



ARTICLE

## Assessing the Potential of Urban Blue Spaces for Sustainable Mobility in Bucharest: A GIS-Based Multi-Criteria Analysis

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Received: 31 March 2026; Accepted: 25 May 2026; Published: 18 June 2026

**ABSTRACT:** Urban blue spaces are increasingly recognized as critical components of sustainable cities. However, a significant gap exists in understanding their role not just as recreational areas, but as functional mobility corridors, especially within urban fabric of Eastern Europe countries. This study addresses this gap by assessing the accessibility and integration potential of blue infrastructure within Bucharest, Romania. The novelty of the research lies in the development of the Blue Areas Accessibility Index (BAAI), using a GIS-based Multi-Criteria Analysis (MCA). Eight spatial parameters were standardized using Likert scale and weighted using the Analytic Hierarchy Process to develop the Blue Areas Accessibility Index (BAAI). The resulting index was validated based on participatory GIS data collected from 103 respondents, offering a hybrid methodological approach that combines objective spatial modelling with subjective citizen perception. Results reveal significant spatial disparities in blue space potential accessibility. Only 1.53% of the city exhibits very high accessibility, primarily concentrated along the main hydrographic networks: Dâmbovița River, Colentina lake chain, and some selected central lakes, while approximately 27% of the territory falls into low or very low accessibility classes, particularly in southern and peripheral parts of the city, in Districts 4 and 5. The model demonstrated strong predictive performance (AUC = 0.816), confirming the reliability of the index. The findings identify key structural barriers, including industrial zones and fragmented infrastructure, that limit the integration of blue spaces into Bucharest's mobility network. This study provides a novel spatial framework for incorporating blue infrastructure into sustainable mobility planning.

**KEYWORDS:** Blue areas; sustainable mobility; GIS; multi-criteria analysis; accessibility; Bucharest

### 1 Introduction

Water represents an indispensable resource for life. Although primarily utilized for food production, hydropower and industrial activities, it also plays a crucial recreational and social role, particularly within urban centers. Nevertheless, within the context of identifying novel alternative transportation modes, the potential of these blue spaces to function as active mobility areas remains largely untapped, especially in cities.

Urban blue spaces are defined as all natural and artificial surface water features located within urban environments, including coasts, rivers, lakes, canals, ponds, and they provide a wide range of positive impacts for inhabitants [1,2]. These elements contribute both to the population's well-being and to public health, and they can also hold economic value by being developed and promoted for tourism purposes [3,4]. However,

the economic and functional viability of aquatic resources is heavily contingent upon the level of accessibility and the quality of infrastructure available to the population [5,6].

Many European countries have strategically invested in and revitalized their urban blue infrastructure, fostering robust social and economic networks. These initiatives have not only significantly enhanced public accessibility to blue spaces but have also led to a strategic expansion of waterborne transport systems, particularly within metropolitan areas [7,8]. Illustrative examples of such transformations are found in Baltic and Nordic cities, such as Tallinn, Stockholm, and Copenhagen, where significant redevelopments of blue spaces have been implemented [9]. Further examples include Warsaw, where the Vistula River has fundamentally shaped the capital's urban identity [10], as well as coastal cities like Barcelona, where the Mediterranean Sea has become a cornerstone of sustainable urban planning [11]. This trend is also evident in major German cities, where urban blue spaces are strategically, leading to systematic efforts to ensure adequate provision and equitable access for the entire urban population [12].

Regarding Eastern European countries, including Romania, much of the 20th century was marked by a centralized urban model that prioritized rapid industrial expansion, over environmental preservation [13]. Consequently, the development and integration of blue spaces were frequently side-lined in favor of intensive urban expansion, leaving these blue areas largely neglected in regional planning agendas. Moreover, Romanian localities generally contain only limited areas of blue infrastructure within their administrative boundaries, with many water bodies located outside the urban cores or along their peripheries [14]. However, recent years have seen a growing interest in blue infrastructure and its connectivity to the broader urban fabric, with several urban planning projects emerging particularly in the form of measures to improve quality of citizens and to mitigate climate extremes, albeit primarily at a theoretical [15,16]. A tangible example of investment in urban connectivity and accessibility is Timișoara. Despite its long-standing history of waterborne freight transport to Serbia, the city has successfully implemented a public water transport system along the Bega Canal, catering to both the local population and tourists [17,18].

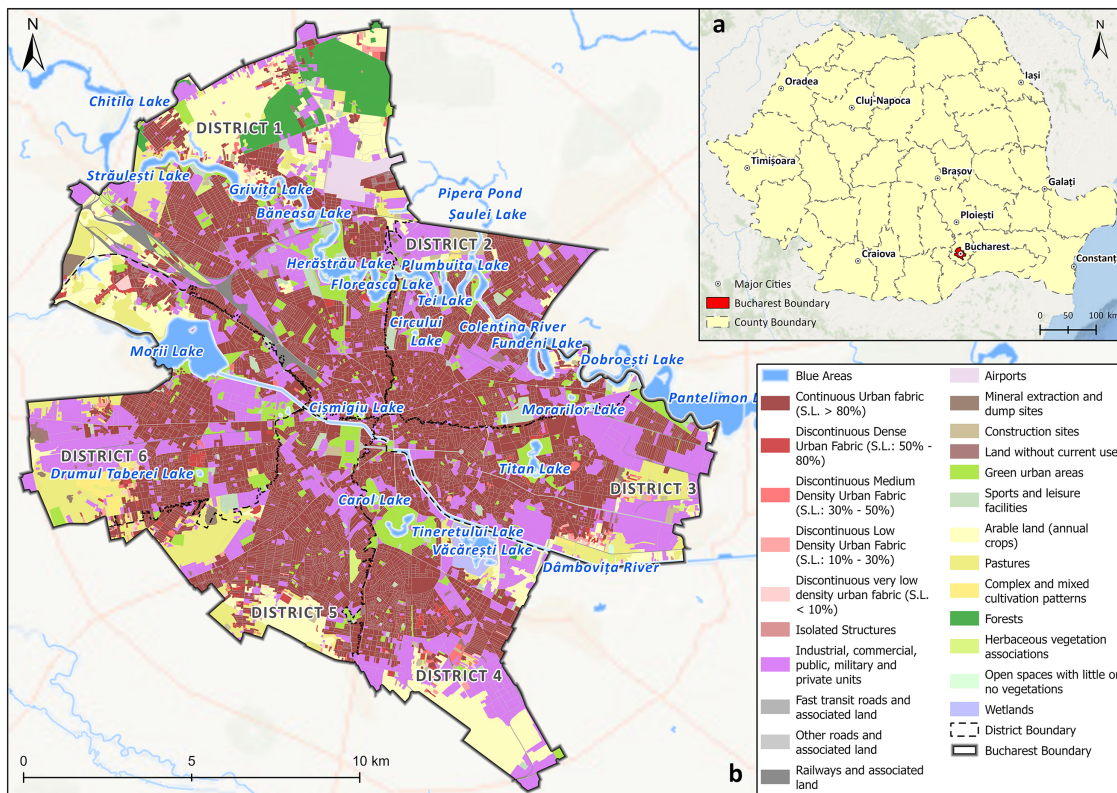
Building upon the theoretical frameworks emerging in recent literature, the capital city of Bucharest presents a significantly more complex challenge due to its dual hydrographic structure, comprising the highly anthropized Dâmbovița River and the mainly natural Colentina chain of lakes. This complexity is further exacerbated by a high degree of urban fragmentation and a chaotic development pattern that has resulted in significant mobility disconnects between the urban center and its emerging areas [19–21]. While this hydrographic network offers substantial potential for alternative connectivity, a systematic evaluation of its suitability remains absent, thereby limiting opportunities for walking, cycling, and recreational transport. This study addresses this gap by employing a GIS-based Multi-Criteria Analysis (MCA) to assess the potential of Bucharest's blue spaces for sustainable mobility. MCA was used in other similar studies regarding the suitability for integrating blue-green infrastructure in major cities undergoing rapid transformation, such as those from India and Ethiopia [22–24]. Furthermore, recent advancements in MCA offer sophisticated frameworks for urban mobility analysis. For instance, the Z-number extension of the Parsimonious Best Worst Method has been used to evaluate travel mode choices in Dublin, while integrating the Analytic Hierarchy Process (AHP) with Parsimonious Preference Information provides a robust approach for socio-economic sustainability assessments in public transport [25,26].

By integrating spatial parameters such as proximity to blue and green infrastructures, cycling routes, and street density, the research evaluates the current accessibility gaps and identifies critical areas where Bucharest's mobility network fails to integrate its blue spaces. This approach provides a data-driven foundation for strategic urban planning interventions aimed at reconnecting these fragmented landscapes at the city scale.

## 2 Materials and Methods

### 2.1 Study Area

The capital city of Bucharest is located in the south-eastern part of Romania, within the Vlăscia Plain, covering an area of approximately 240 km<sup>2</sup> with a resident population exceeding 1.7 million inhabitants. Administratively, the city is divided into six districts and is entirely surrounded by Ilfov County (Fig. 1). The urban blue infrastructure is primarily composed of urban lakes within public parks (e.g., Tineretului, Carol, Cișmigiu, etc.) and the two main rivers, Dâmbovița and Colentina, which transit the city from North-West to South-East. Historically, these water bodies were prone to flooding, leading to an extensive engineering process starting in the 18th century aimed at flood risk mitigation and hydrological regularization [27].



**Figure 1:** Map of the study area a) Location of Bucharest, b) Land cover classes.

Although these blue spaces are now integrated into the urban fabric, Bucharest lacks a strategic framework to leverage its waterfronts as functional mobility corridors. This deficit is a legacy of the pre- 1990 era, which prioritized dense residential expansion over the conservation of aquatic ecosystems, leading to the extensive canalization and concreting of many water bodies that persist to this day [28].

This fragmentation is further reconfirmed by recent studies [29,30], which emphasize the urgent need to reconnect the capital’s ecological river corridors to enhance urban resilience and mobility within the area. However, to achieve this, a comprehensive analysis is required to identify the blue areas most accessible to the population of Bucharest, which offer a wide range of ecosystem services, from recreational activities to economic opportunities [31].

## 2.2 Data Architecture

To evaluate the potential accessibility of blue spaces, Blue Areas Accessibility Index (BAAI) was developed as a composite spatial suitability index. The BAAI measures potential spatial accessibility by identifying areas where the physical environment is conducive to integration into the sustainable mobility network, based on proximity and density drivers. Recognizing its nature as a hybrid construct, the index integrates dimensions of mobility facilitation, environmental synergy and urban attractiveness, identifying the areas with high multi-functional strategic value.

Therefore, eight parameters representing the drivers of sustainable mobility in this context were utilized. These were derived from raw data extracted from various official sources, which underwent manual adjustments to ensure they were fully updated. Both the source data and the specific GIS processes used to generate the final rasters are presented in [Table 1](#).

**Table 1:** Data used in the analysis.

Input Criteria	Data Type	Data Source	Spatial Analysis Processing	Final Parameter
Blue Areas	Vector (Polygon)	Urban Atlas (EEA) with adjustments, 2018	Euclidean Distance	Blue Areas Proximity (m)
Transport Stops	Vector (Point)	General Transit Feed Specification (GTFS), 2025	Euclidean Distance	Transport Stops Proximity (m)
Green Areas (including Forests and Wetlands)	Vector (Polygon)	Urban Atlas (EEA) with adjustments, 2018	Euclidean Distance	Green Areas Proximity (m)
Cycling Routes	Vector (Line)	Bucharest Traffic Police (Brigada Rutieră) with adjustments, 2025	Euclidean Distance	Cycling Routes Proximity (m)
Industrial Areas Buildings	Vector (Polygon)	OpenStreetMap (OSM) with adjustments, 2025	Euclidean Distance	Industrial Areas Proximity (m)
Economic Hubs (commercial and retail buildings)	Vector (Polygon)	OpenStreetMap (OSM) with adjustments, 2025	Euclidean Distance	Economic Hubs Proximity (m)
People per Building	Vector (Point)	Urban Atlas (EEA) with adjustments, 2018	Kernel Density based on residential building centroids	Population Density (pop/sqkm)
Main Streets (Category 1,2,3)	Vector (Line)	OpenStreetMap (OSM) with adjustments, 2025	Kernel Density	Main Streets Density (km/sqkm)

Two main spatial analysis techniques were utilized to map the input criteria. Euclidean Distance was applied to proximity-based parameters to quantify the immediate spatial availability of resources, a method recognized for its effectiveness in strategic planning and feasibility studies where spatial proximity serves as a primary indicator of accessibility [32]. For density-based parameters (Main Streets and Population), Kernel Density Estimation (KDE) was preferred. KDE provides a smoothed, continuous surface that better represents urban dynamics than discrete census units, being frequently used in planning studies at larger scales [33].

To ensure a high degree of spatial precision, all thematic layers were processed at a spatial resolution of 10 m in ArcGIS Pro. This pixel size allows for the capture of fine urban details, such as narrow street segments or small water features, which are often lost at coarser resolutions. Furthermore, to eliminate the edge effect, a 2 km buffer zone was established around Bucharest's city limits. Following the generation of the continuous raster surfaces, each layer was clipped to the official administrative boundary of Bucharest to ensure a consistent and precise study area for the final multi-criteria analysis.

Beyond their technical processing, the selection of these eight parameters is grounded in their functional roles as catalysts for urban connectivity and ecosystem service provision. Each criterion reflects a specific dimension of the urban fabric, ranging from environmental attractors to infrastructural support and socio-economic demand, which collectively define the potential for integrating blue spaces into Bucharest's sustainable mobility network.

Blue Areas Proximity—BAP is the fundamental parameter of the study. Although it might appear redundant, this parameter is frequently utilized in similar studies [23,34], as it represents the primary resource for accessibility. Its inclusion is essential to establish the spatial baseline from which all other mobility and connectivity variables are measured.

Green Areas Proximity—GAP (including parks, forests, and wetlands) was chosen because it synergistically enhances the ecosystem services provided by blue areas. In specialized literature [35], Blue-Green Infrastructure (BGI) is treated as a unified system. Beyond this synergy, green areas provide additional critical benefits, such as acting as acoustic barriers against urban noise and facilitating microclimate thermoregulation.

Cycling Routes Proximity—CRP measures the alternative mobility infrastructure. The presence of cycling paths near blue spaces indicates a high potential for transforming these areas from purely recreational and health spots into functional transit arteries [36].

Transport Stops Proximity—TSP was selected because sustainable mobility also focuses on how easily a citizen can reach a blue corridor using public transit. A subway or bus station located near a blue area transforms a simple riverbank into an intermodal hub, allowing users to seamlessly combine public transport with walking or cycling in a continuous flow.

Industrial Areas Proximity—IAP was selected to model the negative aspect of accessibility. Industrial buildings and concrete platforms create discontinuities in pedestrian flow and degrade the aesthetic quality of the banks.

Economic Hubs Proximity—EHP (office buildings, commercial zones) was included because it represents the daily destinations of the population. By evaluating the proximity of from these centers, we can determine if blue infrastructure has the potential to become a viable route for utilitarian commuting.

Population Density—PD provides the human dimension of the analysis. Population density was included to prioritize blue spaces that serve the largest number of residents. A blue space located in a high-density area provides vital ecosystem services to large masses of people, representing areas where investments in accessibility yield the highest social return.

Main Streets Density—MSP indicates the vascularization of the territory. A high density suggests easy access from neighborhoods to the hydrographic axes, serving as a primary facilitator for urban flow.

### 2.3 Methodology

The operational workflow of the BAAI model is synthesized in Fig. 2, illustrating the multi-stage process from data acquisition to final validation. The framework integrates diverse spatial datasets from Urban Atlas, OpenStreetMap, and local authorities, which are subsequently processed using Euclidean Distance and Kernel Density tools. Following the reclassification and weighting stages based on the Analytic Hierarchy Process (AHP), the data are aggregated via raster calculator to generate the final accessibility index, which is then subjected to a validation phase to ensure the reliability of the spatial outputs.

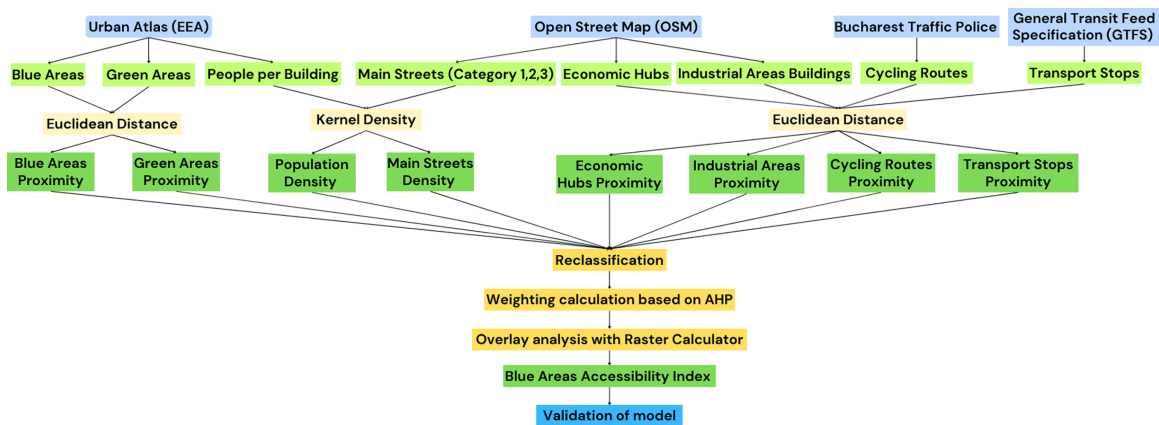


Figure 2: Workflow of the analysis.

Following the identification of the key determinants for blue space potential accessibility, they underwent a standardization process. Raw spatial data (Euclidean distances and densities) were transformed into a 1-to-5 Likert scale, where a value of 1 signifies low accessibility and a value of 5 represents high accessibility [37]. Technically, each parameter was initially divided into five classes, subsequently being reclassified with their respective scores from 1 to 5. This reclassification stage ensures the comparability of thematic layers, allowing for their mathematical aggregation through the following Weighted Sum formula:

$$BAAI = \sum_{i=1}^n (w_i \times P_i)$$

where:  $BAAI$  = Blue Areas Accessibility Index,  $w$  = weights,  $P$  = Parameter Score,  $i$  = Index of the parameter.

Table 2 presents the scores and weights assigned to each parameter. Regarding the proximity-based criteria, these were classified based on distance, following the principle that a shorter distance results in higher accessibility. The only exception to this logic is the distance to industrial areas, which utilizes an inverse criterion; here, proximity represents a constraint or restriction, thereby receiving a lower score to reflect its negative impact on pedestrian accessibility.

The thresholds for the 1–5 Likert scale were derived from a combination of international walking standards (for mobility variables) and local urban planning norm, ensuring that the ordinal framework remains contextually grounded.

**Table 2:** Parameters scores and weights.

Parameters	Classes					Weight (%)
Blue Areas Proximity (m)	0–200	200–400	400–800	800–1200	1200–4640	33.1%
Transport Stops Proximity (m)	0–200	200–400	400–600	600–800	800–1586	20.4%
Green Areas Proximity (m)	0–200	200–400	400–800	800–1200	1200–2318	12.1%
Cycling Routes Proximity (m)	0–200	200–400	400–600	600–800	800–7143	9.2%
Industrial Areas Proximity (m)	0–100	100–300	300–500	500–1000	1000–2153	2.1%
Economic Hubs Proximity (m)	0–200	200–400	400–800	800–1200	1200–2731	3.1%
Population Density (pop/sqkm)	0–1	1–2336	2336–7397	7397–15,962	15,962–99,280	14.9%
Main Streets Density (km/sqkm)	0–0.86	0.86–2.12	2.12–3.69	3.69–5.47	5.47–12.91	5.1%
Scores	1	2	3	4	5	100%

The classification thresholds were established using a hybrid approach tailored to the nature of the spatial data. For density-based parameters (Population and Main Streets), the Quantile method was applied to ensure a balanced distribution of scores across Bucharest’s diverse urban fabric, effectively capturing the contrast between hyper-dense cores and transitional areas. In contrast, for proximity-based parameters, the intervals were defined based on pedestrian accessibility standards (e.g., 15-min city), ensuring that the scores reflect the physical reality of human mobility [38].

For example, the public transport user is highly sensitive to distance, typically seeking a walk of under 400 m (approx. 5 min). According to Stojanovski [39], a distance of 600 m (approx. 7–8 min) represents the maximum threshold for convenient access to a transit point. Beyond this value, accessibility is significantly reduced as the effort becomes a deterrent. The same principle was applied to Cycling Routes, considering the physical effort involved in reaching the specialized infrastructure. For Blue Areas, Green Areas, and Economic Hubs, the classification follows the 10-min walk rule (approx. 800 m). While public transit requires tighter proximity to remain competitive, urban dwellers are generally willing to walk up to 10 min to access high-quality environmental amenities or employment centers. However, it is important to note that the 300–400 m threshold (a 5-min walk) remains the most common metric used in urban studies for these specific categories, representing the optimal distance for high-frequency interaction [40].

Regarding Industrial Areas, the classification thresholds were calibrated based on a generalized average derived from the sanitary protection distances stipulated in the Romanian Ministry of Health’s Order no. 119/2014 [41]. While these distances vary in legislation depending on the specific industrial activity, a simplified average was adopted for this model to maintain consistency across the entire study area. These thresholds (100, 300, 500 m) acknowledge that industrial presence functions as a barrier to the quality and accessibility of blue spaces, with the negative impact being most acute within the immediate vicinity of these sites.

To determinate the relative importance of each criterion ( $w_i$ ) the Analytic Hierarchy Process (AHP) was employed. This method has seen increasing application in recent years across various studies, serving as a foundational tool for the identification of decision-making criteria [42]. The core of this tool involved the construction of a pairwise comparison matrix (Table 3) where each factor was evaluated against the others using Saaty’s 1–9 fundamental scale [43]. The logical consistency of the prioritization was validated through a Consistency Ratio (CR) of 0.06. As this value is below the 0.10 threshold established by the Saaty scale, the robustness of the weights used in the model is confirmed. This systematic approach allowed for the conversion of qualitative expert judgments into quantitative weights.

**Table 3:** Pairwise comparison matrix.

Parameters	BAP	GAP	CRP	TSP	IAP	EHP	PD	MSD
BAP	1	3	5	3	7	7	3	5
GAP	0.333333	1	2	0.333333	7	6	0.5	3
CRP	0.2	0.5	1	0.333333	7	5	0.333333	3
TSP	0.333333	3	3	1	7	5	2	4
IAP	0.142857	0.142857	0.142857	0.14	1	0.333333	0.2	0.333333
EHP	0.142857	0.166667	0.2	0.2	3	1	0.2	0.333333
PD	0.333333	2	3	0.5	5	5	1	3
MSD	0.2	0.333333	0.333333	0.25	3	3	0.333333	1

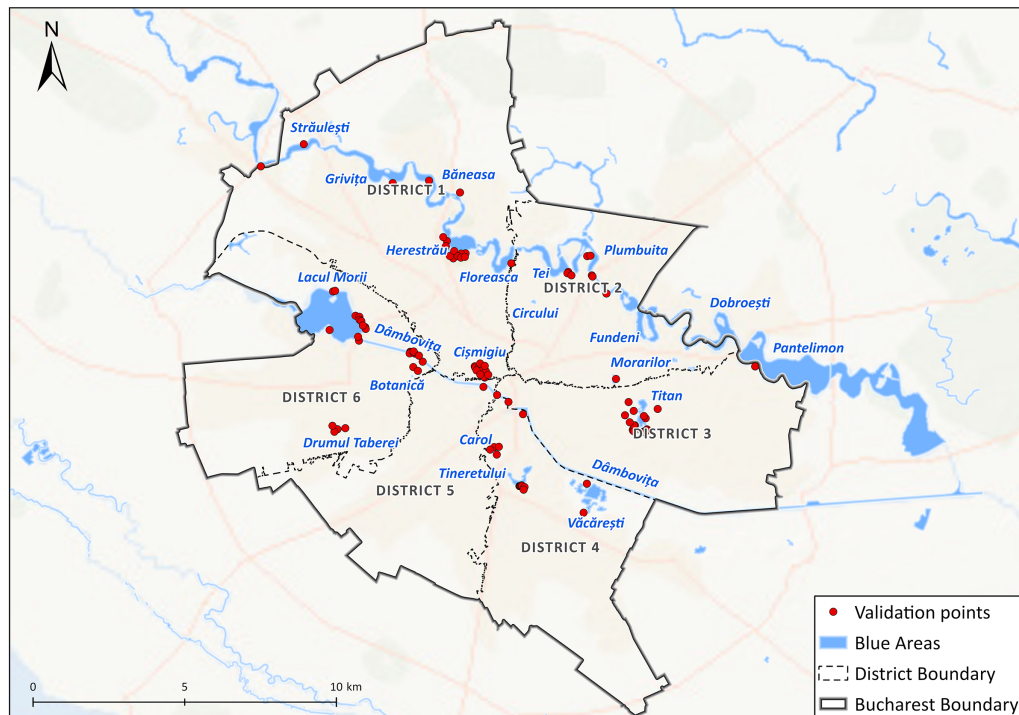
After establishing the scores for each class and the weights for each parameter, the Blue Areas Accessibility Index (BAAI) was calculated using the Raster Calculator tool of ArcGIS Pro. The process involved a Weighted Linear Combination (WLC) of the eight input layers. The resulting raster dataset, with values ranging from 1 to 4.94, reflects the integrated accessibility level across the study area. These continuous values were then reclassified into five distinct qualitative classes, as presented in [Table 4](#), to facilitate a clear spatial interpretation of the accessibility gradients.

**Table 4:** Final classes for BAAI.

Values Interval	Classes
1–1.5	Very Low
1.5–2.5	Low
2.5–3.5	Moderate
3.5–4.5	High
4.5–4.94	Very High

To validate the potential accessibility of blue spaces, this study employed the *Presence-Only Prediction (MaxEnt)* tool integrated within the ArcGIS Pro environment. This machine learning algorithm was selected for its robust ability to model complex spatial distributions using only presence data [44], thereby avoiding the subjectivity inherent in defining absence within the context of urban space utilization.

The validation dataset was generated through a Public Participation GIS (PPGIS) approach, using the Google My Maps App. Integrating PPGIS data is essential for bridging the gap between theoretical models and the lived experience of residents, serving as a transformative tool that incorporates local knowledge into land use and urban planning [45,46]. As a result, a total of 103 presence points ([Fig. 3](#)) were collected through, field research, where 103 random respondents, inhabitants of the city, were asked to identify on a map the specific blue spaces they frequent most often. While we acknowledge a potential spatial bias towards well-known blue spaces, the distribution of points across the city provides a representative snapshot of how perceived accessibility aligns with the calculated BAAI. During the modelling process, these presence points were analyzed against a massive dataset of 1,095,387 background points distributed across Bucharest, ensuring high spatial resolution and significant statistical power.



**Figure 3:** Validation points across the study area.

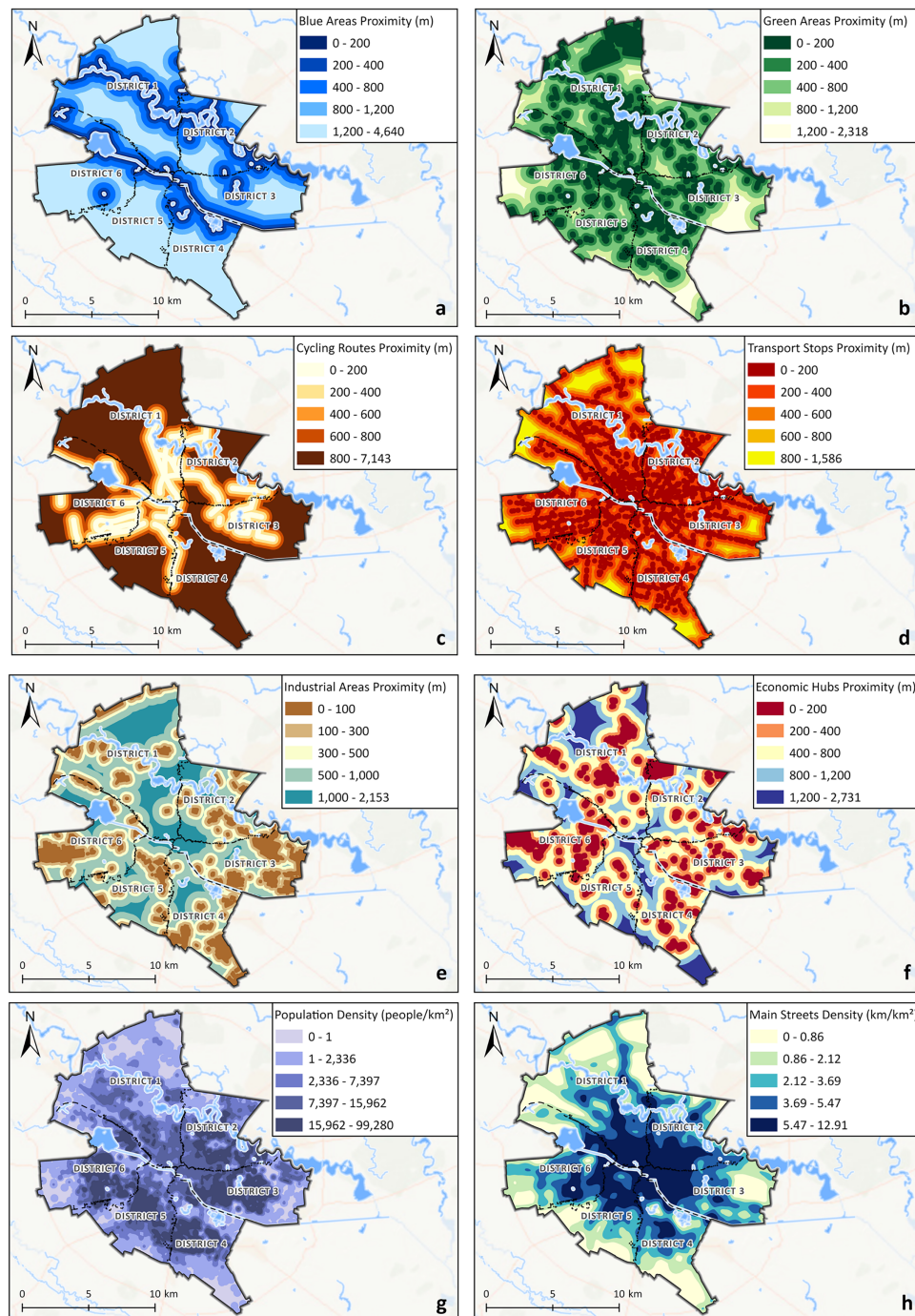
To evaluate the internal consistency of the model and the interdependencies between the spatial predictors, a Pearson correlation analysis was performed. This step ensures that the variables integrated into the BAAI do not exhibit extreme multicollinearity and that each factor contributes significantly to the final accessibility index.

### 3 Results

#### 3.1 Spatial Distribution of Key Accessibility Factors

Fig. 4 illustrates the spatial distribution of the primary factors employed in this analysis. As shown in Fig. 4a, the proximity to blue spaces reveals that shorter distances are concentrated along the central and northern axes, while a significant portion of the capital remains underserved, with distances exceeding 1200 m from these areas. Fig. 4b displays the proximity to green spaces, where a more extensive presence is observed in the southern and peripheral zones of the municipality. However, certain areas remain at a considerable distance from green infrastructure, particularly within Districts 1, 3, and 4.

Regarding cycling routes (Fig. 4c), these are relatively scarce and unevenly distributed across the city, with a higher prevalence in Districts 1, 3, and 6. Morii Lake stands out as the water body with the most extensive cycling infrastructure along its shores, which continues westward via the Chiajna promenade and eastward along the Dâmbovița riverbanks. Finally, Fig. 4d presents the proximity to transport stops, showing a distribution that covers nearly the entire surface of Bucharest. The very short distances between stops indicate high accessibility to public transit, although certain areas, such as the Băneasa Forest region, still exhibit precarious access.



**Figure 4:** Key parameters proximity and density **a)** blue areas, **b)** green areas, **c)** cycling routes, **d)** transport stops, **e)** industrial areas, **f)** economic hubs, **g)** population density, **h)** main streets density.

Fig. 4e illustrates the distance to the primary industrial areas within the capital. These zones are predominantly concentrated in the peripheral regions, with a significant cluster in the south-central part of District 5, specifically the Progresul industrial platform, which acts as a functional barrier that disconnects dense residential areas from potential blue corridors. The largest distances from these industrial sites are recorded in the central and northern parts of the city. Fig. 4f displays the proximity to economic hubs, which

are situated across most key strategic points of the capital. However, a lower density is observed along the central North-South axis, a result of the high concentration of residential buildings in those areas.

The distribution of population density (Fig. 4g) is a key factor, as it identifies the inhabitants potentially served by blue spaces. The highest density values are located in Districts 2, 3, 5, and 6, primarily along the central urban corridor of Bucharest, while the lowest density values are found in the northern part of District 1 and the southern periphery of District 4. Fig. 4h, representing the density of main streets, reveals the structural fabric of urban mobility, highlighting a robust radial-concentric network. While the highest concentration is found in the central area, high density levels also extend along the main boulevards that connect Bucharest to its satellite towns.

### 3.2 Spatial Pattern of the Blue Areas Accessibility Index (BAAI)

The final BAAI map (Fig. 5) for the Municipality of Bucharest, resulting from the multi-criteria analysis, illustrates that the highest theoretical levels of accessibility are consistently found in the immediate vicinity of water bodies, although some variations exist. Areas with “Very High” accessibility cover 1.53% of the territory. These are primarily clustered around Drumul Taberei, Titan, and Cișmigiu lakes, as well as specific sections of the Colentina chain, including Herăstrău, Plumbuita, Floreasca, Tei, and Dobroești. Regarding the Dâmbovița River, very high accessibility is concentrated in the western sectors between Morii Lake and Unirii Square, while other sections maintain a “High” accessibility status.

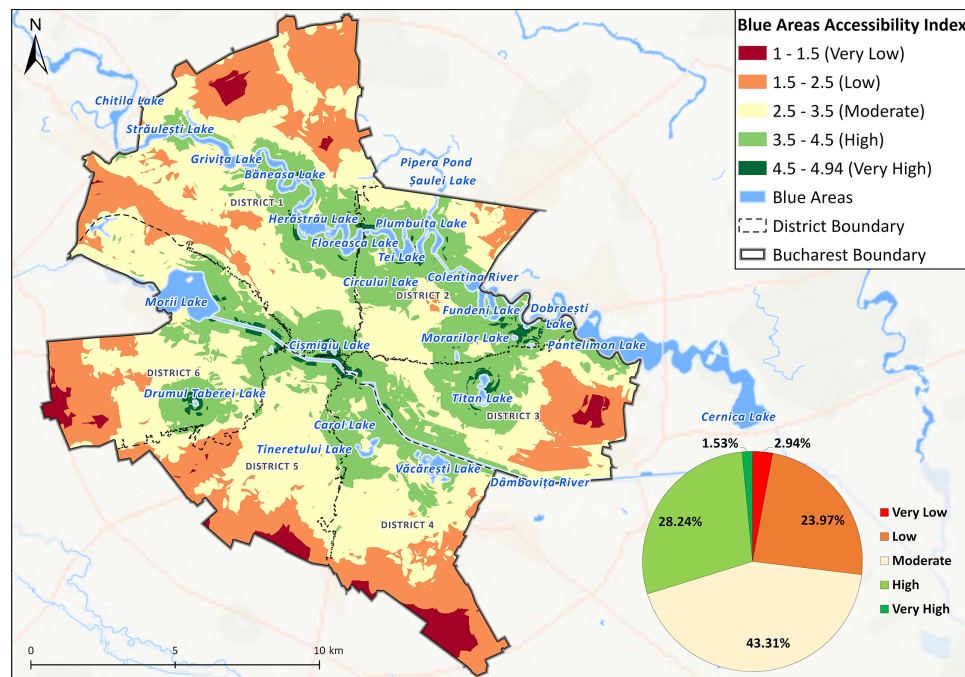


Figure 5: Blue areas accessibility index for Bucharest.

Overall, “High” accessibility accounts for 28.24% of the area, meaning that nearly 30% of Bucharest benefits from superior access to blue spaces. However, a significant portion of the capital (43.31%) is characterized by only “Moderate” accessibility. This tier predominantly covers the southern regions and the transitional areas between the two main hydrographic arteries. Notable gaps are observed on the western shore of Morii Lake, which remains undeveloped, and around northern lakes like Grivița and Străulești,

which lack sustainable mobility infrastructure. Furthermore, certain sectors near Tineretului and Văcărești Lakes also exhibit lower-than-expected accessibility.

At the opposite end of the spectrum, the city's peripheral zones, particularly in the south-west, record the lowest accessibility levels. These areas suffer from a lack of nearby water bodies (including those in the surrounding Ilfov County), a deficit in cycling infrastructure, and the presence of extensive industrial zones. Consequently, approximately 27% of Bucharest's territory falls into the "Low" (23.97%) and "Very Low" (2.94%) categories.

### 3.3 Comparative Analysis of Accessibility Levels across Bucharest's Districts

Fig. 6 illustrates the distribution of relative BAAI values across Bucharest's administrative districts. As observed, District 2 exhibits the highest accessibility potential, with approximately 60% of its territory falling into the "High" and "Very High" categories. This performance is directly associated with the presence of the Colentina lake chain in the north-eastern part of the capital. It is followed by District 3, which shows good accessibility over 40% of its area, primarily driven by the strategic location of Titan Lake.

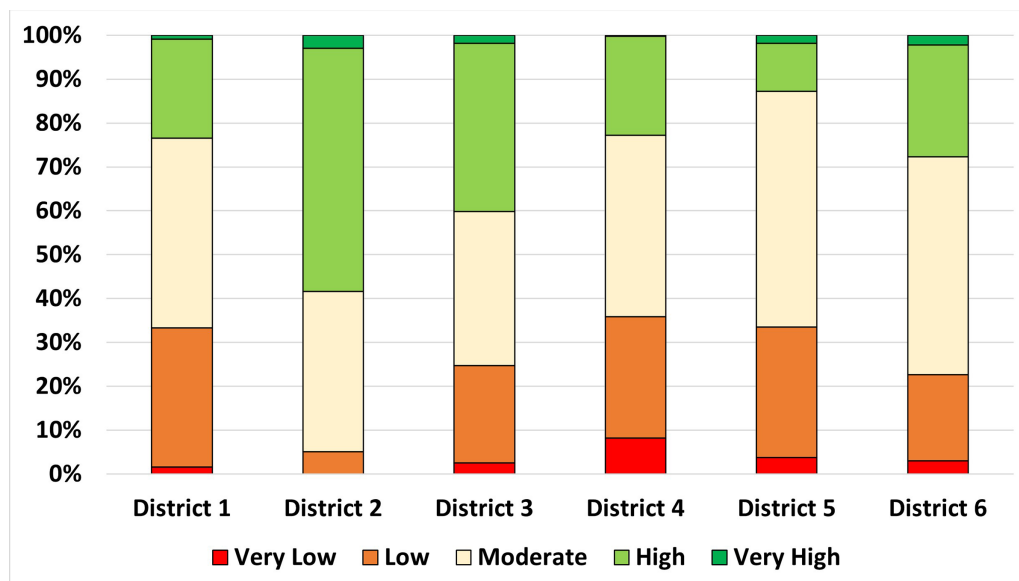


Figure 6: Distribution of BAAI by district in relative values.

In contrast, the lowest accessibility levels are found in District 4, where approximately 35% of the territory is classified as "Low" or "Very Low". This occurs despite the presence of major blue spaces such as Tineretului, Carol, and Văcărești lakes within its boundaries. Similarly, District 5 displays low accessibility, with roughly 34% in the lowest classes and only about 12% reaching high or very high accessibility levels. This trend is correlated with a general lack of blue spaces, with the exception of the Dâmbovița River, and the existence of numerous industrial zones that restrict easy access to transport stops.

Furthermore, more than half of this district's territory falls within the "Moderate" accessibility class. District 1 is also characterized by significant low-accessibility areas (33%), a result partly influenced by its large geographical scale, as it is the city's largest district. Finally, District 6 shows a distribution ranging from moderate to good accessibility, with Morii Lake and Drumul Taberei Park serving as the primary polarizing blue spaces in the region.

### 3.4 Model Validation

The model achieved an Area Under the Curve (AUC) of 0.8161, indicating a good ability to discriminate between high-accessibility zones and random locations. The Omission Rate of 0.1553 further confirms the model's reliability, suggesting that only a small fraction of known accessible locations were incorrectly classified as "Low" by the BAAI algorithm.

The robustness of the results is reinforced by the Regression Coefficients, where the primary accessibility variable (BAAI) demonstrated a positive influence with a value of 1.5678. This suggests a stable relationship across the study area, with values ranging from 1.57 to 4.95 in the training dataset, ensuring that the model remains sensitive to local spatial variations without over-fitting. The validation process successfully classified 87 out of 103 presence points within the predicted high-accessibility areas. Meanwhile, background points were filtered to ensure that only 427,064 points (approx. 39%) were assigned a presence probability above the 0.5000 cutoff. This strict c-log-log link function ensures that the final BAAI map remains a conservative and a theoretical representation of Bucharest's urban reality, effectively integrating the participatory data into a validated spatial index. However, this validation should be viewed as indicative rather than conclusive. The presence points reflect revealed recreational preferences and familiarity, which, while overlapping with accessibility, are also influenced by the popularity of specific well-known lakes.

A sensitivity analysis was performed to evaluate the impact of weighting on the final BAAI index. An alternative model was calculated by assigning equal weights to all criteria. The spatial correlation between the AHP and the Equal Weights models yielded a Pearson coefficient of  $r = 0.91$ , indicating a very high level of stability. This suggests that the spatial patterns of blue space accessibility in Bucharest are consistent and not overly sensitive to the subjective input of the AHP process.

The internal consistency of the Blue Area Accessibility Index (BAAI) is quantitatively validated by the Pearson correlation matrix (Fig. 7) which reveals significant synergies between the final index and its underlying spatial drivers. All analyzed relationships reached a high level of statistical significance ( $p < 0.001$ ), confirming the robustness of the selected variables.

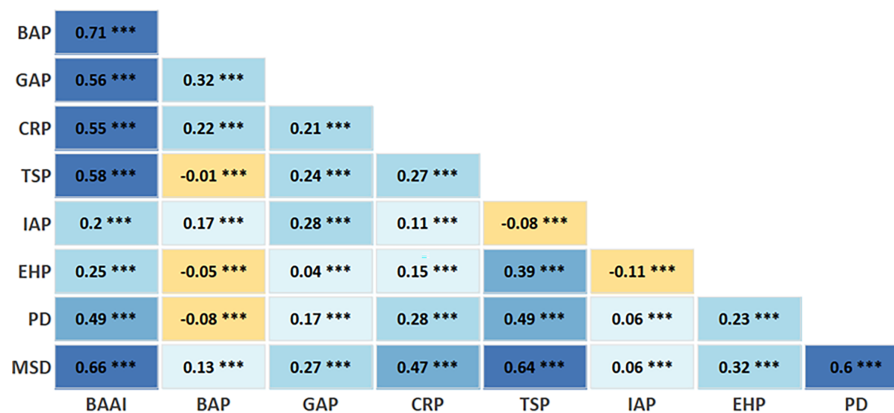


Figure 7: Pearson correlation matrix \*\*\* denote statistical significance at the 0.001 levels.

The BAAI demonstrates its strongest individual link with Blue Area Proximity (BAP,  $r = 0.71$ ), which confirms that physical proximity to water remains the fundamental pillar of accessibility in Bucharest. This is closely followed by the Main Streets Density (MSD,  $r = 0.66$ ), a correlation that validates the "urban fabric" hypothesis by proving that the primary street network acts as the functional catalyst required to activate access to blue spaces. Furthermore, the index shows a strong alignment with Transport Stop Proximity

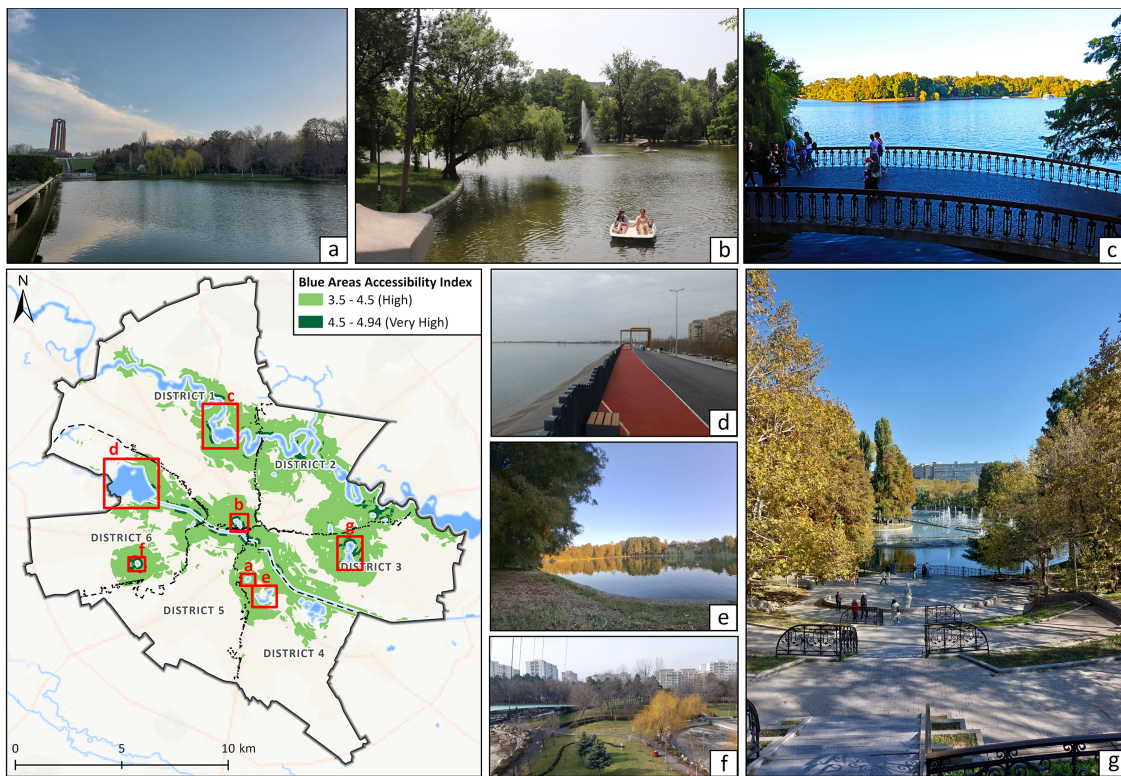
(TSP,  $r = 0.58$ ), indicating a strategic connection between public transit nodes and high-potential recreational zones, while its relationship with Population Density (PD,  $r = 0.49$ ) suggests that the model effectively identifies areas where social demand coincides with the availability of blue infrastructure.

Beyond the final index, the matrix shows key structural relationships within Bucharest's urban morphology, such as the strong correlation between Population Density and Street Density ( $r = 0.60$ ), which reflects the logical clustering of residential intensity along major transport arteries. Similarly, the link between Transport Stops and Street Density ( $r = 0.64$ ) highlights the concentration of transit services within the primary road network. Notably, the minor negative correlations observed between BAP and Population Density ( $-0.08$ ) or BAP and Public Transport ( $-0.01$ ) are particularly revealing, as they indicate that Bucharest's most water-rich areas are not necessarily the most densely populated or the best served by transit. This spatial mismatch justifies the implementation of the BAAI as a multidimensional tool capable of capturing accessibility disparities that simple proximity measures would overlook

#### 4 Discussions

The spatial distribution of the Blue Area Accessibility Index (BAAI) highlights specific urban clusters where the synergy between water resources and urban infrastructure is most effective. Consequently, Fig. 8 illustrates some of the most accessible blue zones and the characteristics that establish them as significant hotspots. These are located especially in green areas, suggesting the synergy between the two types of infrastructure. For instance, the lakes in Carol Park (Fig. 8a) and Cișmigiu Gardens (Fig. 8b) exhibit high accessibility due to their central location and the presence of nearby tourist attractions. While Carol Park hosts several landscape and historical elements of notable value [47], Cișmigiu Gardens benefits from its proximity to major hotels such as Corinthia, Novotel, and Continental, as well as cultural attractions including the National Museum of Art of Romania, the Romanian Athenaeum, the Old Town area, and the university campus, which increases accessibility from multiple directions [48]. However, the presence of the Filaret industrial zone creates a barrier that limits pedestrian permeability and disconnects the Carol Lake from the surrounding residential fabric. In Nanchang, China, the Qingshan Lake is also located in the central part of the city and is surrounded by residential areas, having a trail that connects the areas around the lake [49]. According to Wang et al. [50], these characteristics sum up the main factors for accessibility: proximity, socio-psychological factors and knowledge (collective impressions about the blue area or park). The domains of accessibility are applicable to lakes Cișmigiu and Carol, as both of them have similar infrastructure built around them and their position in the city center.

In northern Bucharest, Herăstrău Lake (Fig. 8c), located within King Michael I Park, also demonstrates high accessibility due to extensive public transport connections (subway, bus lines) and the presence of nearby cultural and recreational attractions, such as The National Village Museum or the Arch of Triumph [51]. However, a more nuanced pattern emerges around Morii Lake (Fig. 8d), where accessibility is strictly dependent on the quality of the built environment. Our findings align with the observations of Zhang et al. [36], in Rotterdam, who noted that urban blue spaces become significant hubs for active mobility (walking, running, and cycling) only when supported by green, well-connected paths. This similarity is particularly evident on the eastern bank of Morii Lake, where recent investments in cycling infrastructure have mirrored the Rotterdam model, leading to higher accessibility rates and increased recreational usage as a running lane. Conversely, the low accessibility found near Giulești and the Roșu canal [52], highlights the need to invest and promote green and connected infrastructures for a sustainable mobility.



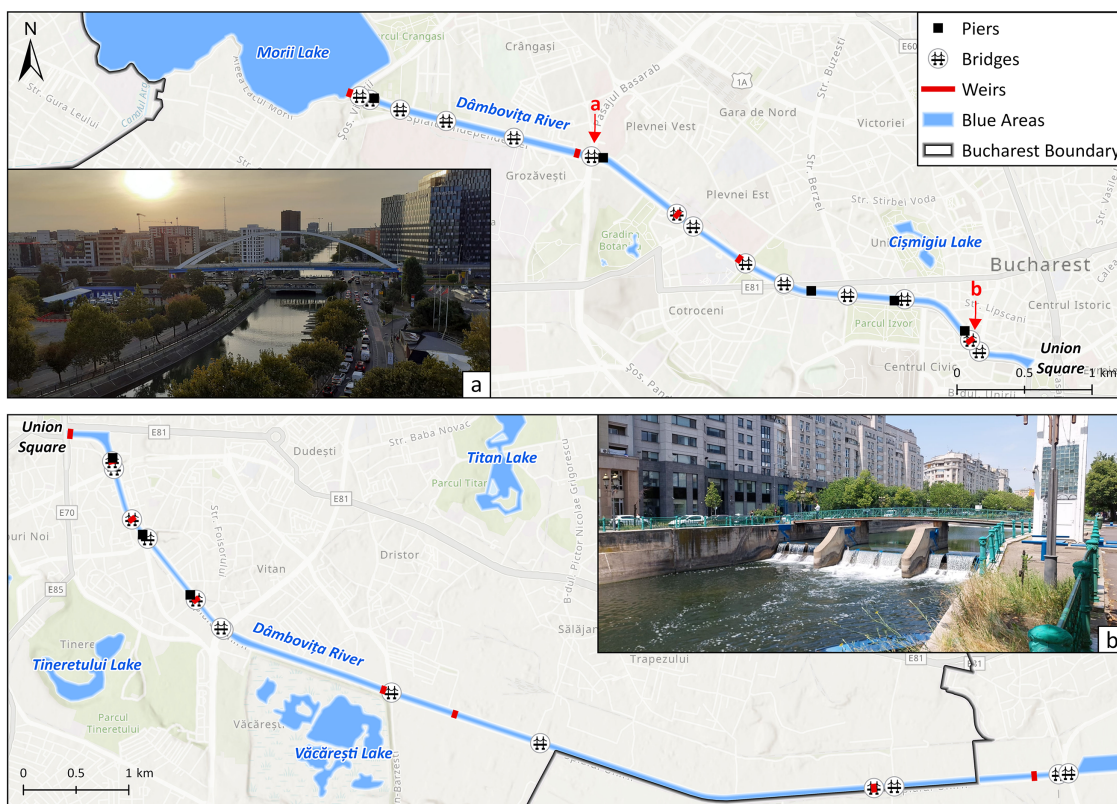
**Figure 8:** Main blue areas with highest accessibility **a)** Carol Lake, **b)** Çișmigiu Lake, **c)** Herăstrău Lake, **d)** Morii Lake, **e)** Tineretului Lake, **f)** Drumul Taberei Lake, **g)** Titan Lake, (Photos: Authors, 2025).

The lake within Tineretului Park (Fig. 8e) shows higher accessibility in the southwestern and northeastern sectors, mainly due to the proximity of major avenues and nearby metro stations. The internal layout of the park facilitates multiple access routes connecting the waterfront to high-traffic areas [53]. In contrast, the northwestern and eastern sectors present moderate accessibility, partly due to fewer pedestrian paths and amenities, particularly on the southeastern island where vegetation remains largely unmanaged. This observation aligns with Smith et al. [54], whose research in Glasgow identifies cleanliness and maintenance as critical leverage points for equitable blue space access. By conceptualizing maintenance as a dynamic management variable, our findings suggest that policymakers must prioritize active site stewardship over spatial proximity to enhance the functional quality and salubrity of urban green assets.

Similarly, the lakes in Drumul Taberei Park (Fig. 8f) and Titan Lake (Fig. 8g) demonstrate how accessibility is reinforced by strong transport connectivity and dense surrounding urban functions. The lake in Drumul Taberei Park benefits from multimodal transport infrastructure, including multiple metro stations, bus routes, and tram lines, while its proximity to Iuliu Maniu Boulevard, one of the city’s most heavily trafficked corridors, and the presence of schools and commercial areas contribute to high accessibility levels [55]. Titan Lake, located near densely populated neighbourhoods such as Titan and Dristor, illustrates how the transformation of former industrial zones into mixed residential and commercial areas can further enhance accessibility. In this case, extensive public transport infrastructure and the development of commercial facilities such as ParkLake Shopping Center have strengthened the lake’s role as an important recreational hub [56]. Conversely, Albania had a comparable development after 1990, former industrial areas being demolished and replaced by residential areas, or for private economic activities, some of them being concentrated around Farka Lake, in the eastern part of Tirana [57].

Besides the accessibility, the lakes also benefit from numerous leisure facilities such as paddle boats, rowing boats (Cișmigiu and Drumul Taberei Lake) and motorboats with high capacity (on Herăstrău and Titan lakes), features which could be developed more in order to attract a bigger number of visitors [58,59]. For future planning, water bodies could also be used for public transportation, especially on Herăstrău, due to the big size of the lake.

Regarding the Dâmbovița River (Fig. 9), the high values of the BAAI index confirm its status as the primary blue corridor of Bucharest. Unlike isolated parks, this linear blue space intersects multiple urban sectors, providing a continuous path that aligns with high Main Streets Density (MSD,  $r = 0.66$ ) and public transport connectivity. However, its current utility for active water-based transport is severely limited by structural bottlenecks. Specifically, the presence of low-clearance bridges (Fig. 9a) and weirs (Fig. 9b) prevents the establishment of continuous water transport or recreational boating routes, creating a paradox: while the river is highly accessible from the banks, it remains disconnected as a navigable waterway.



**Figure 9:** Dâmbovița River in the western (top) and eastern (bottom) sectors of Bucharest highlighting key infrastructure a) Grozăvești Bridge, b) River weirs, (Photos: Authors, 2025).

Nevertheless, as a future planning vision, recreational activities could be organized on short river segments between sills, specifically in areas where piers provide direct waterfront access. There are also instances where water public transportation and leisure activities work, like in the case of the water taxi in Dhaka, on the Hatir Jheel Lake or the Saigon River bus in Ho Chi Minh, as solutions for the rush hour traffic congestion [60,61]. However, in the context of Bucharest, such developments would require complementary feasibility studies to move beyond the structural accessibility baseline established in this research. To achieve this, essential parts were engineering and management, through building terminals, attracting investments,

reducing costs for the population and careful urban planning [62], things that could be used further to encourage inland water transportation on Dâmbovița River.

Despite being validated both statistically and in the field, this study is subject to certain limitations that warrant further consideration. A primary limitation is the use of Euclidean distance as a proxy for accessibility. While this approach provides a consistent spatial baseline, it serves as a loose approximation of actual movement, as it does not account for specific urban barriers, fragmented frontage conditions, or discontinuous waterfront access characteristic of Bucharest. Consequently, the BAAI results should be interpreted as an assessment of potential spatial proximity rather than a network-based pedestrian route analysis [63,64]. In addition, the Blue Area Accessibility Index (BAAI) could be further refined by incorporating qualitative factors such as waterfront amenities, environmental quality, and seasonal recreational activities, which may also influence the attractiveness and usability of urban blue spaces.

In the context of recent methodological trends, it is important to acknowledge the emergence of advanced MCA extensions, such as those incorporating Z-numbers or spherical fuzzy sets into the AHP Process and Best Worst Method [25,65]. While these frameworks are highly effective at addressing uncertainty in transport studies, they were not adopted for the current BAAI model. The decision was based on the necessity of providing a straightforward, deterministic tool that remains accessible to urban planning. By avoiding the high computational complexity associated with fuzzy extensions, this study prioritizes model transparency and ease of implementation, though these advanced methods remain relevant benchmarks for future sensitivity refinements. Furthermore, future research lies in transitioning toward fuzzy-based Multi-Criteria Analysis (MCA) to better handle spatial uncertainty. Recent applications in diverse urban contexts, such as Brazil and Egypt, have already demonstrated how combining fuzzy logic with GIS and remote sensing can refine transportation service management and accessibility modeling [66,67]. While the current BAAI model prioritizes a deterministic approach for immediate practical use, integrating such fuzzy extensions in future iterations would allow for a more sensitive analysis of Bucharest's complex and evolving urban fabric.

## 5 Conclusions

The assessment of Bucharest's aquatic network through the Blue Areas Accessibility Index (BAAI) provides a pioneering spatial framework for integrating blue infrastructure into the city's sustainable mobility agenda. By employing a GIS-based Multi-Criteria Analysis, this study transitions from a simple proximity inventory to a functional diagnosis of urban connectivity.

The BAAI model reveals a significant spatial disparity between blue space integration and social accessibility across Bucharest's districts. The analysis highlights significant geographical inequities across Bucharest's administrative districts. While District 2 emerges as a leader in accessibility (60% coverage) due to the Colentina lake chain, Districts 4 and 5 face critical deficits. In these sectors, the socialist industrial acts as a functional and aesthetic barrier, effectively isolating large residential clusters from the Dâmbovița River's potential as a mobility corridor.

The reliability of the BAAI is statistically confirmed by the *MaxEnt validation model*, which achieved an AUC of 0.8161, indicating a strong predictive performance. The high Pearson correlation between the final index and Main Streets Density ( $r = 0.66$ ) validates the urban fabric hypothesis: water accessibility in Bucharest is not merely a matter of distance, but is fundamentally activated by the structure of the primary road network.

The BAAI map serves as a data-driven foundation for targeted urban interventions and future planning. The results suggest that transforming the Dâmbovița River into a continuous transit artery requires

more than just bank accessibility; it necessitates addressing specific structural bottlenecks, such as low-clearance bridges and weirs, which currently hinder its functional continuity. By overcoming these physical constraints, the river could be upgraded from a fragmented blue feature into a high-capacity sustainable mobility corridor.

Future developments of the BAAI model should consider transitioning toward Fuzzy-based Multi-Criteria Analysis (MCA) to better manage the spatial uncertainty of urban infrastructure. Additionally, Machine Learning (ML) offers a powerful tool for addressing these complex urban problems. By utilizing ML algorithms, future research can move beyond linear estimations to identify hidden spatial patterns, automate the identification of accessibility gaps, and develop predictive models for urban planning. These advanced computational approaches will allow for a more dynamic and precise understanding of Bucharest's evolving urban fabric.

The Blue Areas Accessibility Index developed in this study provides more than just spatial data; it offers a roadmap for reconnecting the urban fabric with its natural blue-veins. Ultimately, the water should no longer be a forgotten boundary, but the primary catalyst for a healthier, more connected city.

**Acknowledgement:** This research was conducted as part of the CIVIS Interdisciplinary Perspectives on Sustainable Mobility Course at the University of Salzburg. We would like to express our sincere gratitude to Professor Martin Loidl and Professor Dženeta Karabegović for their invaluable guidance, expertise, and support throughout the development of this study.

**Funding Statement:** The authors received no specific funding for this study.

**Author Contributions:** The authors confirm contribution to the paper as follows: Conceptualization, Mihnea-Ştefan Costache; methodology, Mihnea-Ştefan Costache; software, Mihnea-Ştefan Costache and Simona-Elena Paraschiva; validation, Mihnea-Ştefan Costache, Simona-Elena Paraschiva and Teodora-Patricia Pătru; formal analysis, Mihnea-Ştefan Costache; investigation, Mihnea-Ştefan Costache, Simona-Elena Paraschiva and Teodora-Patricia Pătru; resources, Simona-Elena Paraschiva and Teodora-Patricia Pătru; data curation, Mihnea-Ştefan Costache; writing—original draft preparation, Mihnea-Ştefan Costache; writing—review and editing, Simona-Elena Paraschiva and Teodora-Patricia Pătru; visualization, Mihnea-Ştefan Costache and Simona-Elena Paraschiva; supervision, Mihnea-Ştefan Costache. All authors reviewed and approved the final version of the manuscript.

**Availability of Data and Materials:** The data that support the findings of this study are available from the Corresponding Author, Mihnea-Ştefan Costache, upon reasonable request.

**Ethics Approval:** Not applicable.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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