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A Hybrid Ecological Typology Proposal Based on Structural and Functional Connectivity for the Büyükçekmece Lake Basin: An Integrated Decision Support Framework

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Abstract

Anthropogenic pressures increasingly threaten ecological connectivity and basin-scale ecological sustainability in peri-urban landscapes. This study proposes a Hybrid Ecological Typology framework for the Büyükçekmece Lake Basin (Istanbul, Türkiye), integrating Morphological Spatial Pattern Analysis (MSPA), Analytic Hierarchy Process (AHP), and Minimum Cumulative Resistance (MCR) analysis within a unified spatial decision-support system. The framework is applied to a 67,627.06 ha basin area, including a 25,976.99 ha terrestrial focus area. The results indicate a structurally heterogeneous landscape dominated by interior habitat zones (85.94%) distributed across 93 core patches. Despite this dominance, ecological connectivity is maintained through a highly fragmented network of 484 landscape elements, where limited bridge (0.08%) and branch (0.62%) structures highlight structural vulnerability. Edge-dominated zones (12.87%) further reflect strong anthropogenic fragmentation pressures. Connectivity analysis identifies 10 key habitat patches with dPC (Probability of Connectivity index) values exceeding 5% and 12 strategic ecological corridors supporting basin-scale ecological flows. The proposed hybrid typology delineates five functional planning categories: conservation areas (22.72%), ecological corridors (1.91%), restoration areas (1.63%), sustainable use areas (0.51%), and controlled development areas (8.11%). Although high-quality habitat cores dominate the basin, ecological connectivity remains spatially constrained, with bottleneck zones (0.89%) concentrated along transportation corridors that significantly reduce landscape permeability. Overall, the findings demonstrate that basin-scale ecological sustainability in peri-urban environments is governed not only by habitat quantity but also by the interaction between spatial configuration and resistance structures. The framework provides a transferable decision-support tool that bridges landscape ecology theory with spatial planning practice for basin management and ecological network design.

Keywords: hybrid ecological typology; landscape connectivity; Büyükçekmece Lake Basin; ecological security pattern; watershed spatial planning; peri-urban landscapes

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1. Introduction

Urbanization remains one of the most pervasive processes transforming natural landscapes. Habitat fragmentation, biodiversity loss, and the degradation of ecosystem services are among the most well-documented consequences of this process [1–3]. Watersheds located in peri-urban areas experience this pressure with particular intensity; a persistent

tension is created in these zones between rising construction demands on one hand and drinking water security and ecological continuity requirements on the other [4,5]. Under these conditions, preserving landscape resilience and connectivity is becoming an increasingly high-priority issue for both ecological conservation and spatial planning [6,7].

The Büyükçekmece Lake Basin, one of Istanbul's vital drinking water resources, provides a concrete example in this regard. Accelerating construction and transportation investments in recent years have subjected the basin to severe transformation pressures [5,8]. The fragmentation and edge effects exerted by transportation infrastructure on habitats constitute one of the primary drivers accelerating this process [9]. The fragmentation of green spaces and the weakening of corridor continuity directly threaten their ecological functions and long-term water quality [10–12]. Nevertheless, a spatial model that synthetically evaluates structural connectivity, functional connectivity, and habitat suitability within the Büyükçekmece Lake Basin has not yet been developed. This situation creates a significant research gap regarding hybrid ecological typology approaches capable of guiding land-use planning and identifying conservation–restoration priorities [11,12].

Three complementary methodological approaches have been developed in the literature. MSPA analyzes the geometric structure of green spaces to define core habitats and the connecting elements between them [13–15]. The MCR–LCP framework models potential ecological movement pathways through resistance-based landscape surfaces [16–18]. AHP-based habitat suitability assessments determine potential habitat zones by integrating multi-criteria ecological variables [19–21].

These methods are mostly implemented independently, leaving the simultaneous evaluation of structural and functional connectivity limited [22–24]. However, it is well known that habitats appearing structurally connected may exhibit low permeability from a functional perspective. Therefore, integrating different connectivity components is essential to reliably determine conservation and restoration priorities [24–26].

This study aims to evaluate the structural and functional connectivity patterns of the Büyükçekmece Lake Basin by integrating MSPA, MCR–LCP, and AHP approaches within a hybrid ecological typology framework (Figure 1).

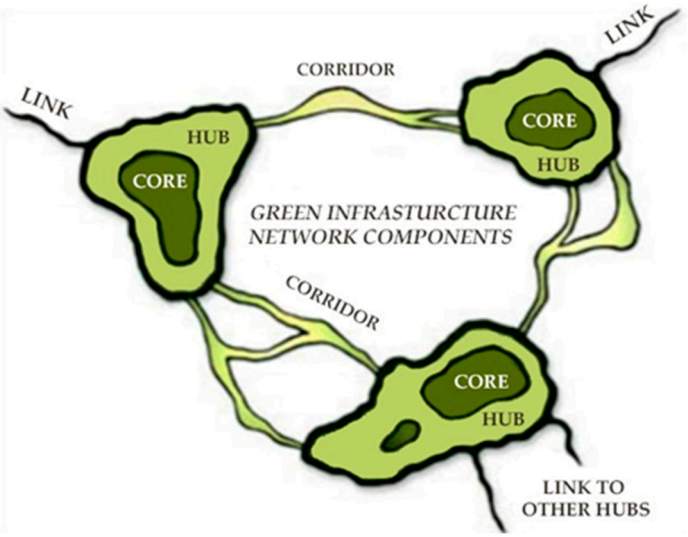

Figure 1. Components of the green infrastructure network within the framework of the green network approach [27].

By combining habitat morphology, ecological resistance, corridor functionality, and habitat suitability within a unified assessment framework, this study aims to identify priority conservation, restoration, and sustainable use areas. The proposed approach is

expected to provide practical planning guidance at the watershed scale while offering a transferable methodological framework for watershed ecosystems experiencing similar urbanization pressures [4,11,12,28,29].

Based on the conceptual integration of structural and functional connectivity approaches, the study is guided by the following hypotheses:

H1. *The integration of MSPA, AHP, and MCR-LCP approaches provides a more comprehensive assessment of ecological connectivity and prioritization than the application of individual methods alone.*

H2. *Structurally important habitat cores do not necessarily spatially coincide with functionally important ecological corridors, reflecting the distinction between habitat configuration and ecological flow processes.*

H3. *The proposed hybrid ecological typology framework can identify restoration-priority areas and connectivity bottlenecks that may remain undetected when structural or functional connectivity approaches are applied independently.*

2. Materials and Methods

2.1. Study Area

The Büyükçekmece Lake Basin is positioned as a geographical and ecological threshold at the western periphery of the Istanbul metropolitan area, at the intersection of the Eastern Thrace and Northwestern Marmara ecosystems.

The basin is situated between latitudes 41°00′–41°15′ north and longitudes 28°20′–28°40′ east, encompassing a drainage and surface water catchment area of approximately 430 km^2 (Figure 2) [5].



Figure 2. Geographical location of the Büyükçekmece Lake Basin [5].

The 620 km^2 basin is bounded by six districts: Esenyurt and Beylikdüzü to the east, Silivri to the west, Çatalca and Arnavutköy to the north, and Büyükçekmece to the south (Figure 3) [5].



Figure 3. Districts located within the Büyükçekmece basin [5].

Located on the European side of Istanbul, the Büyükçekmece Lake Basin is a critical drinking water reservoir and a strategic hub for regional ecological continuity. Originally a lagoon, it was converted into a freshwater reservoir in 1989 and is fed primarily by the Karasu and Delice streams. Beyond its hydrological role, the basin provides essential ecosystem services, including habitat integrity, biodiversity support, and carbon sequestration (Figure 4) [5].

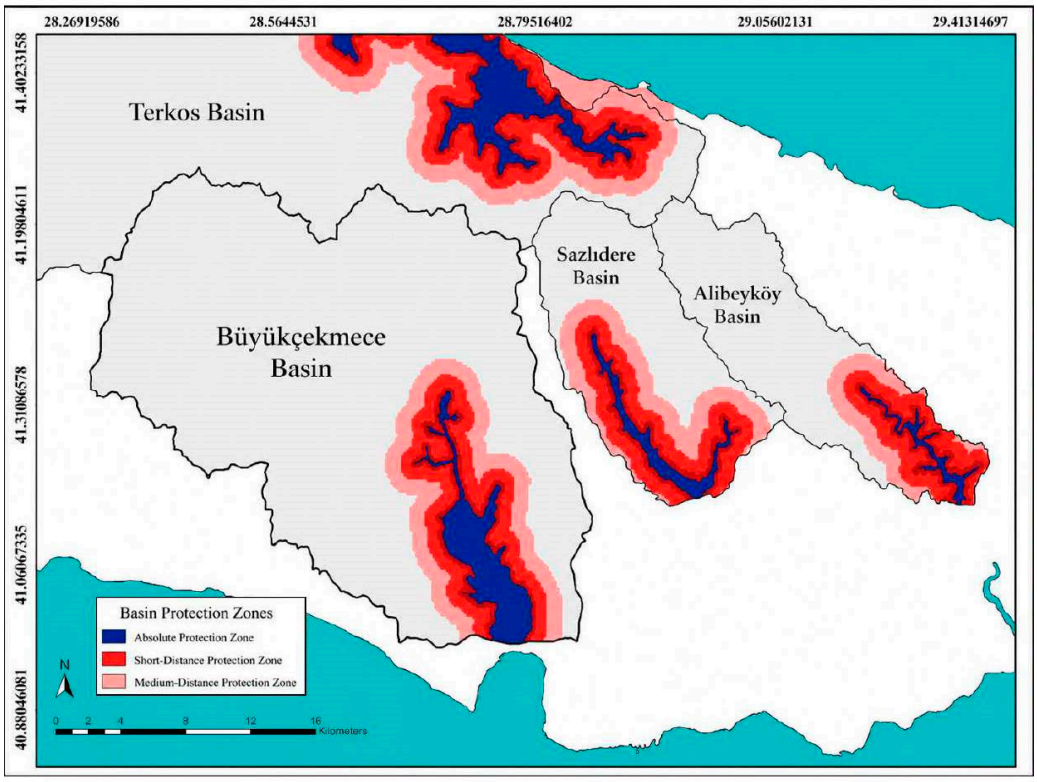

Figure 4. Neighboring basin of the Büyükçekmece Basin [5].

The basin is an internationally significant wetland, recognized under Ramsar criteria and as an Important Bird Area (IBA). It provides a critical refuge for globally threatened species, including *Branta ruficollis* and *Testudo graeca*, alongside diverse waterfowl such as

Ciconia ciconia and *Phoenicopterus roseus* [5]. However, the area faces severe fragmentation from rapid urban–industrial expansion and major transportation corridors (D-100, TEM, and the Northern Marmara Highway) [3,4,8,29]. This complex landscape—transitioning from northern broad-leaved forests and riparian reed beds to dense southeastern urban zones—highlights the necessity for the proposed hybrid ecological typology. By integrating MSPA, MCR-LCP, and AHP methodologies, this framework provides a comprehensive spatial framework for assessing connectivity and managing the basin's intense land-use pressures [11,12].

2.2. Datasets and Preprocessing

The spatial database was compiled from multi-institutional and international sources, standardized to the WGS 1984 UTM Zone 35N coordinate reference system to ensure geometric consistency. Area calculations were performed in hectares. Table 1 details the datasets, their sources, spatial characteristics, and analytical roles.

Table 1. Datasets used in the study and their respective analysis objectives.

Dataset	Data Source	Characteristics	Role in Analysis
CORINE Land Cover (2018/2024)	Copernicus Land Monitoring Service [30].	Vector/Raster	Macro-scale land cover classification and habitat/matrix differentiation.
Digital Elevation Model (DEM)	USGS/SRTM [31].	Raster (30 m)	Topographic analyses (slope, aspect) and generation of the hydrological flow network.
Sentinel-2 Satellite Imagery	European Space Agency (ESA) [32].	Raster (10–20 m)	Normalized Difference Vegetation Index (NDVI) generation and detection of current biomass density.
Landsat 8/9 Satellite Imagery	USGS [33].	Raster (30 m)	Land use validation and comparative spatial accuracy assessment.
Transportation Network	OpenStreetMap (OSM) [34].	Vector (Line)	Anthropogenic pressure vector and input for the MCR-based resistance layer (*C*).
Watershed Boundary and Protection Zones	Istanbul Water and Sewerage Administration [5].	Vector (Polygon)	Delineation of the study area boundaries and identification of statutory zoning constraints.
Institutional Spatial Data	Istanbul Metropolitan Municipality [35].	Vector	Delineation of administrative boundaries and anthropogenic pressure analysis focused on urban sprawl.

Land-use patterns were derived from CORINE (2018/2024) databases, with class boundaries refined using Sentinel-2 and Landsat 8/9 NDVI data [30,32,33]. Topographic and hydrological variables were extracted from a Digital Elevation Model (DEM) [31]. The CORINE 2018 and 2024 datasets follow the same standardized classification framework and nomenclature, allowing temporal comparison of land-cover patterns. Before spatial analyses, both datasets were harmonized according to the study classification scheme to ensure consistency in ecological connectivity assessment. The accuracy assessment of CORINE products was based on the official validation framework of the CORINE methodology.

To represent anthropogenic resistance in the Minimum Cumulative Resistance (MCR) analysis, transportation networks and urban built-up areas were integrated [4,16,18,24,36–40]. All datasets were standardized to a 30 × 30 m spatial resolution and a unified projection system to ensure analytical consistency across the watershed. This resolution was selected to provide a consistent representation of landscape-scale habitat structures, ecological barriers, and connectivity patterns, while acknowledging that finer-scale micro-corridors and narrow bottleneck areas may require higher-resolution datasets [41,42].

Following spatial standardization, the total basin area of 67,627.06 ha was subject to systematic delimitation prior to ecological analysis. Artificial/built-up areas (3410.20 ha) and industrial/transportation infrastructure (1080.60 ha) were excluded as absolute spatial barriers due to their lack of ecological habitat function. Consequently, all subsequent ecological analyses—including MSPA, MCR–LCP, and AHP—were conducted over a total terrestrial study area of 25,976.99 ha.

2.3. Software and Analytical Tools

Spatial analyses, multi-criteria overlays, and map production were conducted using ArcGIS 10.8 [43]. The modeling workflow utilized specialized toolkits for structural and functional connectivity.

Structural Connectivity: MSPA was performed via GuidosToolbox v3.0 to classify landscape elements into core areas, bridges, loops, edges, branches, perforations, and islets [13–15,44].

Functional Connectivity: Linkage Mapper v3.1 was used to identify least-cost pathways, ecological corridors, and pinch points. The Minimum Cumulative Resistance (MCR) framework integrated anthropogenic and topographic constraints to map movement potential [16–18,45].

Habitat Suitability: The Analytic Hierarchy Process (AHP) determined criteria weights using Expert Choice v11.5. Weighting reliability was confirmed with a Consistency Ratio (CR) < 0.10, meeting Saaty's thresholds for decision reliability [19–21,46,47].

2.4. Hybrid Ecological Typology Framework

The proposed framework integrates structural and functional connectivity with habitat suitability into a unified analytical platform. Its architecture synthesizes Morphological Spatial Pattern Analysis (MSPA), the Minimum Cumulative Resistance–Least-Cost Path (MCR–LCP) framework, and the Analytic Hierarchy Process (AHP) within a GIS-based Multi-Criteria Evaluation (MCE) framework [13,16–21,37,39,46].

Unlike conventional studies that assess structural and functional connectivity in isolation, this framework merges habitat morphology, movement potential, and suitability into a singular ecological typology. This holistic approach enables the simultaneous evaluation of landscape structure and ecological flow processes, providing a consistent analytical foundation for identifying conservation priorities, restoration opportunities, and ecological corridors. The methodological workflow and implementation sequence are detailed in Figures 5 and 6.

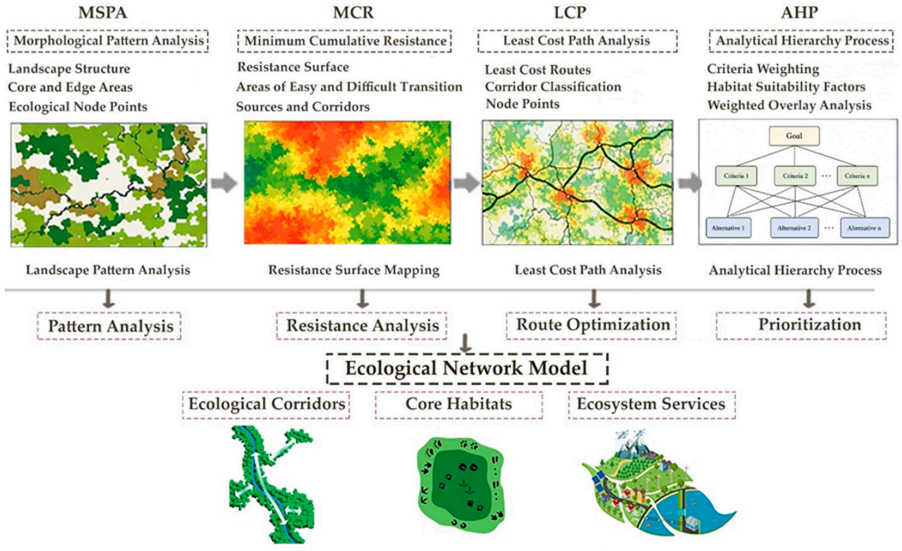

Figure 5. Ecological network modeling workflow.

1. DATA PREPARATION AND PREPROCESSING

Raw Dataset	Standardization	Common Coordinate System

Binary Input Raster Data

Foreground: Habitats	**Background:** Barriers and Non-Habitat Matrices

2. STRUCTURAL CONNECTIVITY MODELLING: MORPHOLOGICAL SPATIAL PATTERN ANALYSIS (MSPA)

Parameter Definition and Analysis Settings (GuidosToolbox 3.0)

Edge Width: 1 Pixel (30 × 30 m)	Connectivity: 8-Neighbor	Morphological Transition: Erosion / Dilation

Identification of MSPA Morphological Structural Components

CORE	ISLET	PERFORATION	EDGE	LOOP	BRIDGE	BRANCH

Filtering and Thresholding Process (Node Selection)

Minimum Core Areas: Source Nodes		Potential Ecological Transitions
Structural Threshold: ≥10 ha	Functional Threshold: dPC > 5%	Probability of Connectivity Index (dPC)

OUTPUT: MSPA CLASSES AND STRUCTURAL CONNECTIVITY

FUNCTIONAL CONNECTIVITY MODELLING (MCR–LCD)

3. COST SURFACE GENERATION: MINIMUM CUMULATIVE RESISTANCE (MCR) ANALYSIS

Resistance Surface Classification and Suitability Score Assignment Based on MSPA Classes (ArcMap 10.8 / ArcGIS Pro)

Highly Permeable Surfaces Resistance Value: 0-13.9 Resistance Level (R): Very Low Resistance Score (C): 1.00	**Strongly Connected Zones** Resistance Value: 13.9-27.8 Resistance Level (R): Low Resistance Score (C): 0.67	**Supportive Buffer Zones** Resistance Value: 27.8-41.5 Resistance Level (R): Low–Moderate Resistance Score (C): 0.67	**Fragmented Transition Areas** Resistance Value: 41.5-55.5 Resistance Level (R): Moderate Resistance Score (C): 0.33
Weak Connectivity Zones Resistance Value: 55.5-69.4 Resistance Level (R): Moderate–High Resistance Score (C): 0.33	**Anthropogenic Landscape Matrix** Resistance Value: 69.4-83.3 Resistance Level (R): High Resistance Score (C): 0.00	**Severely Interrupted Areas** Resistance Value: 83.3-97.1 Resistance Level (R): Very High Resistance Score (C): 0.00	**Barrier Zones** Resistance Value: 97.1-110 Resistance Level (R): Barrier Resistance Score (C): 0.00

4. ROUTE OPTIMIZATION: LEAST-COST DISTANCE ANALYSIS (LCD) (Linkage Mapper Toolkit)

Lowest Resistance Areas	Low Resistance Values	High Resistance Values
Potential Ecological Corridors	Permeable Areas	Barrier / High-Friction Areas

5. CORRIDOR EXTRACTION (MCR/LCD)

Corridor Slice Method: Potential Ecological Corridors

Corridor Class: Corridor Core MCR Range: 2–3.8 Permeability: Very High	Corridor Class: Highly Permeable Band MCR Range: 3.8–7.4 Permeability: High	Corridor Class: Moderately Permeable Band MCR Range: 7.4–9.2 Permeability: Moderate	Corridor Class: Weak /Marginal Area MCR Range: 9.2–20 Permeability: Low

Thin Operation: Extraction of Corridor Centerlines

OUTPUT: MAIN ECOLOGICAL CORRIDOR SKELETON

6. PRIORITIZATION: HABITAT SUITABILITY ANALYSIS (AHP)

PARAMETER DEFINITION (ANALYSIS SETTINGS)

Land Cover Type	Suitability Score	Distance to Water (m)	AHP Class	Suitability Score	Slope (%)	AHP Class	Suitability Score
Forest Areas	1	0–125	Very Close	1.00	0–10	Highly Suitable	1.00
Grassland / Open Areas	1	125–250	Close	0.70	10–25	Suitable	0.80
Semi-Natural Areas	0.85	250–500	Moderate	0.40	25–40	Moderately Suitable	0.50
Agricultural Areas	0.65	>500	Far	0.10	40–70	Low Suitability	0.20
Residential Areas	0.45				>70	Unsuitable	0.00
Industrial Areas / Roads	0.2						

7. MATHEMATICAL CONSISTENCY VALIDATION

Pairwise Comparison Matrix	Consistency Index (CI)	Consistency Ratio (CR)	Habitat Suitability Score

OUTPUT: HABITAT SUITABILITY AREAS

8. HYBRID ECOLOGICAL TYPOLOGY MODELLING (MSPA-MCR-LCD-AHP)

Ecological Network Model

▼

Habitat Suitability Areas

▼

Min–Max Normalization

▼

Weighted Overlay & Hybrid Ecological Scoring (H)

▼

OUTPUT: ECOLOGICAL TYPOLOGY CLASSES

Conservation Area	Ecological Corridor	Restoration Area	Sustainable Use Area	Controlled Development Area
▼	▼	▼	▼	▼
Zone 1–8	Zone 1–6	Zone 1–3	Zone 1–2	Zone 1–3

Figure 6. Integrated methodological workflow of the hybrid ecological typology framework.

2.5. Structural Connectivity Modeling: Morphological Spatial Pattern Analysis (MSPA)

Morphological Spatial Pattern Analysis (MSPA) provides an objective and reproducible framework for assessing structural connectivity and habitat fragmentation by classifying landscape patterns based on topological principles [13–15,47–50]. It transforms binary raster data into seven distinct morphological classes, core, islet, perforation, edge, loop, bridge, and branch, to quantify landscape structure and identify spatial connectivity patterns [13–15,48–50]. Recent MSPA-based studies have demonstrated its applicability in ecological network analysis, habitat connectivity assessment, and landscape pattern evaluation. These studies also indicate that MSPA outputs may vary depending on methodological parameters, including foreground definition, connectivity rules, and edge width selection; therefore, parameter settings should be carefully defined according to the research objective and spatial characteristics of the study area [47–50].

To evaluate the Büyükçekmece Lake Basin, harmonized CORINE-based land-cover classes from the 2018 and 2024 datasets were categorized as "foreground" or "background" according to their ecological functions and landscape permeability characteristics [13,30,51]. Natural and semi-natural land-cover classes, including forest areas, shrublands, and other habitat-supporting areas, were defined as foreground elements because they represent potential habitat sources and landscape components contributing to ecological continuity. In contrast, artificial surfaces, settlements, industrial areas, and transportation infrastructures were classified as background elements due to their high resistance characteristics and barrier effects on ecological movement. This classification approach was consistent with the objective of identifying ecologically meaningful structural patterns rather than purely geometric landscape configurations.

Consistent with the study's analytical framework, an 8-neighbor connectivity rule and a one-pixel edge width (30 × 30 m) were adopted to ensure a consistent representation of habitat continuity and edge effects [41]. The 8-neighbor connectivity rule was selected because it considers horizontal, vertical, and diagonal connections among habitat cells, providing a more realistic representation of ecological continuity in heterogeneous landscapes. The one-pixel edge width was selected to correspond with the spatial resolution of the input land-cover data and represent landscape-scale edge effects consistently across the basin. These settings, implemented in GuidosToolbox v3.0, enable the systematic mapping of connectivity features as detailed in Table 2.

Table 2. MSPA landscape structural classes and topological definitions.

MSPA Class	Landscape Structure and Topological Definition
Core	Core habitats unaffected by edge effects are classified as small, medium, and large core areas.
Islet	Isolated patches: Small, disjointed habitat patches that are completely disconnected from other core areas.
Perforation	Internal perforation: Perforated inner boundaries or openings within the interior matrix of core habitat patches.
Edge	Edge perimeter: The outer boundary zone of a core area interacting with the surrounding matrix.
Loop	Alternative loops: Circular or loop-like structural pathways that connect different parts of the same core area.
Bridge	Structural bridges: Linear structural corridors that directly connect two or more distinct core areas.
Branch	Structural branches: Linear elements connected to a core area at only one end, terminating within the matrix.

Considering the basin-scale objective of this study, the 30 m spatial resolution was considered appropriate for identifying landscape-scale habitat structures, ecological cores, and connectivity patterns. Although finer-scale micro-corridors and narrow bottleneck zones may require higher-resolution datasets (e.g., LiDAR or sub-meter imagery), the selected resolution provides a consistent and comparable representation of habitat configuration across the Büyükçekmece Lake Basin. Therefore, MSPA results were interpreted

as landscape-scale structural connectivity patterns rather than fine-scale species-specific movement pathways.

The MSPA framework can be expressed as

$$MSPA = f(i,r)$$

where i represents the binary input raster and r denotes the morphological pixel radius (edge width) controlling edge effects and connectivity relationships among habitat patches [13,51].

Following MSPA classification, strategic source nodes for the subsequent MCR–LCP analysis were identified by considering habitat patch size and the Probability of Connectivity index (dPC) [51–57]. Core habitat areas were selected as ecological source nodes because they represent relatively continuous and internally connected habitat structures with high structural integrity. To avoid the inclusion of small and ecologically insignificant patches, a minimum habitat area threshold of 10 ha was applied during source node selection. This threshold was adopted based on previous ecological network and MSPA-based connectivity studies, where minimum patch size criteria have been applied to distinguish functionally meaningful habitat cores from highly fragmented landscape elements. In addition, a dPC contribution threshold of >5% was used to identify habitat patches with a significant contribution to the overall ecological network structure [57]. This threshold is consistent with previous connectivity assessment approaches in which dPC contribution values are used to prioritize habitat patches with high structural importance within ecological networks. Bridge and loop classes [13–15,56,57] were not used as source nodes but were retained as critical structural connectivity elements supporting ecological linkages among core habitats. No shape-based threshold was applied during source node selection, as the objective of this study was to identify ecologically significant habitat structures based on continuity, area extent, and contribution to landscape connectivity rather than morphological complexity alone.

Suitability values (M) were then assigned to each MSPA class according to their contribution to structural connectivity and ecological continuity [14,15,48,49]. Particular attention was given to the islet class, which represents small and isolated habitat patches [50,52,57,58].

Although structurally disconnected, such patches may function as ecological stepping stones in fragmented landscapes and therefore contribute to species dispersal and landscape permeability [52,57]. Through this scoring framework, a quantitative hierarchy was established to translate structural landscape patterns into planning-oriented ecological priorities (Table 3) [15,49].

Table 3. Suitability values (M) assigned based on MSPA classes.

MSPA Components	MSPA Value (M)	Landscape Priority Level
Core	1.00	Primary Priority (Absolute Core Habitat)
Bridge	0.85	Secondary Priority (Critical Connectivity/Corridor)
Loop	0.70	Tertiary Priority (Alternative Flow/Path)
Edge	0.50	Moderate Buffer Zone
Branch	0.35	Low Priority (Marginal Corridor/Low-Permeability Segment)
Islet/Perforation	0.20	Minimal Contribution/Stepping Stone Habitat
Background/Others	0.00	Non-Suitable Matrix

The MSPA outputs were integrated into the connectivity framework as primary structural components, providing a quantitative basis for the subsequent MCR-, LCP-, and AHP-based analyses [13–21].

2.6. Functional Connectivity Analysis: MCR and LCP

2.6.1. Minimum Cumulative Resistance (MCR) Analysis

The Minimum Cumulative Resistance (MCR) analyses evaluated functional connectivity and habitat isolation by integrating landscape distance with land-cover resistance [16,18]. This framework provides a quantitative measure of ecological permeability, identifying potential movement pathways across heterogeneous landscapes [17,37,56]. Core habitat patches identified through MSPA were incorporated into the MCR analysis as source nodes [13–18]. Potential ecological transitions between these sources were determined by minimizing the cumulative resistance encountered by species movement across the landscape matrix [17,37].

To represent functional permeability, a resistance surface was generated using cost–distance algorithms [16–18]. This approach is consistent with ecological security pattern studies that integrate MSPA-derived structural information with resistance-based spatial modeling frameworks [59]. Resistance values (R_i) were assigned according to the relative ecological permeability of land-cover types, following literature-based resistance assumptions commonly adopted in MCR-based ecological connectivity studies [16–18,37,56]. Natural and semi-natural habitats were assigned low resistance values, agricultural areas intermediate resistance values, and urban areas and transportation infrastructure high resistance values due to their barrier effects on ecological connectivity [16,37]. The assigned values represent relative movement costs rather than absolute ecological thresholds.

The MCR model is defined as

$$MCR = f_{\min} \sum_{j=n}^{i=m} (D_{ij} \times R_i)$$

where MCR represents the Minimum Cumulative Resistance value, *Dij* is the spatial distance between habitat nodes *i* and *j*, and *Ri* is the resistance coefficient assigned to each raster cell.

Based on the resulting resistance surface, the landscape was classified into hierarchical resistance zones ranging from highly permeable ecological cores to highly restrictive anthropogenic matrix areas. These resistance classes were derived from the cumulative resistance values generated by the MCR analysis and interpreted according to their relative ecological permeability and functional connectivity characteristics, following previous ecological network studies [16,60,61]. This classification enabled the identification of transition zones, corridor buffers, and movement bottlenecks within the ecological network (Table 4).

Table 4. Spatial and ecological functions based on MCR levels.

Resistance Range	Resistance Level	Ecological Function and Spatial Importance
0–13.9	Very low	Absolute core habitat areas with the highest permeability.
13.9–27.8	Low	Resilient transition zones with strong connectivity; ecological flow is optimal.
27.8–55.5	Moderate	Corridor perimeter buffer zones; suitable for tolerant species.
55.5–83.3	Moderate–high	Fragmented anthropogenic landscapes; mobility is restricted to specific directions.
83.3–110	High	Impervious urban matrix; ecological movement is completely obstructed.

The resulting resistance values assigned to each land-cover category are summarized in Table 5. For modeling purposes, the assigned resistance values represent standardized relative resistance classes, where the lower and upper boundaries indicate the permeability gradient within each land-cover category. These ranges reflect the relative ecological permeability of landscape components rather than fixed species-specific thresholds.

Table 5. Resistance values determined according to land cover classes.

Landscape Category	Land Cover Type	Resistance Value
Core and Natural Areas	Natural forest structures, lake surfaces, wetlands, and riparian zones.	1–8
Semi-Natural Areas	Natural grasslands, pastures, shrublands, heathlands, and orchards.	10–30
Agricultural Areas	Intensive agricultural lands, fallow lands, and rural settlement fabric.	30–50
Barrier/Artificial Matrix	Dense urban fabric, industrial zones, mining sites, and highways.	70–110

Cumulative resistance outputs were transformed into functional suitability scores (*C*) ranging from 0.00 to 1.00 using Min–Max normalization, where higher scores indicate greater permeability and lower scores reflect ecological barriers (Table 6) [21].

Table 6. Functional suitability scores (*C*) assigned according to MCR resistance surfaces.

Resistance Class	Assigned Suitability Score (*C*)	Permeability Characteristics of the Landscape
Very low and low resistance	1.00	Fully Permeable/Barrier-Free Corridor Zone
Moderate resistance	0.67	Semi-Permeable/Resilient Buffer Zone
Moderate–high resistance	0.33	Low-Permeability/Restricted Threshold Zone
Barrier, high, and very high resistance	0.00	Impermeable/Absolute Spatial Obstacle

In this study, the resistance surface was developed using a landscape-based approach rather than a species-specific movement model. Resistance values represent the relative ecological permeability of land-cover types and anthropogenic pressures at the landscape scale. Therefore, the MCR analysis aims to identify general ecological connectivity patterns, potential movement pathways, and landscape-level permeability gradients rather than predicting the movement behavior of a particular species. This approach is consistent with regional ecological network planning studies where the objective is to support spatial decision-making through generalized connectivity assessments.

2.6.2. Least-Cost Path (LCP) Analysis

The least-cost path (LCP) analysis was used to model ecological flows and identify least-resistance corridors between habitat source nodes based on the MCR-derived resistance surface [16,52]. By incorporating environmental resistance, LCP analysis provides a spatial representation of potential ecological movement pathways across heterogeneous landscapes [37,62–64]. The analysis identified corridor pathways, transition zones, and bottlenecks that constitute the functional connectivity component of the ecological framework [56,57,65,66].

2.6.3. MCR-LCP Corridor Extraction and Optimization

To improve spatial interpretability, ecological corridors identified through the MCR–LCP (Minimum Cumulative Resistance–Least-Cost Path) framework were refined using the Corridor Slice method, which delineates resistance-based movement zones rather than simple linear pathways [24,45].

Building upon the structural analysis (Section 2.5), a thinning operation was applied to extract the central axis of each corridor, producing a simplified skeleton representing

the primary connectivity network across the Büyükçekmece Lake Basin [13,14,45]. This framework enables the identification of connectivity gaps and restoration-priority areas for ecological network planning and resistance-based restoration strategies [11,61].

2.7. AHP-Based Habitat Suitability Analysis

Habitat suitability was assessed using the Analytic Hierarchy Process (AHP) based on Saaty's 1–9 scale [19,46]. Four variables—land cover, proximity to water resources, anthropogenic pressure, and topographic constraints—were integrated to evaluate habitat viability within the Büyükçekmece Lake Basin [20,21]. Land-cover classes were ranked according to ecological quality and disturbance level (Table 7) [1,12].

Table 7. Habitat suitability scores based on AHP and distance to land cover.

Land Cover Class	Ecological Significance for Habitat	Suitability Value
Forest areas	Natural and continuous habitat structure; primary shelter and foraging area.	1
Pastures/Open spaces	Open habitat components providing feeding and movement opportunities for certain species and contributing to landscape ecological functionality.	1
Shrublands/ Semi-natural areas	Partially preserved habitat continuity; low suitability for specialist species.	0.85
Agricultural lands	Disrupted habitat integrity; conditional suitability for tolerant species.	0.65
Settlement areas	Intense anthropogenic pressure; low suitability with high disturbance levels.	0.45
Industrial zones/ and roads	Artificial surfaces; highly unsuitable areas acting as complete habitat sinks.	0.2

Proximity to water resources was assigned higher suitability values given its positive influence on habitat quality, species persistence, and ecological continuity (Table 8) [66–71].

Table 8. Habitat suitability scores based on AHP and distance to water resources.

Distance to Water (m)	Ecological Significance for Habitat	AHP Class	Suitability Value
0–125	Primary riparian buffer zone; high moisture, microclimate, and shelter function.	Very close	1.00
125–250	Secondary hydrological corridor; high species mobility and functional transition zone.	Close	0.70
250–500	Transitional landscape matrix; aquatic–terrestrial ecotone transition.	Moderate	0.40
>500	Terrestrial surface detached from hydrological influence; minimal riparian connectivity.	Distant	0.10

Anthropogenic pressures, including the TEM motorway, D-100 highway, and urbanized areas, were defined as high-resistance barriers reducing landscape permeability [9,31,37,52,67]. Slope was included as a topographic variable influencing movement costs and corridor continuity, with steeper terrain assigned lower suitability values (Table 9) [16,57].

Table 9. Habitat suitability evaluation based on slope gradients.

Slope (%)	Ecological Significance for Habitat	AHP Class	Suitability Value
0–10	High soil stability and water retention; minimal barrier to species movement.	Very suitable	1.00
10–25	Stable terrain with balanced runoff; moderate ecological connectivity.	Suitable	0.80
25–40	Increasing slope gradient; localized erosion risk and reduced mobility.	Moderately suitable	0.50
40–70	High erosion risk and rapid runoff; weak landscape continuity.	Low suitability	0.20
>70	Steep slopes with mass wasting risk; strong barrier and spatial isolation.	Unsuitable	0.00

Normalized weight coefficients were derived from the pairwise comparison matrices, and mathematical consistency was verified using the Consistency Ratio (*CR*). All matrices satisfied the accepted threshold of $CR < 0.10$, confirming the reliability of the derived weights [19]. The AHP procedure is governed by the following equations.

Pairwise Comparison Equation:

$$Aw = \lambda_{max} w$$

where A denotes the pairwise comparison matrix, w represents the criterion weight vector, and λ_{max} corresponds to the principal eigenvalue of the matrix.

Consistency Index:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

where CI is the Consistency Index and n is the number of criteria included in the comparison matrix.

Consistency Ratio:

$$CR = \frac{CI}{RI}$$

where CR is the Consistency Ratio and RI is the Random Index associated with the matrix size. A CR value lower than 0.10 indicates acceptable consistency within the pairwise comparison process.

The final habitat suitability score was calculated as

$$S = \sum_{i=1}^{n} (W_i \times r_i)$$

where S is the final habitat suitability score, w_i is the normalized weight of criterion i, and r_i represents the suitability score assigned to each criterion class.

Criterion weights were determined through literature-based pairwise comparison matrices using Saaty's 1–9 scale [19,46]. The normalized comparison matrix was used to derive the weight coefficients, and mathematical consistency was evaluated using the Consistency Ratio (CR). The calculated CR value was 0.0079, which is below the accepted threshold of 0.10, confirming the high consistency of the AHP weighting process [19,46]. The standardized habitat suitability scores (S) used in the hybrid ecological typology framework are presented in Table 10.

Table 10. Standardized habitat suitability scores (*S*) used in the hybrid ecological typology framework.

AHP Suitability Class	Suitability Score (*S*)
Very suitable	1.00
Suitable	0.80
Moderately suitable	0.60
Low suitability	0.40
Unsuitable	0.00

2.8. Hybrid Ecological Typology Model (MSPA-MCR-AHP)

First, all raster layers were normalized to a 0.00–1.00 scale using Min–Max normalization [20,21]. The standardized layers were then integrated within a GIS-based Multi-Criteria Evaluation (MCE) framework by combining three complementary ecological dimensions: MSPA-derived structural connectivity (M), MCR–LCP-derived functional connectivity potential (C), and AHP-based habitat suitability (S) [11,20,21]. Rather than representing independent spatial overlays, these components were integrated to represent habitat configuration, ecological movement potential, and habitat viability within a unified ecological assessment framework.

The normalization function is expressed as

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

where X_{norm} represents the standardized cell value, (X) is the original raster value, and X_{min} and X_{max} denote the minimum and maximum values within the corresponding dataset, respectively.

The Hybrid Ecological Score (H) was calculated for each raster cell as

$$H_{score} = \frac{M + C + S}{3}$$

where H_{score} represents the Hybrid Ecological Score and M, C, and S refer to the standardized scores for MSPA structural connectivity, MCR–LCP functional connectivity potential, and AHP habitat suitability, respectively. Higher H values indicate greater ecological integrity and connectivity potential, whereas lower values represent fragmented or environmentally constrained landscape units [11,39]. For planning applications, H values were classified using the Natural Breaks (Jenks) method into five ecological typology classes [72].

2.9. Model Validation

To evaluate the internal consistency of the hybrid ecological typology framework, a spatial consistency assessment was conducted by overlaying MSPA-derived core habitats, MCR–LCP connectivity networks, and AHP-based habitat suitability maps in a GIS environment. The degree of spatial correspondence among these independently generated outputs was used as an indicator of framework coherence and ecological plausibility. Areas exhibiting high spatial overlap were interpreted as ecologically significant zones, whereas mismatches were considered potential restoration or transition areas.

The validation strategy adopted in this study was designed to assess the internal consistency of the integrated modeling framework rather than perform species-specific ecological validation. Because the primary objective of this research was to develop a transferable landscape-scale spatial decision-support framework, external validation using field surveys, species occurrence records, telemetry data, or long-term biodiversity monitoring datasets was beyond the scope of the present study. Nevertheless, the high degree of spatial agreement among the independently generated model components provides

indirect evidence supporting the robustness and ecological coherence of the proposed framework. Future studies should integrate indicator species data, field observations, and biodiversity monitoring datasets to further evaluate the ecological performance of the identified corridors and planning typologies under real-world conditions.

Overall, the results demonstrate that the proposed framework exhibits strong internal spatial consistency and provides a reliable spatial decision-support approach for watershed-scale ecological planning [11,39].

3. Results

3.1. MSPA-Based Landscape Structure Analysis

The MSPA analysis revealed a hierarchical ecological structure in the Büyükçekmece Lake Basin composed of core habitat areas and connectivity elements linking these habitats. Core habitats accounted for 85.94% of the total habitat pattern, indicating that spatially continuous natural areas constitute the main structural component of the ecological network [13–15]. A total of 93 core habitat patches were identified, with large core patches representing 69.67% of the core area. These core areas were mainly concentrated in the northwestern forest ecosystems and southwestern wetland complexes, forming the primary ecological source zones of the basin (Table 11; Figure 7) [13–15,41].

Table 11. Spatial distribution and area metrics of landscape structural classes.

MSPA Analysis (Map Color)	MSPA Class	Landscape Structure and Topological Character	Area (%)	Number of Patches (n)
	Core (S)	Small interior habitat patch	10.55	86
	Core (M)	Medium interior habitat patch	5.72	3
	Core (L)	Large interior habitat patch	69.67	4
	Total Core	Absolute interior habitat zones total	85.94	93
	Islet	Small and isolated disjointed habitat patch	0.03	8
	Perforation	Internal perforation/openings within core areas	0.44	4
	Edge	Outer edge perimeter subject to boundary effects	12.87	58
	Loop	Circular pathway within the same core patch	0.01	1
	Bridge	Structural connectivity corridor between distinct cores	0.08	18
	Branch	Linear element connected to a core at only one end	0.62	302

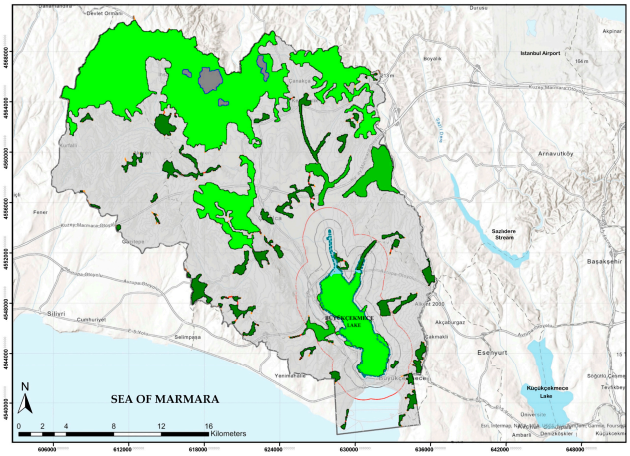

Figure 7. MSPA landscape structure classes and their spatial distribution.

The landscape comprises 484 patches, including 58 edge patches (12.87%), four perforation patches (0.44%), 302 branches (0.62%), 18 bridges (0.08%), one loop (0.01%), and eight islets (0.03%) [13–15,48,51]. Based on MSPA classification, three structural landscape

zones were identified: core-dominated conservation areas, structural corridors composed of bridge and branch elements, and fragmented edge-dominated zones influenced by anthropogenic pressure [15,24,45].

Core habitat importance was evaluated using the Probability of Connectivity (dPC) metric [6,7,50], showing that connectivity is influenced by both patch size and spatial configuration.

Accordingly, core habitats were grouped into large forest cores, lakeshore cores, narrow connecting cores, and small isolated patches. Large forest cores exhibited the highest connectivity values, while smaller patches function as secondary linkage elements within the network [57,58].

Overall, MSPA and dPC results indicate that the basin maintains a structurally connected ecological system dominated by core habitats, while connectivity is sustained through a limited but functionally important set of structural linkage elements [13–15,57,58].

3.2. MCR-Based Resistance Surface and Ecological Permeability

The MCR-based resistance analysis reveals the spatial distribution of resistance surfaces and ecological permeability across the basin [16–18,37,52]. The analysis focuses on the permeability gradient controlling ecological flow potential within the landscape matrix rather than discrete corridor delineation [16–18].

Results indicate that the basin is predominantly characterized by medium-to-high resistance conditions, covering 66.79% of the total area. This suggests generally limited ecological permeability and constrained species movement under anthropogenic pressure.

Low-resistance areas account for 22.98% of the basin and represent the main functional movement zones supporting ecological continuity [16–18]. High-resistance areas comprise 6.65% of the landscape and act as critical barriers restricting ecological connectivity (Table 12; Figure 8) [9,37,52,67].

Table 12. Resistance classes and ecological functions based on MCR analysis.

MCR Class (Map Color)	Resistance Range	Spatial Significance and Function	Ecological Characteristics
Very low	0–13.9	Most permeable matrices	Highly optimal for species movement; potential core corridor areas
Low	13.9–27.8	High-connectivity facilitation zones	Continuous movement capacity; primary ecological linkage zones
Low–moderate	27.8–41.6	Supportive ecological buffer areas	Transitional ecotones supporting main migration corridors
Moderate	41.6–55.5	Zones prone to initial fragmentation	Areas characterized by declining permeability
Moderate–high	55.5–69.4	Zones of weakened corridor continuity	Vulnerable linkage pathways and bottlenecks
High	69.4–83.3	Under-pressure landscape matrix	Constrained areas with hindered ecological transitions
Very High	83.3–97.1	Fragmented and disrupted zones	Highly restricted zones with minimal dispersal capacity
Barrier	97.1–110.0	Points of severed ecological connectivity	Critical barrier zones and absolute spatial obstructions

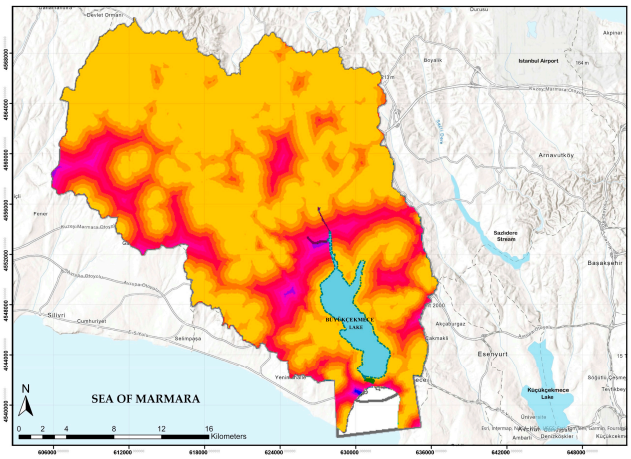

Figure 8. Spatial distribution of resistance surfaces based on MCR analysis.

Spatial patterns show that low-resistance zones are mainly associated with northern forested areas and semi-natural lakeshore environments, whereas high-resistance zones coincide with urban settlements and transportation corridors. Overall, ecological permeability decreases toward the southern and eastern parts of the basin, while relatively permeable surfaces persist along the northern axis, forming potential pathways for ecological flow [9,16,18,31,65].

3.3. LCP-Based Ecological Connectivity and Corridor Analysis

The Corridor Slice and least-cost path (LCP) analyses reveal that ecological connectivity in the Büyükçekmece Lake Basin is organized as continuous permeability bands governed by spatial variation in landscape resistance rather than discrete linear corridors [16–18,25,56]. This indicates a multi-layered connectivity structure within the landscape matrix.

3.3.1. Permeability Structure of Ecological Corridors

Corridor Slice analysis identifies four distinct permeability zones (Table 13; Figure 9). Very high permeability core zones account for 22.98% of the basin, representing the main ecological backbone and high-continuity areas that sustain core habitat connectivity. High permeability corridors represent 3.58% and function as secondary linkage zones supporting inter-core ecological flow.

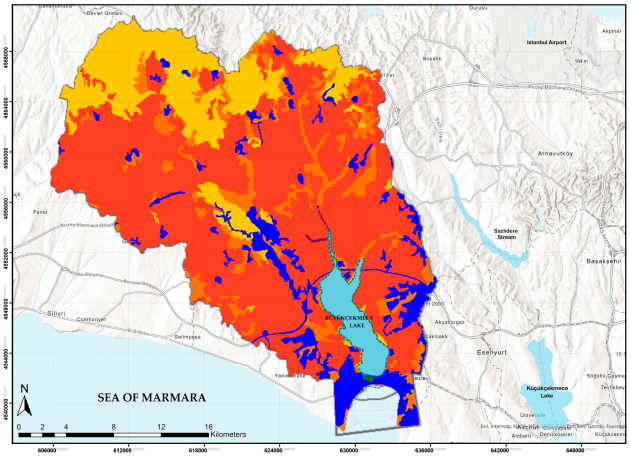

Figure 9. Permeability levels of ecological corridors based on Corridor Slice analysis.

Table 13. Permeability classes and spatial distribution of ecological corridors based on Corridor Slice analysis.

Corridor Slice Class (Map Color)	Slice Range	Permeability Level	Area (ha)	Ratio (%)	Ecological Characteristics
Very high permeability core zone	2–3.8	Very high	15,540.70	22.98	High-continuity areas forming the main corridor backbone and core connectivity skeleton of the ecological network.
High permeability corridor	3.8–7.4	High	2421.05	3.58	Primary corridor zones providing strong ecological flow and supporting inter-core connectivity.
Moderate permeability matrix	7.4–9.2	Moderate	45,168.11	66.79	Buffer and transitional zones allowing limited species movement under increasing landscape resistance.
Low permeability/ barrier zone	9.2–20	Low	4497.20	6.65	Fragmented areas characterized by high resistance restricting ecological flow and requiring restoration.
Total			**67,627.06**	**100.00**	entire study area/watershed total.

Figure 9 illustrates the spatial distribution of permeability levels across the basin, highlighting the concentration of high-permeability zones within forested landscapes and semi-natural habitat complexes. Moderate permeability matrix areas dominate the landscape, with 66.79%, forming transitional zones where species movement is possible but increasingly constrained by landscape resistance. Low permeability and barrier zones cover 6.65%, representing fragmented areas with high resistance effects that restrict ecological flow and require priority restoration (Table 13). Resistance-based classification confirms this spatial pattern (Table 14; Figure 10), showing that low-resistance areas correspond to optimal ecological flow zones, while increasing resistance progressively reduces connectivity and fragment continuity across the basin [16,18,37,57].

Table 14. Spatial distribution of corridor bands based on resistance classes.

Resistance Class (Map Color)	Class Range	Area (ha)	Ratio (%)	Ecological Characteristics
Low	2–3.8	15,540.70	22.98	Primary ecological flow zones with high permeability and optimal species movement linkages.
Moderate	3.8–7.4	2421.05	3.58	Transitional buffer zones providing complementary connectivity between low-resistance areas.
Moderate–high	7.4–9.2	45,168.11	66.79	Dominant landscape matrix with constrained ecological flow and reduced connectivity.
High	9.2–20	4497.20	6.65	Critical threshold areas exhibiting barrier effects and disrupting ecological continuity.
Total		**67,627.06**	**100.00**	Entire study area/watershed total.

3.3.2. Source–Target Connectivity Structure

MCR–LCP analysis reveals a clear source–target–pathway configuration within the basin (Table 15; Figure 11) [13–15,37,39]. Northern forest ecosystems function as primary source areas (12,828.10 ha), while Büyükçekmece Lake and associated wetlands (2800.00 ha) function as target zones. These components define the directional structure of ecological flow across the landscape.

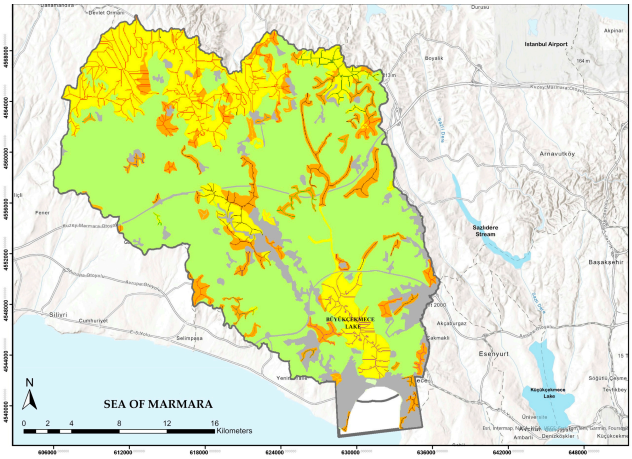

Figure 10. Distribution of corridor bands based on resistance classes.

Table 15. Source–connectivity–target components of the ecological network based on MCR–LCP analyses.

Connectivity Class (Map Color)	Landscape Feature Type	Area (ha)	Spatial Function	Ecological Characteristics
Source Areas	Northern forest blocks	12,828.10	Ecological source point; genetic pool and species source	Core area of high significance
Target Areas	Büyükçekmece Lake and wetlands	2800.00	Focus area of connectivity; habitat destination node	Critical ecological focal point
Connectivity Axes	Identified LCP paths	-	Main ecological line ensuring source–target interaction	Corridor backbone

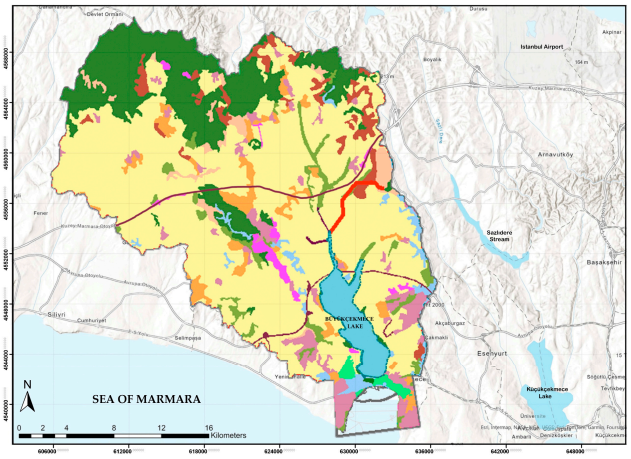

Figure 11. MCR–LCP connectivity axes between source and target.

Together, these components establish the fundamental source–connectivity–target structure of the basin-scale ecological network, indicating that ecological flow is primarily organized around interactions between forest habitats and the lake–wetland system [16,17,39,52].

The least-cost paths connecting these components represent the main connectivity backbone of the basin, forming the most efficient movement routes under current resistance conditions. However, bottleneck zones along these pathways indicate structurally sensitive segments where ecological flow is constrained by anthropogenic barriers and habitat fragmentation [10,16–18,37,67].

3.3.3. Integrated Interpretation of Connectivity Dynamics

Overall, ecological connectivity in the Büyükçekmece Lake Basin is not organized as a single linear corridor system but as a spatially continuous, multi-layered permeability network. The integrated interpretation of MSPA, MCR–LCP, and habitat suitability outputs indicates that species movement is facilitated through multiple resistance-dependent pathways shaped by habitat quality, landscape configuration, and anthropogenic pressure [16–18,52,68].

The identified connectivity structure highlights both dominant ecological flow axes and spatially explicit vulnerability zones, particularly where high-resistance surfaces intersect with critical movement pathways. The spatial agreement observed among structural connectivity, functional connectivity, and habitat suitability layers supports the internal consistency of the framework and its applicability for watershed-scale ecological assessment [11,39].

In this context, the hybrid ecological typology framework provides a spatial decision-support approach for identifying ecological corridors, prioritizing restoration areas, and supporting landscape-scale conservation planning under increasing urbanization and infrastructure pressure [4,28,69,70].

3.4. Analytic Hierarchy Process (AHP)-Based Habitat Suitability Analysis

Habitat suitability in the Büyükçekmece Lake Basin was assessed using four environmental variables widely reported in the literature: land cover, distance to water resources, anthropogenic pressure, and slope [19–22,24]. Criterion weights were derived using AHP through literature-based pairwise comparisons following Saaty's 1–9 scale. These variables represent key controls affecting habitat quality, landscape permeability, and species movement at the basin scale [7,20,22].

The normalized pairwise comparison matrix was used to calculate the criterion weights, and the consistency of the AHP weighting process was evaluated using the Consistency Ratio (CR). The calculated CR value was 0.0079, indicating a highly consistent weighting procedure (CR < 0.10).

Model performance was evaluated using a Global Sensitivity Analysis (GSA) framework applied to the multi-criteria decision-making (MCDA) outputs [59,60,63,66,69], assessing stability under parameter variation and reducing uncertainty in GIS-based spatial decision-support results.

3.4.1. Land Cover Dynamics and Habitat Quality

Agricultural areas dominate the basin landscape, covering 64.39% of the total area, followed by forest areas (18.98%) and semi-natural shrublands (6.40%) (Table 16). Urban settlement patches (5.05%) and industrial–transportation areas (1.60%), although limited in extent, contribute disproportionately to landscape fragmentation due to their linear and impermeable structure, reducing structural and functional connectivity [67].

Pastures and grasslands (3.58%) function as transitional stepping-stone elements between urban expansion zones and the agricultural matrix, supporting local-scale species movement [57].

The ecological suitability classification indicates pronounced spatial heterogeneity in habitat quality across the basin (Table 17; Figure 12) [72].

Table 16. Spatial distribution and ecological/anthropogenic roles of land cover classes.

Land Cover Class	Area (ha)	Ratio (%)	Ecological/Anthropogenic Role
Agricultural areas	43,560.00	64.39	Most extensive landscape matrix
Forest areas	12,828.10	18.98	Northern ecological core; primary source area
Semi-natural transitional shrublands	4325.31	6.40	Natural buffer and ecotonal transition zones
Artificial/Settlement areas	3410.20	5.05	High-resistance anthropogenic matrix; urban expansion zone
Pastures and grasslands	2422.85	3.58	Semi-natural stepping-stone habitats; local biodiversity refugia
Industrial zones and transport infrastructure	1080.60	1.60	Linear and point barriers; severe fragmentation zones
Total	**67,627.06**	**100.00**	Entire study area/watershed total

Table 17. Habitat suitability classes and spatial distribution based on land cover.

Habitat Suitability (Map Color)	Suitability Class	Area (ha)	Ratio (%)	Ecological Characteristics
1.00	Very Suitable	5171.40	19.91	Natural/continuous habitat; highest nesting and foraging potential
0.80	Suitable	5293.08	20.38	Strong habitat functionality; localized topographical constraints are present
0.60	Moderate	5193.37	19.99	Fragmented integrity; restricted ecological functionality
0.40	Low	5223.79	20.11	High anthropogenic pressure; degraded habitat quality
0.00	Unsuitable	5095.35	19.61	Built-up/intense agricultural areas; severe ecological disconnection
	Total	**25,976.99**	**100.00**	Assessed terrestrial habitat area/Total baseline

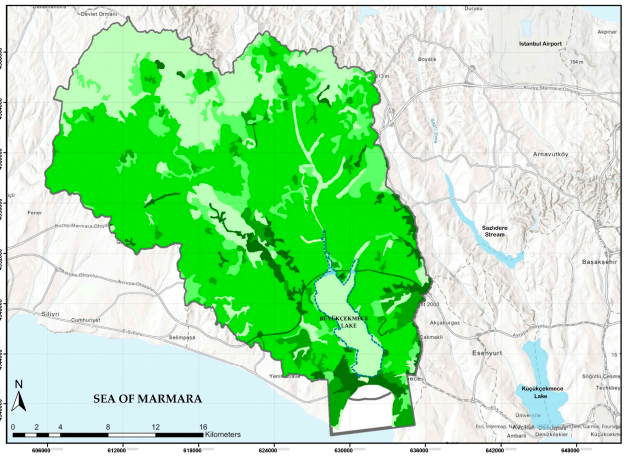

Figure 12. Habitat suitability based on land cover and its spatial distribution.

Habitat suitability values were classified into five ecological suitability classes based on land-cover characteristics and their relative ecological functionality (Table 17). The "highly suitable" (19.91%) and "suitable" (20.38%) classes are predominantly associated with forest blocks in the north and semi-natural landscape patches, representing areas with relatively

high habitat integrity and ecological functionality. In contrast, the "medium" (19.99%), "low" (20.11%), and "not suitable" (19.61%) classes are mainly distributed across areas affected by intensive agricultural activities, urban settlements, transportation infrastructure, and other anthropogenic pressures (Table 17; Figure 12) [72].

The spatial distribution patterns presented in Table 17 demonstrate that high-quality and resilient habitats do not form a continuous ecological structure throughout the basin; rather, they occur as fragmented patches influenced by urban sprawl, highway barriers, and intensive agricultural activities. This fragmented landscape configuration confirms that ecological network integrity and functional biodiversity flow in the Büyükçekmece Lake Basin depend on maintaining and strengthening the limited corridor connections among remaining high-quality habitat patches, which are increasingly vulnerable to further narrowing and fragmentation [11,25,65].

Further habitat suitability components based on additional ecological parameters are evaluated in the subsequent sections to provide a more comprehensive understanding of spatial constraints and functional ecological responses across the basin.

3.4.2. Hydrological Proximity and Riparian Buffer Functions

Habitat suitability exhibits a clear dependency on hydrological proximity, with higher values concentrated in areas close to water resources and a gradual decrease with increasing distance. The highest suitability values occur within the first two buffer zones (0–250 m) surrounding Büyükçekmece Lake and its tributary network, indicating a strong spatial coupling between hydrological proximity and habitat quality (Table 18; Figure 13) [5,67,68].

Table 18. Habitat suitability scoring according to distance to water resources.

Suitability Score (Map Color)	Distance Class	Distance to Water (m)	Ecological Characteristics and Functionality
1.00	Very close	0–125	Primary riparian buffers characterized by high moisture availability and microclimatic regulation.
0.70	Close	125–250	Secondary hydrological corridors supporting species movement and transitional connectivity.
0.40	Moderate	250–500	Ecotonal transition matrices representing gradual shifts between aquatic and terrestrial systems.
0.10	Distant	>500	Terrestrial areas with minimal riparian influence and reduced ecological support.

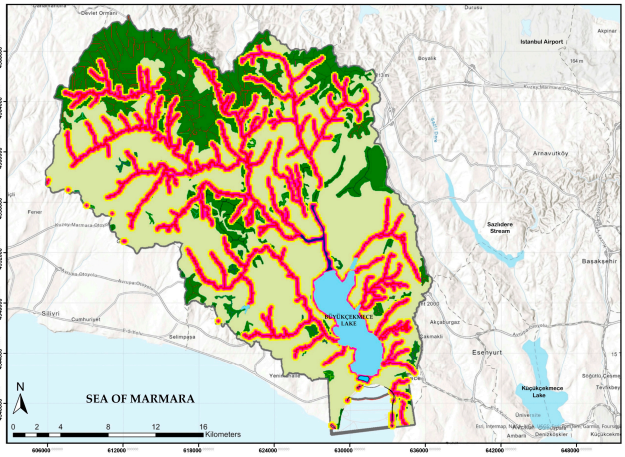

Figure 13. Habitat suitability based on distance to water resources and their spatial distribution.

Riparian environments show a distinct functional gradient, ranging from primary buffer zones with high moisture availability and strong microclimatic regulation to secondary hydrological corridors that support species movement and ecological transition. These are followed by ecotonal transition zones between aquatic and terrestrial systems, while distal terrestrial areas exhibit minimal riparian influence and reduced ecological support capacity [68,70,71].

3.4.3. Topographic Influence on Habitat Suitability

Slope gradient is identified as the primary topographic factor influencing habitat suitability [20,72]. Low-slope areas are associated with higher suitability values due to greater soil stability and water retention capacity [31,63], whereas steep slopes correspond to lower suitability as a result of increased erosion risk and surface runoff [53,63]. An inverse relationship between slope gradient and habitat suitability is observed, with spatial distributions presented in Table 19 and Figure 14.

Table 19. Habitat suitability scoring according to slope gradients.

Suitability Score (Map Color)	Suitability Class	Slope (%)	Ecological/Topographical Characteristics
1.00	Very suitable	0–10	Maximum soil–water stability; highly permeable transition zone
0.80	Suitable	10–25	Strong habitat functionality; moderate topographical constraints and balanced surface runoff
0.50	Moderately suitable	25–40	Increasing slope gradient; localized erosion risk and constrained species mobility
0.20	Low suitability	40–70	High erosion risk and accelerated surface runoff; weak habitat continuity
0.00	Unsuitable	>70	Absolutely steep slopes; physical barrier effect and minimal habitat potential

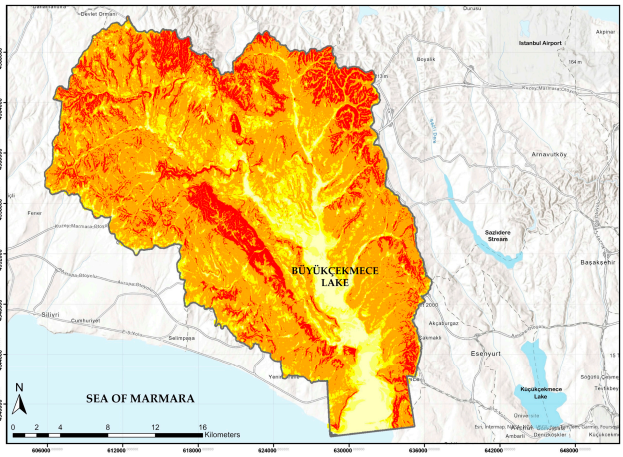

Figure 14. Habitat suitability based on slope and its spatial distribution.

Overlay analysis shows strong spatial correspondence between MSPA-derived core habitats and high suitability zones [11–13], while low suitability areas coincide with transportation infrastructure and dense urban regions, indicating their role as structural barriers to ecological continuity [37,60,61,67].

Connectivity results indicate a clear gradient structure across the basin (Table 20; Map 15). Ecological permeability is unevenly distributed, with medium-resistance areas accounting for 19.99% of the study area [38,59], reflecting partial but constrained ecological flow under landscape resistance effects [40,57,65].

Table 20. Connectivity classes based on AHP suitability scores and spatial distribution.

AHP Score (Map Color)	Connectivity Class	Area (ha)	Ratio (%)	Ecological Characteristics
2.61–9.24	Very high	5171.40	19.91	Very low landscape resistance; maximum ecological permeability and flow potential.
9.24–22.48	High	5293.08	20.38	Low landscape resistance; suitable transition and dispersal areas for species movement.
22.48–35.73	Moderate	5193.37	19.99	Moderate resistance matrix; potential connectivity and buffer zone characteristics.
35.73–48.98	Low	5223.79	20.11	High landscape resistance; restricted permeability and limited dispersal opportunities.
48.98–62.23	Very low	5095.35	19.61	Very high resistance matrix; absolute barrier effect and severe fragmentation/isolation risk.
	Total	**25,976.99**	**100.00**	**Assessed terrestrial surface/Total baseline**

3.4.4. Identification of Bottleneck Zones via MCR–LCP Framework

The evaluation of MCR–LCP analyses reveals the presence of significant narrowing and vulnerability zones (bottlenecks) along the primary ecological connectivity axes extending from the high-quality source areas in the north to the target wetland areas in the south [16,18,45]. These bottleneck zones were interpreted by considering the functional connectivity outputs of the MCR–LCP model together with the structural connectivity patterns derived from MSPA and habitat suitability information obtained from the AHP model (Tables 20 and 21; Figures 15 and 16) [19,20,45]. The results indicate that ecological flow is heavily restricted in specific segments within the high-resistance landscape matrix [37,41].

Table 21. Corridor suitability classes based on AHP suitability scores and spatial distribution.

AHP Score (Map Color)	Corridor Suitability	Area (ha)	Ratio (%)	Ecological Characteristics
2.61–9.24	Very Suitable	5171.40	19.91	Main axes characterized by low landscape resistance and high permeability.
9.24–22.48	Suitable	5293.08	20.38	Buffer zones supporting functional ecological connectivity.
22.48–35.73	Moderate	5193.37	19.99	Potential transition zones under landscape fragmentation risk.
35.73–48.98	Low	5223,79	20.11	High-resistance areas characterized by constrained ecological flow.
48.98–62.23	Unsuitable	5095.35	19.61	Barrier zones where ecological continuity is severely disrupted.
	Total	**25,976.99**	**100.00**	**Assessed terrestrial surface/Total baseline**

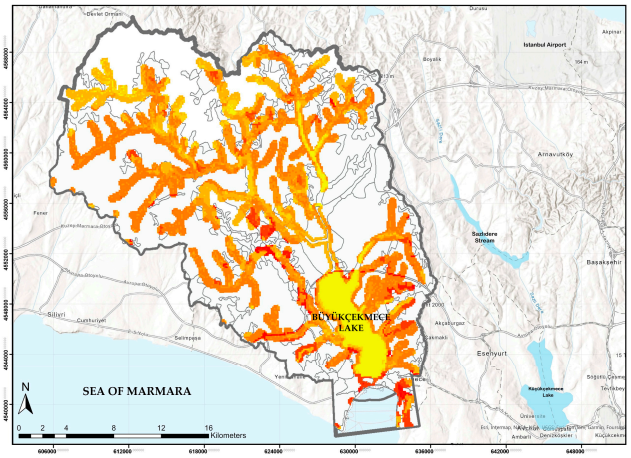

Figure 15. Distribution of AHP-based connectivity and resistance classes.

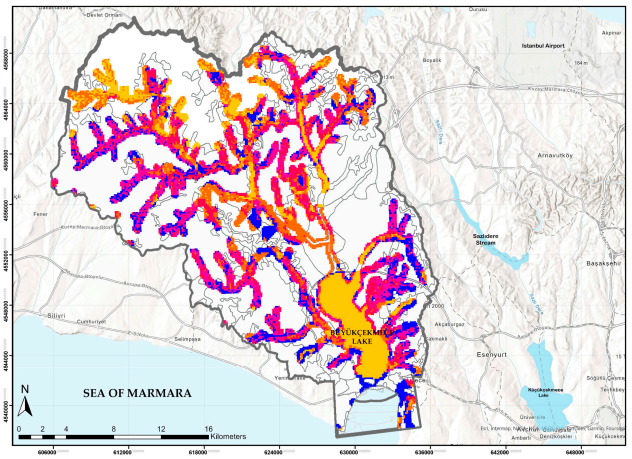

Figure 16. AHP-based corridor suitability areas.

4. Spatial Planning Implications of the Hybrid Ecological Typology Framework

The hybrid ecological typology framework integrates MSPA-derived structural connectivity, MCR-based functional connectivity, and AHP-derived habitat suitability as complementary ecological dimensions within a unified spatial assessment framework. Rather than representing independent spatial layers, these components collectively define ecological integrity, movement potential, and habitat viability, which are translated into planning-relevant typologies for conservation, restoration, connectivity management, and land-use regulation [11,12,16,37].

The integrated assessment reveals a continuous ecological–urban gradient across the Büyükçekmece Lake Basin, where ecological integrity, connectivity, and resistance patterns define distinct planning priorities. Habitat cores, corridors, restoration zones, and anthropogenic landscapes function as an interconnected spatial system, enabling the identification of priority areas for protection, connectivity maintenance, ecological rehabilitation, sustainable use, and controlled development at basin and neighborhood scales (Table 22; Figure 17).

Table 22. Hybrid ecological typology classes, multi-criteria score matrix, and spatial distribution across the watershed.

Typology Class (Map Color)	Suitability (*S*)	MSPA Category (*M*)	Landscape Resistance (*C*)	H-Score Range	Area (ha)	Share (%)	Cumulative Ratio (%)
Conservation Area (Zones 1–3)	Very Suitable/ Moderate	Core	Low	1.00–0.87	10,777.95	15.94	22.72
Conservation Area (Zones 4–5)	Suitable/ Moderate	Core	Moderate	0.89–0.82	4416.05	6.53	
Conservation Area (Zones 6–8)	Very Suitable/ Moderate	Bridge	Low	0.95–0.82	169.06	0.25	
Corridor (Zones 1–6)	Suitable/ Moderate	Core/Loop/ Bridge	Moderate/Low	0.77–0.66	1237.58	1.83	1.83
Restoration Area (Zones 1–2)	Low/ Moderate	Bridge/Edge	Moderate	0.64–0.59	716.85	1.06	1.06
Sustainable Use Area (Zones 1–2)	Low	Isolated/ Urban	High	<0.50	341.28	74.39	74.39
	Total				**67,627.06**	**100.00**	**100.00**

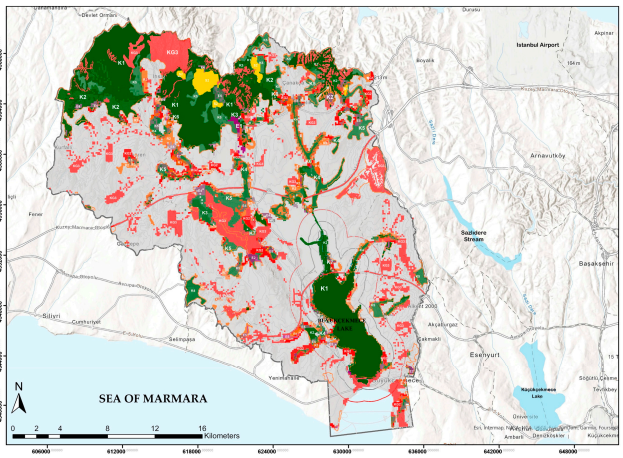

Figure 17. Spatial distribution of hybrid ecological typology classes.

This spatial configuration demonstrates that ecological structure is organized as a continuous gradient rather than isolated patches, where interactions between structural connectivity, resistance, and habitat suitability define clear thresholds for planning decisions. The resulting typology provides an operational framework for aligning ecological integrity with land-use planning and managing urban expansion within a unified spatial decision-support system [11,12,37].

4.1. Conservation Areas

Conservation areas (22.72%) constitute the ecological backbone of the basin, concentrated around Büyükçekmece Lake and northern forest systems. These zones exhibit high habitat suitability and strong structural continuity (Table 23) [11,13,19].

Table 23. Spatial and proportional distribution of core conservation zone sub-classes across the basin.

Conservation Sub-Classes (Map Color)	Matrix/MSPA Characteristics	Area (ha)	Basin Ratio (%)	Cumulative Conservation Share (%)
Conservation Area 1	Very High Suitability/Core Habitat	8280.27	12.24	53.90
Conservation Area 2	Very High Suitability/Core Buffer	1923.67	2.84	12.52
Conservation Area 3	Moderate Suitability/Transition Core	574.01	0.85	3.74
Conservation Area 4	High Suitability/Secondary Core	1368.16	2.02	8.91
Conservation Area 5	Moderate Suitability/Resilient Core	3047.89	4.51	19.84
Conservation Area 6	Very High Suitability/Bridge (Critical)	47.75	0.07	0.31
Conservation Area 7	Moderate Suitability/Bridge (Structural)	72.13	0.11	0.47
Conservation Area 8	Very High Suitability/Bridge (Small Corridor)	49.18	0.07	0.32
Total	**Büyükçekmece Conservation Zones Total**	**15,363.06**	**22.72**	**100.00**

Conservation areas 1–3 are primarily located in Akalan, İhsaniye, İnceğiz, and Subaşı, representing core ecological units of high ecological significance (Figures 18–20). They play a central role in hydrological regulation and habitat continuity [11,13,37].

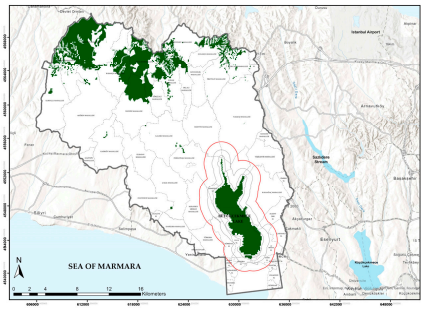

Figure 18. Conservation area 1.

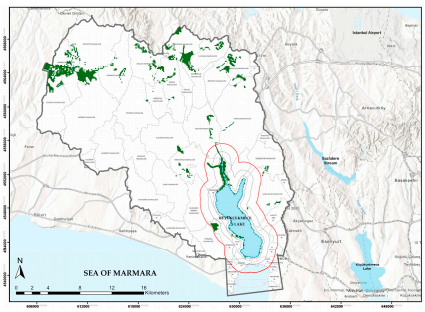

Figure 19. Conservation area 2.

Conservation areas 4–5 extend across Dağyenice, Kaleiçi, Kabakça, and Kızılcaali, functioning as transitional linkage systems that maintain connectivity between larger habitat complexes (Figures 21 and 22) [16,18,25].

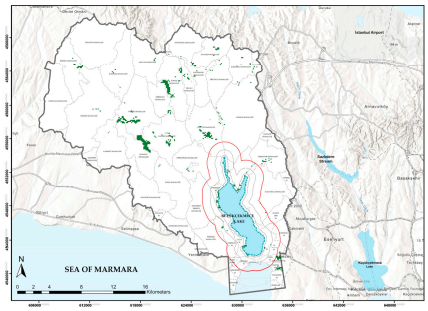

Figure 20. Conservation area 3.

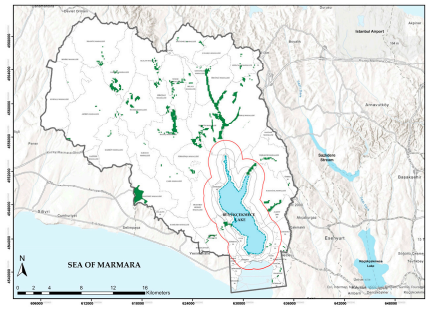

Figure 21. Conservation area 4.

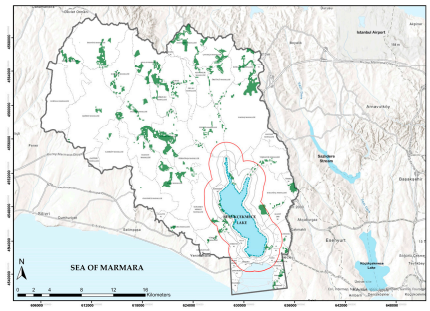

Figure 22. Conservation area 5.

Conservation areas 6–8 are spatially distributed in Kabakça, Türkoba, Ferhatpaşa, and Kestanelik (Figures 23–25). Despite their limited extent, these micro-scale patches function as stepping-stone nodes that support local connectivity and ecological continuity within fragmented landscape structures [57,58].

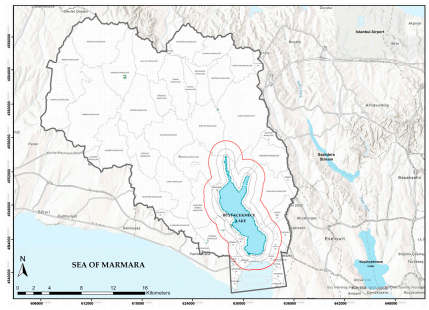

Figure 23. Conservation area 6.

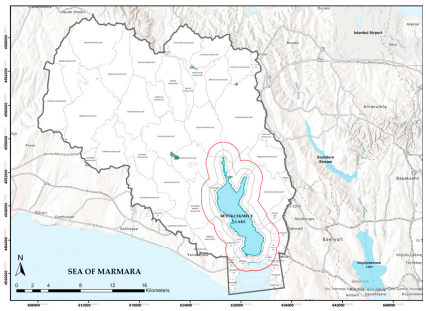

Figure 24. Conservation area 7.

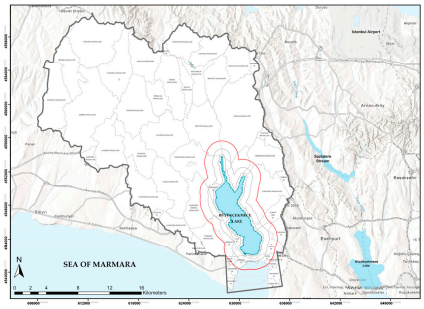

Figure 25. Conservation area 8.

4.2. Ecological Corridors

Ecological corridors (1.83%) represent linear connectivity structures derived from MSPA and MCR–LCP frameworks (Table 24) [13–16,18].

Table 24. Spatial and proportional distribution of ecological corridor sub-classes across the basin.

Corridor Sub-Classes (Map Color)	Model Characteristics	Area (ha)	Basin Ratio (%)	Cumulative Corridor Share (%)
Corridor 1	Primary Connectivity Backbone (North–South Axis)	407.02	0.62	30.50
Corridor 2	Complementary Local Transition Path	178.50	0.23	13.38
Corridor 3	High-Sensitivity Bottleneck (Critical Threshold)	47.29	0.08	3.54
Corridor 4	Macro-Scale Natural Area Connection	162.64	0.25	12.19
Corridor 5	Semi-Natural Landscape Integration Corridor	334.80	0.57	25.09
Corridor 6	Fragmented Alternative Local Transition Path	104.25	0.16	7.81
Total	**Ecological Corridor Network Total**	**1334.50**	**1.91**	**100.00**

These corridors maintain functional ecological flows between habitat cores by preserving continuity across heterogeneous resistance surfaces [16,18,37].

Corridors 1–3 constitute the primary connectivity backbone of the basin, whereas corridors 4–6 provide complementary linkages that enhance network redundancy and ecological resilience [25,57,58].

Primary corridors 1–3 form the main north–south ecological axis extending through Subaşı, Kaleiçi, and Kabakça (Figures 26–28) [16,18,45].

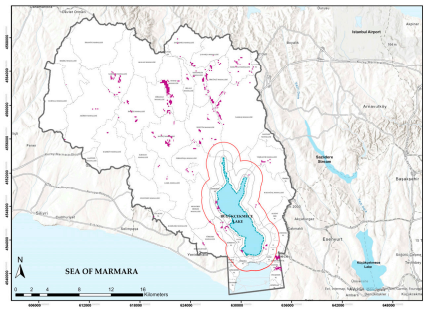

Figure 26. Corridor 1.

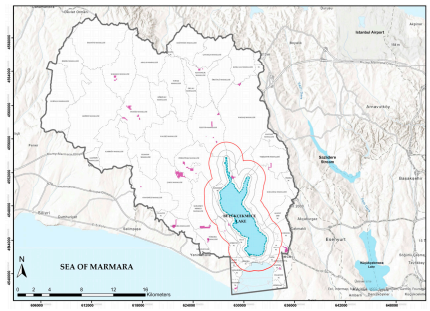

Figure 27. Corridor 2.

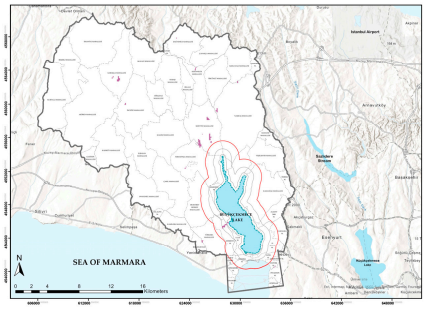

Figure 28. Corridor 3.

Secondary corridors 4–6 are distributed across Ferhatpaşa, İzzettin, Kamiloba, and Akören, supporting lateral ecological connections throughout the basin (Figures 29–31). They should be designated as a "Macro-Ecological Transition Zone" and protected from anthropogenic pressures that may disrupt regional ecological connectivity [16,18,25].

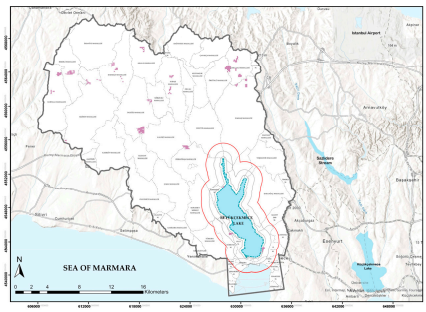

Figure 29. Corridor 4.

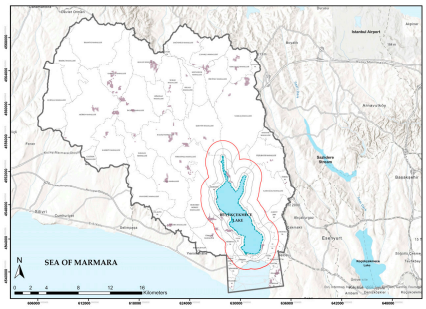

Figure 30. Corridor 5.

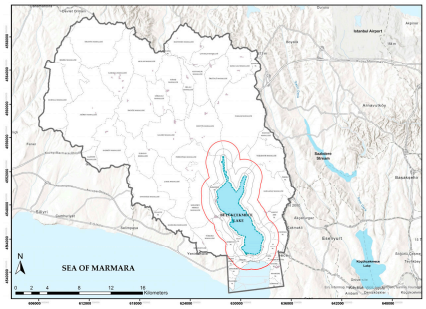

Figure 31. Corridor 6.

A critical bottleneck segment identified along the Kabakça–İzzettin axis represents a structurally sensitive section of the corridor network where connectivity disruption may increase landscape fragmentation (Figure 28; Table 24) [37,52,67].

4.3. Restoration Areas

Restoration areas (1.63%) represent fragmented ecological zones located at connectivity bottlenecks and degraded habitat patches, where ecological functionality is reduced due to landscape fragmentation and anthropogenic pressure (Table 25) [37,61,67]. These areas delineate spatial discontinuities within the ecological network where restoration potential is highest.

Table 25. Spatial and proportional distribution of ecological restoration sub-classes across the basin.

Restoration Sub-Classes (Map Color)	Landscape Repair & Restoration Characteristics	Area (ha)	Basin Ratio (%)	Cumulative Restoration Share (%)
Restoration Area 1	Connectivity-Restoring Core Corridor Thresholds	266.92	0.39	24.21
Restoration Area 2	Macro-Scale Widespread Landscape Intervention Zones	452.26	0.67	41.03
Restoration Area 3	Coastal–Inland Integration and Wetland Buffer Zones	383.19	0.57	34.76
Total	**Ecological Repair and Restoration Network Total**	**1102.37**	**1.63**	**100.00**

Restoration area 1 is concentrated in Kabakça, İnceğiz, and İzzettin, where opportunities exist to reconnect fragmented habitat patches. Peripheral patches in Muratbey Merkez, Nakkaş, and Kestanelik function as stepping-stone elements supporting local-scale connectivity (Figure 32) [57,58,61].

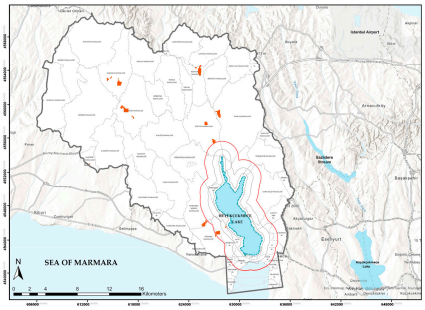

Figure 32. Restoration area 1.

Restoration area 2 exhibits a dispersed spatial pattern centered on İzzettin, Kaleiçi, and İhsaniye, with additional fragments in Kabakça, Akören, and Yeşilbayır (Figure 33; Table 25), reflecting widespread connectivity disruption across multiple sectors of the basin [37,61,67].

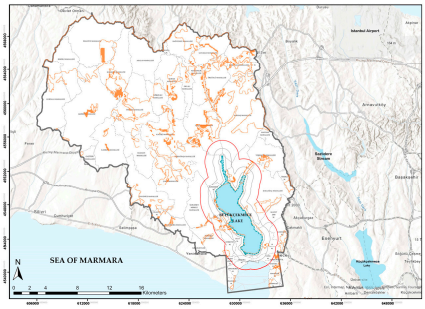

Figure 33. Restoration area 2.

Restoration area 3 is concentrated in İnceğiz, Kabakça, and Çakıl, extending toward Akören, Subaşı, Kestanelik, and Kızılcaali (Figure 34; Table 25), forming transition zones between lakeshore ecosystems and upland habitats [16,18,37].

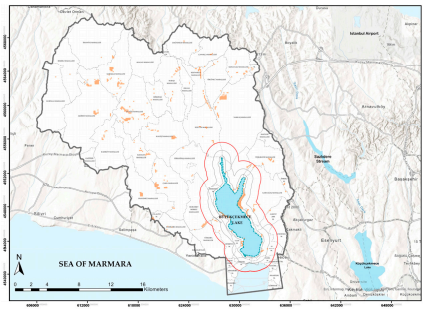

Figure 34. Restoration area 3.

4.4. Sustainable Use Areas

Sustainable use areas (0.51%) function as buffer interfaces between conservation and anthropogenic systems, maintaining partial ecological permeability while accommodating controlled land-use activities (Table 26) [27,28,63]. These areas mediate the transition between natural habitats and developed landscapes, reducing fragmentation intensity within the ecological network [37,63].

Sustainable use area 1 is concentrated in Kızılcaali and represents a localized agro-ecological transition zone (Figure 35) [23,27].

Sustainable use area 2 is distributed across Dağyenice and Akalan, forming a semi-continuous agro-ecological matrix that supports landscape continuity between natural and urbanized areas (Figure 36) [27,63].

Table 26. Spatial and proportional distribution of sustainable land use sub-classes across the basin.

Sustainable Use Sub-Classes (Map Color)	Landscape Integration & Land Use Characteristics	Area (ha)	Basin Ratio (%)	Cumulative Sustainable Use Share (%)
Sustainable Use Area 1	Local Transition and Pilot Agro-Ecological Buffer Zone	47.94	0.07	14.05
Sustainable Use Area 2	Ecologically Oriented Sustainable Agriculture and Production Axis	293.34	0.44	85.95
Total	**Sustainable Land Use Management Areas Total**	**341.28**	**0.51**	**100.00**

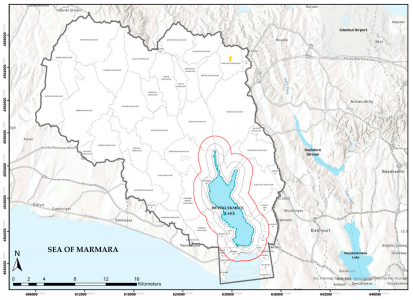

Figure 35. Sustainable use area 1.

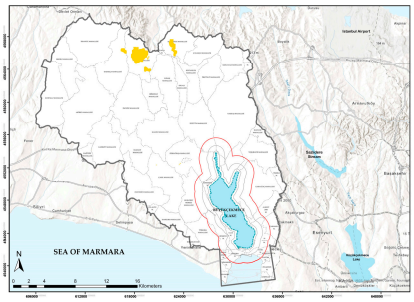

Figure 36. Sustainable use area 2.

4.5. Controlled Development Areas

Controlled development areas (8.11%) represent regulated expansion zones where development is concentrated under high ecological constraint, primarily in the southern and eastern sectors of the basin (Table 27) [4,10,63]. These areas are characterized by low ecological suitability and reduced landscape permeability due to intensive urban pressure [10,37,67].

Table 27. Spatial and proportional distribution of controlled development sub-classes across the basin.

Controlled Development Sub-Classes (Map Color)	Planning Character and the Role of the Spatial Matrix	Area (ha)	Basin Ratio (%)	Cumulative Sub-Class Share (%)
Controlled Development Area 1	Peripheral Growth Boundary and Threshold Management Buffer	42.01	0.06	0.77
Controlled Development Area 2	Intra-Basin Urban Pressure Foci and Buffer Zones	757.44	1.12	13.82
Controlled Development Area 3	Macro-Scale Sustainable Urban Development Potential	4681.91	6.92	85.41
Total	**Controlled Spatial Development Areas**	**5481.36**	**8.11**	**100.00**

Controlled development area 1 is concentrated in Yassıören and functions as a localized threshold interface between natural and urbanized landscapes (Figure 37) [16,18,65].

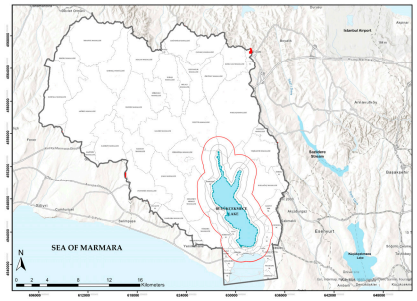

Figure 37. Controlled development area 1.

Controlled development area 2 is distributed across İnceğiz, Türkoba, Ferhatpaşa, Akören, Oklalı, and Subaşı and is characterized by proximity to hydrological systems and associated ecological sensitivity (Figure 38) [9,31,67].

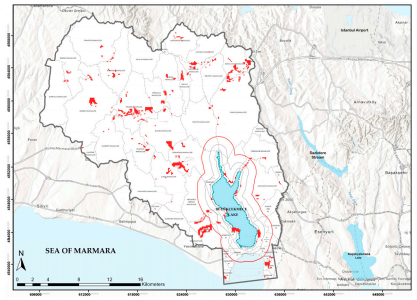

Figure 38. Controlled development area 2.

Controlled development area 3 extends across İhsaniye, Kaleiçi, Karaağaç, Yeşilbayır, Ovayenice, Çanakça, and Dağyenice, representing the main urban expansion belt within the basin (Figure 39) [4,8,63].

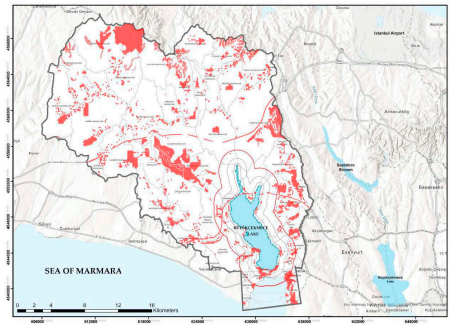

Figure 39. Controlled development area 3.

5. Discussion

5.1. Integration of Multi-Criteria Decision Support Models and the Hybrid Ecological Typology Framework

The hierarchical integration of AHP-based habitat suitability, MSPA-derived structural connectivity, and MCR-based functional resistance enables the spatial identification of functional bottlenecks that are often overlooked in single-dimensional landscape analyses [11,41]. This integrated approach improves the interpretation of ecological structure by simultaneously addressing habitat quality, spatial configuration, and landscape permeability [11,41,43].

In this context, this study does not aim to provide an empirically validated predictive model but rather an internally consistent spatial decision-support framework integrating structural, functional, and suitability-based ecological indicators.

The principal contribution of this study is the development of a hybrid ecological typology framework that synthesizes complementary ecological dimensions into a unified spatial decision-support system. Unlike conventional approaches that treat structural and functional connectivity separately, the proposed framework integrates these components to capture the multidimensional nature of landscape connectivity in rapidly urbanizing systems [12,43]. This integration enables the transformation of complex multi-layer ecological outputs into operational planning categories, thereby providing a transferable decision-support structure for conservation prioritization, restoration planning, and spatial governance in fragmented watershed systems [24,27,59].

Within this integrated structure, the spatial distribution of typological classes demonstrates a highly differentiated landscape organization: conservation areas (22.72%) represent the ecological backbone of the system, ecological corridors (1.83%) form structural connectivity pathways, restoration areas (1.63%) identify fragmented and functionally constrained zones, sustainable use areas (0.51%) act as buffer interfaces between ecological and anthropogenic systems, and controlled development areas (8.11%) define regulated expansion zones under high urban pressure. These proportions reflect a strongly asymmetric ecological–urban gradient within the watershed.

The results further indicate that structurally important habitat cores do not necessarily coincide with functionally important ecological corridors, emphasizing a decoupling between landscape structure and ecological flow processes [11,16,18,41,43]. This finding highlights the necessity of integrated pattern–process approaches for reliable connectivity assessment in heterogeneous landscapes.

5.2. Strategic Restoration and Adaptive Land Management: Integrating Nature-Based Solutions

The analysis indicates that restoration-priority areas (1.63%) are spatially concentrated within a limited number of connectivity bottlenecks rather than being uniformly distributed, suggesting that targeted interventions may yield disproportionately high gains in connectivity. These areas spatially coincide with fragmented edge zones (12.87%), where urban expansion and agricultural pressure intensify structural degradation [24,27].

Connectivity bottlenecks along the Kabakça–İnceğiz–İzzettin axis represent structurally constrained segments where high-resistance surfaces and fragmented habitat configurations overlap. These conditions significantly reduce ecological flow continuity at the basin scale. In this context, Nature-Based Solutions (NbSs), including corridor reinforcement, riparian restoration, and green infrastructure interventions, emerge as effective mechanisms for improving landscape permeability and reducing barrier effects [4,27,37].

The framework further supports adaptive land management by translating connectivity outputs into spatially explicit planning categories. The observed distribution of sustainable use areas (0.51%), where a dominant agro-ecological matrix contrasts with a limited pilot zone structure, indicates spatial asymmetry that may increase vulnerability under future land-use pressure scenarios. This highlights the importance of context-sensitive planning strategies that balance ecological integrity with development dynamics [23,29].

The prioritization of ecological areas should also be considered within a scale-dependent planning perspective. Although conservation areas, ecological corridors, restoration zones, vulnerability zones, and connectivity bottlenecks represent key ecological components, their relative importance may vary according to planning scale and spatial context. Therefore, these areas should be evaluated from the watershed scale to sub-watershed, neighborhood, and local implementation scales by considering existing land-cover patterns, ecological functions, and development pressures.

At the watershed scale, the identified ecological cores, corridors, and bottleneck areas provide strategic guidance for ecological network conservation and regional land-use

decisions. At lower planning scales, however, detailed assessments are required to define appropriate land-use interventions and restoration actions according to local conditions. In metropolitan landscapes such as Istanbul, where ecological characteristics and urban pressures differ between spatial contexts, ecological priorities should be integrated into upper-scale strategies and lower-scale implementation plans through adaptive and context-sensitive planning approaches. These priorities should also be periodically reviewed and updated in response to changing land-use conditions, ecological processes, and development pressures to support adaptive ecological planning.

5.3. Topological Role of Critical Thresholds and Micro-Scale Corridors

Although conservation areas 6, 7, and 8 collectively represent only 0.25% of the basin, they function as critical structural linkages between larger habitat complexes and contribute disproportionately to overall connectivity [37,50,57]. This confirms that ecological importance is not solely determined by spatial extent but also by network position.

The MSPA results identify 484 landscape patches, including 302 branches and only 18 bridge elements, indicating a structurally imbalanced network dependent on a limited number of functional connectors [13–15,48]. Structural connectivity is predominantly maintained through linear corridor-like elements, with limited reliance on bridge-based linkages, thereby increasing the system's sensitivity to localized disturbances. Additionally, eight isolated islets (0.03%) and four perforations (0.44%) reflect early-stage fragmentation processes, signaling increasing structural vulnerability [10,37,48].

Within this configuration, micro-scale corridors, stepping-stone habitats, and narrow linkages emerge as essential components of ecological networks, as their loss may result in disproportionate declines in overall landscape cohesion [57,58]. These results collectively highlight that network stability is governed not only by habitat extent but also by topological position and connectivity hierarchy.

5.4. Comparison with Previous Connectivity Studies

The findings are consistent with previous studies demonstrating that structural and functional connectivity represent complementary but non-equivalent dimensions of ecological systems [6,7,53]. Structural models effectively describe habitat configuration, while functional approaches better capture ecological flow dynamics.

MSPA-based models have been widely used to identify habitat cores and fragmentation patterns, whereas MCR-based models and least-cost path analysis are effective in delineating functional movement corridors and resistance-driven ecological flows [13,15–17,39]. However, these approaches are often applied independently, limiting their ability to represent integrated landscape dynamics [43].

This integration improves the realism of connectivity modeling in urbanizing landscapes and enhances its applicability for spatial planning.

A key contribution is the translation of complex ecological outputs into operational planning typologies, enabling direct use in land-use regulation and watershed-scale ecological governance [11,12,24,59].

5.5. Evaluation of Research Hypotheses

H1 is supported, indicating that the integrated MSPA–AHP–MCR framework provides a more comprehensive representation of ecological connectivity than single-method approaches [11,16,43].

H2 is supported, confirming that structurally important habitat cores do not always coincide with functionally important ecological corridors, reflecting a decoupling between spatial structure and ecological flow [16,18].

H3 is supported, demonstrating that the hybrid framework improves the identification of restoration-priority areas and connectivity bottlenecks, particularly in structurally fragmented and high-resistance zones [37,61].

5.6. Limitations and Future Research Directions

5.6.1. Study Limitations

The resistance parameters and AHP weights were derived from published literature and expert-informed ecological assumptions, introducing a degree of subjectivity into the modeling process. Although this approach is widely adopted in multi-criteria ecological assessments, it may influence model sensitivity and the resulting connectivity patterns [19,41,60].

The proposed hybrid ecological typology framework was developed as a scientific spatial decision-support tool rather than a directly implementable land-use planning instrument. Consequently, practical implementation of the proposed planning typologies depends on additional socio-economic, legal, and institutional factors, including land ownership patterns, existing zoning regulations, development pressure, governance capacity, and stakeholder priorities. These implementation-related factors were beyond the scope of the present study and should be incorporated during subsequent planning and policy-making processes.

The framework represents a static snapshot of current landscape conditions and therefore does not incorporate temporal dynamics such as future land-use change, urban growth, or climate change scenarios [29,57].

In addition, the framework is designed as a species-independent landscape-scale assessment and does not explicitly account for species-specific dispersal behavior, habitat preferences, or ecological requirements. Species may differ in their responses to corridor width, substrate characteristics, habitat quality, and landscape barriers. Since this study focuses on landscape-scale ecological network planning, the model adopts a generalized resistance and suitability approach based on landscape permeability rather than species-specific movement parameters. This approach enables the development of a transferable spatial decision-support framework at the watershed scale; however, future research could further refine the model by incorporating focal species data, functional groups, telemetry observations, or expert-based species movement parameters.

Finally, although uncertainty was partially addressed through methodological evaluation procedures, including the AHP consistency assessment (CR = 0.0079), a comprehensive uncertainty propagation analysis covering all stages of the modeling framework was not conducted. Potential uncertainty sources may arise from input data preprocessing, land-cover classification, resistance value assignment, AHP-based weighting procedures, and MCR-based connectivity modeling. Future research should incorporate formal uncertainty propagation approaches, such as Monte Carlo simulations or probabilistic sensitivity analyses, to quantify how parameter uncertainty and data variability influence ecological connectivity outputs and spatial prioritization results.

5.6.2. Future Research Directions

Future research should focus on improving the predictive and adaptive capacity of ecological connectivity assessments by incorporating species-specific movement data, dynamic land-use change scenarios, and climate change projections. These extensions would enable a more process-oriented understanding of ecological responses under future environmental and anthropogenic pressures [16,29,53].

Methodological developments integrating Circuit Theory, graph-based connectivity metrics, and agent-based modeling may provide further insights into multi-scale con-

nectivity dynamics and ecological network resilience [18,37,53]. In addition, comparative applications across different ecological and socio-spatial contexts are required to evaluate the transferability and adaptability of the proposed hybrid ecological typology framework [11,12].

Future studies may also explore the integration of real-time monitoring data, remote sensing-based change detection, and participatory planning approaches to strengthen the framework as an adaptive decision-support system for long-term ecological planning and landscape governance [11,12,43].

6. Conclusions

This study developed a hybrid ecological typology framework to analyze the spatial and functional heterogeneity of the Büyükçekmece Lake Watershed under intense peri-urban transformation pressure. By integrating Morphological Spatial Pattern Analysis (MSPA), Analytic Hierarchy Process (AHP), and Minimum Cumulative Resistance (MCR) analysis, the framework synthesizes multi-layer geospatial information into a unified spatial decision-support structure applicable at the watershed scale.

The results demonstrate that habitat extent alone is insufficient to explain ecological condition in complex landscapes. Although interior habitat zones dominate the system, the landscape exhibits a fragmented configuration characterized by discontinuous habitat patches, limited structural connectors, and a pronounced edge-dominated matrix. This indicates that ecological integrity is not determined solely by habitat quantity but by spatial configuration and connectivity structure.

Connectivity analysis further reveals that ecological flow is maintained through a limited number of critical corridors and nodes, while localized bottleneck zones represent key constraints on basin-scale permeability. These constrained areas highlight the spatial unevenness of ecological functionality and emphasize the importance of topological position in addition to habitat extent.

A key outcome of this study is the translation of multi-dimensional ecological outputs into operational planning categories, including conservation, ecological corridors, restoration, sustainable use, and controlled development. This typological structure provides a direct linkage between ecological analysis and spatial planning decision-making, enabling more targeted and hierarchical land-use strategies in fragmented watershed systems.

Overall, the proposed framework offers a transferable decision-support approach for identifying ecologically constrained areas and prioritizing intervention zones in rapidly urbanizing landscapes. It contributes to landscape ecology and spatial planning by integrating structural, functional, and suitability-based analyses into a single operational model that can support multi-scale ecological governance.

Future research should incorporate temporal land-use dynamics and species-specific movement data to improve predictive accuracy and extend the applicability of the framework under changing environmental conditions.

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