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Water-Sensitive Urban Design in Istanbul: An Ecological Corridor Framework from the Ömerli Basin to the Tuzla Coastal Zone

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Abstract

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Water-related hazards in urban environments are intensifying due to rapid urbanization and climate change, with flash-flood risks increasingly evident in Istanbul. Conventional gray infrastructure alone cannot adequately address the interconnected hydrological and ecological pressures affecting metropolitan landscapes. This study develops a GIS-based Water-Sensitive Urban Design (WSUD) framework for the Ömerli Basin–Tuzla corridor, integrating flood vulnerability assessment, urban pressure evaluation, and ecological connectivity modeling through multi-criteria evaluation and the Minimum Cumulative Resistance model. The analysis identifies spatial conflict zones where flood exposure, urban development pressure, and ecological fragmentation converge, revealing a pronounced north–south gradient across the corridor. Based on these findings, a corridor-scale blue–green infrastructure framework is proposed to guide targeted nature-based interventions. The study contributes to metropolitan-scale WSUD research by demonstrating how integrated territorial analysis can support spatially differentiated planning and climate-resilient urban development in rapidly urbanizing coastal regions.

Keywords: Water-Sensitive Urban Design (WSUD); nature-based solution; urban watershed; blue-green infrastructure; ecological corridor; urban flooding.

1. Introduction

Since the first Industrial Revolution, the world has undergone global changes in life dynamics linked to a significant increase in the world's population and its patterns of consumption (Duarte, 2006), contributing to what is widely described as the Anthropocene era. Accordingly, global ecological systems, including both biotic and environmental components, have been significantly degraded. Human activities are seen as a contributing factor to climate change, which manifests through a range of hazards affecting both urban and natural systems, including flooding, drought, sea-level rise, water quality degradation, and extreme heat events. Since 1967, records indicate that Istanbul has experienced approximately 13 flood events, causing major damage, confirming that the flood risks have been intensifying since then due to multiple reasons, such as unplanned development, especially in areas that are more vulnerable to rainfall and natural flood zones, as well as the city's conventional drainage system no longer being effective for such floods (Kömüşcü & Çelik, 2013). Flood mitigation strategies are often reactive, focusing on drainage expansion rather than addressing the underlying spatial and ecological causes of flood vulnerability. In direct relation to major flood events across Europe, the European Union Floods Directive, adopted in 2007, highlighted the limitations of traditional flood-defense approaches that rely primarily on structural engineering solutions (Mysiak et al., 2013; Neuhold, 2017).

The rise in the frequency and intensity of floods is attributable to changes in precipitation patterns and glacial melt (Bates et al., 2008). The environment's reduced capacity to absorb large amounts of water, exacerbated by global warming and climate change, results in more frequent and severe flooding events, with forecasts indicating a global intensification in the coming years (Trenberth et al., 2003). According to Najafi et al. (2024), flooding disasters could result in major impacts affecting more than one billion people globally. Beyond their immediate impacts, these flood events reflect a deeper transformation in the relationship between cities and natural water systems. The shift from natural landscapes to heavily urbanized environments has disrupted the balance of the natural hydrological cycle. The natural water cycle represents the continuous circulation of water without much human interference. Thus, the natural cycle includes three main processes: first, evaporation and transpiration; second, precipitation; and third, infiltration, percolation, and runoff (Booth & Jackson, 1997). In contrast, the urban water cycle is subject to greater human intervention, hindering its natural flow, where the steady growth of urban areas escalates the impervious surfaces and the disappearance of natural waterways and green spaces, producing more surface runoff and, consequently, increasing flooding, degradation of water quality and groundwater resources, and a diminution of amenity in urban communities (Iftekhar and Islam, 2023). These changes also increase the volume and velocity of stormwater runoff and essentially reorganize the local hydrology (Meng,

2022). Singh and Kandasamy (2009) assert that stormwater is now an essential part of catchment runoff yet remains underutilized.

In response to these challenges, Water-Sensitive Urban Design (WSUD) has emerged as an innovative approach to the organization of urban water systems. According to Wong (2006), it is founded on incorporating water-cycle management into the framework of city planning and design, which is accomplished by integrating the existing drainage systems with various other decentralized techniques, such as green infrastructure (GI) systems (Bujak et al., 2025). The WSUD framework is an Australian-made concept that has been developed to tackle urban water challenges; currently, its principles are being investigated and adjusted across different global contexts, such as the United States and Europe (Thurston, 2011). The central idea behind this approach is a strategic shift away from traditional, highly centralized water-management infrastructure and toward the intentional development of more sustainable, resilient, and habitable urban landscapes (Chadfield et al., 2024). A key strategy for attaining this vision involves utilizing green infrastructure and nature-based solutions that are appropriate for supporting the ecological functionality of the urban environment (Wong et al., 2020; Afara et al., 2024). On the other hand, the world is promoting similar concepts, such as Water Wise Cities and Sponge Cities, to address similar challenges. The concept of a sponge city is based on integrating nature into its practical solutions, which has been implemented in some Chinese cities, indicating a high potential as an effective urban water management strategy (Wishart et al., 2021). This concept was first introduced in China in April 2012 to address urban water-related challenges through the principles of ecological priority and low-impact development. In contrast to other "sponge" definitions, using the term "sponge" refers to an urban environment that is adaptable to environmental changes and water-related disasters; accordingly, during rainfall events, the rainwater is absorbed, stored, permeated, and purified, then released to be utilized when required (Li et al., 2021).

According to Hoban (2019), Water-Sensitive Urban Design (WSUD) approaches can be conceptually organized into two principal categories: avoidance measures and mitigation measures. These categories were defined according to the hierarchy of the decentralized rainwater management system, which distinguishes between strategies that prevent rainwater accumulation at its source and those that manage and treat it after it accumulates. Additionally, these measures must be integrated within the existing urban system in streets, public spaces, infrastructure, etc., to complement each other at different levels, such as street, city, and neighborhood levels. Various types of interventions, including the strategic elimination of portions of the degraded concrete riverbank and the comprehensive rehabilitation of the riparian zone, are considered in the implementation of WSUD. It also involves the introduction of more dispersed bioretention tanks and the active linkage of these decentralized WSUD layouts to natural waterways, thereby increasing the overall ecological performance and resilience of the urban landscape (Chesterfield et al., 2016; Ball et al., 2019).

Over the past few decades, there has been a discernible shift towards decentralized 'green' solutions to address issues associated with traditional stormwater management (Buurman & Padawangi, 2018; Aziz Amen & Ali, 2025). The Blue-Green Infrastructure (BGI) concept, initiated at the turn of the millennium, represents an environmentally friendly option to control the pluvial and other urban floods (Gledhill & James, 2008; Selman, 2008). Recently, urban planners and architects have been recognizing the potential benefits of integrating water with green infrastructure (GI) in urban settings by appreciating its potential as a multipurpose land use and a tool for adapting to climate change. Similarly, using GI with current drainage systems is gaining growing recognition among sanitary engineers as well (Bujak et al., 2025). Nature-based solutions (NBS) are useful mechanisms for improving the quality of urban environments, especially when natural systems have already been disrupted, polluted, or degraded (Hsieh et al. 2016; Kabisch et al. 2016, 2017; Mariani et al. 2016; Mukherjee et al. 2022). These blue-green networks (BGINs) are a valuable network system that renders urban landscapes less fragmented and more ecologically protected, centered around ecological spaces such as water bodies, green spaces, and linking corridors (Gao et al., 2025). These places include various types of water bodies (e.g., a stream, stormwater drain, irrigation channel, or wetland) and green infrastructure, which includes green elements such as the trees along the street, recreation area, park, and forest ((Valenca Pinto et al., 2023; Chowdhoree & Aziz 2023), which collectively assist the urban environment by storing water, controlling floods, providing habitats, and improving air quality (Zhang et al. 2025). On the other hand, ecological connectivity represents a critical spatial dimension of blue-green infrastructure effectiveness, as fragmented green networks are significantly less capable of regulating stormwater, supporting biodiversity movement, and maintaining ecosystem services at the metropolitan scale (Ahern, 2007). Ecological networks function as the spatial foundation for ecosystem services, playing a critical role in reducing environmental degradation caused by urban fragmentation; blue-green spaces distributed across urbanized landscapes can serve as ecological stepping stones to enhance connectivity and ecological resilience, while ecological corridors contribute to climate adaptation, water security, and resilience against extreme weather events (Feng et al., 2025). Recently, water reemerged as a social medium within the water-management paradigm, bringing citizens closer to the water feature, fostering cohesiveness, and promoting community bonding. This shift is aligned with the social sustainability principle, which is the long-established principle of cost recovery and exclusively technical solutions (Buurman & Padawangi, 2018).

Despite growing recognition of climate-related water risks in Istanbul, current planning practices remain largely fragmented and strongly dependent on conventional gray infrastructure. Existing responses often address localized drainage problems but insufficiently consider watershed dynamics, ecological connectivity, land-use pressure, and the cumulative spatial causes of flood vulnerability. Moreover, while WSUD principles have been widely discussed internationally, their metropolitan-scale application within Istanbul remains limited. This reveals a critical gap between contemporary water-sensitive planning theory and implementable regional strategies for the city. Accordingly, this study develops a GIS-based and spatially integrated framework for the Ömerli Basin-Tuzla corridor on the Anatolian side of Istanbul. The corridor is strategically significant because it links the city's major freshwater watershed, expanding urban districts, ecological landscapes, and vulnerable coastal zones. The study is among the first metropolitan-scale WSUD

corridor assessments in Istanbul to integrate flood vulnerability, urban pressure, and ecological connectivity within a unified decision-support framework. Specifically, the research aims to: (1) evaluate urban development pressure, (2) assess flood vulnerability patterns, (3) model ecological connectivity, (4) identify priority zones for WSUD interventions, and (5) propose a corridor-scale blue–green planning strategy. By combining multi-criteria evaluation and connectivity modelling, the study demonstrates how data-driven territorial analysis can guide nature-based urban design and support resilient metropolitan planning in climate-sensitive urban regions.

2. Materials and Methods

2.1 Study area

The study area is located on the Anatolian side of Istanbul, extending from the Ömerli Basin toward the Marmara Sea coastline, including Tuzla and Pendik; it lies approximately between 40.80° and 41.10° N latitude and 29.17° and 29.65° E longitude, covering an area of approximately 740 km² and extending across several districts on the Anatolian side of Istanbul, fully covering Sultanbeyli, Sancaktepe, Pendik, and Tuzla, while only small, less populated portions of Şile, Kocaeli, Maltepe, and Kartal fall within the boundary. The total population of the fully included districts is approximately 1.95 million, representing the main demographic base of the study area (Turkish Statistical Institute [TÜİK], 2025) (Figure 1). The area is characterized by its strategic hydrological function, ecological sensitivity, and diversity of urban and natural structures, forming an interface between freshwater, marine, and terrestrial ecosystems. Within this context, key ecological patches include the Pendik Valley, Ömerli Basin-Aydos Mountain, and the coastal lagoons.

Notably, the Ömerli Watershed is the principal drinking water source of Istanbul, serving approximately 43% of Istanbul’s drinking water supply (Cüce et al., 2025). These features make the Ömerli-Pendik-Tuzla corridor a crucial and representative testing ground for the implementation of WSUD principles.

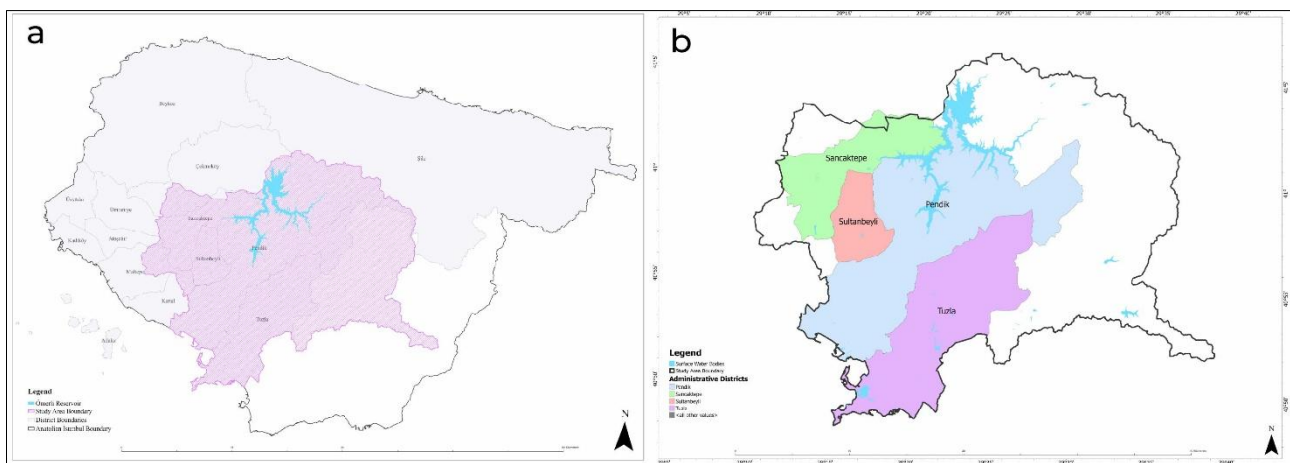


Figure 1. Study area boundary and administrative structure: (a) spatial extent and boundary of the study area within the Anatolian side of Istanbul; (b) administrative districts within the study area.

2.2 Data source and processing.

This research is based on Geographic Information Systems (GIS), which serve as the primary analytical platform for evaluating hydrological, urban, and environmental characteristics. The methodological process is carried out in a series of sequential steps; The first one evaluates urban pressure, the second addresses flood vulnerability assessment, and the third focuses on ecological connectivity analysis. Lastly, all these analytical results are synthesized through a suitability- and connectivity-based framework that facilitates decision-making and special decision-making processes, identifies priority areas for nature-based interventions, and provides a foundation for the design proposal (Figure 2).

The materials used in this study consist mainly of spatial and environmental primary datasets that were obtained from multiple sources, as shown in Table 1, including topographic data derived from a digital elevation model (DEM), land use, land cover data, vegetation indices (NDVI), precipitation, and geological formations. Additional layers, such as slope, stream networks, distance to streams, water bodies, buffer zones, building distribution, and road networks, were derived from the primary datasets using spatial analysis tools in GIS. All datasets were standardized, reclassified, and prepared for subsequent multi-criteria evaluation and connectivity modeling. The DEM dataset was obtained from the USGS Earth Explorer platform (2024) with a spatial resolution of 28.4 m and served as the primary dataset for topographic and hydrological analyses. Landcover data were acquired from the USGS Earth Explorer platform (2025); they were generated using multi-temporal satellite imagery derived from Landsat 8–9, which has a spatial resolution of approximately 32.8 m, and processed through classification techniques within a GIS environment, which were classified into eight categories: water, urban, barren land, sand, heathland, mixed forest, coniferous forest, grassland, and cultivated areas. Land use and road network data were obtained from OpenStreetMap (OSM) (OpenStreetMap contributors, 2025) as vector-based datasets, then processed within a GIS environment to extract relevant spatial features and subsequently used to derive indicators such as road density and urban distribution. The Normalized Difference Vegetation Index (NDVI) was derived from Landsat 8–9 satellite imagery (2025) obtained from the USGS Earth Explorer platform with a spatial resolution of 30 m; it was calculated using the red and near-infrared (NIR) bands following the standard formulation $(NIR - Red) / (NIR + Red)$. Geological formation data were obtained from the Humanitarian Data Exchange (HDX) platform

(Humanitarian Data Exchange [HDX], 2025) and used to represent subsurface characteristics influencing hydrological processes; they were classified into seven main units and further grouped into five permeability levels ranging from very low to high to assess the influence of geological conditions on water infiltration and flow dynamics. Climatic data, particularly precipitation, used in this study were obtained from the NASA Prediction of Worldwide Energy Resources (NASA POWER) database (NASA POWER Project, 2025), using long-term annual average values of approximately 1.4 m. (Figure 3).

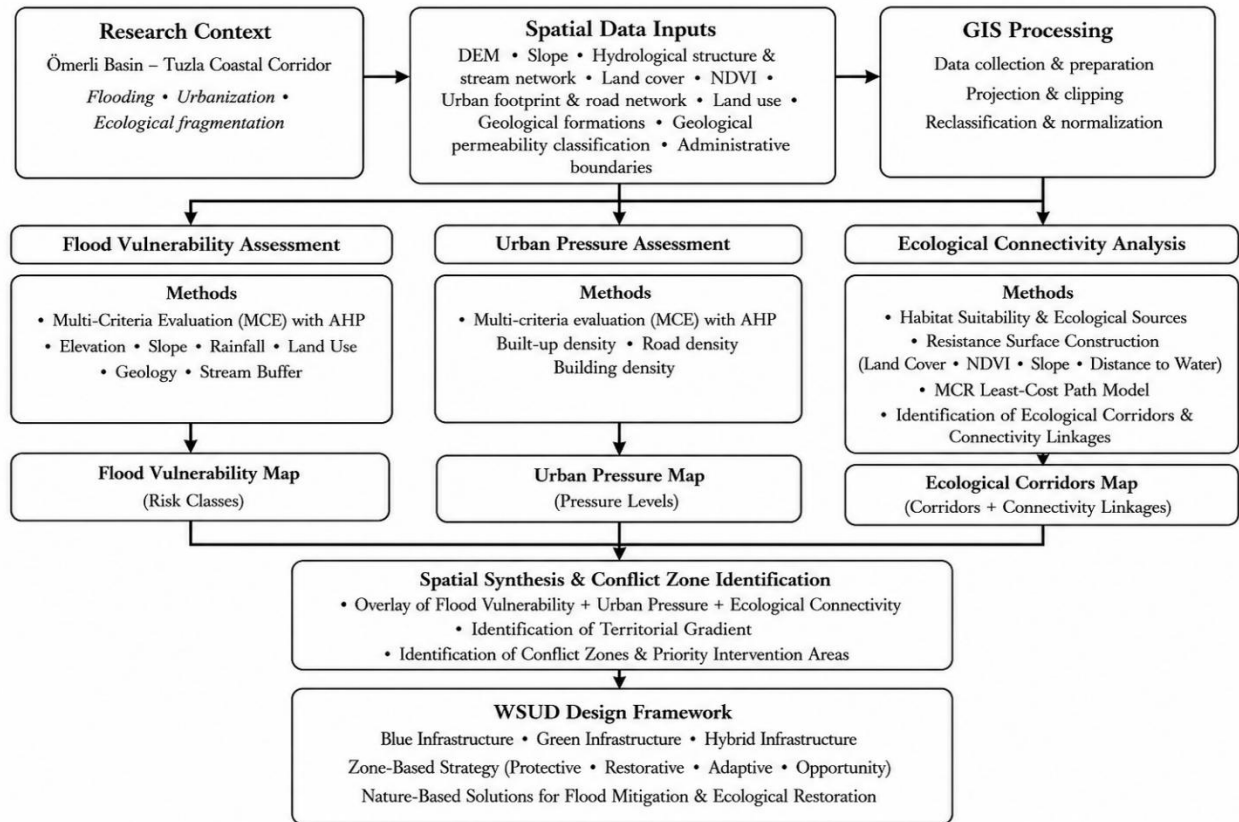


Figure 2. Structure of the Study.

Table 1: Geospatial datasets and sources used in this study.

Dataset	Year	Resolution	Reference
Digital Elevation Model (DEM)	2024	Raster, 28.4 m	U.S. Geological Survey. (2024). USGS Earth Explorer: Digital elevation model dataset. https://earthexplorer.usgs.gov/
Land Cover Classification & NDVI	2025	Raster, ~32.8 m	U.S. Geological Survey. (2025). USGS Earth Explorer: Landsat 8–9 imagery. https://earthexplorer.usgs.gov/
Land Use & Road Network	2025	Vector	OpenStreetMap contributors. (2025). Planet dump. https://www.openstreetmap.org
Geological Formation Data	2025	Vector	Humanitarian Data Exchange. (2025). Geological formation dataset. https://data.humdata.org/
Precipitation / Climatic Data	2025	Tabular	NASA POWER Project. (2025). NASA prediction of worldwide energy resources (POWER) data access viewer. https://power.larc.nasa.gov/
Population Data	2025	Tabular	Turkish Statistical Institute. (2025). Population by districts: address-based population registration system (ADNKS). Retrieved April 30, 2026, from https://data.tuik.gov.tr/

2.3 Analytical Methods

To determine spatial suitability, this study employs a Multi-Criteria Evaluation (MCE) framework, utilizing weighted factor integration as established by Malczewski (1999). Furthermore, to analyze the connectivity between these sites, the Minimum Cumulative Resistance (MCR) model is applied, following Yu’s (1996) approach to landscape ecological security patterns. The MCR model identifies the potential pathways of ecological processes; the 'least-cost' path represents the most efficient corridor for the flow of species or ecological energy across a resistant landscape (Yu, 1996). GIS-based multi-criteria evaluation (MCE) integrates spatial data with decision-making processes by combining multiple criteria and weighting their relative importance to support spatial analysis and planning decisions (Malczewski, 1999). The

weighting values adopted in this study were determined through literature-based expert judgment according to the relative influence of each factor on flood processes, urban intensity, and ecological quality. To assess the internal coherence of the assigned weight structures, pairwise comparison matrices were constructed for each analytical framework following the Analytic Hierarchy Process (Saaty, 1980), and consistency ratios were calculated using the AHP priority calculator (Goepel, 2018). A consistency ratio below 0.10 confirms that the weight hierarchy is logically consistent and suitable for spatial analysis.

2.3.1 Urban Pressure Assessment

Urban pressure was assessed using a Multi-Criteria Evaluation (MCE) approach in GIS, integrating three spatial indicators: built-up density, road network density, and building distribution density. The built-up density layer was derived from land cover data using the focal statistics tool, while road network and building footprint data, originally in vector format, were converted to raster surfaces using the Kernel Density tool. Each layer was reclassified into three levels: low (1), medium (2), and high (3), then integrated through weighted overlay analysis, with built-up density assigned 40% and road network and building density each assigned 30%, reflecting their relative contributions to urban pressure. Criteria selection was informed by GIS-based urban assessment studies identifying impervious surfaces and building concentration as primary indicators of anthropogenic pressure (Pochodyła-Ducka et al., 2025), alongside road network density as a key indicator of infrastructure intensity and surface impermeability (Czyża & Kowalczyk, 2024). A pairwise comparison matrix following the Analytic Hierarchy Process yielded a Consistency Ratio of 0.00, confirming the logical coherence of the assigned weights.

2.3.2 Flood Vulnerability Assessment

Flood vulnerability was assessed to identify susceptible areas that could be subject to inland flooding resulting from surface runoff, rainfall, or nearby watercourses. To achieve this, a multi-criteria evaluation (MCE) approach was applied by integrating DEM, slope, rainfall, land cover, geological permeability, and stream buffer. The DEMs are key factors influencing surface runoff and water accumulation, where areas lying at lower elevations represent areas at greater risk for flooding than areas at higher elevations. Slope influences the speed of surface runoff and drainage conditions. Rainfall represents rainfall-induced runoff, and land cover assesses surface permeability and the degree of urbanization affecting infiltration. The geological formation data correspond to the permeability of the ground component, which indicates the capacity of the ground to absorb and infiltrate water and feed groundwater; when high permeability allows a greater quantity of rainfall to infiltrate than an area with a less permeable feature, it thereby decreases surface runoff volume. The stream buffer identifies areas directly affected by overflow and floodplain dynamics. Criteria selection and weight assignment were informed by established GIS-based flood susceptibility frameworks in the literature (Khosravi et al., 2016; Samanta et al., 2018; Vojtek & Vojteková, 2019; Rahmati et al., 2016), which consistently identify elevation and slope as the dominant conditioning factors in flood hazard assessment, followed by land cover, rainfall distribution, geology, and proximity to stream networks. Although several flood susceptibility studies incorporate a larger number of hydrological and geomorphological variables, Rahmati et al. (2016) demonstrated that reliable flood hazard prediction can be achieved using a limited set of essential conditioning factors when the selected variables adequately represent the dominant flood-generating processes of the study area. Accordingly, the six criteria adopted in this study were considered sufficient and appropriate for the environmental and urban conditions of the Ömerli–Tuzla corridor.

Reclassified criteria were integrated using a weighted overlay analysis tool in GIS to determine the relative importance of each factor in the flood-generating process. Land elevation and slope were assigned the highest weights, 30% and 20%, respectively, as they primarily control the amount of water that flows through an area and accumulates inside. Stream buffer, with 15%, and land cover, 15%, were considered second and third as a moderate weight, while rainfall and geology were assigned a lower weight, 10% each, as they provide necessary support to the primary flood-generating criteria. Criteria weights were determined using the Analytic Hierarchy Process (Saaty, 1980), and the resulting pairwise comparison matrix yielded a consistency ratio of 0.002, below the acceptable threshold of 0.10, confirming the logical consistency of the weight assignments. The weighted overlay output was subsequently classified into five flood vulnerability levels, with level 1 representing the lowest susceptibility and level 5 the highest.

2.3.3 Ecological Connectivity Analysis

This ecological connectivity analysis was developed primarily for detecting the accessibility between ecologically valuable areas and supporting biodiversity, thereby clarifying how natural systems remain linked within the study area. The analysis consisted of three stages: first, extracting ecological resources; second, generating a resistance surface; and third, using the corridor connectivity tool to determine least-cost corridors between ecological sources. Habitat suitability analysis employed a multi-criteria evaluation approach using land cover, NDVI, distance to water bodies, and slope. Each indicator was reclassified on a common scale (1 = least suitable; 5 = most suitable). Land cover was classified according to ecological function: forestlands were assigned the highest suitability value (5), heathland and grassland (4), water bodies (3), agriculture/planned land (2), and urban areas (1). NDVI was reclassified into five vegetation-density levels. Distance to water bodies was considered because of the ecological dependence of certain species on water, where areas within 0–500 m received the highest suitability value (5), decreasing gradually to the lowest value (1) beyond 5000 m. Slope was used to quantify topographical barriers to movement and vegetation growth; slopes of 0–5° were assigned the highest suitability, while slopes greater than 25° received the lowest suitability. The weighted overlay tool integrated these layers. Land cover and NDVI were assigned higher weights, 40% and 30%, respectively, because they directly influence habitat quality, while distance to water and slope were weighted 20% and 10%, respectively. The resulting habitat suitability map provided the basis for identifying ecologically valuable patches serving as eco-sources, where

areas with values of 4 and 5 were extracted as optimal ecological sources. The selection of these criteria is consistent with their established application in ecological connectivity and habitat suitability studies, where land cover, as the dominant factor, alongside NDVI, distance to water bodies, and slope, are widely used to characterize ecological source areas and habitat conditions (Zhai & Huang, 2022; Na et al., 2024; Dang et al., 2026; Yan et al., 2021). The pairwise comparison matrix constructed using the Analytic Hierarchy Process yielded a consistency ratio of 0.031, confirming the logical consistency of the weight assignments.

The resistance surface modeling was established as part of the Minimum Cumulative Resistance (MCR) framework, representing obstacles to ecological movement across the landscape. Areas with high ecological suitability correspond to lower resistance values. The resistance surface was constructed using land cover as the dominant factor, given its primary influence on ecological permeability, habitat fragmentation, and species movement, and slope as a secondary topographic factor, reflecting terrain conditions and movement difficulty across the landscape. The selection of these criteria follows their established application in ecological resistance surface construction (Zhai & Huang, 2022; Dang et al., 2026; Zhang et al., 2022). The pairwise comparison matrix constructed using the Analytic Hierarchy Process yielded a consistency ratio of 0.00, confirming the logical consistency of the assigned weights. Land-cover classes were assigned resistance values based on ecological permeability: forest and grassland received the lowest resistance (1), water bodies moderate resistance (2), agricultural and barren lands higher resistance (4), and urban areas the highest resistance (5). Slope values were similarly reclassified into five resistance classes, where flat slopes (0–5°) were assigned low resistance and steep slopes (>30°) the highest resistance. These parameters were integrated through weighted overlay analysis, with land cover weighted 70% and slope 30%, producing the final resistance surface.

Based on the generated resistance surface and identified ecological sources, an ecological connectivity analysis was performed consistent with the MCR model. The connectivity analysis followed established approaches in which least-cost path analysis and graph-based models are applied to evaluate ecological movement and landscape resistance, with structural connectivity reflecting the physical configuration of landscape elements and functional connectivity reflecting the movement responses of organisms across the landscape (LaPoint et al., 2015).

Following the three individual assessments, the spatial outputs were synthesized through an overlay analysis to identify areas of concurrent risk concentration. Named spatial elements across the study area were assessed against the three analytical outputs and classified according to the number of conditions they simultaneously exhibited: areas combining flood vulnerability class 4 or 5, high urban pressure level, and isolated or weakly connected ecological patches were classified as triple-conflict priority zones; areas meeting two of three conditions were classified as double-conflict zones; and areas meeting a single condition were classified as protective opportunity zones. This classification provides the spatial basis for prioritizing blue-green infrastructure interventions across the corridor.

3. Results

3.1 General Spatial Pattern of the Study Area

The analytical results show a strong north-south spatial gradient within the study area, structured by the three interrelated components: urban development intensity, hydrological vulnerability, and ecological continuity. The northern part, particularly the Ömerli Basin and its surrounding upland landscapes, maintains relatively high ecological integrity, stronger habitat continuity, and lower levels of urban settlement. However, by moving southward, the central and southern zones are increasingly dominated by denser residential and industrial areas and transportation facilities with smaller and fragmented green open spaces. The study area should not be interpreted using a singular environmental variable; rather, it serves as an interdependent complex of watershed systems, urban growth corridors, coastal dynamics, and remnant ecological networks. Accordingly, areas vulnerable to flooding, highly developed areas, and ecologically sensitive areas are often located in proximity to each other. Consequently, creating conflict zones and strategic opportunities for holistic planning interventions.

This north-south transition with various landscape systems and vulnerability and opportunity zones together forms the spatial relationships examined in the following sections.

lower flooding vulnerability, benefiting from higher elevations, a more natural drainage system, high vegetated cover, and lower urban density (Figure 4b).

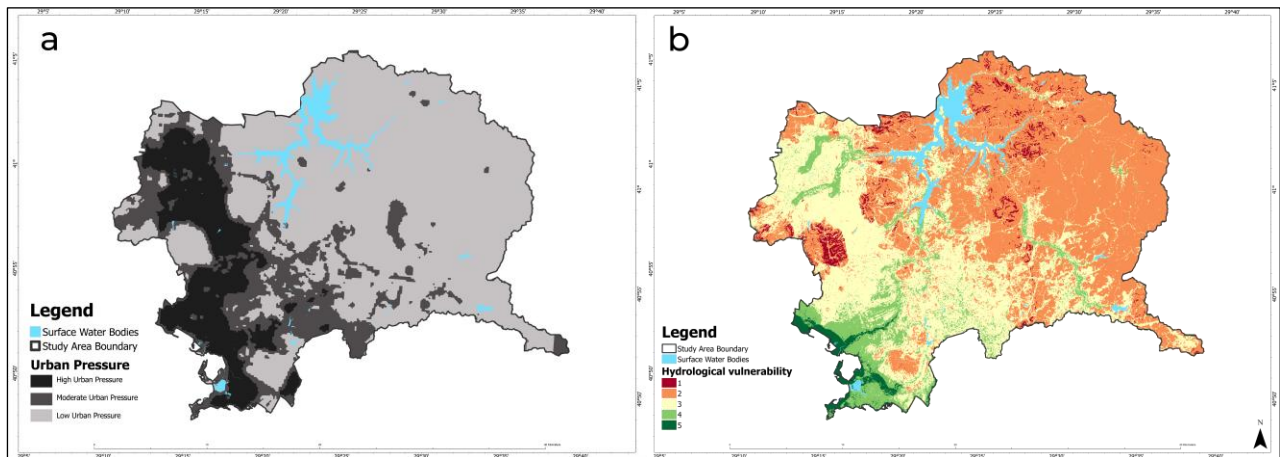


Figure 4. (a) Urban Pressure Assessment map; (b) flood vulnerability assessment map of the study area.

3.1.3 Ecological Connectivity Assessment

The habitat suitability model reveals a heterogeneous but structured ecological distribution across the corridor (Figure 5a). High and very high suitability classes are concentrated mainly in the northern and northeastern sectors, where mixed forest cover, semi-natural landscapes, and lower urban disturbance prevail. In contrast, lower suitability classes dominate the southern zones, where urban development and discontinuous vegetation patterns reduce ecological functioning. Ecological sources comprising suitability classes 4 and 5 collectively cover approximately 387.37 km², representing nearly 50% of the total area (Figure 5b). Larger and more continuous source areas are concentrated around the Ömerli Reservoir, while smaller and more dispersed patches occur around Pendik Valley and Aydos Mountain, indicating that continuity weakens progressively toward the central and southern zones. The resistance surface further reinforces this pattern, with low resistance values concentrated in the northern sector and high resistance values corresponding to dense built areas and major infrastructure corridors in the central and southern sectors, acting as barriers that hinder ecological movement (Figure 5c).

Ecological source analysis revealed a strongly fragmented landscape of 681 total patches. Despite six core patches dominating the ecological source area at approximately 336.12 km², micro-patches accounted for 511 fragments covering only 11.85 km², indicating severe habitat fragmentation and the dominance of highly dispersed ecological remnants across the corridor (Table 2). Connectivity analysis confirmed the severity of this fragmentation. Out of 681 total patches, 667 were classified as isolated with no direct ecological connectivity, while only 10 patches were identified as highly connected, covering a combined area of just 0.8 km² (Table 3). The connectivity model generated 680 primary least-cost corridors and 1,927 secondary potential linkages, with the strongest corridor systems concentrated in the northern and central sectors. These figures collectively demonstrate that functional connectivity remains concentrated in an extremely limited portion of the corridor, reinforcing the critical need for targeted restoration across the fragmented central and southern sectors (Figure 5d).

Table 2: Ecological Patch Structure Classes.

Patch Structure Class	Number of Patches	Total Area (km ²)	Ecological Interpretation
Core Ecological Patches	6	336.12	Represents the main ecological habitat cores with the highest ecological stability and continuity.
Micro Patches	511	11.85	Indicates severe habitat fragmentation and the dominance of highly disconnected ecological remnants.
Medium-Sized Patches	12	19.24	Represents transitional ecological areas with moderate ecological continuity.
Small Patches	152	20.16	Consists of scattered small ecological patches with limited ecological capacity.
Total	681	387.37	

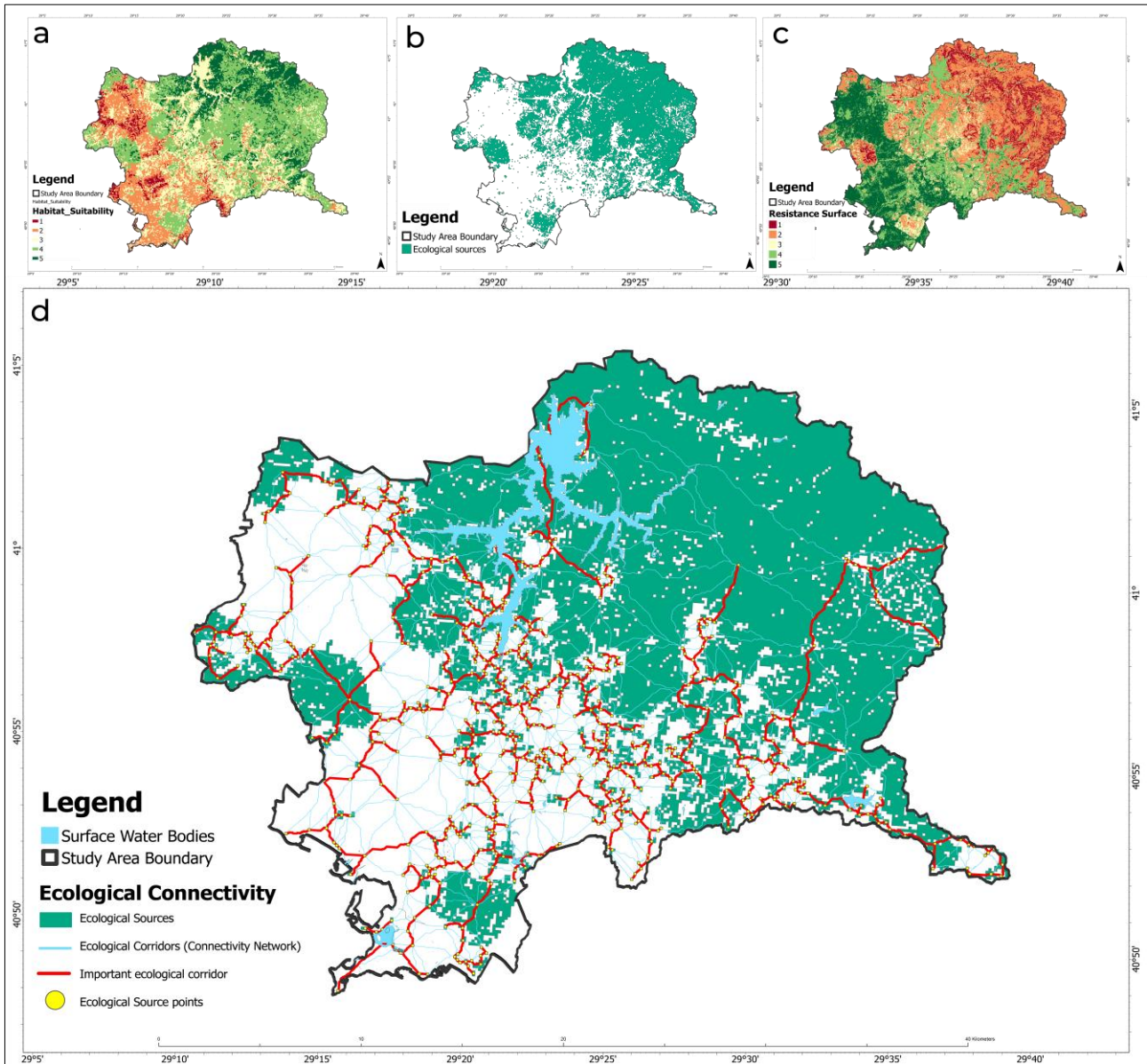


Figure 5. (a) habitat suitability analysis; (b) ecological sources; (c) resistance surface; (d) ecological connectivity network.

Table 3: Ecological Patch Connectivity.

Connectivity Class	Number of Patches	Total Area (km ²)	Mean Distance to Nearest Patch (m)
Highly Connected	10	0.8	0 — patches are directly adjacent or overlapping
Weakly Connected	4	0.1	155.76 — patches are within ~156 m of nearest neighbor
Isolated	667	386.48	No direct connectivity detected
Total	681	387.37	—

3.2 Synthesized Spatial Relationship

Although localized deviations occur across all three zones, the spatial distribution of urban pressure, flood vulnerability, and ecological connectivity reveals a clear dominant north–south territorial gradient in which low-pressure conditions prevail in the northern sector, medium-pressure conditions characterize the central transitional belt, and high-pressure conditions concentrate in the southern sector. Zones are therefore defined by their dominant territorial pattern rather than absolute spatial homogeneity. Overlaying the spatial outputs of urban pressure, flood vulnerability, and ecological connectivity analyses reveals that this gradient is not a specific outcome of any single variable but the result of the simultaneous interaction of three structurally interdependent spatial systems: the urban system, the hydrological system, and the green system. Their combined spatial configuration produces three structurally distinct zones, each exhibiting a

characteristic combination of conditions that together define its dominant spatial character and guide subsequent intervention priorities, as shown in Table 4.

The northern low-pressure-dominated zone retains the strongest ecological and hydrological integrity of the corridor. The urban system remains minimal, with urban land occupying only 4.63% of the zone and settlement patterns dispersed across predominantly rural and natural landscapes. The green system is the most intact of the three zones, dominated by mixed forest (50.42%), farmland (15.88%), and heathland (11.74%), containing all six core ecological patches covering 328.05 km² (66.79% of the zone area) alongside 12 medium-sized and 117 small patches, indicating a relatively continuous ecological structure. The hydrological system is anchored by the Ömerli Reservoir and its surrounding watershed, which functions as Istanbul's principal freshwater source, complemented by natural stream networks and high surface permeability at 91.81% of the zone area. Flood vulnerability remains comparatively low, with very low and low risk classes accounting for 71.70% of the zone, while high and very high vulnerability classes represent only 6.80% combined.

The central transitional medium-pressure zone represents a landscape where all three systems begin to conflict simultaneously. The urban system intensifies considerably, with urban land accounting for 57.82% of land cover and major infrastructure, including Sabiha Gökçen Airport, the Leather Organized Industrial Zone (Tuzla OSB), and arterial highway networks occupying large continuous land surfaces that fundamentally alter local hydrological and ecological performance. The ecological system deteriorates accordingly: six core ecological patches reach into the zone, covering 7.13 km² (5.31% of the zone), while micro-patches proliferate to 245 fragments, and Pendik Valley, which is one of the corridor's most ecologically significant remaining systems, is physically severed from surrounding habitats by airport and industrial land uses. The hydrological system is equally disrupted, with impermeable surfaces rising to 58.07%, the Umur Stream degraded along its corridor through Pendik Valley and adjacent to the industrial zone, and the Kemiklidere Stream partially covered by concrete beneath the airport, removing natural infiltration capacity and concentrating runoff downstream. Flood vulnerability increases accordingly, with high- and very high-risk classes rising to 23.00% combined, while moderate flood risk dominates at 62.90%.

The southern high-pressure-dominated zone presents the most severe conditions across the entire study area, where the urban system dominates completely, with urban land covering 93.12% of the area and dense residential development, shipyard operations, and port infrastructure eliminating virtually all natural surface cover. The green system has effectively collapsed at the patch scale: only two small core ecological fragments remain (0.14 km² combined), no medium patches persist, and only five small patches covering 0.26 km² and 43 micro-patches covering 0.88 km² remain heavily degraded. The hydrological system is correspondingly compromised, with impermeable surfaces reaching 93.12%, natural waterways substantially channelized or reclaimed, and the Balık Lagoon, the only remaining coastal lagoon along the Tuzla coastline, becoming brackish due to the loss of freshwater stream inputs and facing direct pressure from adjacent shipyard operations and construction activity. Flood vulnerability is elevated, with high and very high-risk classes accounting for 34.80% combined and moderate risk dominating at 64.00%, indicating that a substantial proportion of this heavily urbanized zone faces persistent hydrological exposure through both upstream runoff concentration and downstream coastal dynamics simultaneously.

The interaction across all three zones confirms that flood vulnerability, ecological fragmentation, and urban pressure are not independent conditions but spatially reinforced processes concentrating risk within the same landscapes. The least-cost ecological corridor network derived from the MCR connectivity analysis further reinforces this north–south gradient, with 56.5% of pathways concentrated in the low-pressure north, declining to 34.3% in the transitional central zone, and only 8.6% in the high-pressure south, this distribution demonstrates strong spatial alignment with the identified high-risk and ecologically degraded zones, confirming that restoring ecological connectivity along these pathways would simultaneously address hydrological vulnerability and green fragmentation within a single integrated strategy.

3.3 Principal Findings and Priority Area Identification

Building on the zone synthesis results, Table 5 presents a systematic inventory of the green, blue, and urban resources of each territorial zone, characterizing their spatial fabric, dominant conditions, and emerging territorial character (Figure 6). Applying the conflict classification framework to the named spatial elements identified in this inventory, Table 6 identifies fourteen specific areas across the three zones where the convergence of analytical conditions generates either critical conflict or strategic opportunity.

The spatial conflict classification identifies three tiers of priority across the fourteen assessed areas. The highest-priority triple-conflict zones, concentrated predominantly in the central and southern sectors where flood exposure, surface sealing, and ecological isolation converge simultaneously, include the Umur Stream corridor, Kemiklidere Stream corridor, Pendik Valley, Tuzla OSB boundary, Balık Lagoon, the Tuzla Shipyard interface, and the reclaimed coastal shoreline, indicating the need for restorative and adaptive blue-green interventions. Double-conflict zones, including Sabiha Gökçen Airport, the Kuzey Marmara Motorway, O-4/TEM crossings, and the combination of two concurrent pressures, require targeted green adaptive intervention. In the northern zone, the Ömerli Reservoir and its farmland-forest transition margins are classified as single-condition protective opportunity zones, where existing ecological and hydrological integrity must be conserved rather than restored. Bare lands, degraded greenfields, and brownfield patches distributed throughout the corridor represent strategic opportunities for ecological stepping stones and stormwater retention regardless of zone. Together, these systemic conditions and conflict classifications define the spatial foundation from which the design framework and priority intervention strategies are developed.

Table 4: Quantitative spatial characteristics of the three territorial zones.

Zones	Urban Pressure Level	Spatial Characteristic	Classification / Type	Area (km ²)	Percentage within Pressure Zone (%)	Ecological Connectivity / Proposed Corridor
South zone:	Southern high-pressure dominated zone	Surface Permeability	Permeable Surfaces	7.31	6.86%	8.6% of the proposed ecological corridor network (35.88 km) occurs within high-pressure landscapes, suggesting residual and spatially constrained ecological linkages under dense urban and industrial conditions.
			Impermeable Surfaces	99.32	93.12%	
		Land Cover Distribution	Urban	99.31	93.12%	
			Farmland	3.32	3.12%	
			Bare Land	3.01	2.82%	
			Grassland	0.68	0.63%	
			Mixed Forest	0.14	0.13%	
			Heathland	0.1	0.10%	
			Sand	0.06	0.05%	
			Water	0	0.00%	
		Flood Vulnerability Distribution	Very Low	0.07	0.10%	
			Low	1.4	1.30%	
			Moderate	68.21	64.00%	
			High	30.68	28.80%	
			Very High	6.43	6.00%	
		Ecological Patch Structure Class	2 Core Ecological Patches	0.14	0.13%	
5 Small Patches	0.26		0.24%			
43 Micro Patches	0.88		0.82%			
Central zone:	Central transitional medium-pressure zone	Surface Permeability	Permeable Surfaces	55.53	41.37%	34.3% of the proposed ecological corridor network (143.44 km) passes through medium-pressure transitional landscapes, reflecting fragmented but still functional reconnection pathways across urban and infrastructural barriers.
			Impermeable Surfaces	77.94	58.07%	
		Land Cover Distribution	Urban	77.61	57.82%	
			Farmland	24.8	18.48%	
			Grassland	11.38	8.48%	
			Bare Land	9.98	7.43%	
			Mixed Forest	4.43	3.30%	
			Heathland	4.2	3.13%	
			Coniferous Forest	0.49	0.37%	
			Water	0.33	0.24%	
		Flood Vulnerability Distribution	Sand	0.25	0.19%	
			Very Low	1.1	0.80%	
			Low	17.39	13.00%	
			Moderate	84.4	62.90%	
			High	24.81	18.50%	
		Ecological Patch Structure Class	Very High	6.03	4.50%	
6 Core Ecological Patches	7.13		5.31%			
11 Medium-Sized Patches	2.39		1.78%			
78 Small Patches	6.27		4.67%			
North zone:	Northern low-pressure dominated ecological zone	Surface Permeability	245 Micro Patches	5.54	4.13%	56.5% of the proposed ecological corridor network (236.66 km) occurs within predominantly low-pressure landscapes, indicating relatively continuous ecological connectivity associated with large core patches, watershed systems, and permeable land cover.
			Permeable Surfaces	450.98	91.81%	
		Land Cover Distribution	Impermeable Surfaces	38.7	7.88%	
			Mixed Forest	247.66	50.42%	
			Farmland	77.99	15.88%	
			Heathland	57.65	11.74%	
			Coniferous Forest	34.59	7.04%	
			Grassland	25.21	5.13%	
			Urban	22.74	4.63%	
			Water	15.96	3.25%	
		Flood Vulnerability Distribution	Bare Land	7.47	1.52%	
			Sand	0.42	0.09%	
			Very Low	17.7	3.60%	
			Low	334.28	68.10%	
			Moderate	105	21.40%	
		Ecological Patch Structure Class	High	24.45	5.00%	
Very High	8.87		1.80%			
6 Core Ecological Patches	328.05		66.79%			
12 Medium-Sized Patches	16.67		3.40%			
	117 Small Patches	12.91	2.63%			
	231 Micro Patches	5.34	1.09%			

Table 5: Territorial system characterization by zone: green, blue, and urban resources.

	Northern Zone	Central Zone	Southern Zone
Urban Pressure Pattern	Predominantly low pressure	Mixed / transitional medium pressure	Predominantly high pressure
Green Resources / System	Mixed forests; coniferous forest; Black Pine communities; heathland patches; farmland and agricultural vegetation; reservoir-edge vegetation	Pendik Valley (heathland, oak communities, grassland, meadow habitats); fragmented woodland patches; roadside green margins	Fragmented and degraded greenfield patches; bare lands (formerly farmland or greenfield); vegetation on Balik Lagoon margins; planted coastal vegetation on reclaimed shoreline
Blue Resources / System	Ömerli Reservoir; tributary streams; valleys descending from watershed	Umur Stream (degraded, passing through Pendik Valley, residential and industrial areas); Kemiklidere Stream (partially channelized and covered by concrete beneath airport); wetland remnants within Pendik Valley	Balik Lagoon; Umur Stream and Kemiklidere Stream downstream corridor (mouth); minor tributary streams and channelized drainage network
Urban Resources / System	Fragmented rural settlements; Kuzey Marmara Motorway; O-4 / TEM motorway corridors	Sabiha Gokcen Airport; Tuzla OSB (Tuzla Organize Sanayi Bolgesi — leather, chemical, automotive, manufacturing and logistics industries); E-5 highway; E-80 highway; Kurtkoy–Pendik road connection	Tuzla Shipyard; Pendik Shipyard and Port; reclaimed and artificial shoreline; D-100 coastal road; Marmaray railway; dense residential fabric; distributed industrial patches
Extracted Strategic Zones	Ömerli Reservoir and reservoir buffer zone; farmland–forest transition margins; Kuzey Marmara Motorway & O-4 / TEM motorway crossings	Umur Stream corridor; Kemiklidere Stream corridor; Pendik Valley and its wetland remnants; Sabiha Gokcen Airport; Tuzla OSB — Leather & Industrial Zone; E-80 highway & Kurtkoy–Pendik road corridors	Balik Lagoon; Tuzla Shipyard & Pendik Port / Shipyard; reclaimed / artificial shoreline & D-100 coastal road; bare lands, degraded greenfields & brownfield patches
Emerging Territorial Character	Ecological Core Zone	Infrastructure–Ecology Conflict Zone	compound-risk coastal zone

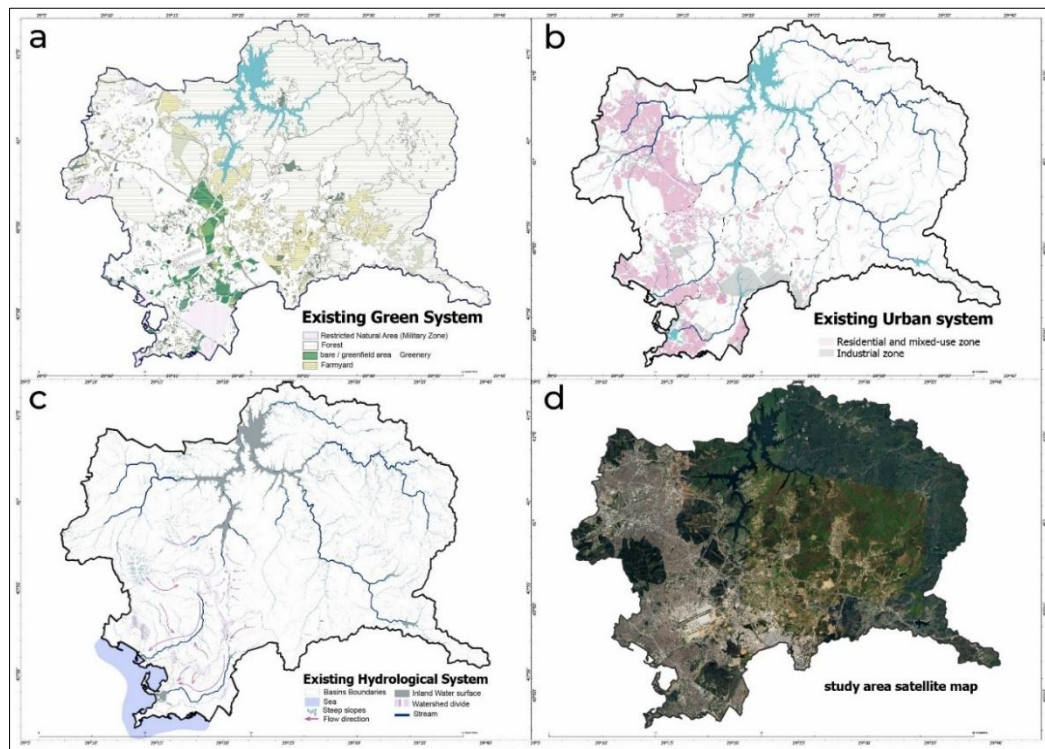


Figure 6. Existing territorial systems of the study area: (a) existing green system; (b) existing urban system; (c) existing hydrological system; (d) satellite imagery of the study area.

Table 6: Spatial Conflict Classification and Priority Area Identification.

Zone	Specific Area	Flood Vulnerability	Urban Pressure	Conflict / Priority Risk Level	Reason for selection
North	Ömerli Reservoir	Low (1-2)	Low	Single — Hydrological	Istanbul's primary drinking water source (~48% supply); directly exposed to agricultural runoff with no buffer zone
North	Farmland-Forest transition margins / Reservoir buffer zone	Low-Moderate	Low	Single — Ecological + Hydrological	No vegetated buffer between farmland and reservoir; sediment and pollutants enter water supply directly
Central / South	Kuzey Marmara Motorway & O-4 / TEM motorway crossings	Moderate,high	Low-Medium	Double — Ecological + Hydrological	Highway infrastructure interrupts habitat continuity across the northern forest core; no ecological crossings present
Central / South	Umur Stream corridor	High (4-5)	High,Medium	Triple — Hydrological + Urban + Ecological	Umur Stream is degraded along its corridor through Pendik Valley, residential areas, and adjacent to the industrial zone, increasing pollution risk and reducing its natural drainage capacity; its lower reach is channelized at the coastal outlet, contributing to flood risk in downstream low-lying areas
Central / South	Kemiklidere Stream corridor	High (4)	High,Medium	Triple — Hydrological + Urban + Ecological	Partially covered by concrete and buried beneath the airport, channelized at the coastal outlet reduces drainage capacity and flood absorption
Central	Pendik Valley	Moderate , High (3-4)	Medium — but surrounded by high-pressure zones	Triple — Hydrological + Urban + Ecological	Nationally significant habitat (<i>Colchicum micranthum</i> , <i>Falco tinnunculus</i> , <i>Lanius collurio</i>); physically severed from corridor by airport and industrial and residential zones.
Central	Wetland remnants within Pendik Valley	High (4)	Medium — adjacent to industrial zone	Triple — Hydrological + Urban + Ecological	Only remaining wetland remnants in central zone; directly adjacent to Tuzla OSB industrial discharge; high pollution risk
Central	Sabiha Gökçen Airport	Moderate , High	Medium	Double — Ecological + Hydrological	Largest single impermeable surface in corridor; buries two streams; generates concentrated runoff with no retention capacity
Central	Tuzla OSB — Leather & Industrial Zone	Moderate-High (3-4)	High,Medium	Triple — Hydrological + Urban + Ecological	Industrial discharge adjacent to Pendik Valley wetlands and Umur/Kemiklidere streams; conventional treatment insufficient under peak flow
Central	E-80 highway corridors & Kurtköy-Pendik road	Moderate (3)	High,Medium	Triple — Hydrological + Urban + Ecological	Major road infrastructure physically fragments the central zone; severs ecological connections between Pendik Valley, Aydos Forest, and corridor patches
South	Balık Lagoon	High (4-5)	Medium — but surrounded by high-pressure zones	Triple — Ecological + Urban + Hydrological	Only remaining coastal lagoon on Tuzla coastline; supports 100+ avifaunal species; directly threatened by shipyard operations, construction, and loss of freshwater input
South	Tuzla Shipyard & Pendik Port / Shipyard	High (4-5)	High	Triple — Urban + Hydrological + Ecological	Natural shoreline replaced by reclaimed and hardened surfaces, Industrial discharge and pollutants drain directly to Marmara Sea and Balık Lagoon margins with no filtration buffer
South	Reclaimed / artificial shoreline & D-100 coastal road	High (4-5)	High	Triple — Urban + Hydrological + Ecological	Land reclamation and road infrastructure have eliminated natural shoreline buffering capacity, increasing coastal flood exposure
North / Central / South	Bare lands, degraded greenfields & brownfield patches	Low-Moderate -high (varies by location)	Mixed (low in North, high in South)	Opportunity — Strategic	Distributed throughout the corridor; low conversion cost; represent strategic opportunities for ecological stepping stones, stormwater retention, and green space creation

4. Discussion and WSUD Design Framework.

The analytical results reveal a structural mismatch between contemporary urban development patterns and the natural hydrological organization of the landscape. The overlap of residential and industrial land uses with high flood-risk zones indicates that substantial portions of recent urban growth have occurred within stream valleys, coastal lowlands, and runoff-sensitive terrains, suggesting that previous development processes have not sufficiently integrated ecological and hydrological constraints into spatial planning. These findings are consistent with broader international research demonstrating that conventional gray infrastructure systems are increasingly insufficient under conditions of rapid urbanization and climate uncertainty, emphasizing that flood resilience depends on restoring infiltration capacity, distributed retention, and landscape-scale water management rather than relying solely on engineered drainage conveyance systems.

The proposed framework translates these analytical findings into a corridor-scale blue–green planning strategy extending from the Ömerli Basin to the Marmara coastline, structured through three complementary infrastructure layers: blue, green, and hybrid (Figure 7). Rather than relying on conventional gray infrastructure, the framework reconceptualizes stormwater as a resource to be retained, filtered, and reused through landscape-based systems, consistent with WSUD principles. The spatial foundation of this framework is the least-cost ecological corridor network derived from the MCR connectivity analysis, which demonstrated strong alignment with flood-vulnerable and ecologically degraded zones, confirming that restoring ecological and hydrological continuity along these pathways can simultaneously address flood risk, ecological fragmentation, and urban environmental degradation within a single integrated strategy.

4.1 Northern Watershed Landscapes: Ecological Core Zone

The most structurally critical vulnerability of the northern zone is the complete absence of vegetated buffer zones along the Ömerli Reservoir boundary, through which surface runoff, sediment, and diffuse agricultural pollutants enter the reservoir directly, progressively threatening Istanbul's primary drinking water supply. The basin also harbors exceptional biodiversity, with at least 37 rare plant species identified within the watershed (Tezer et al., 2015), including endemic and endangered taxa, alongside natural Black pine communities and Thracian oak and hornbeam forests (Yalçın, 2006). Highway systems further compound fragmentation by functioning as linear barriers that interrupt habitat continuity and disrupt natural surface-water flows. Collectively, these findings demonstrate that flood adaptation and water-resource protection cannot be treated as separate sectoral concerns: in the northern zone, they are structurally the same concern. Accordingly, the general target for this zone is protective: to maintain existing permeability levels, prevent further agricultural encroachment on the reservoir boundary, and restore habitat continuity across highway barriers. This is reinforced by İSKİ's Ömerli Baraj Gölü Havzası Koruma Planı, which explicitly identifies flood and landslide events as catastrophic risks within the watershed (İSKİ, 2023). In response, buffer strips and agroforestry systems are proposed adjacent to the reservoir boundary to intercept agricultural runoff and sediment, complemented by permeable surface replacements to progressively restore infiltration capacity across the zone.

4.2 Central Urban Belt: Infrastructure-Ecology Conflict Zone

The central zone's most significant ecological loss is concentrated around Pendik Valley, where heathlands, oak communities, grassland, and meadow habitats persist alongside nationally significant plant and bird populations (Bilgen & Çelen, 2006). The airport and industrial zone physically separate Pendik Valley from surrounding ecological systems, with the airport alone representing approximately 1.63 km² of continuously sealed surface contributing directly to elevated runoff generation. Hydrological disruption operates through two concurrent mechanisms: the degradation of Umur Stream increases pollution risk and reduces natural drainage capacity, while the concreting of Kemiklidere Stream beneath the airport concentrates runoff downstream and directly increases flood exposure in lower-elevation residential districts.

The general target for this zone is restorative: to reduce surface impermeability, rehabilitate degraded stream corridors, and reconnect the fragmented ecological network centered on Pendik Valley. Stream daylighting and floodplain reconnection are proposed along the Kemiklidere and Umur Stream corridors, supported by bioswales, rain gardens, check dams, and step pools distributed along flow pathways to intercept and treat runoff. Bare lands, degraded patches, and brownfields are identified as strategic opportunities for ecological stepping stones, re-establishing linkages between the primary ecological source areas within the northern and central landscapes. Vegetation root systems increase soil macroporosity and infiltration capacity (Stokes et al., 2014; Jarvis & Larsbo, 2023), and tree canopy intercepts precipitation to reduce surface runoff volume (Rahman et al., 2023).

4.3 Southern Coastal Zone: Compound-Risk Coastal Zone

The southern zone is uniquely exposed to flooding through two compounding pathways: upstream runoff pressures from impermeable surfaces and degraded drainage in the central zone, and downstream coastal influences, including sea-level fluctuation and reduced shoreline buffering capacity. The Balık Lagoon represents the zone's most ecologically critical and most vulnerable element. Having lost its natural freshwater stream inputs, the lagoon has become progressively brackish, resulting in the degradation of reed bed habitats (Yılmaz et al., 2018), while proximity to shipyard operations and ongoing construction pressure compound this ecological deterioration. The designation of Tuzla under the UNESCO/IOC CoastWAVE 2.0 Tsunami Ready Recognition Program further underscores the compound coastal risk profile of this zone (IOC-UNESCO, 2025).

The general target for this zone is adaptive: to introduce ecological stepping stones across bare lands and brownfields, establish filtration buffers between industrial operations and coastal water bodies, and protect the Balık Lagoon from further encroachment. Constructed wetlands are proposed along the Tuzla OSB and Balık Lagoon margins to filter discharge before reaching the coastal zone, while hybrid floodable landscape parks and living shoreline systems are

positioned at key convergence points to simultaneously manage water quality, retain stormwater, and restore ecological function. These hybrid landscapes are also designed to provide accessible open spaces and water-sensitive public environments that strengthen community connections to natural systems.

The zone-specific interventions are summarized in Table 7, organized by conflict area from Table 6. Each intervention is directly traceable to its conflict classification, ensuring the framework translates corridor-scale analysis into spatially justified, site-specific planning responses.

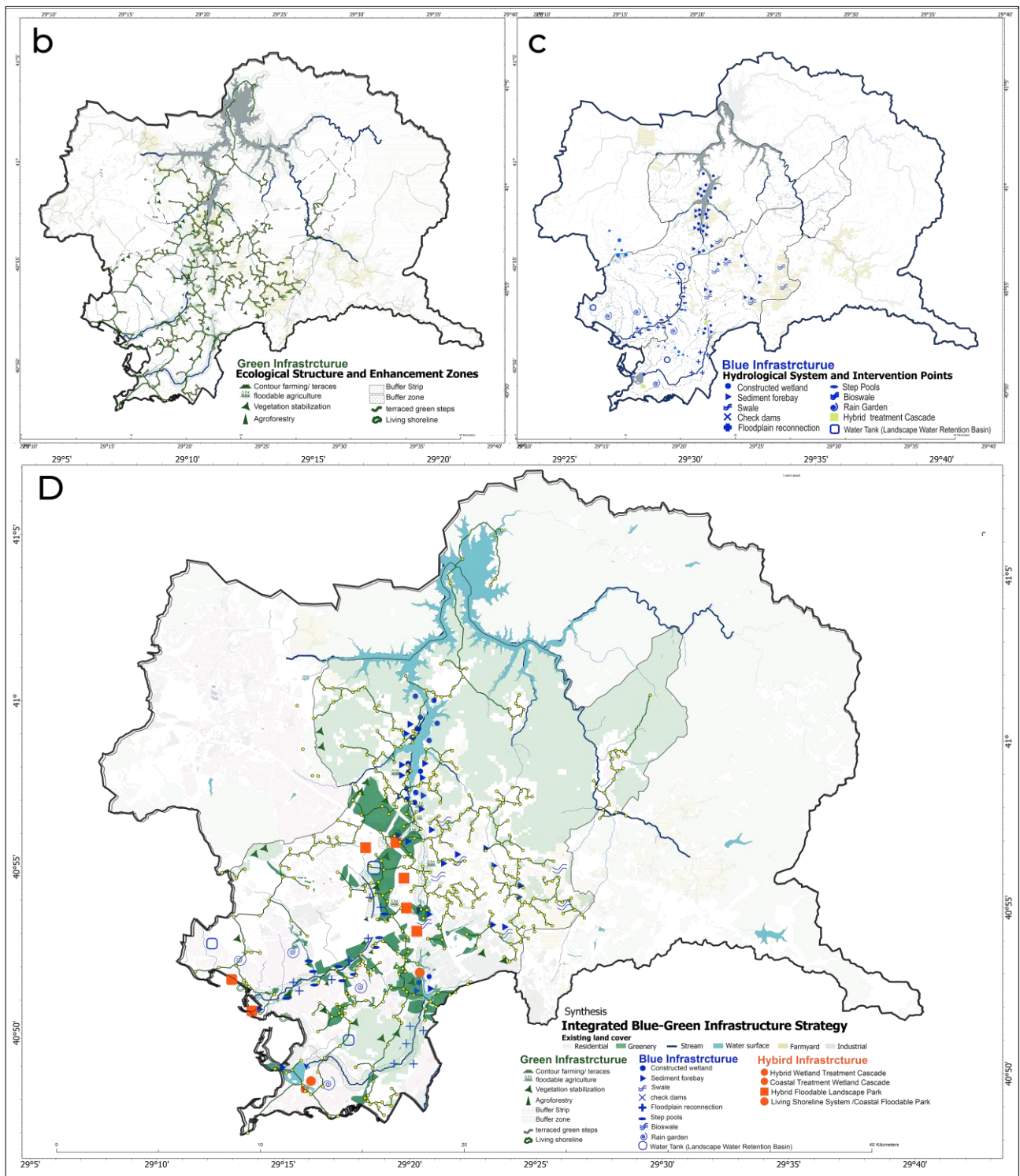


Figure 7. Proposed blue-green infrastructure framework: (a) green infrastructure layer; (b) blue infrastructure layer; (c) integrated blue-green and hybrid infrastructure strategy.

Table 7: Zone-specific blue-green infrastructure interventions proposed for the Ömerli-Tuzla corridor.

Zone	zone Specific Area	Current Condition (Problem)	General Target	Proposed Interventions	Infrastructure Type
North	Ömerli Reservoir & farmland-forest transition margins / reservoir buffer zone	No vegetated buffer between farmland and reservoir boundary; surface runoff, sediment, and agricultural pollutants enter reservoir directly	Protect reservoir water quality; establish agricultural buffer	Watershed buffer strips and agroforestry systems adjacent to reservoir boundary; contour farming and terracing on agricultural slopes; vegetative stabilization of reservoir edges; reforestation of degraded margins; controlled rural development buffers	Green Infrastructure
North	Kuzey Marmara Motorway & O-4 / TEM motorway crossings	Highway corridors act as linear barriers interrupting habitat continuity and natural surface-water flows; no ecological crossings present	Restore habitat connectivity across highway barriers	Ecological crossings (green bridges or underpasses) at key corridor pinch points; vegetated margins and buffer planting along highway edges; restoration of natural drainage pathways disrupted by road embankments	Green Infrastructure
Central / South	Umur Stream corridor	Stream degraded along corridor through Pendik Valley, residential, and industrial areas; lower reach channelized at coastal outlet; high pollution risk; reduced natural drainage capacity	Restore stream ecological function and reduce flood risk	Riparian vegetation restoration along stream corridor; bioswales and swale networks parallel to channelized sections; sediment forebays at key inflow points; floodplain reconnection where spatially feasible; check dams and step pools to slow and retain water	Blue-Green / Hybrid Infrastructure
Central / South	Kemiklidere Stream corridor	Partially covered by concrete and buried beneath airport; channelized at coastal outlet; reduced drainage capacity and flood absorption	Restore stream drainage function and reduce runoff concentration	Stream daylighting and rehabilitation where spatially feasible; bioswale integration along accessible sections; sediment forebays at inflow points; riparian buffer planting along exposed reaches	Blue-Green / Hybrid Infrastructure
Central	Pendik Valley	Nationally significant habitat physically severed from surrounding ecological network by airport and industrial and residential zones; weakly connected patches	Reconnect Pendik Valley to the broader ecological corridor	Ecological corridor restoration along valley systems; habitat reconnection through green bridges and stepping-stone patches; riparian buffer planting; vegetative stabilization of slopes	Green Infrastructure
Central	Wetland remnants within Pendik Valley	Degraded wetland remnants directly adjacent to Tuzla OSB; high risk of industrial pollution; only remaining wetlands in central zone	Protect and restore wetland function; buffer from industrial pollution	Constructed wetlands adjacent to industrial water bodies; ecological buffer planting between industrial zone and wetland remnants; water quality monitoring points	Green Infrastructure / Hybrid
Central	Sabiha Gökçen Airport	1.63 km ² continuously sealed surface; buries stream infrastructure; generates concentrated runoff with zero infiltration capacity	Partially restore infiltration capacity; reduce direct runoff generation	Green roof retrofits on airport rooftops; permeable landscape retrofits on sealed surfaces where feasible; bioswale integration along perimeter corridors; detention basins to intercept and slow concentrated runoff; ecological buffer planting strips around infrastructure edges	Blue-Green / Hybrid Infrastructure
Central	Tuzla OSB — Leather & Industrial Zone	Industrial discharge adjacent to Pendik Valley wetlands and stream corridors; conventional treatment insufficient under peak flow; no ecological buffer	Filter industrial discharge; establish ecological buffer between industry and sensitive areas	Constructed wetlands and hybrid treatment cascade, as filtration buffers between industrial operations and valley water bodies; green roof retrofits on industrial rooftops; bioswale and sediment interception systems along industrial perimeter	Blue-Green / Hybrid Infrastructure
Central	E-80 highway & Kurtköy-Pendik road corridors	Major road infrastructure physically fragments central zone; severs ecological connections between Pendik Valley, Aydos Forest, and corridor patches	Reduce linear fragmentation along road corridors	Ecological buffer planting strips along highway margins; bioswale integration along road drainage channels; stepping-stone habitat patches at key crossing points	Green Infrastructure
South	Balık Lagoon	Only remaining coastal lagoon on Tuzla coastline; becoming brackish due to loss of freshwater inputs; surrounded by residential and industrial land uses; 100+ bird species at risk	Protect and restore the only remaining coastal lagoon	Wetland restoration and reed bed rehabilitation; living shorelines along lagoon margins; ecological filtration systems to improve water quality; establishment of protected buffer zones restricting further construction and land reclamation; integration into regional blue-green coastal resilience network	Blue-Green / Hybrid Infrastructure
South	Tuzla Shipyard & Pendik Port / Shipyard	Natural shoreline replaced by reclaimed and hardened surfaces; industrial discharge and pollutants drain directly to Marmara Sea and Balık Lagoon with no filtration buffer	Filter pollutants before coastal discharge; restore coastal edge ecological function	Constructed wetlands and hybrid treatment cascades as filtration buffers between industrial operations and coastal waters; bioswales and sediment interception systems; living shoreline systems to stabilize and restore coastal edges; coastal wetland buffers	Blue-Green / Hybrid Infrastructure
South	Reclaimed / artificial shoreline & D-100 coastal road	Natural shoreline buffering capacity eliminated by land reclamation and road infrastructure; increased coastal flood exposure	Restore coastal buffering capacity where spatially feasible	Living shoreline systems at accessible coastal edge locations; floodable coastal landscape zones integrated with road corridor; planted coastal vegetation to partially restore shoreline buffering	Blue-Green / Hybrid Infrastructure
North / Central / South	Bare lands, degraded greenfields & brownfield patches	Distributed isolated fragments throughout corridor; formerly farmland or greenfield; potential stepping-stone habitat at low conversion cost	Reactivate as ecological stepping stones and stormwater retention surfaces	Pocket wetlands and small-scale water retention landscapes; permeable open spaces and community green areas; ecological stepping-stone habitats connecting fragmented patches; green infrastructure retrofits on brownfield sites; reactivation as multifunctional social and ecological sponge landscapes	Blue-Green / Hybrid Infrastructure

5. Conclusions

This study developed a GIS-based Water-Sensitive Urban Design (WSUD) framework for the Ömerli–Tuzla corridor, integrating flood vulnerability, urban pressure, and ecological connectivity within a single spatial assessment. The results reveal a pronounced territorial gradient in which ecological integrity progressively declines while urban intensity and hydrological vulnerability increase. The northern watershed landscapes retain strong ecological and hydrological functions, characterized by 91.81% permeable surfaces and six intact core habitat patches, whereas the southern coastal zone is dominated by extensive urbanization, with 93.12% impermeable surfaces and virtually no remaining ecological patch structure. These conditions reflect the cumulative effects of urban expansion and landscape transformation, which have progressively degraded hydrological performance, reduced ecological continuity, and concentrated flood exposure within the same territorial zones, demonstrating that flood vulnerability, urban pressure, and ecological fragmentation are not independent conditions but mutually reinforcing processes.

By synthesizing these spatial relationships, fourteen priority conflict and opportunity areas were identified and classified according to the intensity of overlapping pressures, ranging from triple-conflict zones requiring restorative and adaptive intervention to protective zones where existing ecological and hydrological integrity must be conserved. This classification directly informed a corridor-based planning approach in which blue-green infrastructure serves as the principal mechanism for implementing WSUD principles through context-specific nature-based interventions, including stream daylighting, ecological corridor restoration, and coastal lagoon protection.

By integrating three analytical frameworks within a single corridor-scale assessment, this study contributes to metropolitan-scale WSUD research and demonstrates how data-driven territorial analysis can guide spatially differentiated planning decisions in rapidly urbanizing coastal regions. The results suggest that Istanbul retains sufficient ecological structure to support large-scale blue-green transformation, provided that strategic intervention occurs before ongoing fragmentation becomes irreversible. Although the analysis should be interpreted as a strategic planning framework rather than a predictive hydrological simulation, future research should incorporate field validation, hydraulic modeling, and socio-economic feasibility assessment to support translation from corridor strategy to phased implementation. Nevertheless, the framework provides a practical decision-support approach for integrating water-sensitive planning, ecological restoration, and climate adaptation at the metropolitan scale.

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Conflicts of Interest

The author(s) report no conflicts of interest.

Data Availability Statement

The raw spatial datasets used in this study were obtained from publicly available sources, including USGS Earth Explorer, OpenStreetMap (OSM), NASA POWER, and the Humanitarian Data Exchange (HDX). All GIS processing, spatial analysis, modeling procedures, and derived analytical outputs were conducted by the author during the course of this research. Processed data supporting the findings of this study are available from the corresponding author upon reasonable request.

Institutional Review Board Statement

This study did not involve human participants, personal data, or animal subjects. Therefore, ethical review and approval were not required.

CRedit Author Statement

Raana M.O. Buzghia: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Visualization, Writing – Original Draft, Writing – Review & Editing.

Didem Dizdaroğlu: Supervision, Validation, Writing – Review & Editing.

All authors have read and approved the final manuscript.

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