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Article

Planning Blue–Green Infrastructure for Facing Climate Change: The Case Study of Bucharest and Its Metropolitan Area

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Abstract: Planning for a green–blue infrastructure system around big cities, having the shape of a belt, to connect natural areas—such as green spaces, water, and agricultural land—is a solution for mitigating the challenges of climate change and urban sprawl. In this context, this study presents an innovative information technology solution for assessing the connectivity of the green and blue areas in the metropolitan area of Bucharest, Romania. The solution is to try to stop the sprawl of Bucharest into the adjacent rural areas and answer the need for a green infrastructure providing ecosystem services. The methodology uses datasets compatible with the European databases on environmental issues, CORINE Land Cover 2018 and Urban Atlas, and two tools in the ArcGIS PRO 2.9 software package, namely Cost Raster and Cost Connectivity. Based on the results, we developed a framework for implementing a strategy for the green–blue infrastructure for the Bucharest metropolitan area. Our methodology is a starter for planning a green–blue belt for the metropolitan area of Bucharest and a model of good practice in terms of making green–blue infrastructure part of urban and territorial planning.

Keywords: connectivity; permeability; green belt; GIS; least-cost modeling; urban regeneration

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1. Introduction

An important challenge for urban and spatial planners is ensuring sustainable development [1–3] based on coherent development policies that integrate economic growth and social well-being with environmental conservation, particularly at urban–rural interfaces [4]. Sustainable cities are not only an essential goal for urban planners but also a necessity in addressing climate change issues. Unfortunately, with the worldwide increase in urbanization and density of built infrastructure, green and blue areas are lost, preventing social and cultural interactions between city citizens and decreasing life quality.

Uncontrolled urbanization has led to significant environmental and social challenges such as pollution, loss of biodiversity, and increased exposure to extreme weather events. Today, urban sprawl is part of our reality. This phenomenon, which can be visualized in a landscape [5], involves excessive growth of cities, which grow decentralized, polycentric, suburban, scattered, and in strips, with a low population density [6]. The process of dispersed urban growth (peri-urbanization) creates hybrid landscapes that have mixed characteristics, both urban and rural. In the context of land use, the sprawl of urban areas over the countryside (suburban sprawl) leads to the fragmentation of habitats and makes a contribution to the acceleration of climate change [7]. Limiting the sprawl of cities requires appropriate public policies [8].

In this context, in order to create more sustainable and resilient communities, nature must be brought back into big cities [9,10] because green areas and green infrastructure can positively influence human well-being and health in different ways [11], both mentally and physically [12]. The COVID-19 pandemic has shown that open urban areas are still the most important areas for establishing social contacts among city dwellers, regardless of the technological progress and its effect on the individual's social life (social networks, virtual reality, etc.); thus, their urban importance remains undisputed [13].

Unlike green spaces, green infrastructure does not have a conventional approach; it is a rather broad concept but is unanimously recognized as an opportunity for obtaining social, economic, and environmental benefits [14]. With respect to urbanization and planning, green infrastructure contributes to land preservation and natural resource protection and supports development by optimizing land use to accomplish the needs of people and nature [15,16]. Both green and blue infrastructure have recently become a powerful urban planning tool as they provide solutions to environmental, social, and economic challenges. If it is well planned, the blue–green infrastructure can stop or limit the fragmentation of natural habitats and mitigate the negative effects of climate change [17,18].

With respect to the blue–green infrastructure, a solution for mitigating urban sprawl is planning green belts, green wedges, and greenways that surround or cross the cities. They represent formal strategies for curbing spatial fragmentation by offering green and open spaces closer to the residents, thus connecting cities to rural areas [19].

In large cities, the most difficult problems related to delimiting, assessing, and managing green–blue infrastructure are data collection, assessment of data quality, and the ability to manage large datasets available.

1.1. Green–Blue Infrastructure Connectivity

Underestimating the many values of services provided by natural areas (green spaces, water) is a major cause of insufficient nature protection and management, at least from a sustainable perspective [20,21]. Decision-making procedures aiming to use natural resources should consider not only the directly quantifiable costs and benefits of nature but also the intangible costs and benefits associated with it [22]. Accelerated assessments are therefore needed to make urban areas more sustainable and resilient [23] and restore biodiversity. In the context of urban climate change, appropriate green–blue infrastructure planning helps to ventilate cities, minimize the flood risk, and provide ecosystem services to improve the life quality and health of urban inhabitants (e.g., improve air and water quality, increase biodiversity, reduce energy consumption in buildings, and mitigate the impacts of heat waves and urban heat island effects).

For successful implementation of green–blue infrastructure in urban planning, the integration of ecological principles into urban and territorial planning regulations should be a priority in relation to spatial continuity, multi-functionality, connections with other types of infrastructures, and approaches at multiple spatial scales [24–27].

Landscape connectivity is often used in territorial planning and refers mainly to the potential movement of organisms [28]. Landscape fragmentation, economic development, sprawl of transportation networks, and land cover and use change have reduced the connectivity of habitats and generated artificial barriers along the travel routes of wildlife species, affecting their ability to move safely (i.e., landscape permeability).

As a concept, connectivity was first addressed in relation to landscape and protected areas and later in ecology [29]. Connectivity is important for green–blue infrastructure through its environmental, social, and economic benefits. It is a key pillar for maintaining the dispersal of species and sustaining ecological processes and functioning [30]. Connectivity is strongly influenced by the diversity and spatial distribution patterns of land cover types [31]. It can be preserved through habitat (ecological) corridors, which preserve the flow of animal species. A project aimed at maintaining ecological corridors for large mammals in the Carpathians [32] defined ecological corridors as linear structures of different sizes, shapes, and vegetation cover that improve ecological connectivity in human-modified landscapes.

Ensuring that open spaces remain functionally and spatially connected is crucial for the mitigation of effects and adaptation to climate change and for growing the value of ecosystem services, including health and recreation [33,34]. A method frequently used to measure ecological connectivity is the least-cost model, where the landscape is seen as a surface with energy costs of travel in which least-cost routes can be computed.

This study presents a method for designing a blue–green belt around Bucharest, Romania, by preserving landscape connectivity.

1.2. Evaluation of Landscape Connectivity in the Bucharest Metropolitan Area

For the effective conservation of biodiversity, territorial planning is an indispensable tool at any level, especially for Romania, where economic development is almost constantly a priority over nature conservation, and the legislative vacuum in territorial planning has allowed for a chaotic development of built-up areas, both within and on the outskirts of cities [35].

Today, the impact of climate change in the Bucharest area is more and more obvious. Temperatures increase yearly with new patterns of seasons and precipitations that affect, among others, biodiversity, green spaces, and ecosystems. The present paper proposes a method for planning and preserving the blue–green infrastructure connectivity, using Bucharest metropolitan area as a case study. Peri-urban landscapes are subject to great pressures and that is why it is very important to effectively plan for developing their green–blue infrastructure, taking into account the participation of citizens and all local stakeholders [29,36–39]. In the case of Bucharest, the sprawl occurred over the rural settlements surrounding it.

Throughout its history, planners have used different methods to limit Bucharest's sprawl [40] since the effects of its continuous enlargement have been mainly negative. The "belts" established to stop sprawl were not effective, despite the regulations that prohibited new constructions, and the city grew considerably. At the end of the 20th century, Bucharest was surrounded by a railway, limiting it as a belt and separating the core area from the outer ones. This belt is still important today.

Initially, nature was integrated into the urban fabric, but over time, green spaces from Bucharest and its peri-urban area were lost [41–43]. This is why when planning a blue–green belt as part of its green–blue infrastructure, maintaining its connectivity is absolutely necessary as a tool for urban and spatial planning [44]. A belt composed of natural elements and determined by the main transport routes—roads and railroads—could separate Bucharest from its surrounding rural area. This belt must provide all the advantages of green infrastructure, including connectivity. The choice of such a solution must take into account the city's development vision, its historical and geographical context, social and economic elements, and, last but not least, local governance mechanisms [44].

The lack of plans for managing natural and cultural landscapes with national and local importance has resulted in the degradation of many of them, especially in the Bucharest metropolitan area, leading to their abandonment or irreversible alteration.

Since blue–green infrastructure approaches are relatively new, the techniques are not fully integrated into professional planning and engineering education. An important step in this process is to establish a methodology for preserving landscape connectivity, represented by green and blue areas. Providing such plans is one of the first steps in building the knowledge base regarding the implementation of green–blue infrastructure.

In the present work, the assessment of different types of land cover based on their capacity to provide ecosystem services in the study area was carried out based on the ES matrix model developed by Burkhard et al. [45] and Danziger et al. [46]. Starting from this evaluation, the technical solution used in this paper is original in relation to other similar studies [25,47]. We consider that the use of GIS–Gnarly Landscape Utilities for defining the permeability raster of the study area is an ideal solution supporting connectivity analyses of wildlife habitats. Moreover, it was often used by the experts involved in the project, especially for defining the connectivity of the green–blue infrastructure.

One of the most difficult issues for defining this type of connectivity is data collection and quality and the ability to manage large amounts of available data. For this reason, for the area beyond the limits of Bucharest, we used digital data acquired from the National Cadaster Agency (scale 1:10,000), the National Company for Road Infrastructure Administration, and the National Administration "Romanian Waters" so that their processing corresponds to the structure of the CORINE Landcover database developed by the European Union.

For the Bucharest buildable area, the digital data are taken from the Bucharest General Urban Plan (topographic data), supplemented with digital data regarding the traffic on streets and boulevards and the hydrographic network. These data have been processed in accordance with the structure of the European Urban Atlas database (at the regional level).

Connectivity analysis was carried out with ArcGIS PRO 2.9 Cost Connectivity, allowing us to set a strategic direction and vision for the green–blue infrastructure to be included in the General Metropolitan Development Plan. This strategic vision is also based on the experience of our experts in other similar European projects. The starting point of this vision was "The Green and Blue Infrastructure Strategy" developed by Maidstone Borough Council in 2016 [48].

In order to identify unused or degraded terrains situated on connectivity routes, we used high-resolution images from satellites and a UAV system. Urban plans helped us to identify the ownership regime of abandoned lands. We made several landscape arrangement proposals based on the green–blue elements using AI programs.

2. Materials and Methods

2.1. Study Area

In this work, we considered that the Bucharest metropolitan area consists of Bucharest city and Ilfov County, with its composing settlements (Figure 1). Together, they form the Bucharest–Ilfov Development Region (RO32), one of the eight development regions in Romania. This region is located in the south of the country, near the border with Bulgaria (Figure 2). It covers an area of 1811 sq. km. and has a population of 2,634,690 inhabitants. The peri-urban area, adjacent to Bucharest, consists of settlements and agricultural land and is crossed by a road network, ensuring connections with Bucharest.

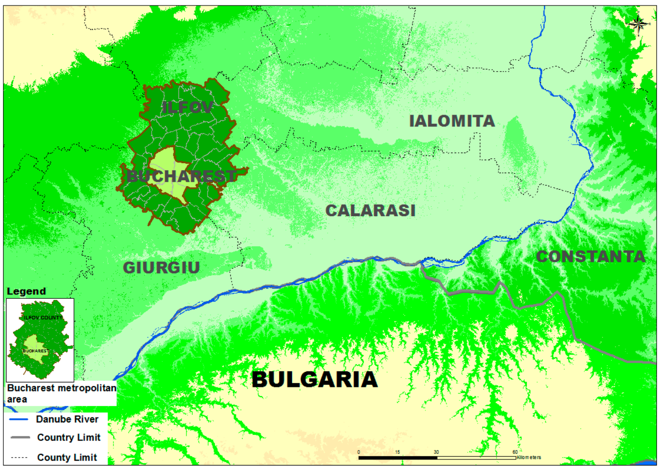


Figure 1. Bucharest metropolitan area, as considered in our study. The map shows its two components: Bucharest city and Ilfov County (Source of the map: the authors, 2024).

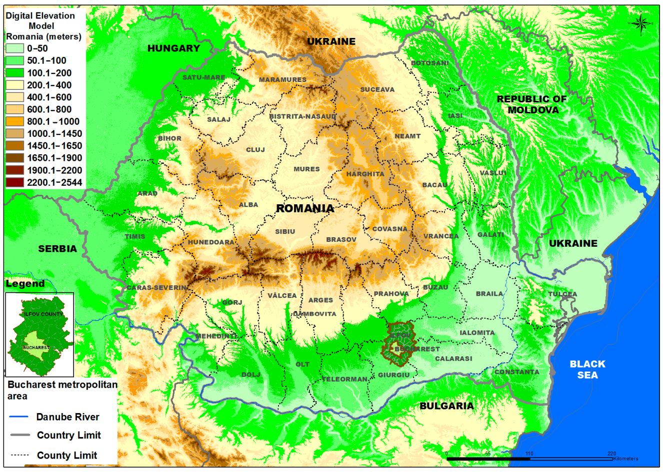


Figure 2. Location of Bucharest metropolitan area on the map of Romania (source of the map: the authors, 2024).

In this study, by "local level" we mean the Bucharest area, and by "regional level" we mean the region beyond Bucharest, namely Ilfov County.

The methodology used in the present study to evaluate the connectivity of green–blue infrastructure within the Bucharest metropolitan area (Figure 3) had, as starting point, the structure of land occupation according to the European programs CORINE 2018 Land Cover, the European Urban Atlas, and the Cost Connectivity tool in the ArcGIS PRO 2.9 software package. What distinguishes the current methodology from other green–blue infrastructure studies is its technical, computer-based component, which is an innovative and original model for the European Union, although studies carried out elsewhere used other computer-based approaches [49].

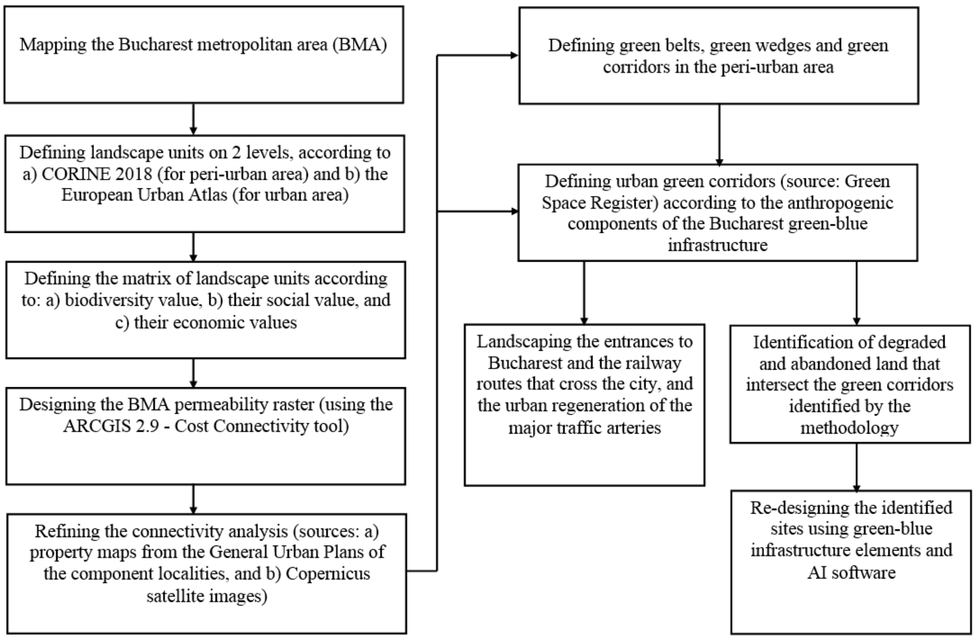


Figure 3. Schematic of the research methodology (Source: Authors, 2024).

Figure 4 shows the land cover in the studied area.

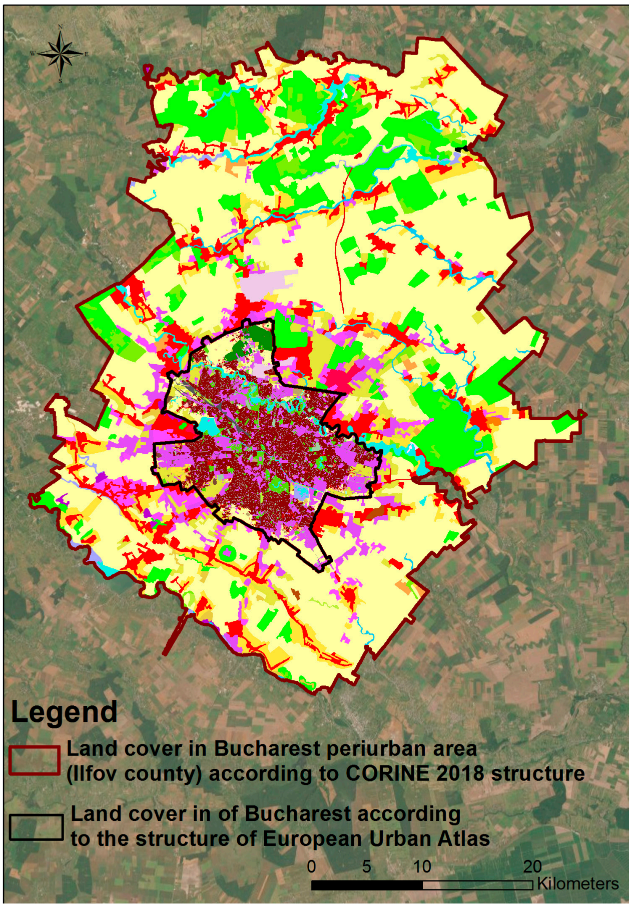


Figure 4. Land cover in the Bucharest metropolitan area, according to the structure of CORINE 2018 and of the European Urban Atlas. In the center (the Bucharest administrative limit, the black line) are built-up areas, and beyond Bucharest, in its peri-urban area (the brown limit), especially in its northern part, are more green spaces.

2.2. Principles Used in Developing the Methodology

The current methodology answers the need to design a green–blue infrastructure that is, on the one hand, functionally connected within Bucharest and, on the other hand, connects Bucharest to its peri-urban area. Following research on similar case studies [50–52], Table 1 presents the principles and measures that we considered necessary to achieve both goals.

Table 1. Principles used to design the green–blue infrastructure in the Bucharest metropolitan area, ensuring its functional connectivity.

Design Principles of Green–Blue Infrastructure in the Studied Area	Objectives, Actions
1. Keep the multifunctionality of open space	Balance the interests of residential developers and usage of open space; Establish priority conservation areas; Design public parks near high-density residential areas; Design surface water management systems; Transform degraded or disused land into green spaces.
2. Protect biodiversity	Design sites as local nature reserves with wildlife protection; Restore wetlands and their wildlife habitats; Create new landscape-scale habitat areas to enable species migration and movement in response to climate change.

Table 1. *Cont.*

	Design Principles of Green–Blue Infrastructure in the Studied Area	Objectives, Actions
3.	Ensure resilience to climate change	Strategic placement of green features (trees, green roofs); Address the expansion of green areas situated inside and outside Bucharest to enhance the microclimate resulting from decreasing temperature and curbing the urban heat islands effect; Enhance functional connectivity of ecosystems; Identify tree and shrub species to be selected for planting; Promote the law on urban natural areas in parliament.
4.	Increase accessibility of the population to green–blue areas	Connect main attractions and recreation areas with high-quality public transport; Create new parks and pocket parks in the neighborhoods in Bucharest; Education and lifelong learning; Promote tourism in green and blue urban and peri-urban areas; Re-establish historical links between heritage assets using green–blue infrastructure.
5.	Improve urban and peri-urban comfort	Maximize historical heritage; Improve the energy performance of urban and peri-urban infrastructure (buildings with low energy consumption); Redesign pedestrian areas, boulevards, and connecting roads between the urban and peri-urban areas, parking areas, and drainage systems.
6.	Involve local authorities and population	Disseminate the green–blue infrastructure concept through mass media; Create opportunities to engage communities and landowners in planning, creating, improving, and maintaining nature-based solutions.

2.3. Data and Software Used

The green–blue infrastructure planning model of the Bucharest metropolitan area, shaped as a green belt, was designed to rely on input data at different scales. The required input data had different levels of quality and homogeneity, which ultimately determined the quality of the results [44].

To begin with, we analyzed the degree of connectivity that can be achieved between the green–blue components included in a green–blue belt around Bucharest. Evaluation of the connectivity of green–blue infrastructure was conducted using the GIS software (ArcGIS 10.8), often used to assess the cost of moving through the landscape [53].

For Bucharest, digital data from its Master Plan were combined with data from the Urban Atlas.

For the area beyond Bucharest (Ilfov County), we used the CORINE 2018 data structure (providing land cover and environmental information) and data from the Master Plans and from the National Cadastre and Real Estate Advertising Agency (providing land registration, property boundaries, and ownership information).

For local analysis (only Bucharest), we used only the green areas greater than 2500 m^2 inside the city and forests adjacent to the buildable area in Bucharest as core areas.

For the metropolitan connectivity analysis, we used the geo dataset containing green areas with maximum biodiversity (core areas).

For the land use assessment, we used data from the National Cadastre and Real Estate Advertising Agency, corresponding to CORINE 2018 data, the topographic elevation of the buildable area in Bucharest, and Urban Atlas data.

A very important role in mapping the green–blue components of Bucharest was played by the Register of Green Spaces (also called Capital's Green Cadastre), which is an information system for registering and keeping track of the green spaces on the city's territory, playing an informative and technical role, but without producing administrative and legal effects. The Green Cadastre is an inventory of trees and green spaces located in the public domain. In the present paper, we considered the following green spaces: parks, gardens, squares, alignment plantations, cemeteries, etc., according to the provisions of

Law no. 24/2007 [54] on the regulation and administration of green spaces in urban areas, republished.

As new tools with strong diagnostic and prognostic capabilities are needed for modeling connectivity to mitigate climate change [55], we used new technologies to combine past data sources with present data.

In order to identify the type of land ownership (especially private), we purchased the Master Plans of the territorial units within the studied area, which show the type of ownership. Plans were obtained in PDF format and required georeferencing.

Data were processed based on the authors' background and work experience in ecology and spatial planning, as well as similar European studies dealing with connectivity and the provision of landscape services.

2.4. Steps Followed in the Proposed Methodology

Starting from the six mentioned principles and using the above data for the Bucharest metropolitan area, our methodology consisted of the following steps:

2.4.1. Phase I

1. Identify blue–green areas with the highest ecological value: wetlands, rivers, lakes, primary forests, critical recharge areas, and intact core areas with high biodiversity potential.
2. Add sites with cultural and landscape values: cultural sites, scenic and historical routes, areas with special landscapes, agricultural areas, etc.
3. Design the connections of these areas to preserve their ecological functions and ensure good accessibility to the landscapes around them. The connection was ensured both at a regional scale, linking forests and rivers of high ecological value, and at a local/urban scale, creating a green urban infrastructure that connects urban public spaces with those landscapes from the surrounding area with the highest value.
4. Identify degraded or isolated lands intersecting connections between green–blue areas; re-plan them according to the green–blue infrastructure principles and to the requirements of the population and local authorities.
5. Permeability analysis

The present methodology differs from those of other similar studies through its computer-based component, which is an original and innovative model for Europe. Thus, the permeability raster was assessed using the Gnarly Landscape Utility tool, compatible with ArcGIS PRO 2.9. The permeability raster refers to the capacity of movement through each landscape element of the studied area.

The permeability analysis was developed first beyond the limits of Bucharest and second at a local level, only for the Bucharest buildable area.

5.1. Permeability in the metropolitan area, beyond the limits of Bucharest

In this case, we assigned relative permeability values for three layers: the first layer is the combined network of national roads and railroads, the second is the hydrographic network, and the third represents the land use based on CORINE 2018 data.

5.2. Permeability in Bucharest buildable area

We also used three layers: the first layer represents the traffic on streets and boulevards of the city, the second considers the hydrographic network, including lakes, and the third layer represents the land use based on Urban Atlas data.

The relative values of permeability for the layers representing the land use at the regional and local levels were assigned according to the final landscape matrix from the manual of green infrastructure functionality assessment [46].

The relative values of the layers of the combined network of national roads and railroads, the hydrographic network, and the traffic of the large streets of Bucharest were assigned starting from the values proposed in *Guidelines for regional*, *inter-regional*, and *cross-border development strategies*, creating ecological corridors [56].

All these layers were uniformized by rasterizing the input datasets to apply the permeability evaluation algorithm.

Datasets for each layer were inserted in an Excel file, resulting in two Excel files: one at the regional level containing the three layers and another one for Bucharest, with its three layers, according to the methodology using the Gnarly Landscape Utilities tool. Applying this tool, we obtained a permeability raster at the regional level and another one at the local level (the buildable area in Bucharest). Finally, using ArcGIS PRO 2.9—Mosaic Datasets—we obtained a common raster of permeability for the entire studied area (Bucharest metropolitan area).

6. Connectivity analysis

In the study area, connectivity analyses had two levels. The first level is the metropolitan area without the buildable area in Bucharest; the second level is the buildable area in Bucharest.

Also, according to ArcGIS PRO 2.9 Cost Connectivity, two layers were used: the permeability layer (of raster type) and the Core Areas layer (of shape type). The last one consists of areas with the highest value of biodiversity.

For the region beyond the limits of Bucharest, the Core Areas layer consisted mainly of existing forests, to which we added forested areas that existed 50 years ago and are now agricultural areas, but there are premises for changing the land cover back to forests.

For the buildable area in Bucharest, we used the permeability raster (layer 1), and for Core Areas (layer 2), we used the forests located in the buildable area, as well as the green areas from this area with more than 2500 square meters, identified in the register of green areas in Bucharest.

The ArcGIS PRO 2.9. Cost Connectivity tool was used to identify the connections between the Core Areas layer both at the regional and local levels.

2.4.2. Phase II

In the second phase of the methodology, after assessing the connectivity, we overlapped the raster results from Phase I with the raster of the type of land ownership. This step was necessary in order to modify the paths of obtained ecological corridors such that they intersect with the minimum number of privately owned lands possible.

2.4.3. Phase III

In this phase, we overlapped the raster obtained in Phase II with existing high-resolution satellite images as a background in the ArcGIS PRO 2.9 software package. We also used data collected with an octocopter-type drone.

3. Results

3.1. Main Components of Green Infrastructure in the Analyzed Area (Bucharest and Its Peri-Urban Area, Forming the Bucharest Metropolitan Area)

In order to evaluate the connectivity of green–blue infrastructure in the analyzed area, we had to analyze the existing green–blue components that play a role in increasing biodiversity and public health.

Using ArcGIS PRO 2.9, we located the following components of green–blue infrastructure—green areas, waters, forests—in Bucharest city and Ilfov County (Figure 5), a perimeter assimilated with the Bucharest metropolitan area.

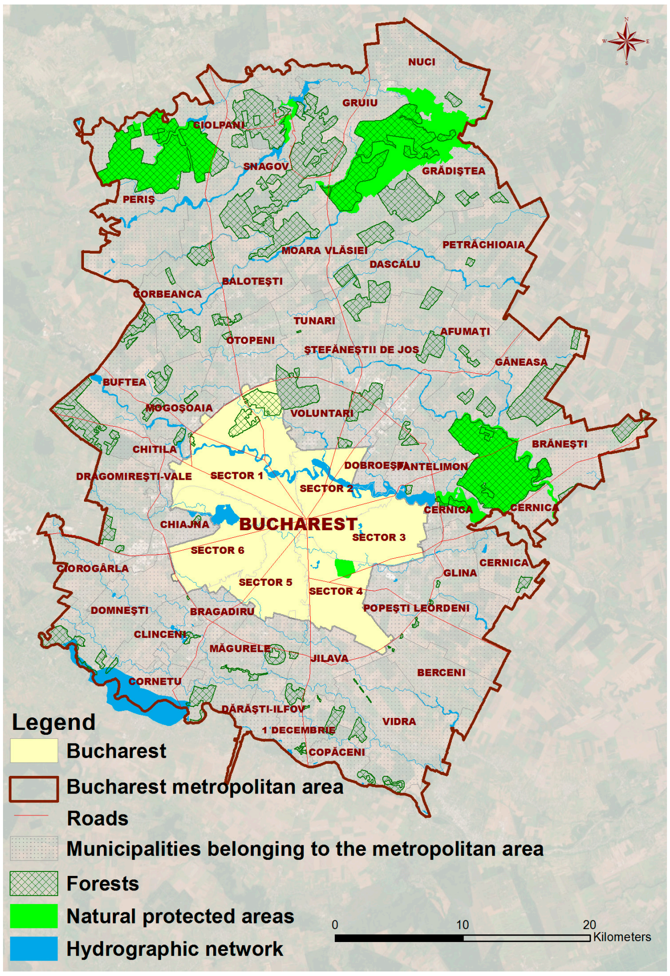


Figure 5. Main elements of green–blue infrastructure in the Bucharest–Ilfov region assimilated to the Bucharest metropolitan area (Source: Authors, 2024).

Green areas

We took into account the fact that there are four natural protected areas of national importance in the Bucharest–Ilfov region: Snagov Lake (100 ha), Snagov Forest (10 ha), Scroviștea protected natural area (3391 ha), and Văcărești Natural Park" (183 ha). Also, five Natura 2000 sites were identified within this region, either SCIs (Scroviștea, 3391 ha; Cernica Lake and Forest, 3267 ha) or SPAs (Scroviștea, 3356 ha; Grădiștea-Căldărușani-Dridu, 6642.30 ha; Cernica lake and forest, 3744 ha).

Waters

We considered natural river courses longer than five km and continuous over the study area as ecological corridors [57]. The rivers Dâmbovița and Colentina are representative, and there are recreation areas on the shores of the lakes formed by the Colentina River. We considered lakes with an area of less than 1 ha as not representing a movement barrier.

Forests

Forests are concentrated in the northern and central parts of Ilfov County and lesser in the southern part. Deciduous forests predominate in the study area. Therefore, in the regional connectivity design analysis, we considered forest areas to be deciduous forests, like most of the grasslands in the area, and as their original destination in the past. We completed the areas of high ecological values with data represented especially by the old forests that appeared in the topographic maps of the studied area from the 1930s and 1950s. If deforested areas have become agricultural land and if the land is owned by the state, then it is much easier for these areas to be reforested to reconnect the green areas through ecological and green corridors.

In addition, we mapped natural components of green–blue infrastructure (parks and hydro network) and anthropic elements with a recreational role (sports arenas) within the core of Bucharest (Figure 6). Herăstrău Park, Carol Park, Cișmigiu Park, IOR Park, Văcărești Natural Park, and Botanical Garden are part of the network of large urban parks and gardens in Bucharest. Rivers (such as Dâmbovița, Colentina, and Ciorogârla) can become ecological corridors. Also, the lakes (Floreasca, Tei, Herăstrău, and Snagov) can be ecological and recreational corridors.

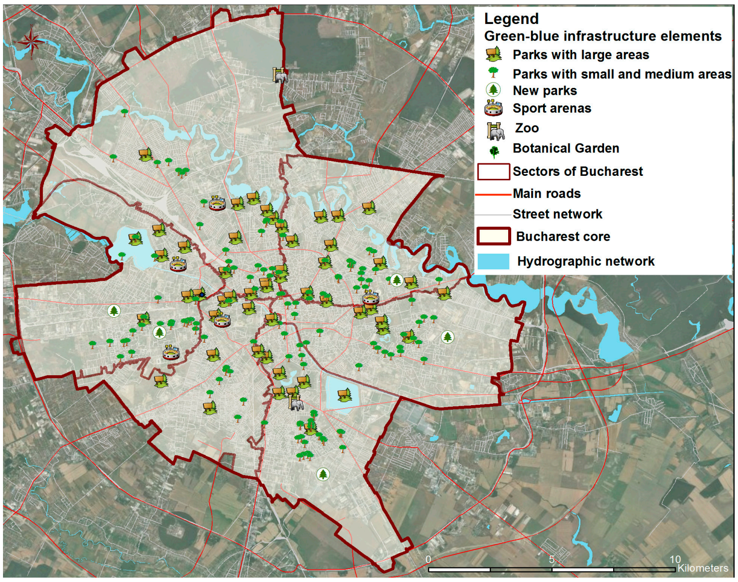


Figure 6. Bucharest city parks (Source: Authors, 2024).

3.2. Connectivity Assessment: Obtaining the Permeability (Movement Resistance) Raster

When the raster processed with the weighted data was implemented in the GIS tool—Cost Raster—we obtained the resistance raster against possible movements through each landscape element of the Bucharest metropolitan area (Figure 7). Landscape elements with lower permeability values correspond to easier movement possibilities.

According to the methodology, connectivity analyses were carried out at the regional level (beyond the limits of Bucharest) and at the local level (buildable area in Bucharest). In both cases, connectivity analyses used the GIS Cost Connectivity tool in the ArcGIS PRO 2.9 software package, a dedicated tool to support connectivity analyses of landscape elements.

In phase I, we identified the corridors connecting core areas based on the mathematical computation of the minimum cost of moving through the landscape, according to the GIS tool (Figure 8).

Based on the green corridors, we found two possible green belts (dots in Figure 8): one surrounding the existing road beltline (the inner one) and another surrounding the future A0 motorway (the outer one, with a larger diameter). However, the first smaller green belt cannot close in its southwest part because high biodiversity green areas (forests) in that area are lacking. Additionally, based on the connections yielded using the Cost Connectivity tool, we have obtained three green wedges (the green–white triangles in Figure 8) along the new radial roads intersecting the second green belt.

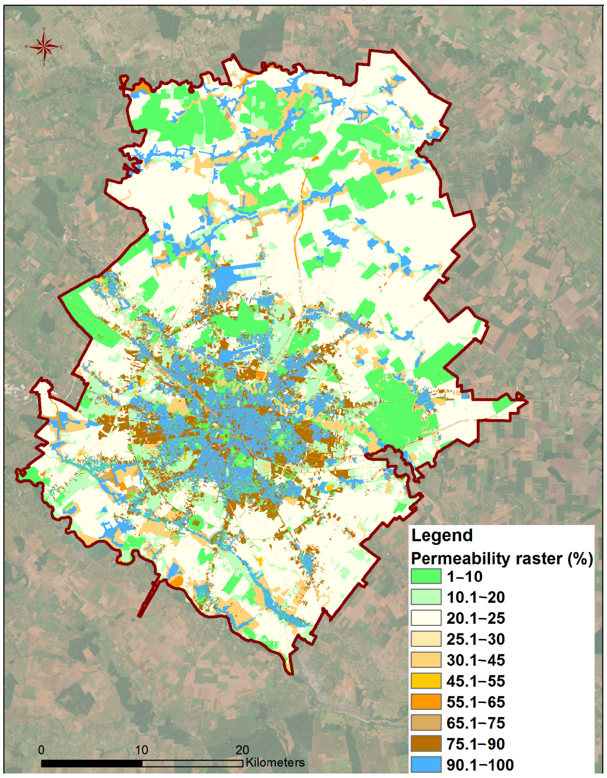


Figure 7. Permeability raster showing the potential ability of organisms to move through each landscape element. Areas colored in bright green are core areas with high connectivity, light green areas have medium connectivity (matrix), and brown areas have low connectivity, containing many constructions (Source: Authors, 2024).

The results show that many ecological corridors at the local level are developing along the major boulevards of Bucharest. That is why there is a need to widen the boulevards and main routes in order to plant trees alongside.

Figure 8 also shows four compact areas (shaded in pink) containing numerous fragmented green spaces, especially in the south and west of Bucharest, where green solutions must be urgently implemented.

These findings indicated the presence of acute conflicts between high-density developments and limited land resources, especially insufficient open space for the population, in the urban area of Bucharest, mainly the city center and some neighborhoods.

According to the methodology, in phase II, after evaluating the connectivity, we overlapped the results with the raster representing the land ownership type in order to obtain an optimal version of ecological corridor routes, i.e., they should intersect the minimum number of privately owned lands possible. Practically, we overlapped the raster containing all Master Plans of the administrative-territorial units in the metropolitan area with the GIS raster obtained in the first phase of the methodology. Reshaping the connectivity corridors by overlapping them with the property raster (data obtained from the Master Plans) so that connectivity corridors intersect the minimum number of private parcels possible.

According to the methodology in Phase III, to realistically assess the connectivity of the green–blue infrastructure in the Bucharest metropolitan area, we overlapped the raster obtained in Phase II with the existing high-resolution satellite images as a background in the ArcGIS PRO 2.9 software package. We also used images and data captured by an octocopter-type drone in the study area. After this phase, we modified the green connections based on field data and obtained an accurate connectivity analysis (Figure 8).

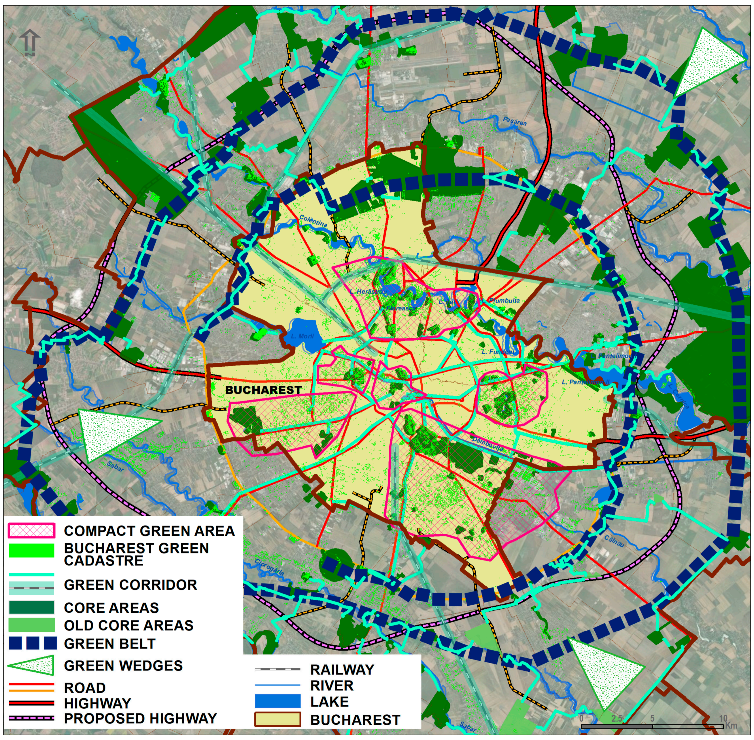


Figure 8. Connectivity analysis of green–blue infrastructure in the Bucharest metropolitan area. The light green lines represent the resulting connections (green corridors) between core areas (dark green in this figure). The results allowed the design of two green belts (dotted blue) and three green wedges (green triangles) in order to preserve the connectivity of landscape elements. (Source of the map: the authors, 2024).

The map representing connecting green corridors also highlighted the hotspots of potential conflict between the continuity of connecting corridors and that of transport infrastructure. These hotspots were precisely identified using satellite and drone images.

4. Discussion

The design of this methodology had a double purpose: first, it is a starter for planning the green–blue infrastructure of the Bucharest metropolitan area, and second, it is a model of good practice for integrating green–blue infrastructure and sustainable development in urban and territorial planning.

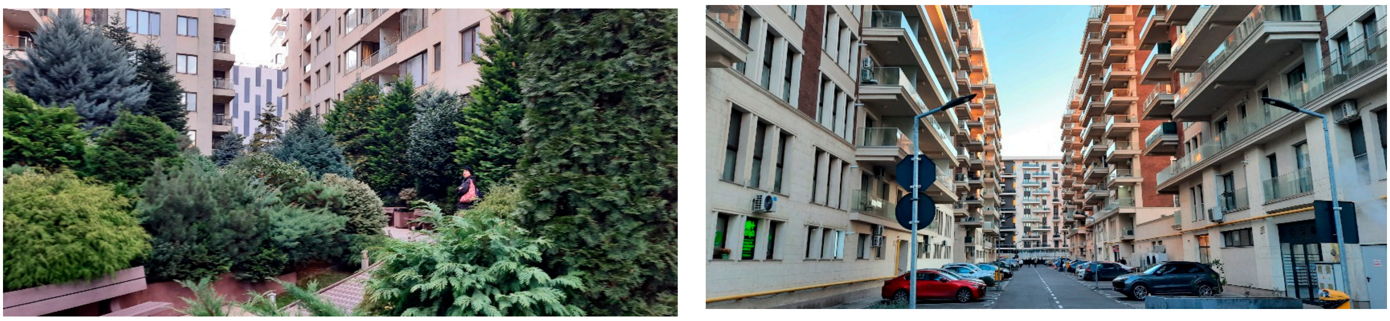
The methodology for assessing green–blue infrastructure connectivity is modern and international, using data types and assessments corresponding to European applications in terms of the GIS solution and quality of processed data.

The use of the Gnarly Landscapes Utility tool gives credibility to the resulting permeability raster, as this tool is widely used in analyses carried out to identify ecological corridors for large mammals [32]. The connectivity analysis was carried out on two levels—regional and local. At the regional level, we used the green cores in the peri-urban area containing the highest values of recreation and nature, and for the built-up area in Bucharest, we used the green cores, part of the green areas that contain the highest values of recreation, nature, and culture.

The experience of authors and other specialists involved in the project that led to this article allowed for important results: at the regional level, we identified two green belts, three green wedges connecting them, and a network of green corridors that create links between green cores (especially forests) and links between green cores and watercourses.

The results demonstrate the need to plan two green belts and several green wedges along the connecting roads between the two beltlines. For this, the following are needed:

- A program of afforestation, especially in the south of the metropolitan area. The results of connectivity analysis imply the construction of ecological corridors with a minimum width of 100 m, which will connect the central cores of green–blue areas. Wherever ecological green corridors are not possible, a network of green spaces connected by transport infrastructure and bicycle paths can be created.
- Greening and renaturing rivers and lakes in the Bucharest metropolitan area and using their banks for sports and recreation, wherever this is possible.
- Green protection curtains alongside agricultural lands and promotion of fruit tree crops.
- Increasing the role of landowners in maintaining the quality of agricultural areas.
- Ecological reconstruction of degraded land and integration of abandoned land into the category of spaces that generate ecosystem services. Unfortunately, the effort to transform degraded and abandoned land within the city and its metropolitan area is made by large investments, especially in shopping centers and malls, and recently by investments in solar panels. Therefore, a balance is needed in changing the use of these lands so that degraded lands on the route of the connectivity corridors are assumed by decision-makers as green areas.
- The design of residential areas so that they contain at least 10% green areas, according to the General Urban Planning Regulation. However, the projects very often consider the green area very close to the designed residential complex as part of its integrated surface. Figure 9 shows two residential complexes, one built in the northern area of Bucharest and the second in the western area of the city. In the northern area, residents benefit from a real green garden, while the residents of the western area do not have any recreation place or children's playground.



(**a**) (**b**)

Figure 9. Positive (**a**) and negative (**b**) examples of designing residential areas in Bucharest (Source: Authors, 2024).

4.1. Validating and Valorizing the Research Results

The proposed information technology solution was developed during several years of research, and each new step was successfully presented and appreciated at national and international conferences and exhibitions of creativity and innovation. However, the study was validated not only by the scientific world but also by stakeholders [58]. Thus, another study is being conducted on implementing a green–blue infrastructure in another city in Romania (Râmnicu Vâlcea). The results are validated by participation in the study of a group of urban planners and information technology specialists who have outstanding results in implementing GIS and spatial technologies.

Currently, the pressure on civil society to design a green belt for Bucharest and increase the green–blue share in its metropolitan area is increasing. The obtained methodology, analyses, and results can represent a starting point in designing this type of green–blue infrastructure within the Bucharest metropolitan area.

At the same time, the proposed green infrastructure matrix resulting from applying the methodology of the current study was submitted to the team responsible for drafting the new Master Plan for Bucharest. At this point, several studies substantiating the plan were proposed and approved. One of these deals with the potential impact of climate change. The green infrastructure in the current study was proposed in the form of GIS vector data as a solution for mitigating the impact of climate change.

4.2. Originality and Effectiveness of the Methodology

The success of our methodology is determined by the quantity and quality of input data. The importance of data for green infrastructure planning is underlined by several studies [59–63]. The methodology uses European environmental databases—CORINE Land Cover 2018 and the Urban Atlas—and two ArcGIS-type tools. Other data from official sources (National Cadastre and Real Estate Advertising Agency, National Administration of Romanian Waters, Bucharest City Hall, Green Cadastre of Bucharest, Master Plan of Bucharest, Master Plan of Ilfov County, etc.) have been made compatible with European environmental data at regional and local levels.

The connecting green corridors were initially designed using the two GIS tools mentioned above and redesigned based on property-type maps and images. Another advantage of the methodology is its ability to identify the correct connections between different elements of the green–blue infrastructure.

Compared to other international studies that had the advantage of using official Management Plans of natural and cultural landscapes with national and local importance, our methodology compensates by its ability to process a lot of quality data and using the computer-based solution chosen for overlapping GIS results and property, satellite, and UAV data.

4.3. Methodological Limitations

Successfully implementing green–blue infrastructure projects relies on the support of different stakeholders: planners, investors, communities, decision-makers, and politicians. Many of them may not be aware of concepts like landscape or ecosystem services and may find scientific approaches somewhat difficult, complicated, and academic [64]. Therefore, to implement a blue–green infrastructure for the Bucharest metropolitan area, it would be useful for the ecosystem services offered by it to be seen as benefits, which are easier identified by stakeholders outside of the scientific realm, which makes the concept of green-blue infrastructure simpler and more effective.

The study also highlighted the need to identify and map abandoned and degraded land and, if possible, change it into green areas. We also presented landscape modeling for such abandoned land in Bucharest. Identification and change of use to green areas must be carried out by multidisciplinary groups coordinated by the Bucharest City Hall with the support of a wide range of stakeholders, as underlined by studies carried out elsewhere [65,66].

4.4. Future Research Directions

In today's Bucharest, green areas are not only fewer than 70–80 years ago, they are also much more fragmented due to the rapid sprawl of residential neighborhoods [67]. For this purpose, apart from the need to define legally protected urban areas, the urgent regeneration of abandoned commercial and industrial areas is an absolutely required tool for Bucharest to meet its sustainability and resilience targets [68].

The increased housing density in Bucharest requires finding and implementing innovative green solutions for urban regeneration, including pocket parks, green roofs, solar roofs, solutions for water drainage, green walls and vertical gardens, permeable pavements, or greening linear transport paths. An example of urban regeneration for a major route in Bucharest is the project proposed by the City Hall for Sector 2 on the urban development of Ștefan cel Mare Boulevard (Figure 10).

Figure 10. Urban regeneration model of the Ştefan cel Mare Boulevard in Bucharest (Source: public data from https://www.ps2.ro/, accessed on 2 August 2024).

4.5. Planning a Green–Blue Infrastructure Strategy in the Bucharest Metropolitan Area

Based on these results and experience in urban and territorial planning, ecology, and environmental engineering, we obtained a framework for implementing a green–blue infrastructure strategy for the Bucharest metropolitan area. Table 2 presents the main problems related to the green–blue infrastructure in the Bucharest metropolitan area based on the results obtained following the application of our methodology and the solutions proposed to address these problems.

Table 2. The main problems identified when planning a green–blue infrastructure strategy for the Bucharest metropolitan area and the proposed solutions.

Themes	Key Problems	Objectives/Solutions
Increase adaptation and resilience to climate change	The territory of the core of Bucharest contains only one built urban area, not an extra urban area, which leads to one of the highest population density values	Planning the two green belts identified in the study
Establish the structural and functional connection between green–blue infrastructure components	Bucharest has a discontinuous and often conflictual relationship with its metropolitan area on issues of common interest aimed at sustainable development	Correlation of local, regional, metropolitan, and national policies
Sustainable water management	There is increased pressure on water resources and endangerment of soil and groundwater quality due to poor management of waste management	In the short term, create green–blue corridors by rehabilitating, regularizing, dredging, and arranging rivers, lakes, and canals, including their banks, for sustainable use by pedestrians and cyclists
Protection of landscape and historical and cultural infrastructure, education, health, and human welfare	Natural and cultural landscapes of national and local importance lack management plans, resulting in the degradation of some urban objectives, historical and architectural	Afforestation of degraded lands and restoration of forest protection curtains consisting of agricultural lands. Create/develop public parks and gardens, including "pocket parks" and urban forests
Conservation of habitat and biodiversity	Forests represent only 16% (25,000 ha) of the metropolitan area, a low share compared to European requirements, and currently, the trend is to reduce the forest stock.	Approval of the law on Urban Natural Areas and designation of new protected areas of local interest

Table 2. *Cont.*

Themes	Key Problems	Objectives/Solutions
Regeneration, land use, and urban development	Reduction of the green area by about 50% (1990–2024)	Develop action plans for the reconstruction and/or restoration of degraded and/or destroyed landscapes and lands and integration of abandoned lands into the category of spaces that generate ecosystem services
Maintain and improve a quality environment under the continuous pressure of urbanization	Decrease green space area inhabitants	Plan public parks and gardens in residential neighborhoods; declare the forests in the metropolitan area as protected in order to stop deforestation

To successfully implement these proposals and remediate existing problems, quick and objective solutions are needed in the short and medium terms. The greening of rivers and lakes and the development of shores by planting diverse plant species is crucial for developing the green–blue infrastructure in the Bucharest metropolitan area. Such areas must be transformed into open recreational spaces for city dwellers.

Also, within this study, we mapped several degraded lands in Bucharest (Figures 11 and 12) and proposed scenarios for urban planning and landscaping for some of them (Figure 13). Through an integrated concept of urban development, we proposed the transformation of currently unused and undeveloped land located close to the Faculty of Sociology and Social Assistance and the Faculty of Chemistry of the University of Bucharest, the Military Academy, and other office buildings into a multifunctional space around a central green one intended to create an oasis of relaxation contributing to the improvement of urban life (Figure 13). Buildings with mixed functions were planned, intended for students and other users, to facilitate their interaction and collaboration.

Figure 11. Vacant land in the Răzoare area (Source: Authors, 2024).

Figure 12. Vacant land in the Răzoare area (Source: Google Maps, 2024).

Figure 13. Landscaping proposal for currently unused land in the Răzoare area, Șoseaua Panduri, Bucharest (Source: created by Ingrid Beatrice Stefania Dumitru within the framework of the project "Bucharest Green Belt—Smart integrated models for sustainable management of urban green spaces (GreenSmartB)", 2024).

5. Conclusions

In the Bucharest metropolitan area, climate change and extreme weather affect human health, nature, and the economy. One of the solutions for adapting to this situation is to better manage the physical natural features of the metropolitan area by planning a green–blue belt composed mainly of forests, green spaces, rivers, and river valleys. Our results are important since they serve as a cornerstone for maintaining the connectivity of green spaces and landscapes. The resulting green–blue belts can provide ecosystem services, including local climate regulation and adaptation.

In order to ensure landscape connectivity in the Bucharest metropolitan area, two concentric green belts were identified using this methodology. The small belt, at the limit of Bucharest's perimeter, could not be closed in its southwestern part because green areas (forests) are lacking. A second green belt, beyond the territorial limits of Bucharest, in its peri-urban area, lies on the planned A0 highway route. Apart from these two green belts, three green wedges are found along radial roads on the second green belt.

Developing green networks is an ambitious enterprise connecting green spaces, roads, rails, and river networks as main elements of urban built areas. Planning green networks involving a wide range of green open spaces can be seen as a multi- and trans-disciplinary effort, requiring the synergy of different disciplines and fields, including urban planning landscape architecture, environmental management, nature conservation, forestry, etc. Defining a framework for the implementation of a possible green–blue infrastructure strategy for metropolitan areas in large cities implies the involvement of experienced urban and landscape professionals.

Planners must integrate green networks into urban development plans, and green–blue infrastructure strategies must take connectivity maps into account. Connecting elements of green–blue infrastructure in a network relies on a very large volume of data covering different spatial scales. Data collection and processing are crucial for obtaining correct results. Romanian data must be compatible with the European spatial environmental data, and connectivity analyses can be carried out using GIS tools (ArcGIS PRO 2.9.) and corrected by overlapping maps and data on the type of property and satellite images (Copernicus) or images acquired with UAV devices.

According to the Green Cadastre of Bucharest, green spaces have a landscape value but are often quite isolated. According to the recommendations of the European Union, these green areas should be connected by green corridors so that the green–blue infrastructure can function. Interconnection at different spatial scales and with a minimum degree of coherence can maximize the multiple benefits of green–blue space systems.

An essential conclusion related to creating a green–blue infrastructure within the Bucharest metropolitan area consists of the need to achieve a general consensus between decision-makers and a common action plan. Capitalizing on historical heritage and protecting and improving it is an important part of green–blue infrastructure planning.

Another important conclusion concerns the need to protect agricultural areas against urban sprawl at the metropolitan level, in which many areas are valuable from landscape and ecological viewpoints. It is important that, in implementing a green–blue infrastructure, decision-makers recognize the role of landowners in maintaining the environmental quality of the areas they own.

Starting from our methodology, a strategy for implementing the green–blue infrastructure in the Bucharest metropolitan area can be developed. Both are well-documented technical solutions for identifying priority conservation areas and can support decision-makers in allocating optimal resources for ecosystem conservation. Moreover, our methodology is applicable to other large cities and metropolitan areas all over the world.

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