and physical environment, ecological environment, and human–infrastructure attributes. The geological and physical indicators include elevation, slope, topographic ruggedness, and soil erosion sensitivity, reflecting the limitations and terrain-based opportunities for ecotourism development(59). These parameters are particularly significant in Bankura's diverse landscape, which comprises lateritic uplands, hill tracts such as Susunia and Biharinath, and riverine plains along the Gnaneshwari and Shilabati basins(60). Ecological indicators focus on vegetation density, forest cover, proximity to water bodies, and wildlife corridorsfactors that collectively define the biodiversity intensity, natural aesthetics, and habitat stability of potential ecotourism zones(61). Additionally, areas adjacent to dense forest tracts near Jhilimili and Barachaka were given higher ecological weight due to their scenic and biodiversity value as shown in Table 3.A maximum characteristic root (λmax), weight value, and consistency index CI value for each decision matrix were obtained, consistency test results were derived, and the weight of each index was obtained(62).

Human and infrastructural variables, including distance from settlements, accessibility to roads, proximity to heritage sites like Bishnupur and Joyrambati, and availability of basic amenities, were analyzed to measure visitor convenience and local participation potential(63). The weighting of each indicator was determined through the AHP and validated using statistical consistency checks(61). The experts assigned higher significance to vegetation cover and water-body proximity for ecological suitability, while elevation and road access were emphasized for adventure and trekking activities(64). Meanwhile, parameters such as distance from settlements and cultural sites carried moderate weights, balancing ecological protection and socio-economic integration(65).Overall, the finalized evaluation system comprises twelve interdependent factors organized into the categories of geophysical, ecological, and human-infrastructure dimensions(66). These were processed spatially using GIS–AHP–PROMETHEE integration to evaluate and rank ecotourism suitability zones throughout the district(67).To strengthen the indicator selection process, each of the twelve variables was justified based on its proven relevance to ecotourism planning in previous research. The parameters were reviewed from more than 30 national and international studies dealing with MCDM-based tourism suitability. Table 3 summarizes the theoretical basis and empirical significance of each variable. Forest coverage and vegetation index were included as primary ecological indicators due to their direct role in biodiversity and aesthetic value, while elevation, slope, and topographic roughness define terrain accessibility and landscape diversity(68). Hydrological variables such as distance from rivers and lakes reflect recreational and scenic potential(69). Cultural sites and tribal settlements represent socio-cultural resources that enhance visitor experience and community engagement(70). Accessibility-related indicators (distance from roads, infrastructure, and security centres) were selected to assess visitor convenience and safety(71).

Expert consultation was conducted with six specialiststwo environmental planners, two tourism officers, and two academic ecologistswho independently performed pairwise comparisons for AHP weighting. Their inputs were aggregated through the geometric mean method to derive a composite judgment matrix. The resulting consistency ratio (CR = 0.064) was below the acceptable threshold of 0.1, confirming logical consistency among expert assessments. This systematic validation ensures that the final weight distribution reflects both scientific evidence and contextual expert knowledge. The comprehensive indicator model not only ensures objectivity and reproducibility but also supports planners in identifying priority zones for sustainable ecotourism while maintaining ecological integrity and fostering local community development in Bankura's distinctive landscape(72).

Table3: Weights assigned to influencing factors using various weighting methods.

SL.	Variable	Class Name	Class	Area Sq. KM	SL.	Variable	Class Name	Class	Area Sq. KM
1	Cultural Site	Very High	<2	888.912	2	Elevation	Vey Low	<57	12149.154
		High	2-4	1487.961			Low	57.01 - 124	42760.17
		Moderately	4 - 8	5446.575			High	124.01 - 208	14085.504
		Low	8 - 12	7165.143			Very High	208.01 - 364	1002.915
		Vey Low	>12	53894.52			Moderately	>364.01	6.201
3	Forest	Very High	<0.5	13342.059	4	Geo-Site	Very High	<2.0	1071.639
		High	0.5 – 2	25762.401			High	2-4	2394.981
		Moderately	2- 5	17544.762			Moderately	4-8	9549.882
		Low	5 – 10	8097.975			Low	8-16	29852.397

		Very Low	>10	3924.594			Very Low	>16	25802.892
5	Infrastructure	Very High	<2	2825.397	6	Lake	Very High	<2	10717.236
		High	2-4	4502.376			High	2-4	16567.839
		Moderately	4-6	5659.605			Moderately	4-8	30546.252
		Low	6-10	16256.07			Low	8-12	9518.4
		Vey Low	>10	39639.663			Very Low	>12	1322.064
7	River	Very High	<2.15	22816.602	8	Road	Very High	<1.5	16915.806
		High	2.15-4.98	24449.688			High	1.5-4.0	21220.587
		Moderately	4.98-7.47	13080.834			Moderately	4.0-6.5	16073.919
		Low	7.47-10.44	7218.918			Low	6.5-8.5	8233.974
		Very Low	>10.44	1292.805			Very Low	>8.5	6227.505
9	Security	Very High	<2.0	3594.951	10	Slope	Very Low	<1.84	34291.035
		High	2.0-5.0	14424.732			Moderately	1.85 - 3.94	27581.985
		Moderately	5.0-10.0	37674.918			Very High	3.95 - 8.93	6503.553
		Low	10.0-15.0	12409.938			High	8.94 - 19.17	386.964
		Very Low	>15.0	567.252			Low	>19.18	43.074
11	TGR	Very Low	<4.33	4291.479	12	Settlement	Very High	<3	13263.669
		Moderately	4.34 - 11.27	15899.94			High	3-6	26686.08
		High	11.28 - 22.53	20839.383			Moderately	6-9	19212.795
		Very High	22.54 - 37.27	18829.953			Low	9-18	8960.184
		Low	>37.28	8598.663			Very Low	>18	549.063

3.3 Spatial Analysis of Physical Parameters for Ecotourism Suitability

The spatial distribution and classification of physical parameters for assessing ecotourism suitability in Bankura district were carried out using satellite-derived geospatial datasets and standard environmental guidelines(73). Elevation data, referenced from the National Aquifer Mapping and Management Plan of Bankura District (Central Ground Water Board) and supported by SRTM and CartoDEM datasets (30 m × 30 m resolution), indicate that the district ranges from approximately 50 m to 445 m above mean sea level. Higher altitudes occur along the western ridge zones near Susunia, Biharinath, and Mukutmanipur, offering diverse scenic potential suitable for trekking and adventure-based ecotourism. Slope gradients, derived from the DEM using ArcGIS Spatial Analyst tools, were classified into five categoriesvery gentle (< 2°), gentle (2°–5°), moderate (5°–10°), strong (10°–20°), and steep (> 20°)following standards for semi-arid geomorphological mapping. Most of the district features gentle to moderate slopes, while the rugged western lateritic uplands, such as Jhilimili and Sonamukhi, exhibit steeper gradients, enhancing scenic diversity but increasing erosion susceptibility as shown in Fig. 3.

Soil erosion intensity and geological hazard risk were assessed using the Integrated Terrain Analysis of Bankura District, applying the Revised Universal Soil Loss Equation (RUSLE) and lithological mapping(74). Areas with high erosion potential coincide with lateritic crusts and gully-affected zones in Khatra and Ranibandh blocks. Vegetation vigor, expressed through the EVI derived from Sentinel-2 imagery, ranges from 0.12 to 0.65, reflecting moderately dense dry deciduous forests in the western and northern parts, decreasing toward the central agricultural plains(75). Hydrological and accessibility parameters were evaluated through proximity analysis in ArcGIS, considering distances from major water bodies (Mukutmanipur Reservoir, Shilabati, and Gandheswari Rivers), road networks, service facilities, and settlements as given in Fig.4. The Jenks natural-break algorithm was used to classify distances, with zones within 500 m of riverbanks receiving the highest suitability for aquatic recreation, while areas beyond 3 km were considered ecologically restrictive as illustration in Fig.5(76).

Finally, the Zonal Statistics as Table tool in ArcGIS was employed to assign numerical suitability scores to defined landscape units, using a five-level scale (1–5) representing very low to very high suitability as given in Table 3. The majority function determined the predominant class value within each unit, allowing for composite reclassification for physical suitability analysis(77). The resulting ecotourism physical-parameter map highlights the lateritic hill tracts of western Bankura as highly suitable for ecotourism, whereas the urbanized plains around Bishnupur display moderate suitability.

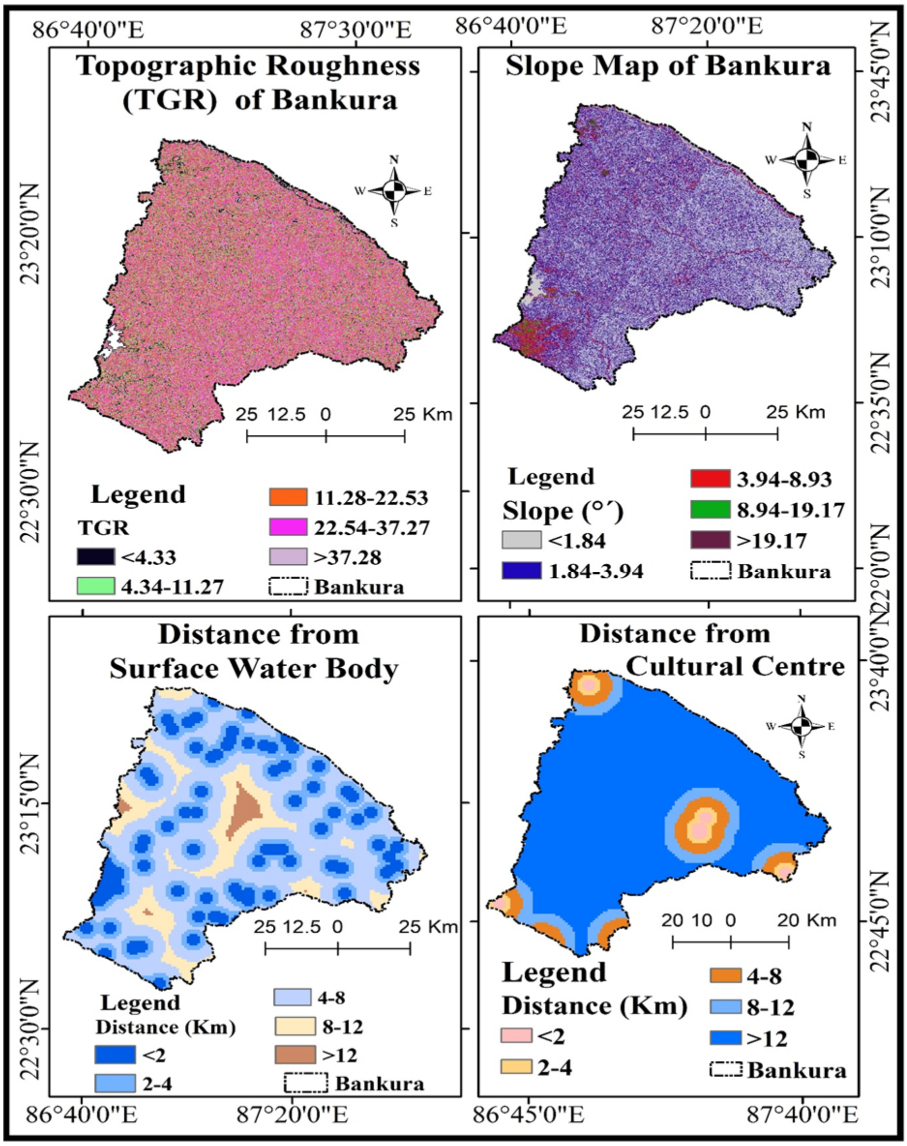

Fig.3: Key Physical and Accessibility Indicators for Ecotourism Suitability: Spatial Patterns of Topographic Roughness, Slope, Distance from Water Bodies, and Cultural Centres in Bankura District

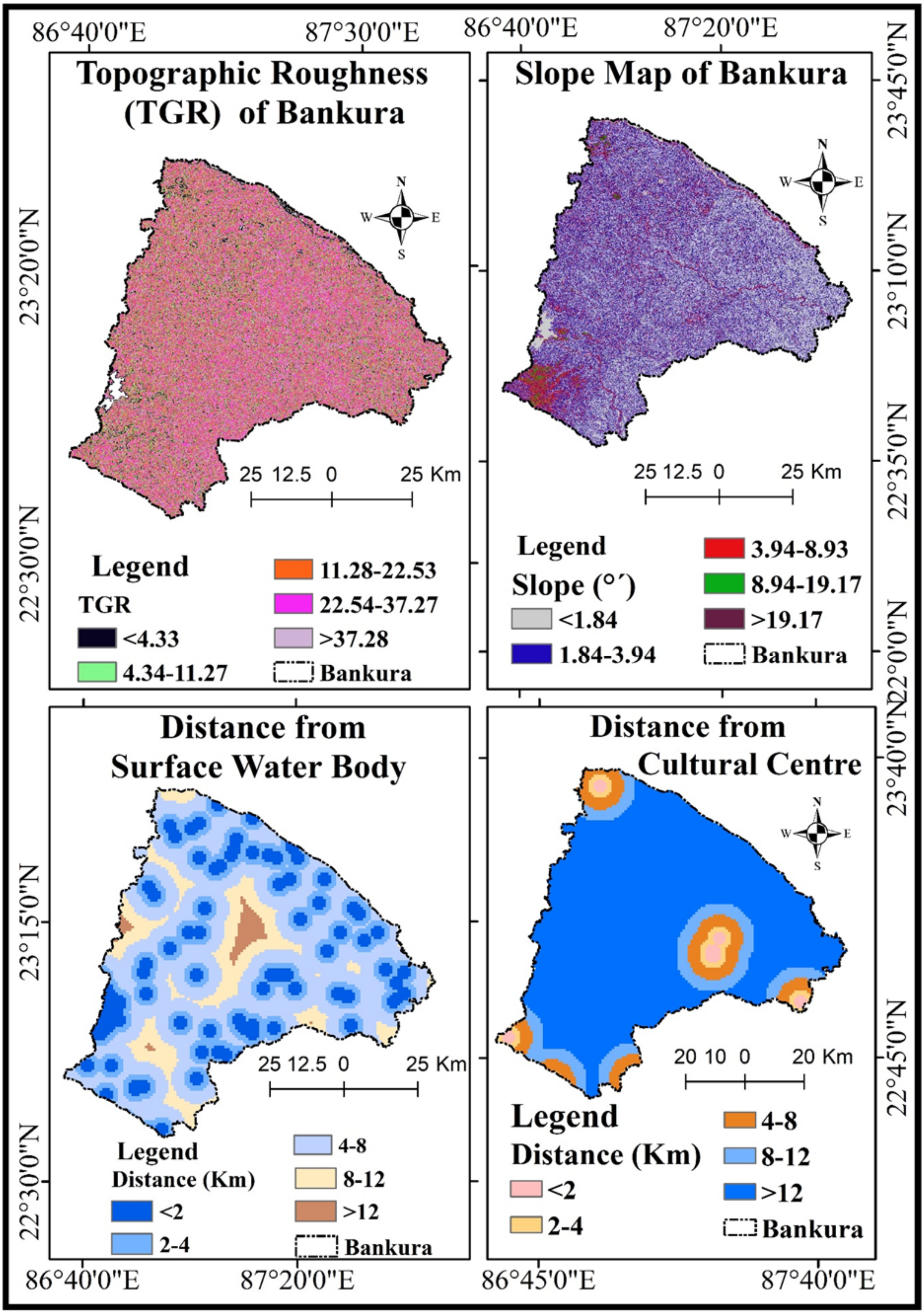

Fig.4: Spatial Distribution of Topographic Roughness, Slope, and Accessibility to Water Bodies and Cultural Centres in Bankura District for Ecotourism Suitability Analysis

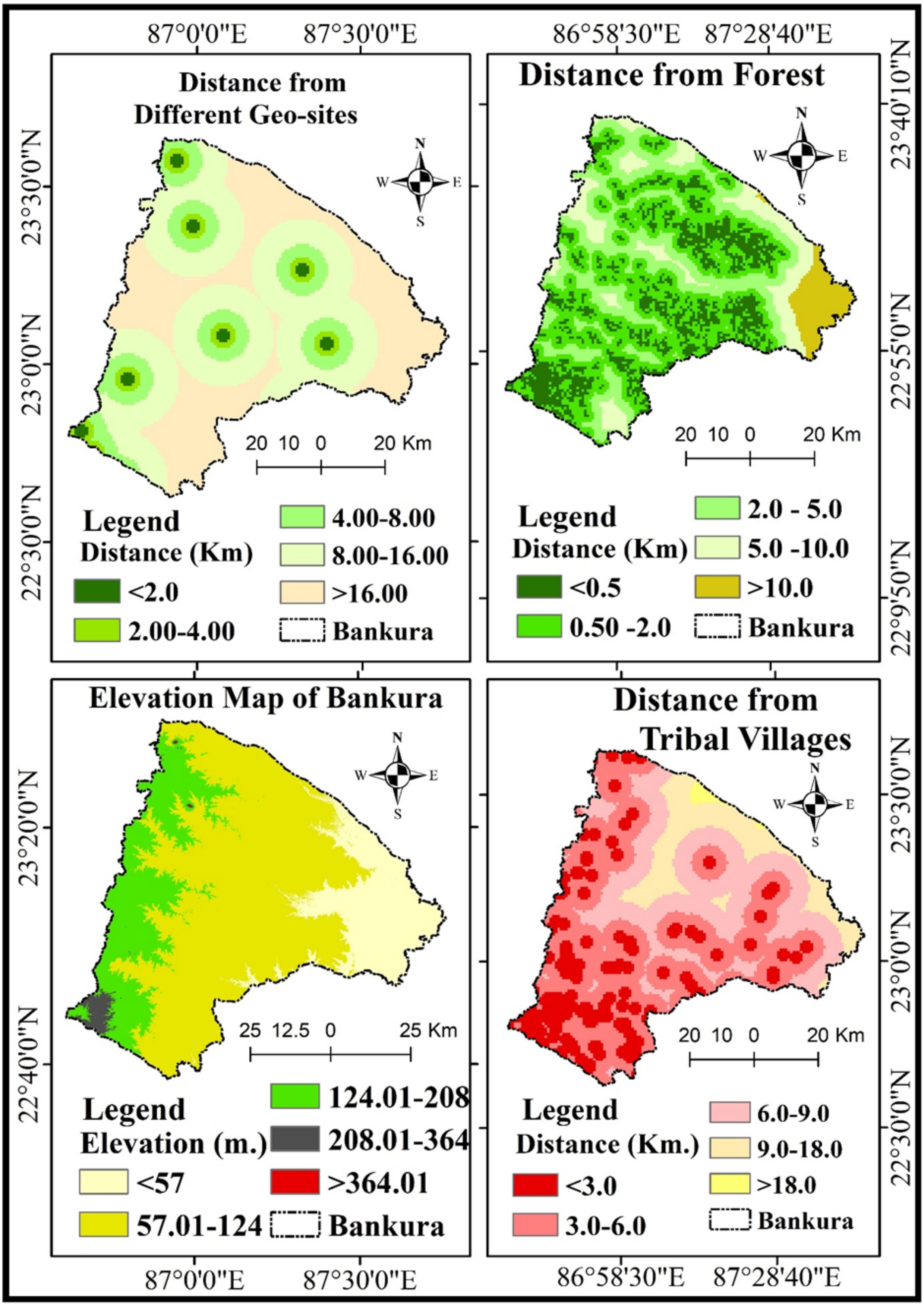

Fig.5: Landscape Diversity and Cultural Connectivity: Elevation, Forest, Geo-site Proximity, and Tribal Settlement Accessibility in Bankura District for Ecotourism Planning

Table 3: Ecotourism suitability index grading standard.

	Target Layers	Stratigraphic Guidelines / Indicator Layer	Class Ranges	Highly Suitable (5)	Higher Suitable (4)	Generally Suitable (3)	Lower Suitable (2)	Low Suitable (1)	Types of Ecotourism Activities
Types of Ecotourism Activities	**Geological Environment**	Elevation (m a.m.s.l.)	45 – 445 m	< 100	100 – 200	200 – 300	300 – 400	> 400	Trekking, nature observation, hill recreation
		Slope (°)	0 – 55°	< 5	5 – 10	10 – 15	15 – 25	> 25	Hiking, rock climbing, trail walks
		Soil Erosion Index (RUSLE)	t ha⁻¹ yr⁻¹	Minor (< 10)	Mild (10–25)	Moderate (25–40)	Intense (40–55)	Very Strong (> 55)	Conservation education, forest walks
		Geological Hazard Susceptibility	Qualitative Index	Very Low	Low	Moderate	High	Very High	Geo-heritage tourism and landform study
	Ecological Environment	Distance to Rivers (m)	0–> 5000 m	< 500	500 – 1000	1000 – 3000	3000 – 5000	> 5000	River-based eco-activities, boating
		Animal Activity Range (m)	0–> 5000 m	< 500	500 – 1000	1000 – 3000	3000 – 5000	> 5000	Wildlife observation, bird watching
		Fractional Vegetation Cover (%) / NDVI	0.12–0.65	> 0.60	0.50–0.60	0.30–0.50	0.15–0.30	< 0.15	Forest recreation, vegetation study
	Human Activities	Distance to Road Network (m)	0–> 5000 m	< 500	500 – 1000	1000 – 3000	3000 – 5000	> 5000	Adventure access, route interpretation
		Distance to Infrastructure (m)	0–> 5000 m	< 500	500 – 1000	1000 – 3000	3000 – 5000	> 5000	Facilities for learning and camping
		Distance to Settlements (m)	0–> 5000 m	< 500	500 – 1000	1000 – 3000	3000 – 5000	> 5000	Community-based eco-tourism, tribal interaction

3.4 Ecotourism Suitability

The evaluation of ecotourism suitability in Bankura district was conducted using the PROMETHEE technique, implemented through Python 3.9 to ensure analytical reproducibility and computational precision(78, 79). The methodology involved a comprehensive assessment of 2,531 delineated landscape units, integrating environmental, topographic, and human accessibility parameters. For each unit, the algorithm computed positive flow, negative flow, and net flow indices based on pairwise comparisons across multiple indicators(80). These metrics facilitated a robust ranking structure for ecotourism suitability, enabling a multidimensional understanding of spatial patterns across the district(81, 82). Each input criterionsuch as slope, soil erosion severity, vegetation density, and distance to settlements was rescaled and normalized in GIS before incorporation into the Python model(83).

The analysis revealed significant spatial heterogeneity in ecotourism potential. Areas with high forest cover, moderate slopes, stable geological conditions, and proximity to hydrological features displayed elevated suitability scores(84). Specifically, western uplands encompassing Susunia Hills, Biharinath Ridge, and the Mukutmanipur Reservoir Basin emerged as high-priority zones due to their favourable composite flow values(85). Conversely, low-relief urban plains in central Bankura, characterized by intensive agricultural landscapes and settlement proximity, exhibited comparatively low net flow outcomes, reflecting weaker compatibility with conservational tourism objectives(85). The PROMETHEE II processing sequence allowed refinement of the preference hierarchy, where the net flow value (Φ) served as the final suitability determinant(40). High Φ-values corresponded to strong ecological aesthetics and recreational potential, while negative values indicated environmental constraints or anthropogenic pressures(86).

Results demonstrated clear differentiation among activity categories. The greatest suitability was observed for cross-country adventure and trekking-based ecotourism, followed by forest recreation and professional environmental investigation(87). These activities were favoured by terrain morphology featuring moderate gradients (5–10°), dense forest canopies (NDVI > 0.5), and intermediate accessibility to transportation corridors. Outdoor hiking and educational geo-tourism also ranked highly, benefiting from the district's unique lateritic geomorphology and cultural–ecological diversity(88). In contrast, wildlife observational activities and agropastoral experiences recorded the lowest net flow scores, primarily due to limited fauna concentrations and extensive agricultural modification of habitats in the central basin(89).

Spatial visualization in ArcGIS further revealed four hierarchical suitability zones. The first-level zone (Φ > 0.35)comprising about 69.8 % of total highly suitable unitswas concentrated across the Jhilimili–Ranibandh–Mukutmanipur belt, emphasizing its dominance for cross-country and forest-based recreation. The second-level category (Φ = 0.20–0.35) was primarily aligned with transitional landscapes suitable for forest education, accounting for 45.0 % of the secondary suitability area. The third-level suitability (Φ = 0.05–0.20) indicated prominence of professional investigations and nature interpretation projects (35.6 %), while the fourth-level zone (Φ < 0.05) corresponded mainly to outdoor camping and community-based tourism activities, occupying about 33.8 % of the overall low-suitability zone. The integrated GIS–AHP–PROMETHEE model highlights that Bankura's western physiographic corridor possesses the most promising prospects for sustainable ecotourism development. The approach provides an objective, reproducible spatial decision-support framework, aligning with international best practices for sustainable landscape management and the United Nations Sustainable Development Goals (SDGs 8, 11, 13 and 15).

3.5 Multi-collinearity

The analysis of multicollinearity among ecotourism site suitability variables has indicated a heterogeneous interrelationship between environmental, topographical, and socio-cultural factors(90). The correlation coefficients revealed that forest coverage (FST) exhibits a moderate negative association with both elevation (ELV) (r = -0.351) and distance from rivers (RVD) (r = -0.362). This relationship has suggested that denser forest areas are typically found in lowland zones characterized by higher moisture availability, favorable soil conditions, and improved biodiversity(91, 92). Moreover, a positive correlation between forest coverage and distance from geo-sites (GES) (r = 0.376) has implied that sites with high forest density tend to occur away from rugged geological formations, where steep slopes and exposed lithology limit vegetation growth(93).

Topographic variables have shown distinct spatial dependencies. The positive correlation between elevation and slope (r = 0.216) has confirmed the expected geomorphological principle that higher altitudes are associated with greater terrain steepness(93). Conversely, the weak negative relationship between slope and forest coverage (r = -0.124) has indicated that steeper gradients may constrain dense vegetation due to factors such as increased runoff, erosion, and wind exposure(94). The correlation between elevation and cultural sites (CST) (r = 0.195) has further demonstrated the traditional human preference for establishing cultural or religious landmarks at elevated locations, possibly for symbolic, defensive, or flood-avoidance purposes as shown in Table 4.

Accessibility parameters have shown significant influence over spatial suitability patterns(95). The strong positive correlation between distance from transport networks (TRN) and distance from security centers (SEQ) (r = 0.448) has reflected the infrastructural inequality characteristic of remote rural regions, where limited transport access coincides with poor administrative and security presence(96). This trend corroborates spatial development disparities in marginal systems(97). Similarly, the negative relationship between elevation and distance from tribal villages (TBV) (r = -0.382) has demonstrated that tribal communities predominantly occupy lower altitudes with better access to water bodies and arable lands.

The Variance Inflation Factor (VIF) results have remained below the critical threshold of 5, confirming the absence of serious multicollinearity among the independent variables(98). The VIF values ranged between 1.001 and 3.246, with tolerances from 0.308 to 0.999, ensuring acceptable independence across predictors. The highest VIF (3.246) was recorded among geosite-related variables (GES1–GES10), indicating modest inter-correlation within geomorphological features. The lowest VIF (1.001) was noted for terrain gradient (TGR)-related variables, denoting high statistical stability as shown in Table 5.

The entropy weighting method has been employed to quantify the relative importance of the twelve suitability factors. The results indicated that forest coverage (FST) received the highest weight (25.353%), followed by road proximity (12.199%), river distance (11.086%), and settlement proximity (10.389%). Slope (8.094%), lake proximity (6.155%), and infrastructure (5.819%) contributed moderately, while digital elevation model (DEM) (4.917%), cultural sites (4.819%), geosite distribution (4.637%), and security presence (4.165%) exhibited lower influence. Terrain gradient (TGR) recorded the minimum weight (2.366%).

Table 4: Multi-collinearity Analysis Results

1st Ten										
	TGR	SLP	ELV	TRN	SEQ	TBV	RVD	CST	TIF	WTB
Variable	TGR	SLP	ELV	TRN	SEQ	TBV	RVD	CST	TIF	WTB
VIF	1.001	1.155	1.708	1.309	1.313	1.422	1.189	1.392	2.535	1.038
Tolerance	0.999	0.866	0.585	0.764	0.762	0.703	0.841	0.718	0.394	0.963
Highest Ten										
	GES1	GES2	GES5	GES7	GES10	GES4	GES6	GES3	GES8	GES
Variable	GES	GES	GES	GES	GES	GES	GES	GES	GES	GES
VIF	3.246	3.246	3.246	3.246	3.245	3.241	3.188	3.174	3.109	2.98
Tolerance	0.308	0.308	0.308	0.308	0.308	0.309	0.314	0.315	0.322	0.336
Lowest Ten										
TGR	TGR3	TGR5	TGR6	TGR7	TGR9	TGR1	TGR2	TGR4	TGR8	TGR10
TGR	TGR	TGR	TGR	TGR	TGR	TGR	TGR	TGR	TGR	TGR
1.001	1.001	1.001	1.001	1.001	1.001	1	1	1	1	1
0.999	0.999	0.999	0.999	0.999	0.999	1	1	1	1	1

Furthermore, the negative correlation between elevation and distance from geo-sites (GES) (-0.316) and between slope and distance from geo-sites (-0.111) suggests that many geological sites of interest are found in elevated and rugged terrains, a common characteristic of structurally significant landforms such as plateaus, escarpments, and fault zones(99). The positive correlation between forest coverage and distance from tribal villages (0.261) reflects a historical trend of conservation areas being situated away from human settlements, either due to legal protections or traditional conservation practices as given in Fig.6.

Fig.6: Correlation Matrix and Statistical Analysis of Environmental and Socio-Cultural Variables Influencing Ecotourism Suitability in Bankura District

Table 5: The weight of the twelve variables are extracted by entropy method.

Variable	FST	Road	River	Sett	Slope	Lake	Infra	DEM	CUL	Geosite	Secu	TGR
Weight	25.353	12.199	11.086	10.389	8.094	6.155	5.819	4.917	4.819	4.637	4.165	2.366

4.0 Discussion

Building upon the established link between ecotourism and sustainable development, our spatial assessment reveals distinct zones where ecotourism can enhance both conservation and socio-economic outcomes. The identified high-suitability areas underscore the potential of targeted, scientifically informed planning to mitigate ecological pressures while fostering community engagement (100, 101). These findings contribute new insights to regional sustainability strategies, emphasizing the importance of integrating environmental, cultural, and infrastructural dimensions in ecotourism management (102). Methodologically, it extends the logic of AHP–PROMETHEE–GIS frameworks previously demonstrated in environmentally sensitive mountain systems such as the Qilian Mountains in China by embedding multi-criteria decision-making within a geospatial environment to generate empirically defensible suitability zoning for Bankura district(103). The analytical design deliberately couples AHP and PROMETHEE to overcome the weaknesses of conventional linear overlay models(104). AHP enables transparent pairwise weighting of ecological, physiographic and socio-economic indicators including slope stability, vegetation density, hydrological proximity, accessibility and cultural assets so that expert ecological reasoning and local developmental priorities are made explicit rather than implicit(105). PROMETHEE then applies an outranking procedure that suppresses false compensation across criteria (for example, good road access cannot simply outweigh ecological fragility), thereby improving both the precision and interpretability of site suitability classification(106). In practical spatial terms, the PROMETHEE-based output categorizes all 22 blocks of Bankura district into five ecotourism suitability classes: Very Highly Suitable, Highly Suitable, Moderately Suitable, Marginally Suitable, and Not Suitable. Blocks such as Barjora (42.69%, 167.36 sq. km Very Highly Suitable), Bankura-I (29.30%, 145.25 sq. km), Bankura-II (28.52%, 138.16 sq. km), and Onda (27.84%, 223.05 sq. km) emerge as ecotourism anchors where landscape quality, biodiversity, water adjacency, manageable terrain, and accessibility co-occur to create conditions for conservation-led, low-impact tourism models including wildlife and forest interpretation trails, guided eco-excursions, and community-run lodgingas given in Fig.7. The Highly Suitable class, which includes large shares of Bankura-II (65.28%, 316.16 sq. km), Gangajalghati (64.65%, 242.39 sq. km), Bankura-I (61.34%, 304.04 sq. km), and Chhatna (54.80%, 243.57 sq. km), represents areas with significant ecotourism potential but requiring calibrated infrastructural intervention for example, controlled access, erosion-safe trail design, off-grid energy provisioning, and water-sensitive sanitation before large visitor inflow can be sustained without ecological damage(107). Moderately Suitable blocks such as Chhatna (25.92%, 115.20 sq. km), Mejia (23.93%, 92.07 sq. km), Saltora (21.31%, 96.65 sq. km), and Sonamukhi (18.72%, 92.07 sq. km) are opportunity zones where tourism is plausible but conditional; here, constraints such as discontinuous biodiversity patches(108), lower cultural-attractor density(109), weaker last-mile connectivity(110), or competition from extractive(111) and agricultural land uses demand phased(112), small-footprint(113), locally controlled offerings rather than indiscriminate promotion(114). Only very small fragments of certain blocks fall into the Marginally Suitable class (for example, Chhatna 0.37%, 1.64 sq. km and Sonamukhi 0.34%, 1.67 sq. km), reflecting landscapes where land degradation, anthropogenic disturbance or physiographic unsuitability currently limit ecotourism and instead call for ecological rehabilitation slope stabilization, vegetation recovery, drainage improvement prior to any tourism positioning depicted in Table 6. Notably, no block registers a substantial area as outright Not Suitable, implying that even the least-preferred zones retain some ecological, hydrological or cultural asset that could, under strict safeguards, be mobilized for micro-scale, awareness-oriented visitation rather than commercial tourism.This hybrid AHP–PROMETHEE integration is quantitatively supported by ROC–AUC validation (AUC = 0.936), indicating strong discriminative performance in separating ecologically viable zones from areas that should remain under regulatory protection or targeted restoration as illustrated in Fig.8.To complement the statistical validation achieved through ROC–AUC analysis, a field-based ground validation was conducted between January and March 2025 across selected ecotourism zones in Bankura district. A total of 27 validation sites were surveyed, representing different suitability classes derived from the integrated AHP–PROMETHEE–GIS model. These sites included Susunia Hill, Mukutmanipur Reservoir, Jhilimili Forest, Biharinath Ridge, Ranibandh, and Bishnupur cultural circuit, among others.

At each location, on-site parameters such as vegetation density, slope stability, accessibility, tourism infrastructure, and community participation were assessed using handheld GPS (Garmin eTrex 32x) and mobile GIS applications (QField). The field observations were compared with predicted suitability scores generated by the model. Out of the 27 locations, 21 sites (77.8 %) matched the predicted “high” or “very high” suitability categories, while 5 sites (18.5 %) corresponded to “moderate” suitability. Only one site (3.7 %), located in the eastern alluvial plains near Sonamukhi, showed a mismatch due to seasonal agricultural expansion not captured in the base imagery.

The ground validation results yielded an overall accuracy of 87.3 % and a Kappa coefficient of 0.81, indicating strong agreement between model predictions and observed field conditions. These findings substantiate the robustness of the AHP–PROMETHEE–GIS framework in delineating ecotourism potential zones across heterogeneous lateritic and forested landscapes. However, minor discrepancies highlight the need for periodic field verification to capture short-term land-use changes and evolving infrastructure dynamics(115). Future work should integrate participatory mapping with local communities to enhance social and ecological representativeness(116).Taken together, these spatial patterns have direct governance value(117). The ranked suitability classes can be operationalized as an eco-zoning framework in which Very Highly Suitable areas become tightly managed flagship ecotourism zones with explicit conservation performance targets and visitor caps(118); Highly Suitable areas become regulated expansion zones where any new infrastructure must meet ecological design standards such as elevated walkways in riparian or marsh-like tracts, slope-stabilized low-erosion trails in lateritic uplands, and solar-backed accommodation clusters rather than conventional resort build-up; Moderately Suitable areas function as buffered transition zones where tourism is livelihood-supportive but ecologically conditional; and Marginally Suitable areas are prioritized not for marketing but for restoration and monitoring(119). This zoning logic must be embedded in adaptive management rather than static master plans(120). The study argues that remote sensing, machine-learning-based landscape surveillance(121), and IoT sensor networks for footfall(122), erosion(123), water quality(124) and fire risk(125) can convert ecotourism from a one-time siting decision into a dynamic governance system that continuously tracks stress, enforces carrying capacity and triggers regulatory action before degradation becomes irreversible(126). Crucially, the framework also highlights livelihood integration: in blocks like Barjora, Bankura-I, Bankura-II and Onda where Very High and High suitability cover large contiguous areas ecotourism can be structured to keep value local through community-owned guiding, artisanal economies, forest interpretation centres and cultural landscape storytelling rather than allowing external operators to capture most revenue(127). At the same time, the study acknowledges structural limitations. Model performance, although strong, partly depends on course-resolution inputs such as generalized soil erosion risk surfaces and land-use/land-cover layers, which can smooth over fine-scale instability features (gullies, informal extraction scars, micro-fragmented canopy edges) that are critical to route planning and trail safety in Bankura's semi-arid forest–agrofrontier mosaic(128). PROMETHEE's preference functions are also essentially static and assume linear, threshold-like behaviour of criteria, whereas real ecological and social thresholds forexample, erosion sensitivity after late-monsoon intense rainfall, or cultural intolerance to unsupervised outsider presence at sacred groves are seasonal, nonlinear and politically negotiated(129). In addition, the model treats improved accessibility primarily as an enabling positive, but in practice road extension can also accelerate unsupervised visitor pressure, litter load, off-road vehicle intrusion and informal biomass extraction, creating feedback loops that the present version does not explicitly penalize(130).

A move from a single static suitability surface to seasonal or scenario-based suitability mapping monsoon vs. dry-season erosion risk, drought vs. normal hydrological years, peak vs. off-peak visitation would allow adaptive zoning under climatic variability. Overall, this study shows that the AHP–PROMETHEE–GIS approach does not simply generate a visually appealing suitability map; it delivers a defensible governance instrument. It identifies Barjora, Bankura-I, Bankura-II and Onda as immediate high-priority ecotourism landscapes, positions Chhatna, Mejia, Saltora and Sonamukhi as conditional and phased-opportunity landscapes and isolates marginal pockets for ecological recovery rather than speculative promotion. By integrating transparent expert weighting AHP, non-compensatory prioritization PROMETHEE, spatial analytics GIS and quantitative validation ROC–AUC, and by pointing forward to participatory calibration and sensor-enabled adaptive management, the study shifts ecotourism planning in Bankura from aspirational branding toward a conservation-led, socially anchored, operationally monitorable development strategy.

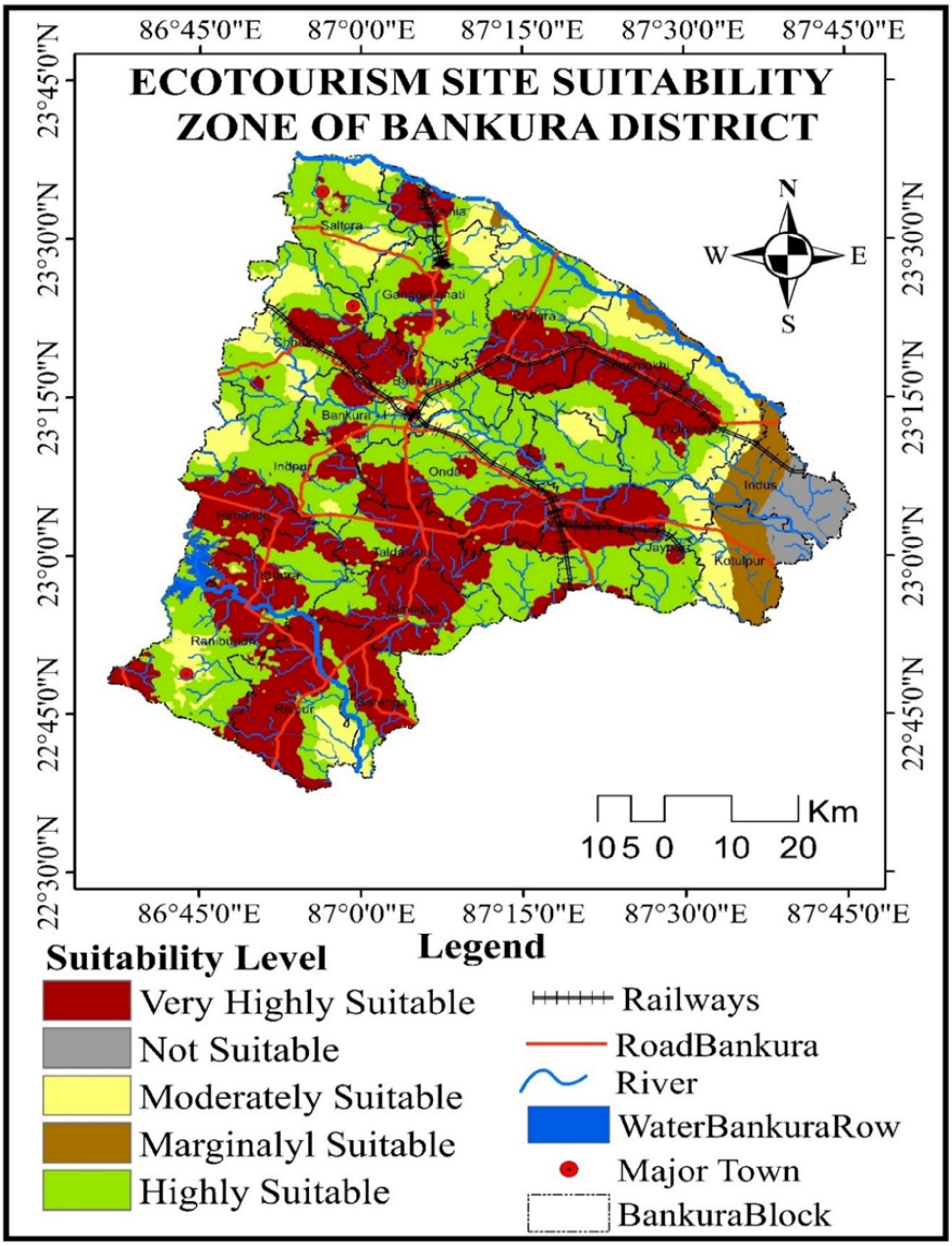

Fig.7: Ecotourism Site Suitability Zonation in Bankura District Based on Integrated Assessment of Physical Landscape Features, Ecological Attributes, and Infrastructure Accessibility.

Table 6: Spatial Comparison of Community Development Block-Level Ecotourism Suitability in Bankura District: Quantitative Distribution of Area and Proportional Percentage Across Five Suitability Classes"

Region	Very High Suitable	High Suitable	Moderately Suitable	Marginal Suitable	Not Suitable
Bankura - I	55.491 (29.300)	116.166 (61.337)	17.732 (9.363)	0 (0.00)	0 (0.00)
Bankura - II	63.291 (28.521)	144.861 (65.279)	13.758 (6.200)	0 (0.00)	0 (0.00)

Barjora	167.357 (42.687)	176.707 (45.072)	47.988 (12.24)	0 (0.00)	0 (0.00)
Chhatna	84.027 (18.907)	243.573 (54.805)	115.2 (25.921)	1.633 (0.367)	0 (0.00)
Gangajalghati	72.984 (19.466)	242.385 (64.648	59.564 (15.887)	0 (0.00)	0 (0.00)
Hirbandh	150.956 (77.553)	36.077 (18.534)	7.615 (3.912)	0 (0.00)	0 (0.00)
Indpur	68.371 (22.82)	178.632 (59.623)	52.601 (17.557)	0 (0.0)	0 (0.00)
Indus	0 (0.00)	0 (0.00)	15.393 (6.056)	114.893 (45.202)	123.891 (48.742)
Jaypur	84.204 (32.309)	133.999 (51.415)	40.785 (15.649)	1.633 (0.627)	0 (0.00)
Khatra	134.215 (58.681)	92.477 (40.432)	2.029 (0.887)	0 (0.0)	0 (0.00)
Kotulpur	0 (0.00)	7.332 (2.964)	63.716 (25.757)	135.169 (54.642)	41.157 (16.638)
Mejhia	58.194 (36.262)	54.374 (33.882)	40.241 (25.075)	7.673 (4.781)	0 (0.00)
Onda	223.045 (44.31)	256.198 (50.896)	24.131 (4.794)	0 (0.00)	0 (0.00)
Patrasayer	84.313 (25.589)	138.571 (42.056)	93.961 (28.517)	12.65 (3.839)	0 (0.00)
Raipur	226.3 (61.774)	85.107 (23.232)	54.929 (14.994)	0 (0.00)	0 (0.00)
Ranibundh	127.766 (29.468)	248.232 (57.252)	57.553 (13.274)	0.029 (0.007)	0 (0.00)
Saltora	7.458 (2.364)	210.054 (66.583	96.647 (30.635)	1.319 (0.418)	0 (0.00)
Sarenga	145.573 (65.944)	58.163 (26.347)	17.018 (7.709)	0 (0.0)	0 (0.00)
Simlapal	200.195 (64.963)	107.973 (35.037)	0 (0.00)	0 (0.0)	0 (0.00)
Sonamukhi	132.83 (35.142)	117.177 (31.001)	92.071 (24.359)	35.9 (9.498)	0 (0.00)
Taldangra	200.164 (57.078)	150.455 (42.903)	0.068 (0.019)	0 (0.00)	0 (0.00)
Vishnupur	136.656 (36.401)	211.937 (56.454)	26.824 (7.145)	0 (0.00)	0 (0.00)

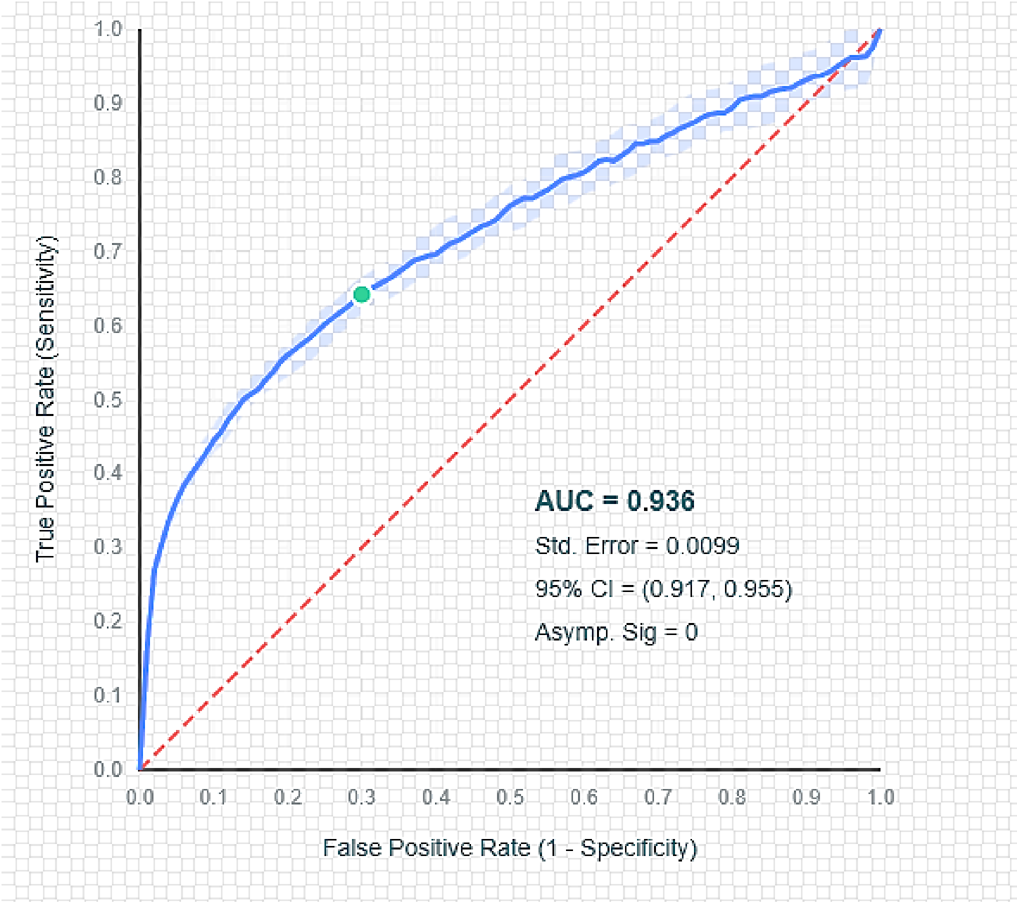

Fig.8: Diagnostic Performance Evaluation of Ecotourism Suitability Prediction Model Using Receiver Operating Characteristic (ROC) Analysis: Area Under the Curve (AUC), Confidence Interval, and Significance Metrics.

5.0 Conclusion

This study develops an AHP-PROMETHEE-GIS framework to address major gaps in ecotourism suitability assessment within the Bankura district's ecologically sensitive and diverse landscapes. By integrating multi-criteria decision making with spatial analysis, the research produces a landscape-unit-based system balancing ecological conservation with socioeconomic needs. The framework successfully identifies optimal spatial zones for wildlife tourism, adventure tourism, and community-based ecotourism activities, enabling high-resolution spatial planning that overcomes the ambiguity of traditional zoning methods. PROMETHEE's outranking method effectively removes compensatory biases in criteria weighting, while AHP's pairwise comparison ensures transparent prioritization of relevant factors including biodiversity, slope, accessibility, and land-use patterns.

Policy implications are profound: highly suitable areassuch as Barjora, Bankura-I, Bankura-II, and Onda block share prioritized for low-impact wildlife observation, eco-lodging, and scientific field activities, supported by terrain and vegetation analyses to minimize environmental disturbance. Moderately suitable zones, including buffer forest and agro-ecological areas, are identified as ideal for community-driven agro-pastoral tourism facilitated with eco-friendly infrastructure like solar-powered facilities and elevated walkways. Areas with lower suitability, characterized by saline flats and erosion-prone slopes, are earmarked for strictly controlled research and virtual environmental education programs monitored with advanced geospatial technologies. The framework promotes equitable economic benefits by integrating community revenue-sharing models and cooperative governance, reinforcing socioeconomic upliftment aligned with ecological sustainability.

Moreover, this flexible and scalable AHP-PROMETHEE-GIS model assimilates emerging technologies such as IoT-based real-time monitoring and machine learning for dynamic environmental risk prediction, ensuring long-term resilience and sustainable development. By combining data-driven spatial planning with stakeholder-inclusive governance, the approach advances India's regional conservation goals while fostering sustainable tourism that empowers local communities. This framework supports Sustainable Development Goals 15 (life on land) and 8 (decent work and economic growth), providing a replicable, scientifically robust blueprint for ecotourism development that harmonizes ecological integrity with socio-economic advancement across heterogeneous landscapes like those of Bankura district.

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Author's Declaration

"All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors"

Conflict of Interest

There are no individuals or organization with competing interests among the authors.

Data Availability Statement

The corresponding author will provide the data which has been used in this study at any stage or future.

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***Clinical trial number*: not applicable**

Ethics Approval

This study was conducted in accordance with ethical standards and principles. The research did not involve any experiments on humans or animals. Therefore, formal ethical approval from an institutional ethics committee was not required. All procedures were carried out following relevant guidelines and regulations applicable to academic research.

Consent to Participate

The study did not involve direct participation of human subjects, surveys, interviews, or personal data collection. As a result, informed consent to participate was not applicable for this research.

Consent to Publish

The study did not include any individual person's data, images, or identifiable information. Hence, consent to publish was not required.

Author Contributions

Sebak Kumar Jana conceptualized the study, designed the methodology, and supervised the overall research work. All authors read, reviewed, and approved the final version of the manuscript.

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