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Article

An Integrated Approach to Mitigation Wetland Site Selection: A Case Study in Gwacheon, Korea

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Abstract: This paper presents an integrated approach to mitigation wetland site selection using functional landscape connectivity and landscape structure. This approach enables landscape designers to evaluate the relative priorities of mitigation wetland areas based on functional landscape connectivity and wildlife mobility, as well as landscape structure, composition, and configuration. The least-cost path method is used to evaluate candidate sites for mitigation wetlands with regard to wildlife movement. A set of assessments for landscape indices using FRAGSTATS was applied to identify suitable mitigation wetland areas on the basis of landscape connectivity, composition, and configuration. The study was conducted in Gwacheon, Korea, where there are plans for regional development that will change the landscape. In the first step, a group of 14 candidate sites is identified via analysis of functional landscape connectivity using the least-cost path method. In the second step, candidate mitigation wetland areas are ranked according to landscape connectivity and composition. The five mitigation wetland areas that were found to be suitable were analyzed based on landscape configuration at the class level. This study demonstrates that functional landscape connectivity and landscape structure are important aspects to consider when identifying suitable sites for mitigation wetland planning and restoration.

Keywords: mitigation wetland; site selection; landscape functional connectivity; landscape structure; landscape connectivity; landscape configuration; landscape composition; landscape indices

1. Introduction

Wetlands are transitional zones between aquatic and terrestrial ecosystems and are rich repositories of biodiversity as wildlife habitats. With their vegetation and ability to filter soil deposits, they provide active water purification [1–4]. In addition, because they are a natural source of water supply, they can control flooding, temperatures, and humidity and have been recognized as important landscape elements in sustainable urban development [5,6]. They can also provide recreational, cultural and social benefit to human society. Since wetlands in the city contribute to urban sustainability from ecological, social, and economic viewpoints, landscape planning for wetland could be a task of great significance to urban sustainable development [3]. The field of landscape planning recognizes the importance of wetlands and advocates for mitigation wetlands through various policies such as "No Net Loss of Wetlands" in different countries. These policies minimize the loss of wetlands caused by land use development across watershed basins [7]. A mitigation wetland is a concept derived from the "No Net Loss of Wetlands" and "mitigation banking" policies that corresponds to constructed or restored wetlands [8,9]. Mitigation wetlands have been adopted to improve urban environment conditions and as a practical strategy for sustainable development. They should be developed on the basis of landscape quality, which could help maximize the benefits from the wetland to the urban area. In order to improve landscape quality in small urban areas, landscape function and structure have to be altered through the establishment of mitigation wetlands. Mitigation wetlands can be positive countermeasures to restore fragmented and isolated biotopes in a regional ecosystem if they are located at suitable sites based on the integrated consideration of functional landscape connectivity and landscape structure.

Functional landscape connectivity refers to relationships between landscape elements regarding wildlife mobility or the flow of resources [10,11], and it determines meta-population persistence in fragmented landscapes [12,13]. The degree of landscape connectivity has a tendency to vary for different species in the same landscape because the landscape configuration or composition of focal habitat surroundings is different according to the spatial scale. In order to conserve the meta-populations of various species, a strategy for assessing or maintaining landscape connectivity is necessary at the regional scale and on larger scales [14]. However, loss of functional landscape connectivity due to urban sprawl interferes with the naturalization and settlement of species within the urban habitat from the core habitat, which leads to simplification of species composition in urban ecosystems [15–17]. Recently, mitigation wetlands have been suggested as a way to reduce the fragmentation of landscape connectivity due to unsustainable urban development. With mitigation wetlands, landscapes can provide healthy biotopes for surrounding ecosystems and improve their ecological functions [18–20]. To improve ecological conditions through site selection for mitigation wetlands, it is important to take into account functional landscape connectivity [10,11]. Functional landscape connectivity provides a basis for identifying suitable locations for constructed wetlands in fragmented urban green areas using the least-cost path method.

Mitigation wetlands have adaptive capabilities that are beneficial for landscape structure. Landscape structure refers to the pattern of a landscape, which is determined by relationships between the characteristics of ecosystem components, such as the sizes, shapes, and types of components. This, in turn, influences the components of landscape structure such as landscape connectivity, composition, and configuration [21]. Landscape connectivity describes the way that landscape patches are linked [22,23]. In other words, landscape connectivity refers to the structural joining or connection between patches. Landscape composition refers to the variety and relative abundance of each type within the landscape. This component is not spatially explicit but is a quantitative measure of the presence and amount or proportion of each patch type. It also quantifies patch richness (number of land-use types) and patch evenness (abundance of different land-use types) [24,25]. Landscape configuration is defined as the spatial arrangement, position, orientation, or shape complexity of patches within the landscape [24]. Measuring the spatial characteristics of patches provides not only the locations of different patch types relative to each other but also to the spatial characteristics, such as shape and core area [24]. Using the components of landscape structure, landscape planners are interested in spatial planning and restoration to improve quality of environment in regional ecosystem [26–30]. Understanding components of landscape structure is helpful for selecting locations for the development or restoration of wildlife habitats, such as wetlands. This selection is performed through the assessment of components by landscape indices [31,32].

This paper presents a geographic information system (GIS)-based site selection approach for mitigation wetland planning based on the integration of functional landscape connectivity and landscape structure. This approach enables landscape designers to evaluate the relative priorities of mitigation wetland areas as a habitat for medium- and large-sized mammals based on connectivity, composition, and configuration. Functional landscape connectivity was analyzed using the least-cost path method. Landscape structural connectivity, composition, and configuration were quantified based on landscape indices using FRAGSTATS. This study describes a process for suitable site selection based on functional landscape connectivity and landscape structure, and this process could be a helpful tool for the implementation of the "No Net Loss of Wetland" policy in sustainable small urban areas.

2. Literature Review

2.1. Wetland Mitigation

Wetland mitigation is a method of managing wetlands as natural elements and using them in a mitigation banking system [33]. In this method, wetlands are constructed in undeveloped areas to prevent potential future damage. This approach allows for the application of compensatory and mitigation measures for wetlands that must be conserved over a wide area [33,34]. USA introduced the mitigation banking concept in the Clean Water Act of 1988 and institutionalized a compulsory "No Net Loss of Wetlands" policy [35,36]. As of 2005, a total of 330 mitigation banks were in operation and permits had been submitted for 169 wetlands, which indicate that wetland replacement is a widespread practice in the USA [37]. Canada also implemented a "No Net Loss of Wetlands" policy in its Environmental

Assessment Act of the early 1990s, and Japan implemented the same initiative in its Nature Rehabilitation Progress Act of 2003 [8]. In comparison, Korea enacted the Wetland Conservation Act in 1999, which required efficient conservation and management of certain wetlands; however, this law did not address all wetlands. Moreover, despite continued progress in land-use planning and the development of industry, no systems existed to recover biotopes in regional ecosystems. In the Wetlands Conservation Basic Plan, the Ministry of Environment in Korea suggested the necessity of introducing a "No Net Loss of Wetlands" policy [8,33]. In response, previous studies indicated that the introduction of foreign systems should be avoided, which inspired the development of appropriate indigenous wetland health evaluation models that considered domestic conditions and the value of the wetlands [38–40].

Mitigation wetlands can be divided into on-site and off-site approaches. In the on-site approach, wetlands that are damaged by economic development can be directly compensated for on-site; the off-site approach reflects the wetland mitigation banking method in which new wetlands are constructed prior to future development [41]. Both methods require the construction of new wetlands within a certain radius of those damaged by development. The Gateway Estate Development Project in the USA and Tongil Bridge and Jangdan projects in Korea are examples of this approach [42]. However, these methods are limited because they are costly and maintain only a fraction of the biotope functions of the wetlands [34,43]. A new approach to wetland mitigation banking is needed, particularly one that can improve the connectivity of fragmented biotopes over a larger scale. Based on such an approach, mitigation wetland projects are no more time-consuming than other restoration projects. Suitable site selection for mitigation banking is also essential. For example, in Illinois, USA, there was a five-fold increase in the number of mitigation wetlands, which included the wetland mitigation bank on the Middle South Platte River, from 46 in 1992 to more than 200 in 1999 [44]. Most mitigation wetlands constructed to date were based on the Habitat Suitability Index (HSI) model [45,46], which sets targets for the subject area and specific species [42,47–49]. However, the HSI is designed to maintain the biotope functions of that specific wetland and does not consider the connectivity of biotopes fragmented by economic development [50,51]. As an alternative, recent studies have demonstrated a quantitative evaluation as a landscape ecological approach. This is because quantitative evaluation considers landscape structure, landscape composition or landscape elements in the biotopes, and landscape function for ecological connectivity [18,52–55]. That is, landscape-level ecological functions can be taken into account in addition to site-level functions.

2.2. Landscape Functional Connectivity

Landscape functional connectivity is a reflection on the behavioral responses of organisms to each landscape component and the entire landscape pattern [22]. Most previous research has focused on analysis or simulation of the movements of specific wild species [56–60]. Measuring functional connectivity involves calculating the time and distance over which a specific species searches for a new habitat patch using various techniques, such as random walk modeling [45,61,62], network analysis [55,63], gravity modeling [64], and the least-cost path method [65]. The random walk is a simple model of diffusion processes that has been used to study the movements of wildlife [45]. The results can be useful for estimating the expected net displacement of animal movements [45]. However, this method is unable to visualize the results using GIS. Gravity modeling and network analysis have become established as promising ways to efficiently explore and analyze landscape or habitat connectivity [63,64]. Network analysis emerged as a branch of operational research concerned with network structure and network optimization with the help of graph theory [55]. Gravity modeling can be used to identify relatively high-quality habitats and to choose the best opportunities for maintaining and restoring connectivity [64]. However, these methods are yet to be fully explored, and integrating landscape metrics in the planning of urban ecological network is complicated. In comparison with prior methods, the least-cost path method, originating from graph theory, is a fast and convenient method of visualizing landscape connectivity in order to predict wildlife corridors using the GIS packages (e.g., ArcMAP). The least-cost path method proposes optimal locations for industry by determining the least-cost production point under the assumption that the demand for products is identical and production costs are different depending on the location. Several researchers have used the least-cost path method for functional assessment of landscape connectivity [53,66–68]. The least-cost path method has been used to identify paths that connect ecologically valuable areas by calculating all cost-surfaces pertaining to wildlife mobility for ecological planning [7,69]. Related research involves analyses of network patterns of local communities [70], road construction and traffic scenarios in industrial areas [71,72], plans for urban green networks and coastal eco-networks [73,74], and green networks through connectivity assessments of wildlife [64,75,76]. In this study, the least-cost path method is used to select the optimal area for replacement wetland that can ecologically compensate for a cost area. It accomplishes this objective by using wetland mitigation banking and noting the ecological connectivity of the cost area [52]. It is a simple and rapid method for increasing landscape connectivity using nodes, patches, and corridors [71,77] and for selecting candidate alternative wetlands locations.

2.3. Quantifying Landscape Structure

Quantifying landscape structure involves focusing on the interactions between ecological processes in the landscape ecology field, including landscape patterns [25,78,79]. Researchers have developed various landscape indices to quantify or measure structural connectivity, composition, and configuration [32,80–83]. Landscape structure is usually quantified for four cases. First, quantifying covers landscape changes through time, such as changes caused by urbanization [25,84]. Second, landscape structure is evaluated to compare two or more different landscapes and analyze, for example, the spatial heterogeneity of different landscapes [25,85]. Third, quantifying landscape structure is useful for land use planning and management [25]. It has been especially informative for comparing alternative areas or investigating suitable sites in land use planning or management [25]. Finally, it enables the analysis movement patterns of organisms and the redistribution of nutrients [25]. In this study, we evaluate components of landscape structure and find suitable sites for mitigation wetlands by quantifying landscape structure. Quantifying landscape structure provides a basis for sustainable land management and urban development planning for regional ecosystems.

For quantifying landscape structures, landscape indices can be used to interpret the changing landscape patterns with regional spatial information [19,86,87]. Landscape indices are useful to evaluate landscape structure of ecological characteristics for mitigated or constructed wetlands [80,82,88]. Landscape indices are calculated using FRAGSTATS [19], a software program that is used to quantify landscape structure. FRAGSTATS was developed by the USDA and Oregon State University. The program analyzes numeric data representing metrics at three levels: patch, class, and landscape. The characteristics of the three levels are used to calculate structural connectivity, composition, and configuration depending on the objective of the study [19,89,90].

Metrics at the patch level are defined for single patches and characterize the spatial structural character and arrangement among patches. For example, the Area (AREA) index measures the patch size and computes the total area regardless of the patch's spatial characters [91]. The Radius of gyration (GYRATE) refers to the average movement distances for each patch's centroid to explain the patch extent [91]. The Patch Perimeter (PERIM) index measures the perimeter of each patch including any internal holes in the patch [91].

Metrics at the class level are integrated over all the patches of a given type within the boundary [19,91]. The class level (patch type) separately quantifies the amount and spatial configuration of the same type patches across the landscape. It is possible to quantify the extent and fragmentation of each patch type in the landscape [19,91]. For example, Class Area (CA) measures the sum of the areas of all corresponding patches [91], and Percentage of Landscape (PLAND) measures the composition ratio of class level patch type in the landscape [26,91], thus representing the number of ecological applications, such as habitat fragmentation. Shape index (SHAPE) measures complexity based on the geometric characteristics of a patch type [91]. Metrics at the landscape level are integrated over all patch types or classes over the full extent of the data [19,91]. The landscape-level metrics generally represent the spatial pattern of the entire landscape mosaic and are interpreted more broadly as landscape heterogeneity indices [91]. Landscape-level indices include Contagion (CONTAG), Patch Cohesion Index (COHESION), and Shannon's Diversity Index (SHDI). CONTAG measures the spread of two or more patch type interspersions and patch dispersion at the landscape level [25]. COHESION is computed from the connectivity information for a habitat [91]. SHDI calculates richness and evenness by using patch proportions [91,92].

Because wetlands are not isolated entities, they should be linked to their surrounding landscape [93]. If each wetland is a fragmented habitat island, then animals will struggle to move between adjacent wetlands [93]. In this case, the class level statistics are more meaningful than the patch-level evaluation [19]. Therefore, quantifying landscape structure should be conducted not simply at the level of patch metrics but also for class and landscape metrics. In complex regional ecosystems, an analysis of landscape structure requires the use of indices at those levels for proper composition of mitigation wetlands in the candidate sites [25].

3. Mitigation Wetland Site Selection

The GIS-based integrated site selection process for mitigation wetland planning in small urban area is shown in Figure 1. First, a small urban area is targeted for mitigation wetland planning. For suitable analysis of the wetlands, the mitigation wetland site selection process consists of four steps. The first step is to collect data about the study site, which may be a small urban area. The second step is to investigate preliminary candidate sites for mitigation wetlands by evaluating their functional landscape connections. The third step is the evaluation of landscape structure, including connectivity and composition at the landscape level, to rank the candidate sites. In the fourth step, analysis of the landscape structure aspect of configuration at the class level is conducted to determine mitigation wetland planning guidelines. Using these steps, suitable sites for mitigation wetlands are selected.

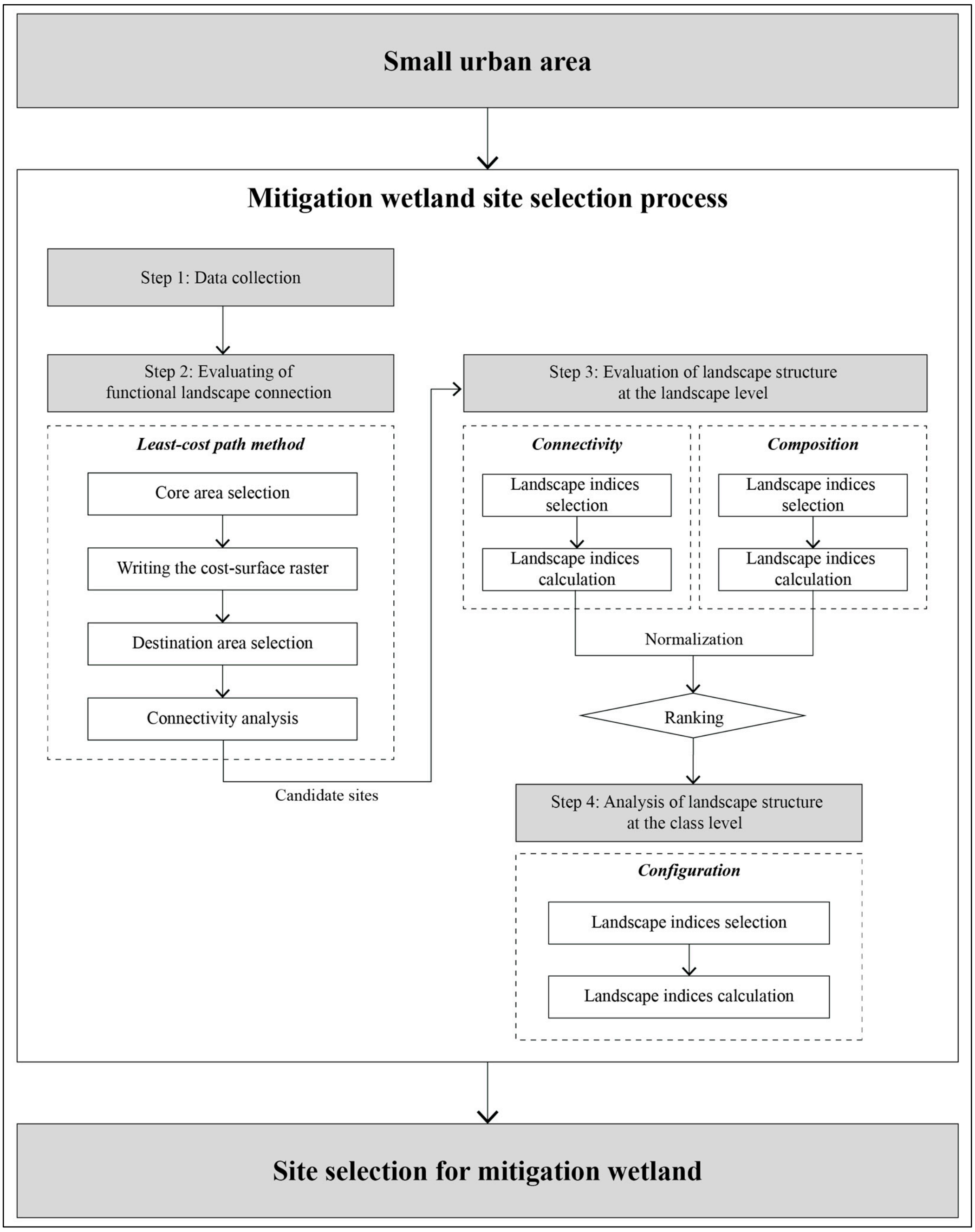


Figure 1. Mitigation wetland site selection process.

3.1. Data Collection

Geographic information at a particular scale is collected, including a land cover map, ecological zoning map, and digital topographic maps. The land cover map displays the surface characteristics of the region, such as the developed area, agricultural area, forest, grassland, wetland, and riparian zones. This layer is used to define a cost-surface relationship to calculate the least cost for wildlife movement. In processing the least-cost path method, each land cover type is used to select core and destination areas for determining connections between habitats in the target area. According to the ecological zoning map, the areas with high ecological preservation value are identified as core areas. For example, the Ministry of Environment in Korea provides the ecological zoning map, including the degree of green naturality (DGN), which is an indicator representing a 0–10 rating of spontaneous plant communities. The areas with high ratings are rich in various species and natural resources. The 0 rating for DGN is an urban drainage channel. Grades 1–3 are developed areas, such as urban areas, residential areas and agricultural areas. Grades 4–7 are mixed areas of development and conservation, and grades 8–10 are areas where the development of industry is prohibited, as well as high-value preservation areas, such as primitive natural forests. The digital topographic map shows terrain (elevation, slope, geographical features, and hydrosphere) using contour lines and is used to identify slope and highway/road information for resistance values of wildlife movement. In addition, the raster version map is needed to make the cost-surface function and to calculate the landscape indices. A thirty-meter digital elevation model (DEM) is included in the creation of the cost-surface raster.

3.2. Evaluation of Functional Landscape Connections

The least-cost path method is used to identify preliminary candidate sites in the target area. The least-cost path method consists of four stages using the spatial analysis tool ArcMAP 10.0 (ESRI). First, the areas with high ecological preservation value, with DGN grades of 8 to 10, are selected as core areas. Second, a cost-surface raster is developed using resistance values for wildlife mobility [7,69]. In a small urban area, medium- and large-sized mammals, whose average body sizes are 40~100cm, inhabited forest and small valleys [42,58]. These mammals have moved to the forest edge and around nearby villages to forage [45]. However, habitats of medium- and large-sized mammals are lost or fragmented by the increase in heterogeneous landscapes, such as development areas, agricultural areas, roads, and highways [94,95]. The cost-surface raster reflects the value for each cell representing the lowest possible cumulative cost of moving to that cell from the nearest source cell [96]. To calculate the cost-surface raster, a land cover map and digital topographic map were collected from the Ministry of Environment and the Ministry of Land, Infrastructure and Transport, respectively. In order to write the cost-surface raster, the resistance values and weight of the land cover type, road density, and highway type affecting the herbivore habitat were set (Table 1). After setting the resistance values, each weighted value was established by summarizing the relative weight cost of each land cover, the densities of roads and highways, and the slopes using the Calculation Cost Surface Tool in ArcToolbox.

Table 1. Variables and resistance values for writing the cost-surface raster.

Component		Resistance value	Weight
Land cover type	Developed area	10	0.65
	Rice paddy	5	
	Cropland	3	
	Greenhouse	5	
	Orchard	4	
	Forest area	1	
	Grassland	2	
	Bare soil	7	

Table 1. *Cont.*

Component		Resistance value	Weight
	Riparian zone	3	
Density of road	0–1 km/km^2	1	0.15
	1–2 km/km^2	2	
	2–4 km/km^2	5	
	4–6 km/km^2	7	
	More than 6 km/km^2	10	
Highway	Less than eight lanes	100	
	More than eight lanes	200	
Slope	$10[1.0 - (1.0/1.0 + e(-(slope - 30)/7))]$	-	0.2

Source: Finke and Sonnenschein [69]; Song *et al.* [94]; Penrod *et al.* [97].

Third, green areas containing agricultural areas, grasslands, and riparian zones on the land cover map are selected as destination areas. Because the green area is critical habitat for wildlife, considerations for wildlife habitat connectivity should be given priority when creating a mitigation wetland in the target area [98,99]. The green areas are regarded as scattered habitats in the urban area. Fourth, an optimal least-cost path between the core area and the destination area is explored, and preliminary candidate sites are selected. Candidate sites are chosen with an area of 5000–40,000 m^2 to attract wildlife. The wetland area of 5000–40,000 m^2 is identified as an ideal condition for creating wildlife habitat and biodiversity [93]. If there are roads or buildings at the candidate sites, then it is not possible to create mitigation wetlands at those sites. The final candidate sites are selected by considering the current land use.

3.3. Evaluation of Landscape Structure at the Landscape Level

FRAGSTATS contributes to wetland site selection by identifying positive and negative landscape structure characteristics and their spatial relationships with the candidate wetlands. Landscape indices typically have high correlations among themselves [100]; thus, the selection of appropriate landscape indices at each metric level is important. Structural connectivity and composition landscape indices are selected to quantify landscape patterns that support wildlife habitats and biodiversity in the target area [91]. Structural connectivity has been shown to be important to the movement of wildlife in the mitigation wetland design [53,93,101,102]. We selected COHESION, which is used to predict habitat connectivity [102]. This index is usually used to analyze the physical connectedness in patterns of spatial heterogeneity or land use [85,103].

Landscape composition is considered an important factor for the diversity of wildlife and fauna. This diversity comprises richness and evenness [91]. SHDI is more sensitive to richness than evenness [91]. In order to calculate the composition in urban spaces and natural spaces, like mitigation wetlands, SHDI is selected by focusing on species richness [93,104–107].

Both the COHESION and SHDI landscape indices are calculated by FRAGSTATS. These landscape-level metrics are useful as a first approximation of landscape patterns and processes, and they can be used to characterize the differences between the planned or designed mitigation wetlands [108].

The COHESION index quantifies the connectivity of habitats as perceived by organisms dispersed in a binary landscape. It is a useful index of habitat connectivity, in which a value of 0 is the minimum that occurs when all patches of habitat are isolated and 1 is the maximum value that occurs when a single patch fills the landscape [102]. The range of COHESION is 0 < COHESION < 100. A COHESION value of 0 means that the data have no single background cell.

$$\text{COHESION(None)}=\left[1-\frac{\sum_{j=1}^{n} p_{ij*}}{\sum_{j=1}^{n} p_{ij}{}^{*}\sqrt{a_{ij*}}}\right]\cdot\left[1-\frac{1}{\sqrt{Z}}\right]^{-1}\cdot(100) \quad (1)$$

p_{ij*} = perimeter of patch ij in terms of the number of cell surfaces.

a_{ij*} = area of patch ij in terms of the number of cells.

Z = total number of cells in the landscape.

SHDI is a species diversity index based on entropy. It is a population measurement of diversity used in landscape ecology [91]. A large SHDI value indicates high species diversity. The range is SHDI≥0, without limit. When SHDI is 0, the landscape includes only 1 patch. If the number of different patch types increases, proportional distribution becomes more reasonable.

$$\text{SHDI(None)} = -\sum_{i=1}^{m}(p_i{}^{\circ}\ln p_i) \quad (2)$$

Pi = proportion of the landscape occupied by patch type (class) i.

After calculating landscape indices, normalization is required in order to determine the ranking of the candidate wetlands because the selected indices differ in their units [109]. Normalization is a well-known method for rescaling data. It scales all numeric variables into the range of 0 to 1 [110] (Equation 3).

$$X', 0\ to\ 1 = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (3)$$

Where

X = each alternative wetland site.

X_{min} = the minima data among all the alternative wetland sites.

X_{max} = the maxima among all the alternative wetland sites.

X', 0 to 1 = the normalized alternative wetland sites between 0 and 1.

The top five candidates for mitigation wetlands are selected by ranking the landscape structure at the landscape level.

3.4. Analysis of Landscape Structure at the Class Level

The five suitable mitigation wetlands are analyzed by class-level indices. The class-level indices show the spatial characters and arrangement, position, or orientation of patches within the class level for landscape configuration. Configuration can be quantified in terms of the connectivity or contagion of patches and patch types [91]. Configuration metrics at the class level might serve as useful indicators for species richness and the edge effect [111]. In order to analyze the five suitable mitigation wetlands, six indices were selected. We selected a suite of commonly used indices to analyze the five suitable mitigation wetlands. Percentage of Landscape (PLAND) explains the amount of the landscape comprising a single patch type [91]. It is used to search for alternative wildlife habitats [53,106,107,112]. Area-Weighted Mean Patch Size (AREA_AM) is commonly used to compare alternative sites [53,113] based on the theory that bigger habitats are more valuable than smaller ones [93]. Landscape Shape Index (LSI), Total Edge (TE) and Edge Density (ED) are related to the edge effect in the field of landscape ecology [104,105,107,113–115]. Total edge in class-level metrics is the most important index used in the study of fragmentation, and many of the class indices reflect the amount of class edge [91]. Edge space describes the preferred area of a particular species, defined by edges and the juxtaposition of different habitats that would increase biodiversity [116]. Interspersion and Juxtaposition Pattern (IJI) is an index for measuring the degree of isolation of the landscape structure. This index is typically used to devise landscape resource management strategies based on isolated patch distribution or to evaluate the isolation of wildlife habitat caused by urbanization [84,93,104,106,114].

Class-level indices typically have a strong impact on local diversity and community structures [111]. Based on landscape configuration, guidelines for mitigation wetlands can be derived that are focused on area, shape edge, and isolation of landscape.

PLAND is the proportion of habitat, and its value ranges from 0 to 100. When PLAND approaches 0, the corresponding patch type (class) becomes increasingly rare in the landscape. When PLAND consists of a single patch type, its value should be close to 100.

$$\mathrm{PLAND}(\%) = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A}(100) \quad (4)$$

P_i = proportion of the landscape occupied by patch type (class) i.

a_{ij} = area (m^2) of patch ij.

A = total landscape area (m^2).

AREA_AM is the calculated area-weight mean patch, which is calculated as the sum of all patches of the corresponding patch type (class). The wetland design guide suggests that the most successful wetlands are 5000–40,000 m^2 [93].

$$\mathrm{AREA\_AM}(m^2) = \sum_{j=1}^{n}\left[X_{ij}\left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}\right)\right] \quad (5)$$

a_{ij} = area (m^2) of patch ij.

x_{ij} = value of a patch metric for patch ij.

LSI ranges from 1 to infinity. If the landscape is composed of a single square patch, the LSI is 1. If the landscape shape becomes more erratic, edges within the landscape of the corresponding patch type will increase.

$$\mathrm{LSI(None)} = \frac{0.25\sum_{k=1}^{m} e_{ik*}}{\sqrt{A}} \quad (6)$$

$e*_{ik}$ = total length (m) of edges in the landscape for patch types (classes) i and k. This includes the entire landscape boundary and some or all of the background edge segments involving class i.

A = total landscape area (m^2).

TE is the total length of all edges and includes the entire landscape boundary and some or all background edge segments involving class i. When TE is 0, there is no class edge in the landscape. When the surface edges of the wetlands are in contact, the value of TE will be higher.

$$TE(m) = \sum_{k=1}^{m} e_{ik} \tag{7}$$

e_{ik} = total length (m) of edges in the landscape for patch types (classes) i and k. This includes the entire landscape boundary and some or all of the background edge segments involving class i.

ED is the edge length per hectare and is equal to the sum of the lengths of all edge segments involving the corresponding patch type. To convert this value to hectares, the total landscape area is multiplied by 10,000.

$$\mathrm{ED}(\mathrm{m}^2) = \frac{E \sum_{k=1}^{m} e_{ik}}{A}(10{,}000) \tag{8}$$

E = landscape boundary and background segments involving patch type i.

e_{ik} = total length (m) of edges in the landscape for patch types (classes) i and k. This includes the entire landscape boundary and some or all background edge segments involving class i.

A = total landscape area (m^2).

IJI considers all patch types present in the entire landscape. If the corresponding patch type is close to only 1 patch type, IJI approaches 0 ($0 < \mathrm{IJI} \leq 100$). If all other patch types are represented equally, then IJI is 100.

$$\mathrm{IJI}(\%) = \frac{-\sum_{k=1}^{m}\left[\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}}\right) ln\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}}\right)\right]}{\ln(0.5[m(m-1])}(100) \tag{9}$$

e_{ik} = total length (m) of edges in the landscape for patch types (classes) i and k.

m = number of patch types (classes) present in the landscape, including the landscape border, if present.

4. Case Study

4.1. Study Area

In order to apply the analytical site selection process for suitable mitigation wetlands sites to a sustainable small urban area (Figure 1), a target area is selected where a new ecological urban plan is required. The target region includes areas with potential for sustainable regional development and other areas that are currently under regional development. Gwacheon was chosen to illustrate an application of the mitigation wetland site selection process. It is located between 126°57′~127°02′E and 37°23′~37°27′N and covers an area of approximately 35.31 km^2 in Korea (Figure 2). Gwacheon is the first planned city after Seoul. Starting in 1982, Gwacheon provided its own administrative functions, but in recent years, the city handed over administrative functions to the Multifunctional Administrative City Construction. Public officials of Gwacheon are trying to redefine the city into an eco-city by managing its natural resources. Therefore, identifying suitable mitigation wetland locations is desirable for supporting the sustainable and ecological goals of Gwacheon. Gwacheon is valued for both its protection of regional biodiversity and contributions to scientific research. Its highest mountains are Gwanaksan and Cheonggyeosan, and there are several medium- and small-sized perennial streams, including the Yangjaecheon, Markgyaecheon, and Galhyuncheon, running through the city. Medium- and large-sized mammals are common in Gwacheon, such as *Hydropotes inermis argyropus, Prionailurus bengalensis, Nyctereutes procyonoides, Mustela sibirica, and Lepus coreanus*.

The Korean water deer, *Hydropotes inermis argyropus,* is a large-sized cervid (shoulder height: 40–55 cm; body length: 90 cm; body weight: 9–14 kg) [117]. Since the deer feed in both lowland and mountainous areas, the deer were originally distributed in some of the richest areas between the grasslands and forested areas of China and Korea [118]. The leopard cat, *Prionailurus bengalensis,* is a medium- to large-sized species (shoulder height: 15–20 cm; body length: 55–90 cm; weight: 2–4 kg) in South-East Asia that lives in a natural forest and around forest edge areas, and is currently listed as threatened by the Ministry of Environment in Korea [119,120]. The raccoon dog, *Nyctereutes procyonoides*, is medium-sized mammal (shoulder height: 30cm; body length: 50–70 cm; weight: 4–10 kg). Since the species is a true omnivore and its seasonal food habits shift as food availability changes, this species lives in various environments such as forests, streams, and man-made parks [121]. *Mustela sibirica and Lepus coreanus* are medium-sized species (body length: 40–50 cm), living mainly in forested areas, and they move to the lowlands or around villages to hunt their prey. Gwacheon hopes to protect and enhance the habitat necessary for this wildlife to flourish.

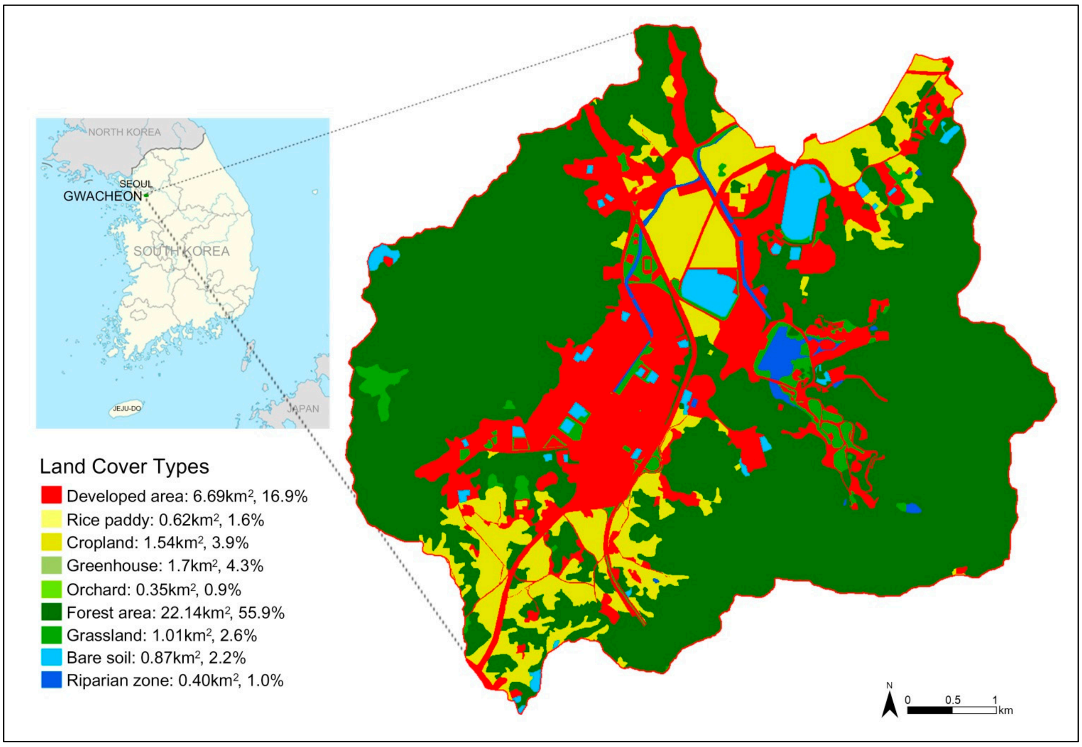


Figure 2. Land cover map of Gwacheon

The fringe of Gwacheon is rich in natural resources, but development is rapidly fragmenting the green areas in the center of the city (Figure 2). The city has been receiving significant attention as an area for new land use and as an area with a need to protect green areas from real-estate developers and government agencies. Accordingly, Gwacheon requires a mitigation wetland that is able to connect the isolated green patches and compensate for damage caused by development. Mitigation wetland site selection is important to achieve sustainability because it can protect undeveloped areas such as forests and riparian zones when planning for future land use and development.

4.2. Data Collection

To gather geographic information, a land cover map (2009, 1:25,000 scale), an ecological zoning map (2007, 1:25,000 scale), and a digital topographic map (2007, 1:25,000 scale) were collected. The land cover map and ecological zoning map were provided by the Ministry of Environment, and the digital topographic map was provided by the Ministry of Land, Infrastructure and Transport.

4.3. Evaluating Functional Landscape Connection

In order to select the preliminary candidate sites where wildlife mobility is high, the functional landscape connectivity of Gwacheon was evaluated using the least-cost path method. The method was applied in four steps (Figure 2).

First, the core area is a natural area with high preservation value, and its surroundings must be protected from developmental damage, such as pollution and land alteration [122]. The core preservation areas were chosen from areas with DGN grades greater than 8 on the ecological zoning map and include important wildlife habitats and primeval or natural vegetation forests. The core areas were located in the west and east, covering approximately 11.02 km^2, 31% of Gwacheon.

Second, the cost-surface raster for mitigation wetlands was determined by considering the topography and land features. The cost-surface raster represented the cost value occurring when moving between cells in the raster grid. The cost-surface raster was based on the resistance values shown in Table 1. The gradation of the shading from black to dark and light grey indicates the range of cost values from high to low. Darker colored areas show a high cost to wildlife movement, and there are currently no advantages for mitigation wetlands in these locations. Lighter colored areas indicate areas where there is a low cost to wildlife movement, where conditions are currently favorable for mitigation wetlands (Figure 3).

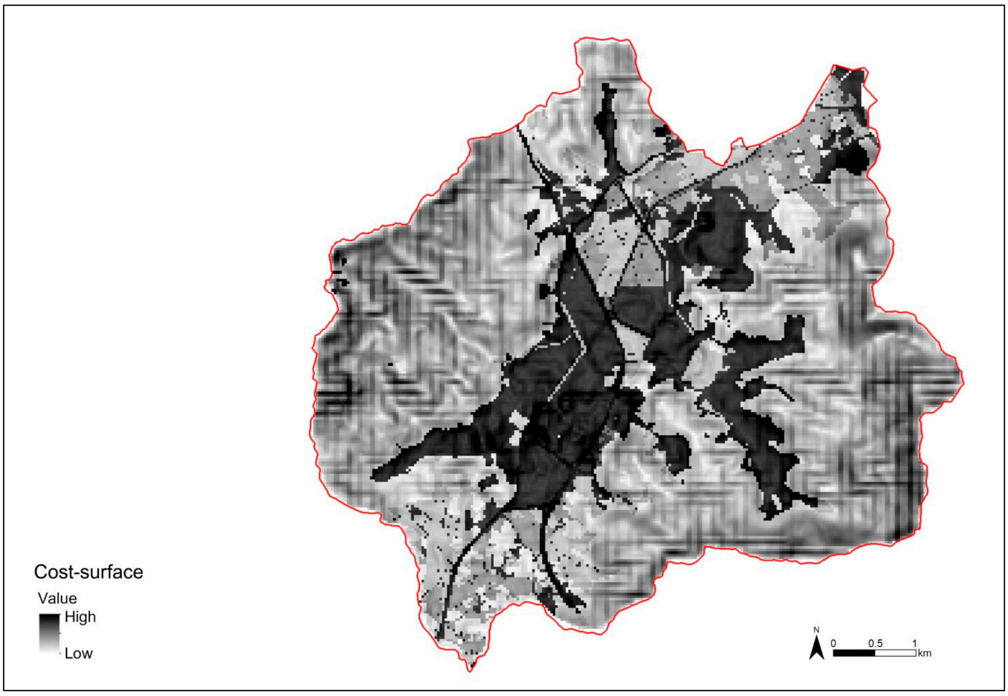


Figure 3. Cost-surface raster map for the mitigation wetlands.

Third, the destination areas were selected green areas and are available for wetland creation based on the land cover map (Figure 4). These green areas are wildlife habitats and connect forest and urban areas. In total, 608 patches of green areas were selected, and their combined size was approximately 8.03 km^2, or 23% of the total area of Gwacheon. The destination areas are green areas that support human activity, such as the Yangjea stream, the Gwacheon reservoir, the Gwacheon Central Park, the Gwacheon Flower Market, the Seoul Grand Park and the Seoul Racecourse Park. These areas connect forests and urban areas.

Fourth, to understand the potential movement of each species pool, the least-cost paths were analyzed. That is, optimal paths connecting the core areas and destination areas were explored through a least-cost path analysis. The optimal paths were created based on the cost-surface raster map. The direction raster began at the core area and ended at a destination green space. Figure 4 shows the results of all calculations connecting the core areas and destination areas to assess the connectivity of landscape patches in Gwacheon. The value of least cost paths is reflected by the gradient color, representing the value of cost-surface. The optimal paths are useful as an initial assessment to allocate suitable mitigation wetland. For each area, the optimal path was explored by connecting the centers of gravity within the core and destination areas (Figure 4) [123].

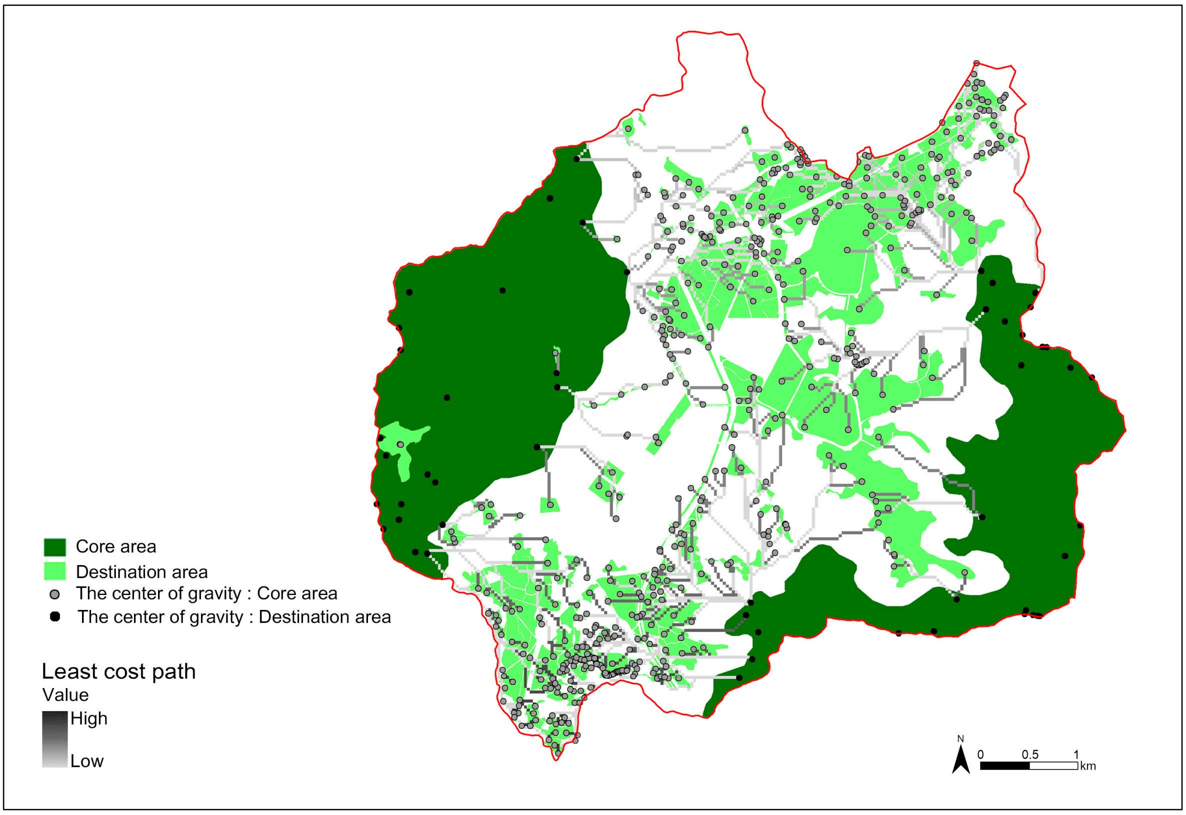


Figure 4. Optimal paths between core and destination area.

In order to narrow the preliminary candidate sites for mitigation wetlands, candidate patches were chosen from a high density of optimal paths or areas intersecting more than three paths. In total, 85 preliminary candidate sites were identified; however, these areas were further narrowed to 18 candidates based on their ability to include a wetland 5000–40,000m^2 in size. Four sites were excluded from the 18 candidates due to adjacent roads or buildings, leaving 14 final candidate sites

(Figure 5). Among the 14 candidates, the largest area is Site F (21,110 m^2) and the smallest area is Site N (5400 m^2). The mean area of the 14 candidates (Site A~N) is 9700 m^2, and the total area is 135,800 m^2. These areas are located near the forest or agriculture areas.

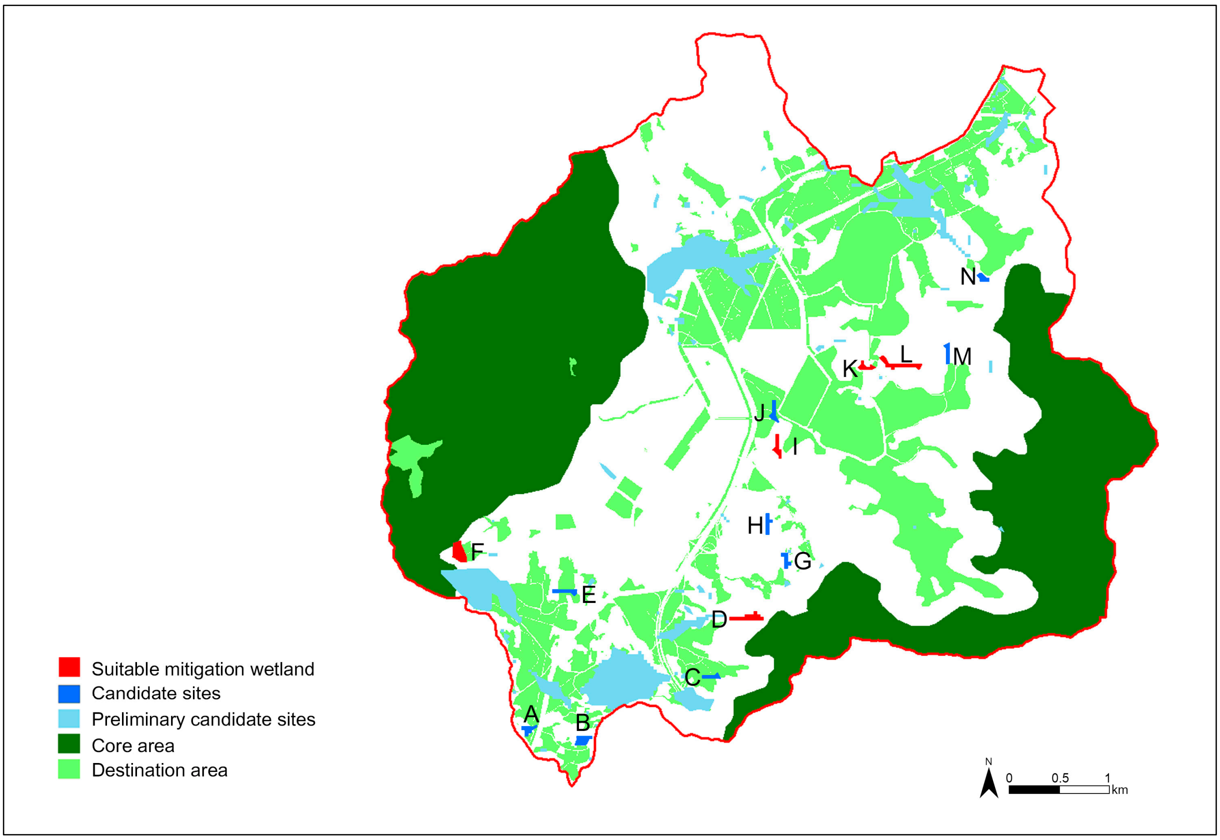


Figure 5. Fourteen candidate sites (Site A to Site N) and suitable mitigation wetland areas (Site I, Site K, Site D, Site F, Site L).

4.4. Evaluation of Landscape Structure at the Landscape Level

The final step in the selection process involved the examination of landscape structure for the candidate sites (Figure 1). Here, the landscape-level metrics for the 14 candidate wetland areas were calculated (Table 2). The COHESION index analyzed the structural connectivity in Gwacheon. Site I had the highest value (95.8076) and was nearly identical to Site K (95.8000), Site D (95.6861), Site H (95.6842), and Site G (95.6813). SHDI values were used for quantifying the composition of the candidate areas. The highest ranked sites for SHDI included Site F (2.0611), Site D (2.0607), Site L (2.0602), Site H (2.0590), and Site G (2.0590). The contribution assessment calculated the differentials based on an exclusion of each of the 14 candidates in turn and then synthesized and analyzed the normalized values. The results for COHESION and SHDI are shown in Table 2. This table shows the ranks of the COHESION and SHDI after normalization of the index values. Calculating the normalized average index values allowed for a final ranking of Site I (0.8931), Site K (0.8595), Site D (0.8128), Site F (0.8039), and Site L (0.7748), which were selected for the final analysis.

Table 2. Index values, normalization, calculated index averages and ranking of candidate wetland sites in Gwacheon.

Ranking	**Candidates for alternative wetland**	**Landscape index**		**Normalization**		
		COHESION	**SHDI**	**COHESION**	**SHDI**	**Average**
1	Site I	95.8076	2.0583	1.0000	0.7863	0.8931
2	Site K	95.8000	2.0577	0.9785	0.7405	0.8595
3	Site D	95.6861	2.0607	0.6562	0.9695	0.8128
4	Site F	95.6842	2.0590	0.6078	1.0000	0.8039
5	Site L	95.6813	2.0590	0.6183	0.9313	0.7748
6	Site H	95.6748	2.0585	0.6508	0.8397	0.7453
7	Site G	95.6738	2.0589	0.6426	0.8397	0.7412
8	Site A	95.6734	2.0584	0.6214	0.8321	0.7267
9	Site J	95.6727	2.0602	0.6177	0.8244	0.7211
10	Site N	95.6725	2.0588	0.6242	0.8015	0.7129
11	Site E	95.6690	2.0611	0.5908	0.8321	0.7114
12	Site C	95.6630	2.0589	0.6203	0.7939	0.7071
13	Site M	95.6620	2.0588	0.5880	0.8244	0.7062
14	Site B	95.4542	2.0480	0.0000	0.0000	0.0000

4.5. Analysis of Landscape Structure at the Class Level

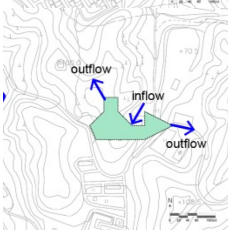
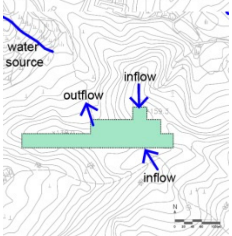
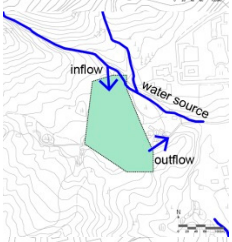
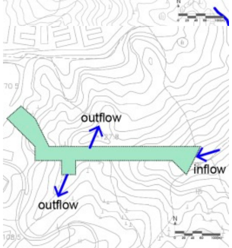
Wetland sites should be located in areas that have minimal disturbance to wildlife habitats caused by the surrounding land use [124]. There are wetland planning guidelines that refer to the importance of properties such as area, shape edge, and isolation [93]. We investigated the landscape configuration using class-level metrics to judge the habitat implications of mitigation wetlands (Figure 1).

According to the priorities of mitigation wetlands, we quantified the landscape structure for class-level metrics (Equations (4)–(9)). The PLAND, AREA_AM, LSI, TE, ED, and IJI landscape indices were calculated for Site I, Site K, Site D, Site F, and Site L. We searched each site's water source for hydrologic functions needed for mitigation wetlands (Table 3).

Site I is rectangular and located in the center of southwest Gwacheon. Site I was the highest ranking among the sites examined based on its connectivity and composition. It has highly contrasting land use types, including development areas, bare soil, and forests. It also exhibited generally low values for PLAND (0.0281%), AREA_AM (9900 m^2), LSI (1.5714), TE (660 m), ED (0.1876 m/ha), and IJI (14.3659%). Increasing the mitigation wetland boundary configuration will improve biodiversity [93,125]. However, boundary values for Site I were lower than those for Site D, Site F, and Site L. To compensate for the weaknesses of Site I, the wetland boundary should have a tortuous design. There is no water source at Site I, as determined by the inflow and outlet paths and estimation of the runoff path of rainwater. Runoff flows north from the east slope.

Site K had the second highest ranking based on a comparison of connectivity and composition. It has an irregular shape, and its land use type is that of forest area. The PLAND (0.0230%), AREA_AM (8100 m^2), TE (600 m) and ED (0.1705 m/ha) values were the lowest among all the selected sites. The LSI (1.6667) and IJI (26.3504%) values, however, were higher than for other sites. Normally, the boundary spatial structure of irregular shapes is better than that of linear shapes for the purposes of diversity. Therefore, when designing the mitigation wetland in Site K, it would be best to keep the shape of the boundary. In addition, the entire mitigation wetland boundary should be expanded for watershed space. We estimated the water source point based on the slope of Site K. The inflow was located in the center of the site boundary, and the outlet was oriented in the east-west direction.

Table 3. The results for five suitable mitigation wetland landscape structures at the class level.

Site	Image	AREA_AM (m^2)	PLAND (%)	TE (m)	ED (m/ha)	LSI (none)	IJI (%)
Site I		9900	0.0281	660	0.1876	1.5714	14.3659
Site K		8100	0.0230	600	0.1705	1.6667	26.3504
Site D		15,300	0.0435	840	0.2387	1.5556	9.2808
Site F		20,700	0.0588	720	0.2046	1.2000	36.5465
Site L		15,300	0.0435	1140	0.3240	2.1111	0.0000

Site D is composed of bare soil. Site D was the third highest ranking when compared on the basis of connectivity and composition. The PLAND (0.0435%), AREA_AM (15,300 m^2), LSI (1.5556), TE (840 m), ED (0.2387 m/ha) and IJI (9.2808%) values were higher than those for many of the other sites. Configuration values were similar to Site F, but the TE and ED values were lower than those of Site F. Therefore, creating irregular shorelines should be considered. This could increase TE and ED by up to 10%–20% for the mitigation wetland. Site D could supply two points of inflow from the north and south sides and one outflow. It should be connected to an existing water source in the north.

Site F is located on the west side and is composed of forest area. It ranks fourth in terms of connectivity and composition, Site F has the highest values for PLAND (0.0588%), AREA_AM (20,700 m^2) and IJI (36.5465%), but its LSI value (1.200) is lower than those of the other sites. Although Site F had high values, the wetland boundary shape was poor. Nonetheless, Site F is the only site containing a traditional water source. Therefore, it could be advantageous to divide the current shape into several small wetlands.

Site L was the fifth highest-ranking site in terms of connectivity and composition. Site L is located in an area composed of forest. The PLAND (0.0435%), AREA_AM (15,300 m^2), TE (1140 m), and ED (0.3240 m/ha) values were similar to those of Site D. The LSI (2.111) value for this site was the highest of the examined sites, and IJI was 0% because the wetland patch type is adjacent to only 1 other patch type in Site L. The results of the landscape structure analysis at the class level helped to assess the different values for each site. Site L does not require changes to its current shape. However, it would be necessary to construct other patch types nearby to improve the IJI value. Site L could be planned to have one point of inflow on the east side and two points of outflow on the north and south sides.

5. Conclusions

Due to the fact that damage to urban natural ecosystems could be minimized by mitigation wetlands, the selection of a mitigation wetland site is very important for sustainable small urban development. When selecting sites for replacement mitigation wetlands in small urban development areas, it is important to consider the functional and structural characteristics of connectivity, composition, and configuration in the landscape ecology. Although these elements are interrelated with high quality wetland ecosystems, current site selection guidelines do not consider the integration of functional and structural ecological patterns for candidate site locations.

In addition to identifying the connectivity and composition characteristics associated with candidate mitigation wetland sites, other land cover features could be included in the GIS-based site selection process as well. This includes the reliability of a consistent source of water at the candidate sites. Without a reliable water source, wetland habitat conditions could suffer during dry periods and the usefulness of the wetland for mitigation may be limited. In addition, stormwater runoff from some land uses known as hot spots can affect the health of wetland plant communities due to high concentrations of certain pollutants. These include vehicle maintenance areas, industrial storage areas, and even landscape nurseries. Expanding the GIS-based analysis to include both of these issues (water supply and quality), along with the ecological function analysis and structure analysis described above, could provide a powerful tool for enriching the biotic and abiotic fabric of urbanized areas.

We developed a GIS-based integrated site selection approach to mitigation wetland planning that considers landscape structure and connectivity within the context of broader ecosystem patterns. The functional connectivity analysis consists of developing an ecological network plan and is conducted to identify alternative wetland candidate sites. To analyze the candidate sites further, COHESION (connectivity index) and SHDI (composition index) are selected from a list of options provided by FRAGSTATS [19]. These metrics are used at the landscape level to evaluate the connectivity and composition of the mitigation wetland candidates. Ranking of the sites is determined by comparing the normalized values of the chosen landscape indices.

Some limitations should be considered when reviewing this study. First, the functional connectivity analysis and quantitative landscape structure assessment were based only on existing geographic data. This reduces the costs of conducting such a study, but it also limits the strength of the conclusions. Practitioners must collect data in the field to verify the land cover information and other site characteristics that affect the landscape structure in ways related to biodiversity and the quality of wildlife habitat. Second, because each of the class-level indices is derived independently, it may not be appropriate to give one index priority over another. Instead of choosing the single best site, it might be better to suggest a subset of high-quality sites for further consideration. Third, we did not target specific wildlife species for habitat evaluation. Instead, the landscape structure analysis was carried out by targeting medium- and large-sized mammals in general. To more accurately assess the impact of the functional and structural connectivity analyses, it would be helpful to review the habitat needs of specific animal species.

A case study that illustrates the usefulness of this approach focuses on the city of Gwacheon, which is located in the capital area of Korea. Candidate wetland areas were identified based on the geological information for Gwacheon and by using a connectivity analysis of the natural areas with high preservation values. Through this analysis, 14 candidate wetland areas were selected. A quantitative analysis of landscape features was conducted for the 14 mitigation wetland candidate sites to identify the top five sites. These five final sites were chosen by calculating the PLAND, AREA_AM, LSI, TE, ED, and IJI indices at the class level and by comparing these values for the purposes of maximizing biodiversity potential. A final review included the examination of water sources and slopes for the final selection of the suitable mitigation wetlands. This tool has the potential to support sustainable small urban planning through the detailed quantitative analysis of site selection of mitigation wetlands. In this case, it can be used to support sustainable small urban development as an improvable urban ecosystem.

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Author Contributions

Jung Lee designed the study and participated in all phases. Jinhyung Chon also participated in the development of the study and provided structural discussion. Christopher D. Ellis helped improve the manuscript and prepare the discussion sections of the text. Yun Eui Choi and Soojin You helped conduct the literature review and case study.

Conflicts of Interest

The authors declare no conflicts of interest.

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