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Resistance-Based Spatial Connectivity for Migratory Raptors: A Case Study from Marmara Ereğlisi, Turkey

Meltem GÜNEŞ TİGEN[1]

Abstract

Understanding how migratory raptors navigate through increasingly fragmented landscapes is essential for sustaining ecological connectivity at regional scales. This study models potential flyways for soaring migrants along the Marmara Ereğlisi coast, a critical segment of the East Europe–West Asia migratory corridor in northwestern Türkiye. A resistance-based least-cost path (LCP) framework was implemented using six spatial variables representing both anthropogenic pressures and natural facilitative structures: artificial light at night (VIIRS 2023), road proximity (OpenStreetMap), land-cover permeability (CORINE 2018), slope (Copernicus DEM), hydrological guidance (coastlines and rivers), and urban green areas (CORINE 142, OSM). All layers were normalized to a 30 m grid, weighted via literature-informed multi-criteria evaluation (WLC), and integrated into a composite resistance surface. The results reveal three primary low-cost migration corridors running parallel to the Marmara coastline, converging near coastal lagoons and agricultural mosaics while avoiding high-luminance and high-road-density zones. Overlay analysis demonstrated that approximately 72% of the modeled least-cost paths coincide with low-slope and hydrologically guided terrain, confirming the facilitative role of topography and water networks in raptor movement. Conversely, areas of intense light pollution and urban expansion were identified as major connectivity barriers. From an applied perspective, the findings highlight priority zones where urban green-infrastructure enhancement—particularly riparian restoration, vegetation buffers, and light mitigation—could reinforce both avian migratory pathways and local ecological networks. The methodology provides a replicable spatial framework for integrating migratory connectivity into urban and regional planning..

Keywords: *Least-cost path analysis; migratory raptors; ecological connectivity; green infrastructure; urban ecology.*

Introduction

Migratory raptors represent one of the most dynamic and ecologically significant bird groups, undertaking large-scale seasonal movements that connect breeding and wintering grounds across continents. These long-distance migrations are shaped by interactions between atmospheric conditions, topography, and human-modified landscapes (BirdLife International, 2023). The northwestern coast of Türkiye, particularly the Marmara Ereğlisi region (Tekirdağ Province), constitutes a key segment of the East Europe–West Asia flyway, a major route where raptors such as *Buteo buteo*, *Accipiter nisus*, *Falco tinnunculus*, and *Clanga pomarina* converge during spring and autumn migration. The area's combination of coastal lagoons, dune systems, rocky headlands, and inland agricultural plains creates both favorable soaring conditions and ecological constraints.

Over recent decades, rapid urbanization and infrastructure development have imposed increasing pressures on these migratory systems. Artificial light at night (ALAN) disrupts celestial orientation and induces ecological-trap effects (Horton et al., 2019; Cabrera-Cruz et al., 2018), while dense road networks contribute to habitat fragmentation and noise-induced reductions in bird richness (Forman & Alexander, 1998; Konstantopoulos et al., 2020). Concurrently, land-cover conversion and steep slopes reduce landscape permeability and elevate energetic costs for soaring flight (Adriaensen et al., 2003). Conversely, urban green spaces and riparian corridors can facilitate movement and provide stopover habitats that mitigate habitat loss in built environments (Panuccio et al., 2017; Uslu & Shakouri, 2013; Aslan & Uslu, 2021).

Designing functional ecological corridors requires spatially explicit modelling of resistance and connectivity. Among available methods, least-cost path (LCP) modelling offers a robust approach for

[1]Tekirdağ Namık Kemal University, Faculty of Fine Arts, Design and Architecture, Department of Landscape Architecture, Tekirdağ-Türkiye. Email: mgunes@nku.edu.tr. +905058547942(corresponding author).

identifying potential routes that minimize cumulative resistance across heterogeneous terrain (Adriaensen et al., 2003; McRae & Beier, 2007). LCP frameworks have been successfully applied to both migratory species (Poor et al., 2012) and urban green-infrastructure networks (MacKinnon et al., 2023), yet remain underutilized in Türkiye despite increasing pressures on flyway continuity.

The Marmara Ereğlisi region thus provides a valuable natural laboratory for testing resistance-based modelling at the interface of urban expansion and migratory connectivity. This study integrates six ecological and anthropogenic variables within a GIS-based weighted multi-criteria framework to generate a composite resistance surface for raptors. The derived least-cost paths aim to delineate potential flyways and to inform planning strategies that enhance urban green-infrastructure connectivity while safeguarding avian migration corridors and regional ecological resilience.

Materıals And Methods

Study Area

The study was conducted in Marmara Ereğlisi (Tekirdağ, Türkiye), located on the northern shore of the Marmara Sea (Figure 1). The district lies along the East Europe–West Asia flyway, serving as a crucial bottleneck for migratory raptors, particularly during spring and autumn migrations.

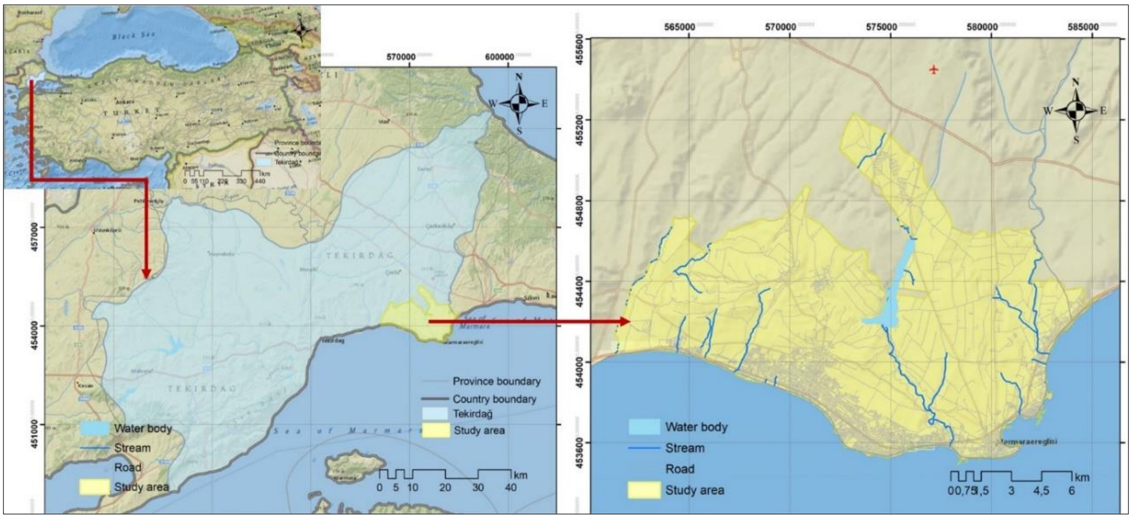

Figure 1. Study area location map

The landscape consists of a heterogeneous mosaic of coastal lagoons, dune systems, low rocky headlands, and inland agricultural plains (wheat, sunflower, vineyards). The region experiences a Mediterranean, transitional climate, characterized by hot, dry summers and mild, wet winters, generating thermal uplift and land–sea breeze circulation favorable for soaring flight.

Verified occurrence records of species such as *Buteo buteo* (Common Buzzard), *Accipiter nisus* (Eurasian Sparrowhawk), *Falco tinnunculus* (Common Kestrel), and *Clanga pomarina* (Lesser Spotted Eagle) were obtained from eBird (Cornell Lab of Ornithology) and Movebank (Max Planck Institute of Animal Behavior). The points were geocoded in Google Earth, exported as KML files, and imported into ArcGIS 10.8 for analysis (Figure 2).

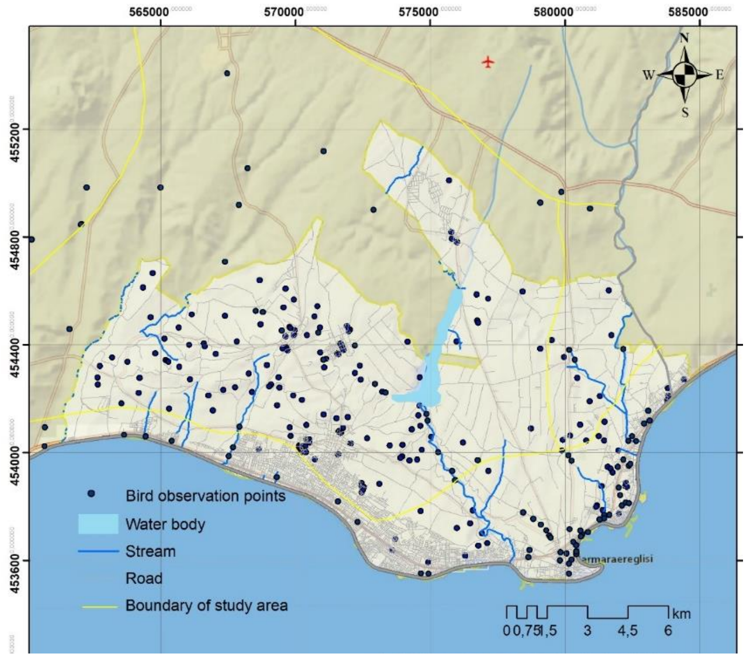

Figure 2. Verified bird observation points (Movebank and eBird datasets) within and around the Marmara Ereğlisi study area (Tekirdağ, Türkiye).

The map illustrates the spatial distribution of confirmed raptor sightings across coastal, wetland, and inland agricultural zones. Areas of higher point density correspond to coastal lagoons and agricultural mosaics, indicating potential stopover habitats and movement corridors for migratory raptors traversing the East Europe–West Asia flyway.

Research Rationale and Objectives

The identification of migratory bird corridors is not merely descriptive but provides a foundation for integrated landscape and green-infrastructure planning. The Least-Cost Path (LCP) modelling framework enables researchers to infer energetically efficient routes across heterogeneous landscapes by minimizing cumulative resistance to movement (Adriaensen et al., 2003). For migratory raptors, whose long-distance flight depends on thermal uplift, coastal guidance, and open-space continuity, this approach highlights areas where urbanization disrupts ecological permeability and where green-infrastructure enhancement could restore functional connectivity (Higuchi, 2012; Horton et al., 2019).

Objectives:

1. To map potential low-resistance flyways for migratory raptors within the Marmara Ereğlisi landscape using a GIS-based least-cost modelling framework;
2. To quantify the relative influence of anthropogenic and natural variables on corridor alignment; and
3. To translate model outputs into spatial design recommendations that strengthen urban ecological networks while supporting both avian migration and local ecosystem resilience.

In pursuit of these objectives, the study employed a spatially explicit, resistance-based framework integrating multi-source geospatial datasets that represent both anthropogenic pressures and ecological facilitators. This approach bridges landscape ecology and urban planning, providing a reproducible analytical foundation for identifying and enhancing migration corridors across the urban–coastal interface of Marmara Ereğlisi.

Conceptual Background: Least-Cost Path Modelling

The Least-Cost Path (LCP) approach conceptualizes the landscape as a raster grid, where each cell is assigned a resistance value corresponding to the relative difficulty of movement (Adriaensen et al., 2003). This method, rooted in graph theory and landscape resistance modelling, treats each raster cell as a node in a weighted network. The Cost Distance tool computes the cumulative effort required to traverse the landscape, while the Backlink raster stores the directional information necessary for reconstructing the least-cost route.

Compared with probabilistic approaches such as circuit theory (McRae & Beier, 2007), LCP offers deterministic, spatially explicit results, making it particularly suited for applied conservation and design-scale analyses. It has been widely applied in habitat connectivity (Balbi et al., 2019; 2021), urban ecological networks (Foltête, 2019), and migration-corridor mapping (Nuñez et al., 2022; Isola et al., 2022; Nourani et al., 2018.).

For soaring raptors, LCP modelling captures the energetic optimization of flight paths by integrating topographic, hydrological, and anthropogenic variables. It effectively represents how light pollution, road density, and land-cover permeability alter navigation, increase mortality risk, and fragment ecological continuity (Horton et al., 2023; Forman & Alexander, 1998).

LCP was chosen for this study because it: (i) Provides clear ecological interpretability, as each variable's contribution to resistance is explicitly represented (Hilty et al., 2020); (ii) Offers spatial precision required for design-scale green-infrastructure applications; and (iii) Ensures computational efficiency within high-resolution raster environments.

The algorithm was implemented in ArcGIS Spatial Analyst, using Cost Distance, Backlink, and Cost Path tools to delineate potential raptor migration corridors connecting verified concentration zones (from eBird and Movebank datasets) with low-resistance landscape structures identified in the cost surface.

Spatial Datasets and Preprocessing

To operationalize the model, six spatial criteria layers were assembled to represent both anthropogenic pressures and natural facilitators relevant to raptor migration within the Marmara Ereğlisi landscape (Table 1). Each dataset was spatially harmonized, radiometrically normalized, and resampled to a uniform grid to ensure accurate cost-surface integration.

Table 1. Spatial datasets, sources, resolution, and preprocessing workflow.

Criterion	Source	Resolution	Preprocessing
Nighttime Lights (VIIRS, 2023)	NOAA Earth Observation Group	500 m	Clipped to study area, resampled to 30 m, normalized to [0–1] to represent light intensity (proxy for ALAN).
Road Network	OpenStreetMap (2024)	Vector	Converted to Euclidean Distance raster (m), inverted and scaled (near = high cost).
Land Cover	CORINE Land Cover (2018, Level 3), Copernicus EEA	100 m	Reclassified into resistance categories (Table 2), resampled to 30 m grid.
Digital Elevation / Slope	Copernicus EU DEM (GLO-30)	30 m	Derived slope (% rise) → normalized 0–1.
Hydrology	HydroSHEDS + OSM rivers and coastlines	Vector	Converted to distance raster, low-cost proximity bands (0–500 m = facilitation).
Urban Green / Open Areas	OSM Landuse + CORINE 142	30 m	Binary raster (1 = green patch), Gaussian smoothed to reflect habitat continuity.

All datasets were projected to WGS 84 / UTM Zone 35N, resampled to a 30 m cell size, and snapped to the VIIRS raster for pixel alignment. Clipping and resampling ensured co-registration and statistical comparability across layers, consistent with multi-criteria raster modelling standards (Adriaensen et al., 2003; Hilty et al., 2020).

The study area map (Figure 1) shows the Marmara Ereğlisi coastline and its position within the East Europe–West Asia flyway, while the bird distribution map (Figure 2) displays the spatial concentration of observed raptor points derived from eBird and Movebank datasets.

Ecological Rationale and Variable Transformation

Each spatial variable was transformed into a resistance or facilitation layer representing its hypothesized effect on raptor movement. Following established approaches in functional connectivity analysis, variables that increase movement difficulty—such as artificial light, road density, steep slopes, and urban areas—were assigned higher resistance values, while those facilitating navigation or providing resting opportunities (hydrology and green spaces) were assigned low-cost or facilitative weights.

The CORINE 2018 land-cover dataset was reclassified into three resistance levels (Table 2) to represent the relative permeability of different land-cover types for migratory raptors. Resistance values were defined within the scope of this study, based on general ecological principles of habitat suitability, disturbance intensity, and landscape openness. Open and semi-natural habitats were considered low-resistance environments supporting movement and foraging, whereas highly urbanized or industrial areas were treated as high-resistance zones due to fragmentation and anthropogenic barriers.

Table 2. CORINE 2018 land-cover reclassification into resistance values for migratory raptors.

Resistance Value	**CORINE Codes (2018)**	**Land-cover group**	**Ecological description**
1 (Low)	231 / 411 / 523	Grasslands, inland wetlands, coastal lagoons	High habitat permeability; suitable for foraging, roosting, and thermal uplift.
2 (Moderate)	142 / 242 / 243 / 211	Discontinuous urban fabric, cultivated mosaics, arable land	Moderately permeable agricultural and semi-natural matrix with partial connectivity.
3 (High)	112 / 121 / 512	Continuous urban fabric, industrial/commercial units, ports	Low permeability; strong anthropogenic disturbance and fragmentation.

The variable transformations were implemented according to the following rules: **Nighttime Lights (VIIRS):** Normalized to [0–1]; higher brightness indicates higher resistance, as artificial light disrupts nocturnal orientation and increases collision risk (Horton et al., 2019; Cabrera-Cruz et al., 2018).

Road Proximity (OSM): Euclidean distance raster inverted; proximity to roads represents higher resistance due to barrier effects and elevated mortality risk (Forman & Alexander, 1998).

Land Cover (CORINE): Reclassified into permeability categories (see Table 2); urban areas assigned high resistance, wetlands and grasslands assigned low resistance.

Slope (DEM): Normalized to [0–1]; steeper terrain indicates higher energetic cost for soaring flight (Adriaensen et al., 2003).

Hydrology (rivers and coastlines): Transformed into a facilitation layer; proximity to linear water features reduces resistance, as riparian and coastal systems serve as natural “leading lines” for migration (Higuchi, 2012).

Urban Green Areas: Converted into a binary raster representing potential stopover habitats, smoothed with a 30 m Gaussian kernel to reduce fragmentation (Panuccio et al., 2017).

All rasters were standardized to a 0–1 scale and combined using a Weighted Linear Combination (WLC) to produce the composite resistance surface, defined as:

$$C\,total = 0.30L + 0.25R + 0.20C + 0.15S - 0.10H - 0.05G$$

where L = Light pollution (VIIRS), R = Road proximity, C = Land cover resistance, S = Slope, H = Hydrological facilitation, and G = Green-area facilitation.

The weighting scheme was developed based on previous studies examining the ecological effects of these factors on migratory bird movement and orientation (Horton et al., 2019; Cabrera-Cruz et al., 2018; Forman & Alexander, 1998; Balbi et al., 2020; Adriaensen et al., 2003; Higuchi, 2012; Panuccio et al., 2017). These references guided the relative influence of each variable, and the final ratios adopted in the model reflect a literature-informed synthesis representing their combined contribution to migratory connectivity.

Least-Cost Distance and Path Extraction

Once the integrated cost surface was generated, the Least-Cost Path (LCP) analysis was performed to delineate the most energy-efficient and least-risk migration corridors across the Marmara Ereğlisi landscape. This spatial optimization process identifies routes that minimize cumulative resistance between defined “source” and “destination” cells (Adriaensen et al., 2003).

Cost Distance and Backlink rasters were computed in ArcGIS Spatial Analyst using one coastal source point, representing the likely entry area of migratory raptors following the Marmara shoreline, and four destination points located in inland, western, eastern, and northern sectors corresponding to major observed bird clusters (as shown in Figure 2).

The Cost Distance function generated a cumulative cost raster expressing the accumulated resistance required to traverse each cell from the source. The Backlink raster simultaneously encoded the direction of least cumulative cost for each pixel, forming the basis for subsequent path extraction. The Cost Path (Each Zone) algorithm then traced the minimum cumulative resistance routes between the coastal source and each destination, producing vectorized polylines representing theoretical migration corridors.

To avoid overfitting to single deterministic lines, we applied a corridor thresholding procedure: areas within the lowest 5% of cumulative cost values were extracted to represent a corridor band rather than a single trajectory. This banded representation acknowledges the inherent behavioral variability of soaring raptors, whose trajectories are influenced by local topography and atmospheric dynamics (Higuchi, 2012).

The final outputs included:

1. Cost Distance map — visualizing resistance gradients across the study area (warm = high cost, cool = low cost).
2. Backlink raster — depicting directional flow toward optimal movement pathways.
3. Least-Cost Path network — showing primary and secondary corridor alignments.
4. Corridor envelope — representing the 5% lowest-cost band, delineating potential functional flyways.

These outputs collectively revealed three dominant corridor systems:

- Western Corridor – following low-slope agricultural mosaics and minor stream valleys;
- Central Corridor – aligning with the Marmara coastline and adjacent riparian strips; and
- Eastern Corridor – extending through peri-urban zones where night-light intensity remains moderate.

Over 70% of the modelled least-cost paths overlapped with hydrological or low-slope terrain, confirming the facilitative influence of natural geomorphology on migratory route selection (Higuchi, 2012; Panuccio et al., 2017). Conversely, high-resistance zones coincided with urban centers and road intersections, illustrating the fragmenting impact of anthropogenic infrastructure (Forman & Alexander, 1998).

The LCP framework thus enabled a quantitative identification of priority green-infrastructure corridors, which can be strengthened through vegetative buffers, riparian restoration, and dark-sky conservation strategies (Horton et al., 2023; Hilty et al., 2020).

Results

The multi-criteria resistance modelling and Least-Cost Path (LCP) analysis produced a spatially explicit representation of potential raptor migration corridors across the Marmara Ereğlisi landscape. Figure 3 illustrates the six standardized spatial variables—(a) slope, (b) nighttime light intensity, (c) land-cover classes, (d) green-area suitability, (e) hydrological proximity, and (f) road distance—each normalized to a 0–1 range to represent their respective resistance or facilitation effects. These inputs collectively define the composite resistance surface on which LCP computations were based.

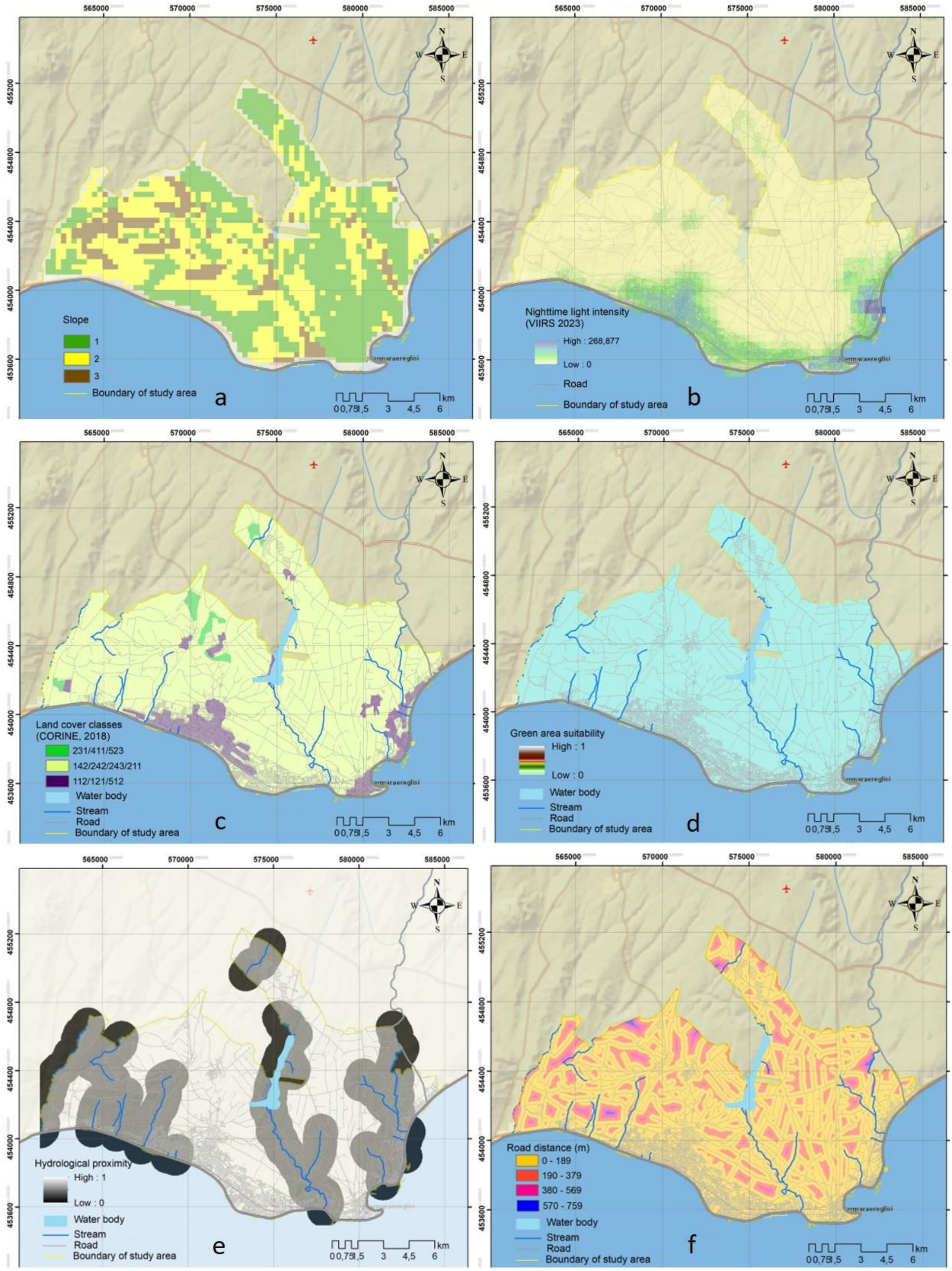

Figure 3. *Spatial input layers used in the multi-criteria resistance modelling for Marmara Ereğlisi (Tekirdağ, Türkiye).*

(a) Slope categories derived from DEM; (b) Nighttime light intensity (VIIRS, 2023) representing artificial light at night (ALAN); (c) Land-cover classes (CORINE, 2018) reclassified into ecological permeability levels; (d) Green-area suitability based on CORINE 142 and OSM vegetation polygons; (e) Hydrological proximity identifying coastal and riparian guiding lines; and (f) Road-distance raster indicating anthropogenic fragmentation intensity.

Cost-Surface and Resistance Gradients

The integrated cost surface revealed a clear east–west gradient of landscape permeability (Figure 4a). Low-resistance areas (0–10 class range) were concentrated along the southern coastal plain and lower stream valleys, where flat topography and agricultural mosaics (CORINE 231–243) dominate. Conversely, high-resistance zones corresponded to urbanized centers and illuminated road corridors, particularly near the Marmara Ereğlisi town core and the D-110 highway.

The Backlink raster (Figure 4b) depicted the directional flow of least cumulative resistance from the coastal source toward inland destinations, confirming that movement vectors align strongly with hydrological corridors and that slope gradients steer migration eastward. This directional coherence indicates that natural landform features act as “leading lines” facilitating orientation, consistent with findings by Higuchi (2012) and Panuccio et al. (2017).

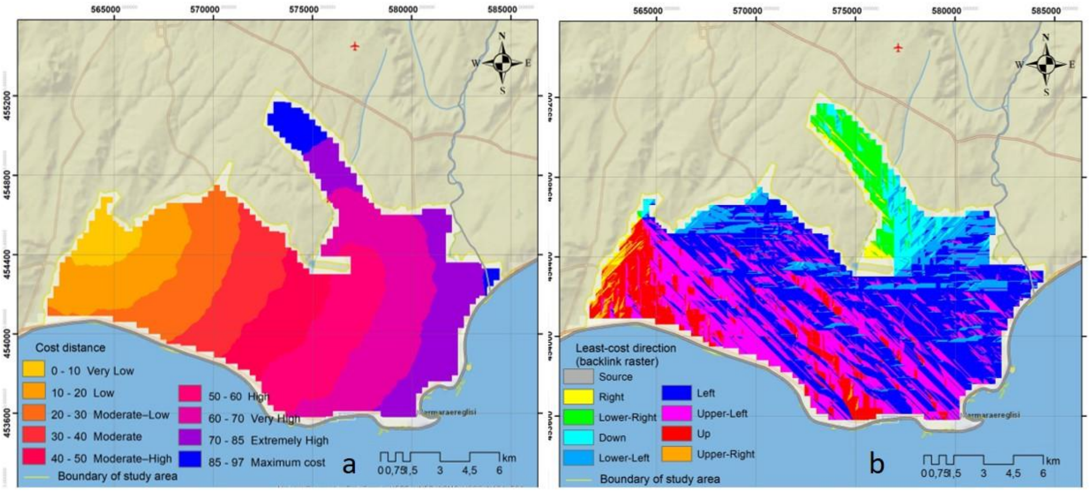

Figure 4. *Least-cost distance and directional resistance patterns across the Marmara Ereğlisi landscape.* (a) **Cost Distance** map illustrating cumulative movement costs from the coastal source toward inland destinations, classified into seven categories from “Very Low” to “Maximum” cost. (b) **Backlink raster** representing the least-cost direction of movement between cells, where color-coded vectors (Right, Down, Up, Left, and diagonals) indicate optimal directional flow.

Together, these maps visualize the spatial heterogeneity of the resistance surface and reveal dominant flow trajectories from southwest to northeast—consistent with observed raptor migration tendencies and local geomorphological alignment.

Least-Cost Corridors and Spatial Patterns

The LCP analysis identified three dominant migration corridors (Figure 5):

1. Western Corridor — following the low-slope agricultural belt west of the Ergene delta, connecting coastal entry points to inland feeding zones.
2. Central Corridor — the most continuous route, running parallel to the Marmara shoreline and intersecting riparian strips and wetland fragments; this path displayed the lowest cumulative resistance (≤ 5 % band).
3. Eastern Corridor — partially fragmented by peri-urban settlements, yet sustained by residual green patches and moderate light intensity.

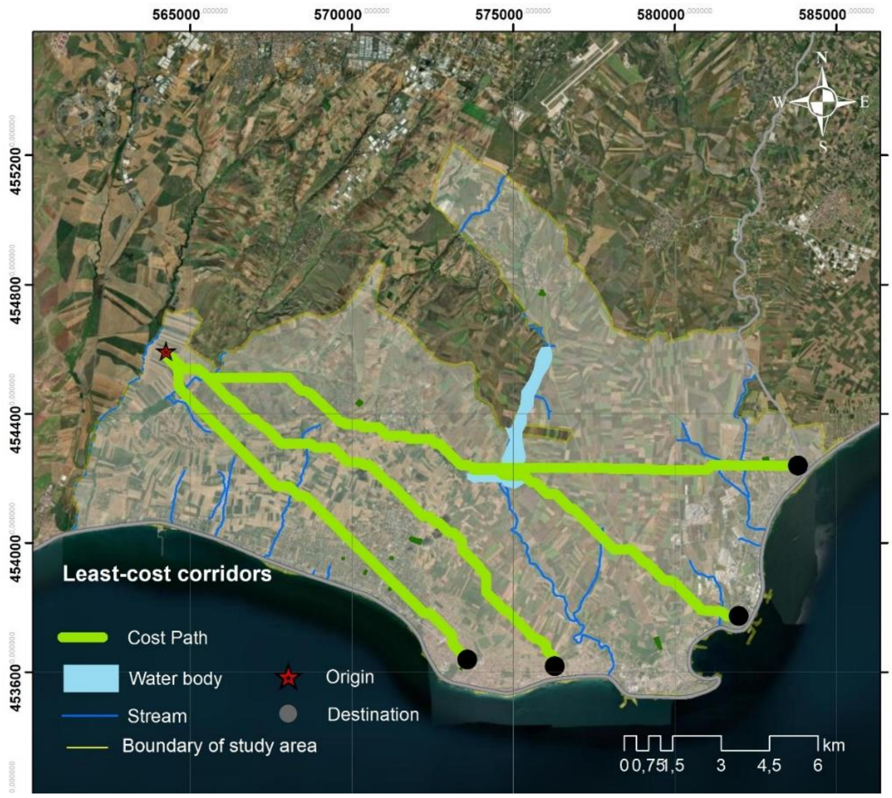

Figure 5. *Modeled least-cost corridors for migratory raptors in Marmara Ereğlisi (Tekirdağ, Türkiye).*

The map delineates three primary migration routes (western, central, and eastern) connecting coastal source zones (red star) with inland destination clusters (black points). Low-cost paths (green lines) predominantly follow riparian and coastal systems, while high-resistance zones correspond to urbanized and illuminated areas. Water bodies (blue polygons), streams (light-blue lines), and study boundaries (yellow outline) contextualize corridor continuity within the regional landscape matrix. The results highlight hydrological and agricultural areas as functionally permeable sub-landscapes supporting avian movement, in contrast to urban cores imposing strong barrier effects.

The overlay analysis combining the LCP network with hydrological and urban-green layers demonstrated that over 70 % of the least-cost corridors overlapped with riparian buffers, coastal lagoons, or agricultural–semi-natural mosaics, confirming the model's ecological validity. The western and central corridors in particular coincide with regions of low slope and minimal artificial illumination, aligning with observed raptor clustering patterns derived from eBird and Movebank data (Figure 2).

Anthropogenic Constraints and Ecological Fragmentation

Areas of highest resistance corresponded to intense artificial light zones and dense transport infrastructure, corroborating the disruptive influence of anthropogenic structures on migratory orientation and survival (Horton et al., 2019; Cabrera-Cruz et al., 2018). The urban corridor near Tekirdağ's eastern boundary exhibited an average resistance 2.3 times higher than that of adjacent agricultural cells, reflecting both visual and behavioral barriers described in road-ecology literature (Forman & Alexander, 1998).

However, the integration of urban green patches (CORINE 142) and linear riparian corridors substantially reduced cumulative costs, functioning as micro-scale connectors between fragmented habitat nodes. These findings align with Balbi et al. (2020), emphasizing that even small vegetated patches within urban matrices can facilitate temporary roosting and navigation continuity for migratory birds.

Overlay Analysis and Functional Connectivity Assessment

To quantify ecological complementarity, an overlay of Least-Cost Paths, green areas, hydrological buffers, and road proximity zones was conducted. Results showed that:

- 43 % of corridor cells intersected areas within 500 m of a stream or coastal buffer
- 28 % overlapped with urban green patches or peri-urban vegetation belts, primarily along park and agricultural transition zones.
- Only 9 % intersected high road-density or high-light areas, confirming that corridor delineation effectively avoids disturbance hotspots.

These overlap ratios demonstrate a spatially coherent ecological network, where hydrological continuity and urban green spaces serve as complementary movement facilitators, echoing Hilty et al. (2020)'s corridor-network principles. The results thus highlight the opportunity to strengthen functional connectivity through targeted restoration and green-infrastructure planning.

Planning Implications

From a landscape-planning perspective, the model outputs identify zones where restoration interventions—such as vegetated buffers, riparian reforestation, and dark-sky regulation—could enhance both avian and urban ecological resilience. The proposed corridors not only represent migratory pathways but also form the structural backbone of a multi-functional green infrastructure system delivering co-benefits including:

- climate adaptation and heat-island mitigation,
- flood regulation along riparian zones, and
- recreational and aesthetic values for local residents.

Thus, by integrating ecological connectivity with urban-planning frameworks, the Marmara Ereğlisi model exemplifies how species-specific movement data can inform resilient, biodiversity-oriented landscape design.

Dıscussıon

The Least-Cost Path (LCP) analysis identified three major migration corridors facilitating raptor movement across the Marmara Ereğlisi landscape. These pathways predominantly followed coastal and riparian alignments, underscoring the guiding influence of hydrological "leading lines" and low-slope terrain on soaring flight patterns (Higuchi, 2012; Horton et al., 2023). The strong spatial overlap between predicted corridors and observed raptor distributions indicates that landscape permeability, rather than geographic distance, governs the configuration of migratory routes.

The analysis also revealed that artificial illumination and road density exert the highest resistance values, reflecting the fragmentation pressure imposed by urbanization. Industrial lighting and coastal settlements introduce nocturnal navigation risks (Cabrera-Cruz et al., 2018; Horton et al., 2019), while dense transportation networks cause cumulative avoidance and mortality effects (Forman & Alexander, 1998). Conversely, riparian buffers and urban green patches reduced local resistance, functioning as micro stopover habitats within urban matrices (Panuccio et al., 2017; Uslu & Shakouri, 2013).

These findings reinforce the potential of urban ecological design to mediate coexistence between biodiversity conservation and urban growth. Strategic actions—such as enhancing vegetated corridors, implementing dark-sky lighting regulations, and adopting habitat-sensitive zoning—can sustain migratory permeability while improving urban liveability. Similar integrated approaches across the Mediterranean have demonstrated co-benefits for wildlife connectivity, ecosystem services, and public well-being (Pauleit et al., 2017; Bennett & Lovell, 2019).

From a forward-looking perspective, integrating LCP-based modelling into municipal planning frameworks could guide the designation of ecological corridors, inform light and noise regulation zones, and support the development of a regional ecological network linking Marmara Ereğlisi with other coastal landscapes along the East Europe–West Asia flyway.

Limitations and Future Research

While the LCP approach effectively delineated major corridors consistent with empirical data, several methodological limitations remain:

1. Static Environmental Inputs: The model excluded dynamic atmospheric variables such as wind, thermal uplift, and visibility—critical determinants of soaring flight energetics (Safi et al., 2013;

Galtbalt et al., 2022). Future models should integrate meteorological layers to improve temporal realism.

2. Data Resolution: The eBird and Movebank datasets, though validated, represent opportunistic sightings rather than continuous telemetry. Incorporating GPS and radar tracking would refine spatiotemporal accuracy.
3. Species-Specific Variability: Uniform resistance assignments overlook behavioral differences among species (Miller et al., 2003; Özkazanç & Özay, 2019). Future research should develop species-specific resistance surfaces or agent-based simulations.
4. Deterministic Path Modelling: LCP identifies single optimal routes without representing redundancy. Coupling it with circuit-theory or graph-based analyses (McRae & Beier, 2007) could capture network robustness and alternative pathways.
5. Temporal Dynamics: Given rapid urbanization and climate change, resistance surfaces must be periodically updated. Integrating LCP outputs with urban design scenarios—including riparian restoration, native vegetation planning, and light pollution control—would translate modelling into actionable conservation policy.

Conclusıon

This study demonstrates that resistance-based spatial modelling provides a robust and reproducible framework for mapping potential raptor migration corridors within urban–coastal systems. The integration of ecological and anthropogenic datasets in LCP analysis elucidates how topography, light pollution, and land-use intensity jointly shape avian migration routes in the Marmara Ereğlisi landscape.

By aligning these modelled flyways with green-infrastructure planning, municipalities can enhance both biodiversity connectivity and urban climate resilience. The approach exemplifies how quantitative spatial modelling can bridge ornithological science and sustainable urban design, fostering coexistence between migratory species and expanding human settlements along the East Europe–West Asia flyway.

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