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Assessing the Habitat Suitability of Dam Reservoirs: A Quantitative Model and Case Study of the Hantan River Dam, South Korea

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Abstract: The main objective of this study was to investigate ecologically healthy regions near a dam reservoir. This study developed a model for assessing habitat suitability as a proxy for the ecological value of reservoirs. Three main factors comprising nine assessment variables were selected and classified as having a habitat suitability (HS) between 0 and 1: (1) geomorphic factors of altitude, slope steepness, and slope aspect; (2) vegetation factors of forest physiognomy, vegetation type, and tree age; and (3) ecological factors of land cover, ecological quality index, and environmental conservation value assessment. The spatial distribution of the nine HS indices was determined using geographic information systems and combined into one HS index value to determine ecologically healthy regions. The assessment model was applied to areas surrounding the Hantan River Dam, South Korea. To verify the model, wildlife location data from the national ecosystem survey of the Ministry of Environment were used. Areas with an HS index between 0.73 and 1 were found to contain 72% of observed wildlife locations. Ecologically healthy areas were identified by adding the indices of each variable. The methods shown here will be useful for establishing ecological restoration plans for dam reservoirs in South Korea.

Keywords: dam reservoir; ecological factors; environmental factors; geographic information systems; geomorphic factors; habitat suitability (HS); restoration

1. Introduction

The primary influence of dam construction is on the surrounding environment and ecosystem of the river. The river changes completely in form and depth as a reservoir. Dam construction also causes habitat isolation through geomorphic separation of habitats, loss of species diversity, disruption to fish migration, and other changes due to variations in the water flow and hydrological regime, detachment of movement corridors, and species composition changes [1–3]. To understand how dam construction affects the ecosystem, there must be a comprehensive evaluation that considers various factors. The World Commission on Dams [2] analyzed how a dam influences the surrounding environment and ecosystem based on an assessment of wildlife species. Chen et al. [4] suggested a conceptual model that analyzes the environmental impact of dams in terms of the ecological network. Although the evaluation was not applied to an actual dam in that study, it was clear that more data are needed for a full quantitative evaluation. Thus far, in South Korea, there have been only a few river ecosystem evaluations or wetland function assessments [5,6]. These assessment methods quantitatively evaluate the current ecosystem, but quantifying the effects of dam construction on the ecosystem remains difficult. Given the negative effects of dams, appropriate planning for ecological restoration and adjustment is required to ameliorate the damage [7,8]. In South Korea, a guide to eco-friendly design was published by the Korea Water Resources Corporation [9], and Koo [10] examined eco-friendly ways to reduce the environmental damage that can occur during dam construction and operation. However, current dam construction and ecological restoration efforts are still insufficient, especially in the creation of restoration plans for individual dams. Therefore, to plan for effective dam reservoir ecological restoration in the future, complementary data should be gathered, including on factors needed for ecological restoration. The type and location of the most severe damage should be predicted quantitatively; standardized restoration plans should not be adjusted to each individual dam.

Geographic information systems (GIS) have been applied for spatial analysis studies of ecological restoration. GIS can be used for spatial analysis assessment, and GIS-based habitat suitability models have previously been applied to specific species [11–13]. For example, Pereira and Itami [12] and Vincenzi et al. [13] suggested a GIS-based habitat suitability (HS) model for red squirrels on Mt. Graham (Arizona, USA) and a clam, *Tapes philippinarum*, in the Mediterranean, respectively. In addition, Kliskey et al. [11] applied pine marten and woodland caribou HS models for scenario testing in the North Columbia Mountains of British Columbia, Canada. Ortigosa et al. [14] developed a model for habitat suitability assessment known as the Valutazione della Vocazionalità Faunistica (VVF). They employed five categories, including morphologic, vegetation, trophic, meteo-climate, and anthrophic variables with GIS and various classification functions, and applied it to *Capra ibex* in Adamello National Park, Italy, for verification. Hirzel and Arlettaz [15] suggested a new HS model using the distance of environmental aspects and the geometric mean. They used bearded vulture habitat in the Swiss Alps as a target habitat and showed that an HS model incorporating the geometric mean was a good trade-off between the two competing constraints of generality and precision. HS studies of dams or reservoirs often focus on fish [16–18], such as carp in the Yangtze River [16], and particular fish habitats in specific rivers, such as fish habitats in the Lancang River in China [17]. Most HS-related studies deal with specific species over a large area. However, ecologically valuable regions near dam reservoir areas must also be investigated because dam reservoirs in South Korea are mostly located near river headwaters that correspond to mountainous areas, where water is abundant. Animals in these areas probably have very specific habitats located around dam reservoirs.

The main objective of this study is to investigate ecologically valuable regions near dam reservoirs, considering a combination of multiple variables using GIS. Specifically, this study aims to (1) develop an HS model to investigate ecologically healthy areas using a selection of significant variables in the main environmental categories; (2) determine wildlife HS indices (HSIs) for species in the Hantan River Dam reservoir; and (3) analyze and assess the spatial characteristics of HSIs. The results of this study will assist with the successful evaluation of ecologically valuable regions near dam reservoir areas and serve as a tool for biodiversity conservation.

2. Materials and Methods

2.1. Study Area

The Hantan River Dam is a flood control dam in Northern South Korea (Figure 1), designed to minimize flood damage in the Imjin River basin. The dam is 85 m high and 705 m long, with a total reservoir capacity of 311.3 million m^3 (Figure 1). The Imjin River Basin is an area that has seen increased loss of life and property damage from flooding as urbanization has rapidly progressed in line with industrial development. The basin area of the Hantan River and the Imjin River is predominantly mountainous, so the river gradient is relatively steep, and many streams pass through the valleys. The uppermost parts of the basin, at the peaks of the mountains, vary in elevation from 1500–1800 m above sea level. Therefore, after rainfall, the inflow of water increases dramatically and is the main cause of flood damage downstream. The Paju-si and Munsam-eup areas, which are at the far downstream end of the Hantan River, are spread out on a large plain. The tide of the Yellow Sea reaches within 30 km of these downstream sites, which have suffered severe flood damage in the past. The Hantan River flood control dam was built to minimize flood damage by controlling the stream stage of the Imjin River within the Imjin River basin, where damage most often occurs during localized torrential downpours [19]. In this study, we chose a target area consisting of all land within 1.0 km of the dam reservoir border [20].

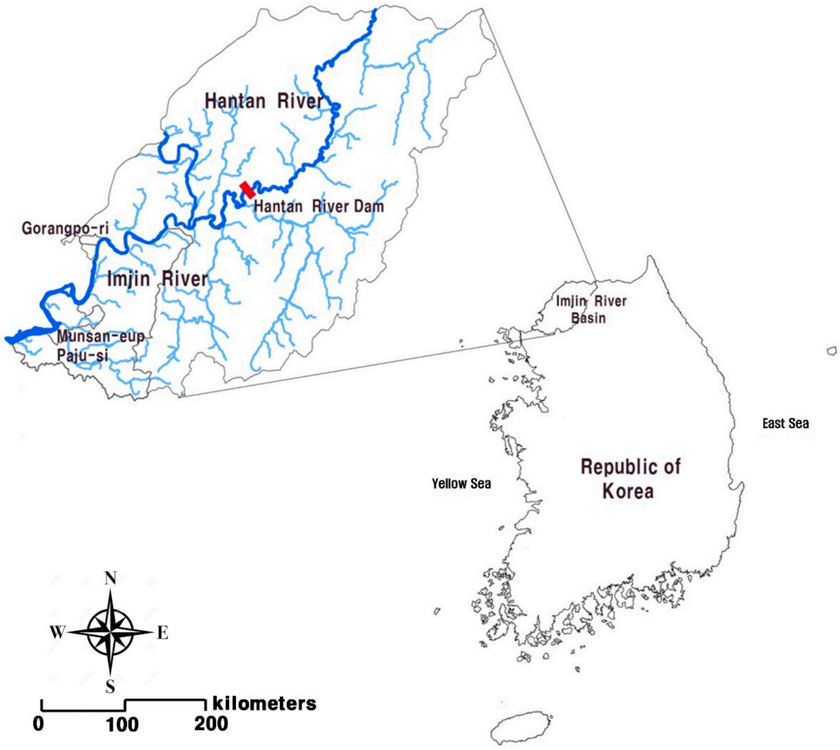


Figure 1. Location of study site (Hantan River Dam) in the Imjin River Basin, South Korea.

2.2. Ecological Value Assessment Model Construction

We classified the factors that affect dam ecosystems into three main categories: geomorphic, vegetation, and ecological. We selected three variables for each category from the United States Fish and Wildlife Service guidelines [21] and bounded these nine variables between 0 and 1, as suggested by Ortigosa et al. [14]. Finally, we spatially overlaid all nine classification maps and produced an average wildlife HS map. Figure 2 shows the spatially-distributed evaluation process for wildlife HSI in the Hantan River Dam reservoir.

We assigned an index of 1.0 to natural habitats or the most suitable conditions for wildlife, and 0.0 to artificial habitats or the most inappropriate conditions for wildlife. The index for each variable was calculated by multiplying the value of each variable by its respective area and summing these values for the total area. To identify the spatial distribution of areas with the highest ecological function, we calculated indices from each ecological variable for each map cell. To analyze and evaluate these indices as a whole, we used the map overlay method of McHarg [22]. The map overlay method is a concept of land analysis that creates a map for each evaluation variable, overlaps the maps, and creates a composite map showing total evaluation values. It is a common application of GIS data [23]. We used the indices between 0–1 for each of the nine variables for individual maps, so the final index (average of individual indexes) was on a scale of 0–1.

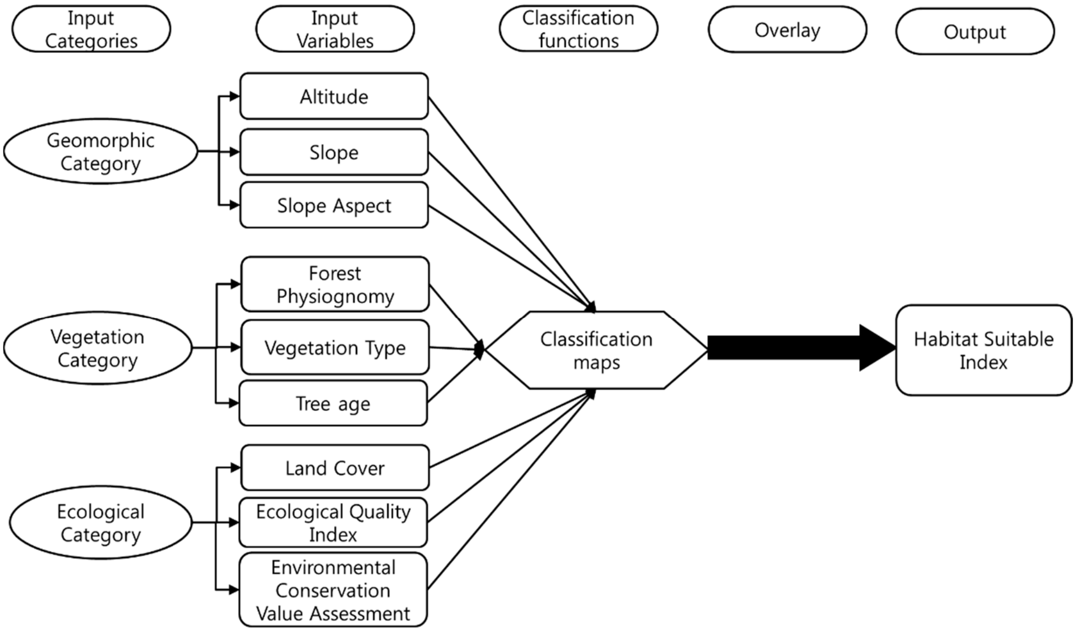


Figure 2. The quantification process of habitat suitability (HS) estimation used in this study.

2.3. Application of Model to Study Area

Figures 3–5 show the specific variables, conditions, and assigned indices used in this study. There are general standards for ideal geomorphic conditions, but they do not accurately reflect specific features of the target dam area.

2.3.1. Classification of Geomorphic Variables

For geomorphic variables, we used a digital elevation model (DEM) map with a scale of 1:25,000 issued by the National Geographic Information Institute, Korea, to extract basic data on altitude, slope steepness, and slope aspect. Figure 3 shows the distribution and classification of altitude, slope steepness, and slope aspect in the geomorphic category for the Hantan River Dam. This study applied the evaluation method of the Instream Flow and Aquatic System Group [24] to determine the ranges of altitude, slope steepness, and slope aspect. The ranges of altitude, slope steepness, and slope aspect were defined as follows: a dominant region (containing over 50% of data) was assigned to 1, and all other regions were assigned to 0.5. As shown in Figure 3a, when the altitude was divided into 10 m intervals, 51.4% of measured altitude values were distributed in the 100–170 m range. Thus, a 1.0-point value was assigned to the 100–170 m section, as it is a region with a high possibility of wildlife presence, and a 0.5-point value was assigned to the remaining regions. For the slope steepness, 59.8% of values were distributed in the 0°–15° section. Thus, a 1.0-point value was assigned to the 0°–15° section, and a 0.5-point value was assigned to the sections with other slope steepness (Figure 3b). For the distribution of slope aspect in the target area, a 1.0-point value was assigned to flat land and to slope steepness that face 22.5°–157.5° (58.1%), and a 0.5-point value was assigned to the remaining slope aspects.

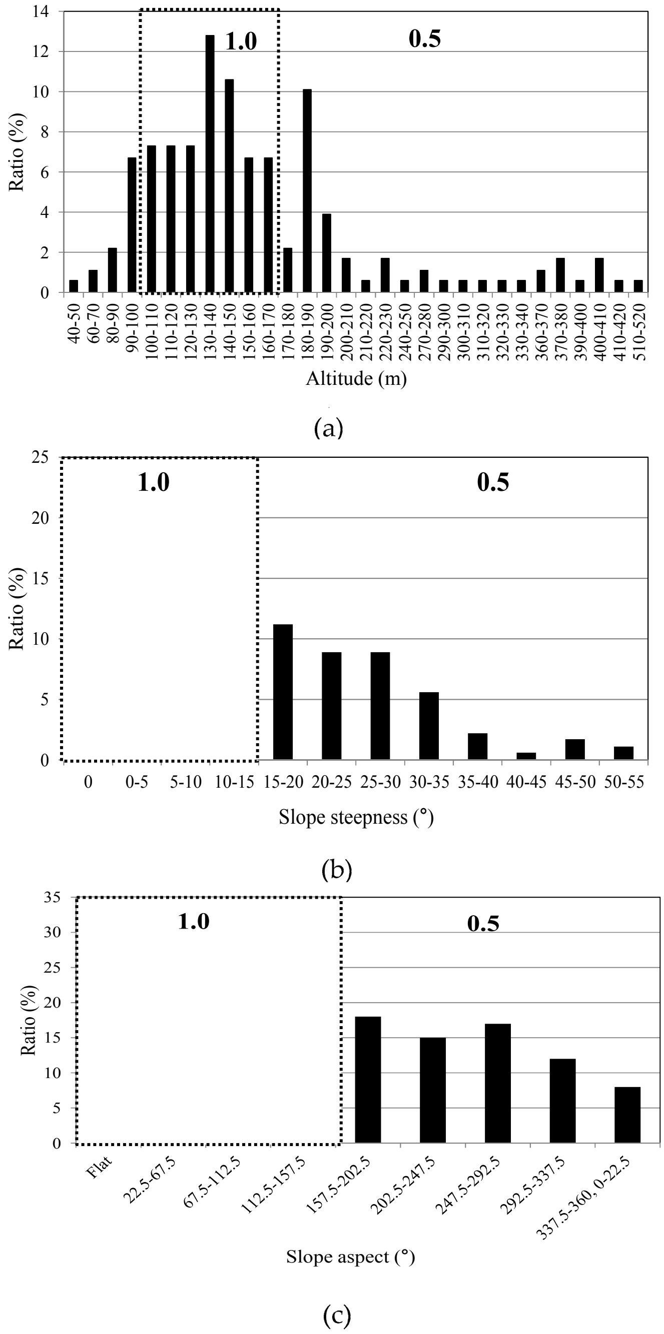


Figure 3. Distribution and classification of geomorphic variables in the Hantan River Dam reservoir area: (**a**) Altitude; (**b**) Slope steepness; and (**c**) Slope aspect.

2.3.2. Classification of Vegetation Variables

For the forest physiognomy category, we assigned indices of 1.0 for natural forest, 0.5 for plantation forest, and 0.0 for unforested areas in Figure 4a. For the vegetation type category, species compositions that were closest to those of natural vegetation were considered the highest class (mixed stand forest, in this case), followed by broadleaf forest and coniferous forest, while unforested areas had the lowest score; indices are 1.0, 0.7, 0.3, and 0.0, respectively, in Figure 4b. Forest age grades were assigned evenly-spaced indices from 1.0 for grade 5 to 0.2 for grade 1, with 0.0 for unforested areas, as shown in Figure 4c.

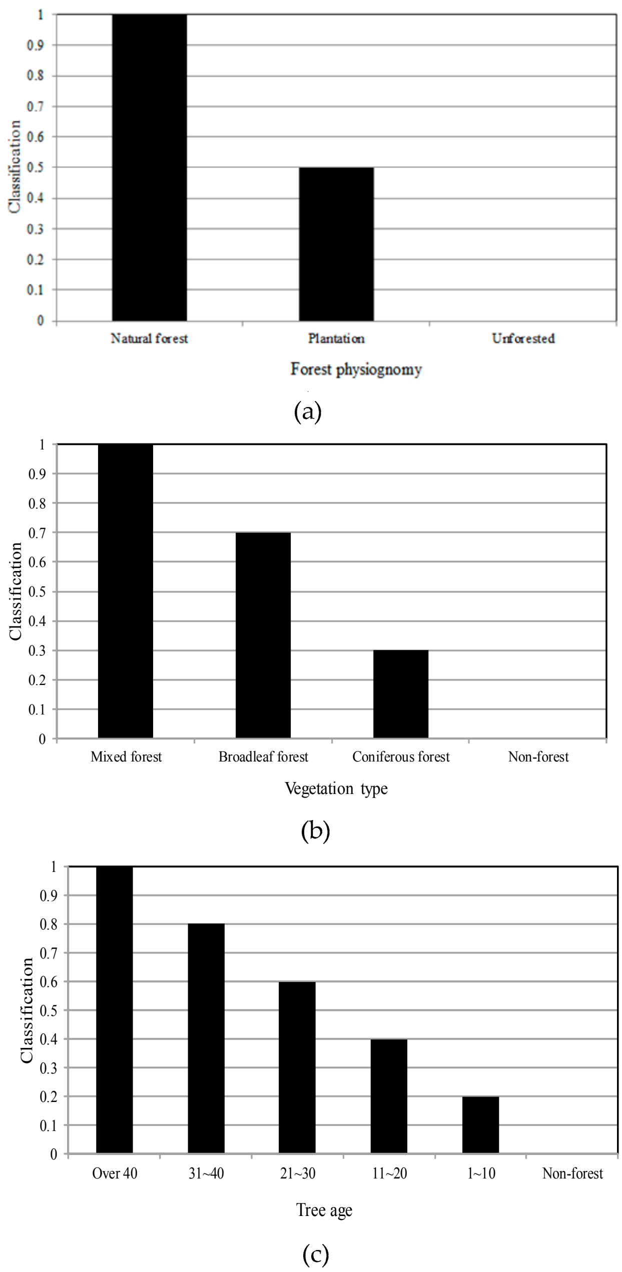
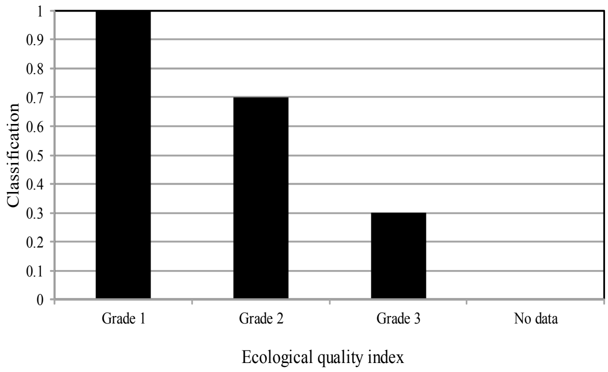


Figure 4. Classification of vegetation variables in the Hantan River Dam reservoir area: (**a**) Forest physiognomy; (**b**) Vegetation type; and (**c**) Tree age.

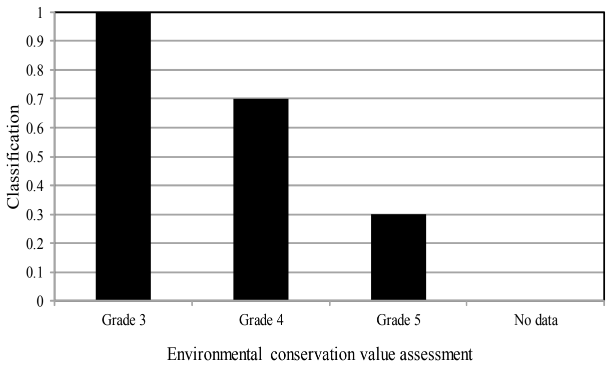
2.3.3. Classification of Ecological Variables

The Ministry of Environment [25] provides an ecological quality index (EQI) map for terrestrial areas that divides the quality of terrestrial ecosystems into three grades. According to the EQI map, Grade 1 indicates areas of natural environment conservation and restoration, grade 2 represents areas that try to promote conservation of the natural environment, and grade 3 characterizes areas in need of development. We summed the areas (km^2) based on grades and applied the indices based on the following classes: 1.0 for grade 1, 0.7 for grade 2, 0.3 for grade 3, and 0.0 for no data. Environmental conservation value assessment (ECVA) is a process of scientifically assessing the geomorphic and environmental features of the land and grading the conservation suitability [26]. The EVCA classifies the entire country into five grades, with grade 1 indicating the most environmentally valuable areas and grade 5 representing those most suitable for development.

Grade 4 is intended for environmentally friendly development. Grade 3 indicates buffer areas between conservation and development. The ECVA map incorporates 67 assessment values based on criteria of naturalness, diversity, rarity, vulnerability, and stability [27]. For EVCA classification, a value of 1.0 is used for grade 3, which is the area that has the highest class within the target area, 0.7 is used for grade 4, 0.3 for grade 5, and 0.0 for no data, as shown in Figure 5. Medium-resolution land coverage from the Korea Ministry of Environment was used to determine existing land use and coverage as of 2007. Gawond-do [28] and Kang et al. [29] suggested land cover standards for wildlife habitat suitability. Land cover was indexed according to these studies: natural forest was given a value of 1.0, natural grassland and coppice were 0.8, pastures and orchards were 0.6, rice paddy farms or arable land were 0.4, other cultivated areas were 0.2, and urbanization promotion and residential areas were approximately 0.0.



(a)



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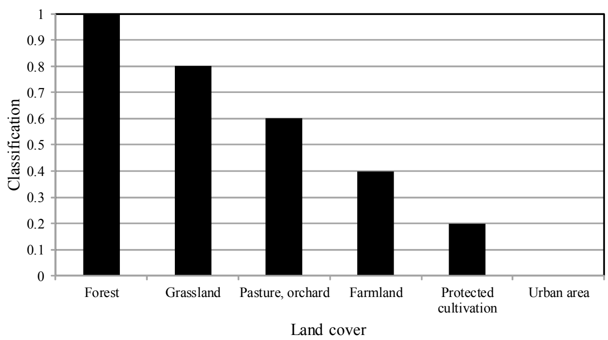

(c)

Figure 5. Classification of ecological variables in the Hantan River Dam reservoir area: (**a**) Ecological quality index; (**b**) Environmental conservation value assessment; and (**c**) Land cover.

2.4. Verification of the HS Model

The ecological monitoring data were based on the environmental impact assessment of the Hantan River Dam and the wildlife survey data collected after the environmental impact assessment. Data were extracted from each dataset and used in an analysis with ArcGIS 10.0 (ESRI Inc., Redlands, CA, USA). The target area was divided into a 10 m × 10 m grid. The monitoring data were assigned to each cell of the converted map.

The national ecosystem survey of the Ministry of Environment has been performed at ten-year intervals to establish systematic nationwide natural conservation measures based on the 'Natural Conservation Law into Natural Environment Conservation Act', and the third survey was the latest to be completed. The second and third national ecosystem surveys were performed between 1997 and 2005 and between 2006 and 2012, respectively. Territories were divided by water systems and forests, and the survey was conducted on a representative mountain within the territory. A map-sheet-based survey was performed, where a single sheet of a topographic map with a 1:25,000 scale was selected as the survey unit and was divided into a nine by nine grid (2′30″ along the latitude and longitude), with each cell surveyed [30,31]. The national ecosystem survey in Korea contains data uncertainty because wildlife habitats are indirectly presumed from traces and excrement. However, this study adapted the national ecosystem survey data because wild animal species data are very limited in Korea.

Although all species cannot be evaluated with the same criteria because each species has its own characteristics, the evaluation process in this study is suggested for general evaluations, such as the selection of dam reservoir sites. Therefore, this evaluation method will be useful for overall HS but cannot show the HS for specific wildlife. In addition, this study does not consider the uncertainty of observed wildlife habitat data because the survey period was long (1997–2013), and we assumed all environmental changes from dam construction were greater than the uncertainty within surveys. The order of wildlife migration is adapted from habitat monitoring analysis based on land cover in the Han River. Based on these studies, the indices were unequally assigned considering the degree of their effects on wildlife migration, resulting in the following order: urbanized area and residential area > greenhouse cultivation > rice paddy and field farmland > pasture and orchard > natural grassland and shrub forest > natural forest along the Han River, South Korea [28,29].

3. Results

3.1. Spatial Assessment of Geomorphic Variables

Figure 6 and Table 1 show the results of the geomorphic variable classification based on Figure 3. Classification areas of 0.5 and 1.0 were relatively close and the dominant classification area is slightly more than 50% of the total area in Table 1. Figure 6 shows the spatial distribution of geomorphic variable classification indices. The geomorphic variables of altitude, slope steepness, and slope aspect have high indices at the reservoir borders and in upstream areas of the reservoir.

Table 1. Classification area of the Hantan River Dam reservoir in geomorphological variables.

Variables	Classifications	Grading Standard	Area (10^3 m^2)	Percent (%)
Altitude	Recessive area (others)	0.5	367,020	48.6
	Dominant area (100–170 m)	1.0	388,165	51.4
Slope steepness	Recessive area (others)	0.5	303,584	40.2
	Dominant area (0°–15°)	1.0	451,601	59.8
Slope aspect	Recessive area (others)	0.5	316,423	41.9
	Dominant area (Flat, 22.5°–157.5°)	1.0	438,762	58.1

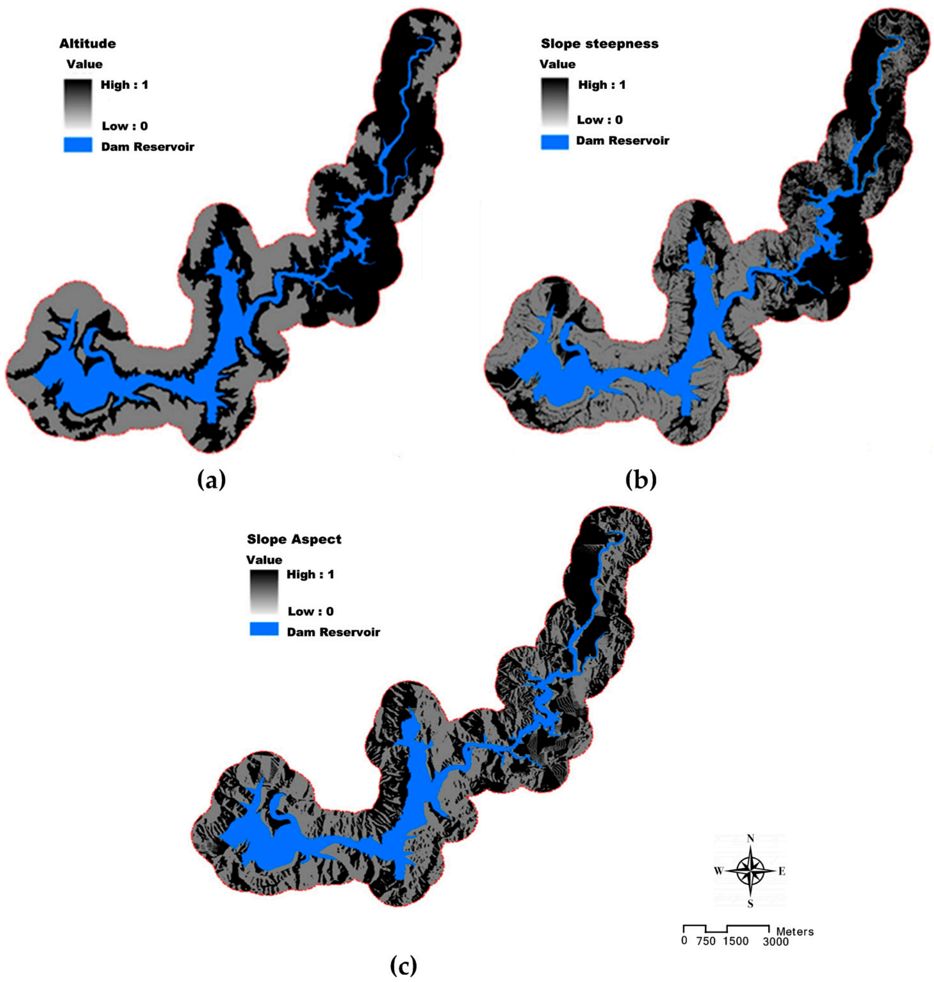

Figure 6. Spatial classification of geomorphic variables: (**a**) Altitude; (**b**) Slope steepness; and (**c**) Slope aspect.

3.2. Spatial Assessment of Vegetation Variables

The results of the spatial classification of vegetation variables are represented in Figure 7 and Table 2. Generally, all three vegetation variables show similar results. The vegetation variables of forest physiognomy, vegetation type, and tree age show high scores in the downstream area and to the west of the midstream reservoir, while geomorphological variables show high scores upstream of the reservoir. In particular, forest physiognomy shows high scores both upstream and downstream of the reservoir (Figure 7a). Table 2 shows that natural forest for forest physiognomy, unforested area for forest type, and 21–30 years for tree age were the dominant classifications, respectively.

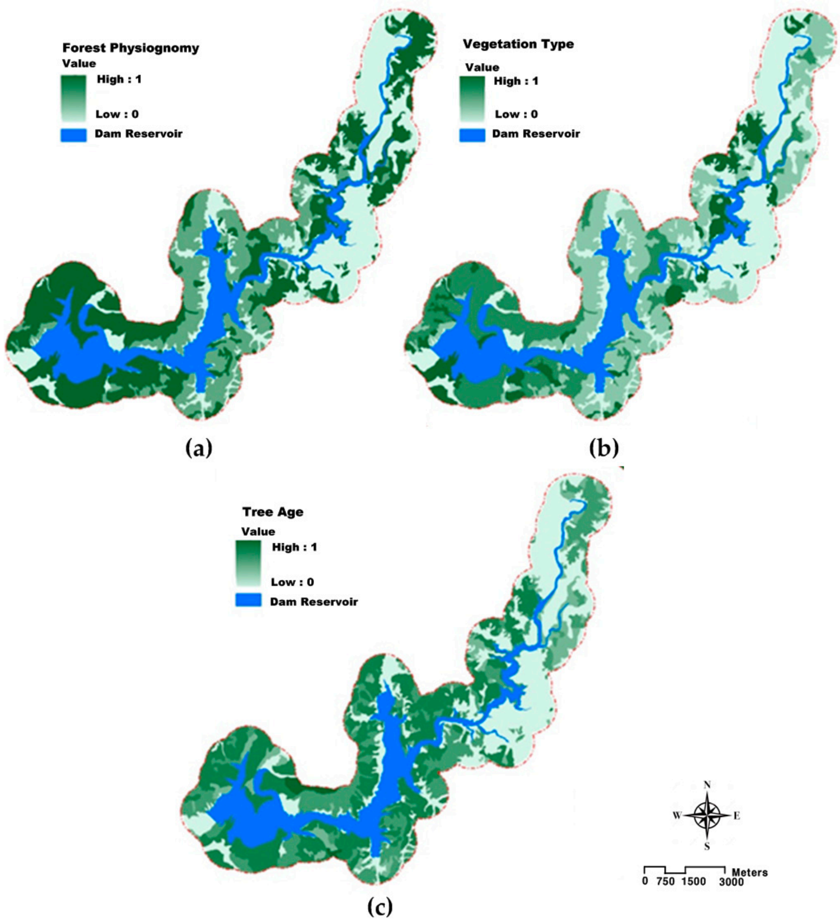

Figure 7. Spatial classification of vegetation variables: (**a**) Forest physiognomy; (**b**) Vegetation type; and (**c**) Tree age.

Table 2. Classification area of the Hantan River dam reservoir in vegetation variables.

Variables	Classifications	Grading Standard	Area (10^3 m^2)	Percentage
Forest physiognomy	Unforested	0.0	258,531	34.2
	Plantation	0.5	181,311	24.0
	Natural forest	1.0	315,343	41.8
Vegetation type	Non-forest	0.0	258,531	34.2
	Coniferous forest	0.3	234,790	31.1
	Deciduous forest	0.7	175,655	23.3
	Mixed forest	1.0	86,209	11.4
Tree age	Non-forest	0.0	258,531	34.2
	1~10	0.2	0	0.0
	11~20	0.4	60,795	8.1
	21~30	0.6	173,131	22.9
	31~40	0.8	254,994	33.8
	Over 40	1.0	7734	1.0

3.3. Spatial Assessment of Ecological Variables

Figure 8 and Table 3 show the results of the spatial assessment of ecological variables. Dominant classes in ecological variables are grade 2, no data, and forest for EQI, ECVA, and land cover, respectively, as shown in Table 3. EQI and land cover indices showed very similar spatial HSI distributions and were high predominantly from the midstream to the downstream reservoir areas and to the northwest of upstream areas. The ECVA only had high indexes in patches that coincided with high scores for EQI and land cover variables as well. Land cover indices were high predominantly in the downstream reservoir area (Figure 8c), and each of the vegetation variables had high indices primarily in the downstream area (Figure 7), which implies that the downstream area should have high overall ecological indices. As shown in Figure 8, the areas with high vegetation variable indices also have high ecological nature status indices, and tend to be vegetation preservation areas.

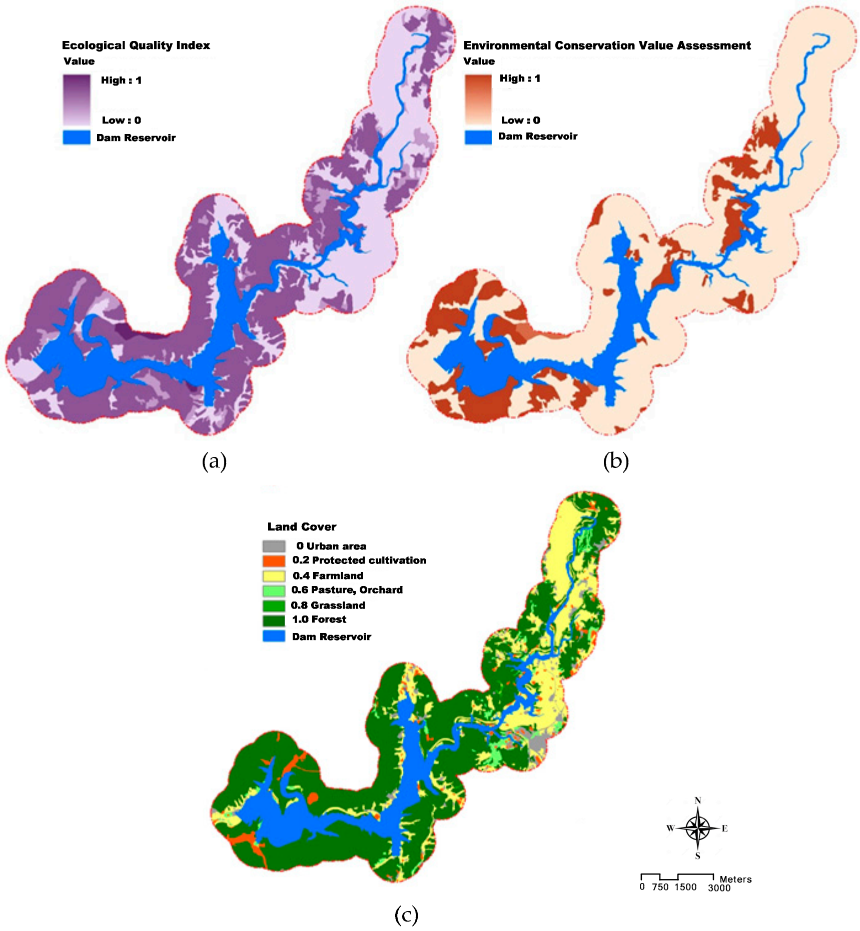

Figure 8. Spatial classification of ecological variables: (**a**) Ecological quality index; (**b**) Environmental conservation value assessment; and (**c**) Land cover.

Table 3. Classification area of the Hantan River Dam reservoir in ecological variables.

Variables	Classifications	Grading Standard	Area (10^3 m^2)	Percent (%)
Ecological quality index	No data	0.0	280,316	37.1
	Grade 3	0.3	51,209	6.8
	Grade 2	0.7	416,944	55.2
	Grade 1	1.0	6716	0.9
Environmental conservation value assessment	No data	0.0	595,280	78.8
	Grade 5	0.3	6716	0.9
	Grade 4	0.7	153,189	20.3
	Grade 3	1.0	0	0.0
Land cover	Urban area	0.0	0	0.0
	Protected cultivation	0.2	33,969	4.5
	Farmland	0.4	26,278	3.5
	Pasture, orchard	0.6	184,085	24.4
	Grassland	0.8	22,942	3.0
	Forest	1.0	487,911	64.6

3.4. Spatial Assessment of Combined Overall Variables

The map generated using the overlay method is shown in Figure 9. After dam construction, the total study area changed from 906,457 × 10^3 m^2 to 755,185 × 10^3 m^2 (83.3% of the pre-dam area) owing to the rise in water levels. The total area of each evaluation index value (0–1) is shown in Table 4. The area with an index value of 0.64–0.73 was the largest, at 20.0% of the total study area. The area with an evaluation index of less than 0.27 was only 6.8% of the total area. Ecologically healthy areas, i.e., those with cumulative evaluation indexes >6.5, accounted for 20.3% of the total area (0.73–0.82, 9.6%; 0.82–0.91, 9.7%; 0.91–1, 1.0%).

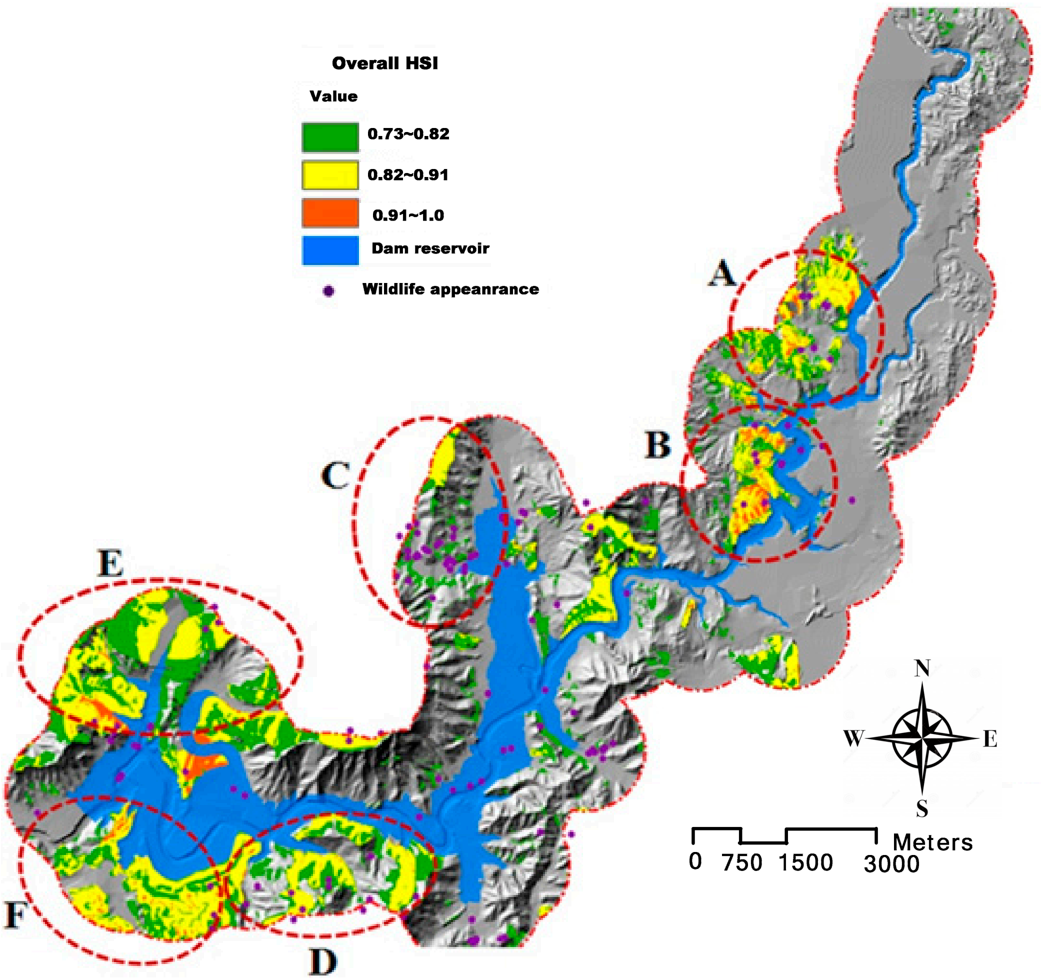

Figure 9. HSI values and wildlife locations in the Hantan River Dam reservoir area.

Figure 9 overlays the ecological quality map with observed wildlife locations from national ecosystem survey data from the Ministry of Environment [29]. This study assumed that superior wildlife habitats and ecologically healthy areas have an HSI between 0.73 and 1 in Table 4. Areas with an HSI between 0.73 and 1 contain 72% of observed wildlife locations, as shown in Figure 9. The ecologically healthy areas are concentrated into six large areas (A–F in Figure 9). The wildlife appearances are low in A and B, at 7% and 8%, respectively, and on the eastern side of the upper stream, where wildlife was not observed. Land use in this area is mostly fields and paddies, as shown in Figure 8c, which explains the low ecological indices in this area; a forest patch on the western side of the reservoir also had a low ecological index. The areas labeled C and D have relatively high HSIs and wildlife appeared frequently, at 24% and 11%, respectively, demonstrating that the results of this study are reliable. However, for the areas labeled E and F, no wildlife appearances were noted, despite the high HSIs. Although E and F represent relatively high classifications in terms of vegetation and ecological variables (Figures 7 and 8), wildlife appearances were rare, at 6% and 3%, respectively. This may be a problem of accessibility, linked to the presence of fences and other restrictions. To confirm the reliability of our results, comparison with more site data will be needed. However, as our study was conducted with all available data, the results are assumed to be reliable because estimated high HSI areas (0.73–1.00) in this study matched with 72% of observed wildlife habitats locations.

Table 4. Evaluation results for ecological areas of the Hantan River Dam. HSI: Habitat Suitability Index.

Overall HSI	Area (10^3 m^2)	Percent (%)
0.04–0.09	37	0.0
0.09–0.18	1275	0.1
0.18–0.27	60,764	6.7
0.27–0.36	169,932	18.7
0.36–0.45	23,647	2.6
0.45–0.55	20,593	2.3
0.55–0.64	113,426	12.5
0.64–0.73	181,640	20.0
0.73–0.82	87,199	9.6
0.82–0.91	87,740	9.7
0.91–1.00	8932	1.0
Dam reservoir	151,272	16.7
Total	906,457	100

4. Conclusions

This study presented the impacts of geomorphic, vegetation, and ecological variables to an ecologically healthy area in the Hantan River Dam reservoir, South Korea, because dam construction affects those variables. We applied a standardized HSI score for each variable to quantify the nine selected variables in geomorphic, vegetation, and ecological categories. Our method can be applied to other cases, where the standardized HS index can be used to assess ecologically healthy areas near dam reservoirs. Indices such as these can also be used to plan individual ecological restoration strategies for other dam reservoir areas. The assessment model developed in this study evaluates ecologically healthy areas around dam reservoirs and can be used to make ecological restoration plans in the future. By analyzing the area and determining the ecologically healthy area, which means the area suitable for wildlife habitat, using various variables, locations of restoration points can be selected, and habitat restoration plans can be made for specific taxa by analyzing observed wildlife locations. Although this study focused on the dam reservoir area based on terrestrial animals, a similar model could, and should, be created for the effects on rivers and reservoir environments. To do so, hydraulic and water quality effects, riverbed structure, and other variables should be included as evaluation variables. Application of this HSI-based evaluation model to dam reservoirs, as well as qualification of the ecological value of the surrounding areas must be carried out through a long-term survey, and subsequent improvement to the model should follow in the future.

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Conflicts of Interest: The authors declare no conflict of interest.

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