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Mapping Ecological Connectivity among Isolated Freshwater Habitats Using Landscape-Based Spatial Analysis

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Abstract: Ponds, tanks, wetlands and small lakes are examples of freshwater ecosystems which house aquatic diversity. However, agriculture, urban development and drainage systems continue to cause fragmentation of these ecosystems. In this study, a spatial methodology based on a landscape approach that employs remote sensing, GIS, landscape metrics, least cost path analysis and graph theory was developed to map connectivity between isolated freshwater habitats in a 100 km² landscape. A total of 24 patches amounting to 3.84% of the total landscape were mapped, while 58.33% were found to be isolated. There were nine least cost corridors and habitat patches H03 and H10 were identified as important corridors. An ecosystem restoration scenario increased the Probability of Connectivity from 18.60% to 31.40%. The framework supports corridor restoration and conservation prioritization.

Keywords: Freshwater Habitats; Ecological Connectivity; Landscape Fragmentation; GIS; Remote Sensing; Least-Cost Path; Habitat Corridors; Spatial Analysis.

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I. Introduction

Background of the Study

Freshwater ecosystems like lakes, ponds, wetlands, rivers, and reservoirs are important ecological components providing diverse aquatic life, maintaining ecological balance, and offering a range of ecosystem services (Field & Parrott, 2022). These aquatic ecosystems are involved in water regulation, nutrient cycling, sediment trapping, and supporting both aquatic and terrestrial food chains (Erős et al., 2012). Nevertheless, due to expanding agricultural lands, urbanization, construction, changes in drainage, and landscape transformation, freshwater landscapes are being strongly modified. These anthropogenic impacts result in dividing formerly contiguous aquatic ecosystems into fragmented spatially isolated habitat patches.

The concept of ecological connectivity refers to the ability of aquatic organisms and ecological processes to move between habitat patches across a landscape (Luque et al., 2012; (Matos et al., 2019). The first concept of connectivity includes structural connectivity which is connected with the distribution of habitats within the landscape and their proximity. Functional connectivity deals with specific movements of species and landscape permeability (Ding et al., 2025). Fragmentation and spatial isolation can restrict dispersal, limit genetic exchange, reduce recolonization following local disturbances, and increase the probability of population decline. These effects are particularly important for small ponds, seasonal wetlands, and isolated freshwater habitats that depend on connections with surrounding aquatic ecosystems for long-term ecological persistence (Miao et al., 2019).

Habitat assessment for freshwater habitats traditionally focuses on factors such as habitat size, patch density, and Euclidean distance without taking into account land cover features, artificial barriers, and landscape resistance (Johnson & Host, 2010; McCullough et al., 2019). The above methods will thus likely understate the ecological isolation experienced by some organisms while ignoring movement corridors. The inclusion of indicators of spatial fragmentation, connectivity analysis, modeling of landscape resistance, and corridor identification in assessing freshwater habitats will give an in-depth insight of the habitats

(Bishop-Taylor et al., 2015). This integrated framework supports systematic conservation prioritization, habitat restoration planning, and sustainable freshwater landscape management (Phillipsen et al., 2015).

Research Gap

The current study was triggered by four gaps. First, there is no integration of the distribution of freshwater habitats and the fragmented landscape. Second, the concept of landscape resistance is overlooked during assessments of connectivity of isolated water bodies. Third, key habitat patches for restoration are not detected on the basis of connectivity analysis (Bishop-Taylor et al., 2015). Fourth, restoration corridors connecting isolated freshwater habitats are not prioritized sufficiently in a spatial context. Filling these gaps requires an integrated approach based on remote sensing, landscape metrics, least cost path modeling and graph analysis.

Research Objectives

There were four main aims for this study. The first one was the delineation and mapping of the isolated freshwater habitats through remote sensing and GIS. The second one was the quantification of landscape fragmentation through spatial landscape metrics. The third one was the estimation of ecological connectivity through least cost paths and graphs. The fourth one was the identification of priority freshwater habitats and ecological corridors for conservation and restoration. These objectives provide an ordered sequence that guides the presentation of the results.

Research Questions

Four research questions were developed to guide the analysis. What are the spatial patterns of freshwater habitat distribution in the study landscape? What are the most significant land cover properties for habitat fragmentation? What are the key freshwater habitat patches that provide connectivity for the movement? Where conservation efforts need to focus in order to enhance connections among separated water bodies? Answering the above questions will create a link between spatial distribution of habitats and the processes involved in movement. This way one can provide the managers with information on how to focus conservation efforts.

This paper is further divided into four sections. Section 2 presents the study area, spatial data used in the study, pre-processing of satellite imagery, landscape fragmentation indices, least cost paths and graph analysis for habitat connectivity. In section 3, habitat distribution, fragmentation, ecological corridors and key patches of habitat connectivity will be discussed. Ecological implications, corridors significance and conservation efforts will be discussed in section 4. Finally, Section 5 concludes the study by summarizing key findings, limitations, and future research directions.

II. Materials and Methods

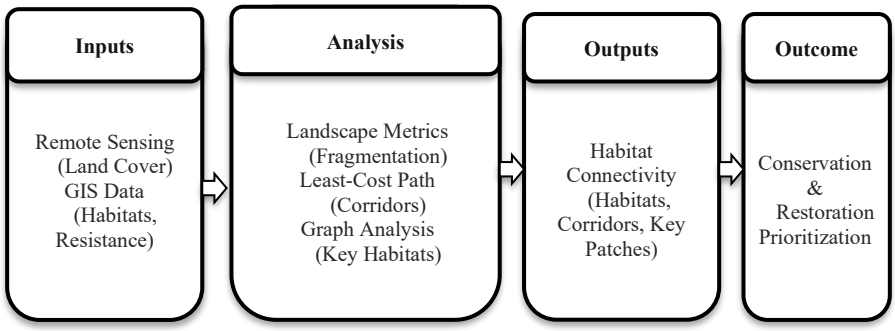


Figure 1: Conceptual Framework for Mapping Ecological Connectivity Among Freshwater Habitats

Figure 1 demonstrates the framework designed for the integration of remote sensing and GIS with the spatial analysis based on the landscape approach. The landscape metrics provide information on the fragmentation of the habitat, the least cost path models help to identify the potential ecological corridors and the graph-based analysis helps to determine the critical habitat patches, facilitating informed conservation planning, habitat restoration, and sustainable freshwater ecosystem management.

Study Area

The experiment was carried out in a freshwater landscape of area 100 sq km located in Tamil Nadu, India. This landscape contains several isolated ponds, irrigation tanks, small wetlands, and various drainage structures connecting them. The landscape has a semi-arid to sub-humid tropical climatic condition receiving rainfall mainly from the northeast monsoon season, with gentle undulating topography suitable for irrigation by tanks. Agricultural lands form the major portion of the matrix with villages and roads, as well as barren areas and scrub land. Major anthropogenic pressures include crop expansion, village and road development, groundwater extraction and modification of natural drainage lines, all of which influence the size, isolation and persistence of freshwater habitats.

Data Collection and Sources

The spatial data utilized is listed in table 1 below. Satellite images from Sentinel-2 were used for mapping waterbodies and vegetation cover (McCullough et al., 2019), while satellite images from Landsat 9 were used for land cover classification. The SRTM digital elevation model was used for terrain and drainage modeling, while the road network was derived from OpenStreetMap to act as barriers. The images were collected during a similar period to ensure uniformity in water extents.

Table 1: Spatial Datasets and their Applications

Dataset	Source	Resolution	Application
Sentinel-2 imagery	Copernicus	10 m	Water and vegetation mapping
Landsat 9 imagery	USGS	30 m	Land-cover classification
Digital elevation model	SRTM	30 m	Elevation and terrain analysis
Land-use data	Satellite classification	10–30 m	Landscape resistance
Waterbody boundaries	GIS digitisation	Variable	Habitat patch identification
Road network	OpenStreetMap	Vector	Barrier identification
Drainage network	DEM/GIS extraction	30 m	Hydrological pathway mapping

Satellite Image Preprocessing

The cloud minimized images were then processed with atmospheric corrections and cloud masking before appropriate spectral bands were chosen. The waters were highlighted through the use of Normalized Difference Water Index (NDWI) and Modified Normalized Difference Water Index (MNDWI) as shown by equations 1 and 2. Afterwards, land classification and habitat boundary extraction were done, and results were verified through independent validation samples (Phillipsen et al., 2015; Ding et al., 2025). Thresholds for water bodies were set locally due to variability in thresholds based on turbidity, vegetation cover, and season.

$$\mathrm{NDWI} = \frac{\mathrm{Green}-\mathrm{NIR}}{\mathrm{Green}+\mathrm{NIR}} \qquad (1)$$

$$\mathrm{MNDWI} = \frac{\mathrm{Green}-\mathrm{SWIR}}{\mathrm{Green}+\mathrm{SWIR}} \qquad (2)$$

Land-Use and Land-Cover Classification

Landscape was categorized into five classes, namely agricultural land, built-up land, natural vegetation, fresh water, and barren or open land (Table 2). Supervised classification model was trained using sample images; accuracy assessment was performed using error matrix (Field & Parrott, 2022). Agricultural land

made up 42.10% of the landscape, while fresh water constituted only 3.84% of the total area, which clearly shows that aquatic habitat is a smaller component of the landscape.

Table 2: Land-Use and Land-Cover Classification of the Study Landscape

Land-cover category	Area (km²)	Area (%)	Ecological relevance
Agricultural land	42.10	42.10	Potential runoff and habitat pressure
Built-up area	18.00	18.00	High artificial disturbance
Natural vegetation	25.00	25.00	Movement-supporting matrix
Freshwater bodies	3.84	3.84	Primary aquatic habitats
Barren/open land	11.06	11.06	Variable movement resistance
Total	**100.00**	**100.00**	

Landscape Fragmentation Analysis

The fragmentation metrics were based on the following calculations for patches number (NP), patches density (PD), mean patch area (AREAMN), edge density (ED) and largest patch index (LPI), provided in table 3 (Miao et al., 2019). The following formulas include: N – patches number, A – the area of the whole landscape, AT – the area of total freshwater habitat, Amax – the area of the largest patch, E – total freshwater habitat edge length. All metrics were calculated using FRAGSTATS and QGIS software and the resolution of analysis and connectivity value were the same for all indicators.

Table 3: Landscape Metrics and their Mathematical Descriptions

Metric	Formula	Interpretation
Number of patches (NP)	$NP = N$	Total identified habitat patches
Patch density (PD)	$PD = \frac{N}{A} \times 100$	Patches per 100 ha
Mean patch area ($AREA_{MN}$)	$\mathrm{AREA_{MN}} = \frac{A_T}{N}$	Average habitat patch size
Edge density (ED)	$ED = \frac{E}{A}$	Habitat boundary per unit landscape
Largest patch index (LPI)	$LPI = \frac{A_{\max}}{A_T} \times 100$	Dominance of the largest patch

Landscape Resistance Surface

Resistance surfaces are used to show how hard it is to move through each land cover category. Resistance values from 1 to 100 were assigned to five categories (see table 4). Freshwater and natural vegetation had the lowest resistance while built-up areas had the highest resistance. These values are modelling assumptions that have to be calibrated according to the target organism or process. Hydrological channels and barriers need to be taken into account when dealing with aquatic animals (Johnson & Host, 2010). If there are multiple spatial variables involved, the resulting resistance value is calculated using equation (3) below, where wi is the weight of variable i.

$$R(x) = \sum_{i=1}^{n} w_i R_i(x) \qquad (3)$$

Table 4: Landscape Resistance Values Assigned to Land-Cover Classes

Land-cover category	Resistance value	Resistance level
Freshwater bodies	1	Very low
Natural vegetation	5	Low
Agricultural land	30	Moderate
Barren/open land	50	High
Built-up area	100	Very high

III. Results and Analysis

Spatial Distribution of Freshwater Habitats

The spatial analysis resulted in the detection of 24 patches of freshwater habitat covering a total habitat area of 3.84 km² (Table 5). It is seen from the mean patch area of 0.16 km² that the habitat is composed of many small patches of habitat instead of a large continuous aquatic habitat. The biggest patch occupies an area of 0.62 km² which constitutes 16.15% of the total habitat area, showing the lack of domination of any water body within the habitat.

Table 5: Spatial Characteristics of Freshwater Habitat Patches

Parameter	Result
Total study area	100.00 km²
Number of freshwater patches	24
Total freshwater habitat area	3.84 km²
Mean patch area	0.16 km²
Largest patch area	0.62 km²
Smallest patch area	0.04 km²
Freshwater habitat coverage	3.84%
Patch density	0.24 patches per 100 ha
Largest patch index	16.15%

Landscape Fragmentation Assessment

The landscape fragmentation was analyzed based on patch configuration and connectivity categories (Table 6). Among the total of 24 patches, 14 (58.33%) were isolated, 7 (29.17%) were moderately connected, and only 3 (12.50%) were highly connected. This indicates that the freshwater landscape is fragmented, and most of the habitat patches do not have any connection to their neighbors. Isolation of such patches makes it essential to determine the intermediate habitat which can serve as connecting corridors, especially when there is agricultural and developed land between such disconnected patches.

Table 6: Classification of Freshwater Habitat Connectivity

Connectivity category	Number of patches	Percentage
Isolated habitats	14	58.33
Moderately connected habitats	7	29.17
Highly connected habitats	3	12.50
Total	**24**	**100.00**

Landscape Connectivity Indicators

Table 7: Landscape Fragmentation and Connectivity Indicators

Indicator	Baseline value	Ecological interpretation
Number of habitat patches	24	Spatial distribution of habitats
Mean patch area	0.16 km²	Relatively small habitat units
Largest patch index	16.15%	Limited dominance of one patch
Patch density	0.24 per 100 ha	Habitat patch frequency
Edge density	0.186 km/km²	Habitat boundary characteristics
Habitat coverage	3.84%	Freshwater proportion of landscape
Mapped corridor links	9	Modelled connections
Isolated habitat proportion	58.33%	High spatial isolation

Table 7 presents a summary of the fragmentation and connectivity indices. There were 24 patches with an average size of 0.16 km² and patch density of 0.24 per 100 hectares; the landscape is thus characterized by numerous and relatively small habitat fragments. The edge density index was found to be 0.186 km per km², while the area covered by water features was 3.84%. There were nine corridor connections between patches, and 58.33% of the habitat fragments remained isolated from others.

Ecological Corridor Identification

The least-cost paths analysis on the resistance surface provided nine possible corridors (Figure. 2(a&b)). Three were high-priority, four were moderate, and two were low-priority corridors. The shortest corridor among these was C6 with a length of 0.80 km and cumulative resistance of 12.8, while the longest corridor was C8 with length 2.75 km and cost 43.2, which implies that the landscape within this corridor is more difficult for movement. The cumulative cost is not an actual distance.

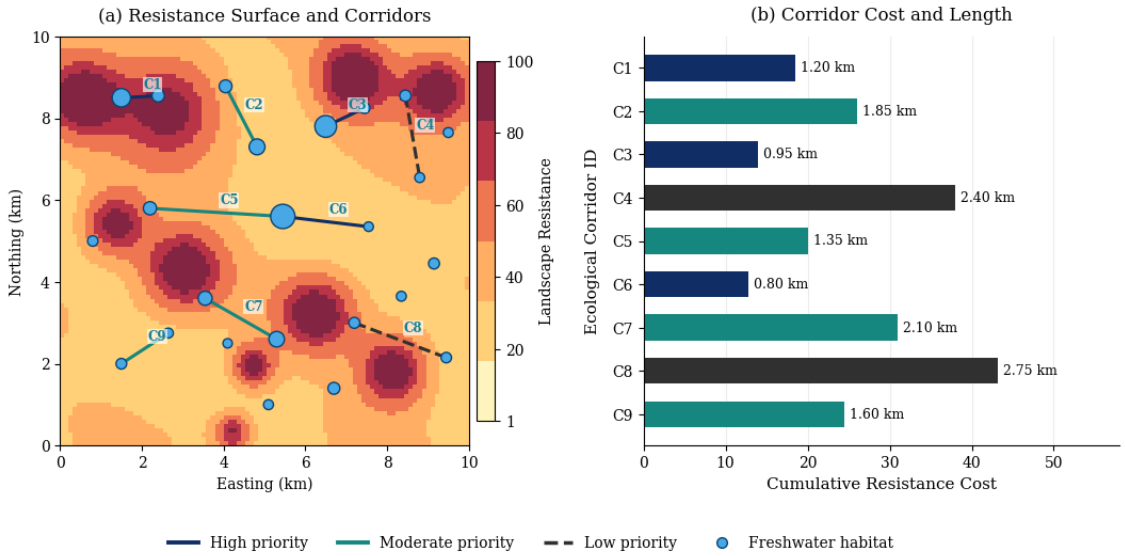


Figure 2(a&b): Least-Cost Ecological Corridors Over the Landscape Resistance Surface (A) And Corridor Cost and Length (B)

Habitat Connectivity

Table 8: Graph-Based Connectivity Characteristics of Selected Habitat Patches

Habitat patch	Degree centrality	Betweenness centrality	Connectivity role
H01	3	0.42	Major connector
H03	4	0.68	Critical connector
H06	2	0.21	Intermediate habitat
H08	3	0.51	Major connector
H10	4	0.75	Critical connector
H14	2	0.18	Intermediate habitat
H16	3	0.39	Supporting habitat
H19	1	0.08	Peripheral habitat
H22	2	0.14	Supporting habitat

The contribution of individual habitats to the network was evaluated using graph analysis (Table 8). H10 and H03 were the two habitats with highest betweenness centrality values, 0.75 and 0.68 respectively, having four graph links in both cases, which were termed as critical connectors. H08 and H01 were considered as major connectors while H19 was having the least value, 0.08. It means that the removal of the critical connectors would lead to reduction in connectivity of the habitat network.

IV. Discussion

Fragmentation of the landscape can have an impact on the connection of freshwater ecosystems through altering the extent and the spatial configuration of habitat areas. The identification of 14 separated patches suggests high ecological isolation due to the expansion of agriculture, urban development and disruption of drainages. The presence of nine ecological corridors shows that there are possible connections between the patches using natural vegetation and riparian zones; but limitations such as seasonal water, artificial obstacles and disconnection of the water flows could limit the movements of aquatic organisms. Hence, field studies should be conducted to confirm the functionality of these connections.

In this research, the application of graph-based connectivity analysis revealed that H10 and H03 were considered to be key habitat connectors as these habitat areas are maintaining ecological connections between isolated freshwater ecosystems. In addition to graph centralities, the integration of habitat area, landscape resistance, and connectivity measures increases the value of this approach for prioritizing conservation efforts in a better way through identifying strategic habitats. The proposed framework supports habitat protection, corridor restoration, barrier management, sustainable land-use planning, and long-term ecological monitoring. Compared with individual assessment approaches, this integrated spatial framework provides a comprehensive basis for freshwater conservation decisions.

V. Conclusion

This research paper proposes a landscape-based approach for assessing connectivity between isolated freshwater ecosystems through remote sensing, GIS, landscape metrics, least-cost modeling and graph analysis. Analysis of the 24 habitats resulted in the fragmented network with 58.33% of isolated habitats, as well as in mapping of the nine corridors that would connect them. Two habitats, H03 and H10, are crucial for connection, while restoration of a hypothetical landscape increased the Probability of Connectivity from 18.60% to 31.40%. This approach provides evidence for the need for corridors' restoration, habitat protection and sustainable landscape management. There are several aspects that have to be considered. Firstly, satellite image waterbody identification is sensitive to changes in water level and presence of clouds. Secondly, resistance values will be species specific and require ecological validation. Thirdly, least-cost paths show potential connections but not actual ones. Fourthly, hydrological barriers and seasonal connectivity require further field research. Finally, results of connectivity analysis on graph will be influenced by the chosen dispersal thresholds and other network assumptions and sensitivity analysis can be conducted. Future research could combine the use of machine learning based classification of water bodies, species distribution modeling, hydrologic network modeling and circuit theory to determine alternative routes for movement. Field survey-based observation of biodiversity, seasonal hydrological connectivity, and specific dispersal information for species could make the estimations more robust. Future long-term monitoring based on multi-seasonal satellite imagery and ecological movement could be used to evaluate freshwater connectivity corridors.

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