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Development of the Wetland Condition Index (WCI) by Combining the Landscape Development Intensity Index (LDI) and the Water Environment Index (WEI) for Humid Regions of China

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Abstract: Human use and management have a marked effect on wetland from different scales; it is necessary to develop a multi-scale integrated method to assess wetland conditions. So, this research aids the development of the wetland condition index (WCI) for humid regions of China by combining two main sub-indices: (i) the landscape development intensity index (LDI), which assesses human-dominated impacts; and (ii) the water environment index (WEI), which assesses changes in water quality and phytoplankton. We measured terrain and land use in the watersheds of wetlands using remote imaging data with geographic information systems (GIS) software. Also, we monitored the physical and chemical variables of the water bodies of 27 wetlands in urbanized and moderately urbanized areas in Nanjing City of China for this study. There were significant inconsistencies between the city's level of development and the values of the WCI and its sub-indices. The WCI of urbanized areas was better than that for moderately urbanized areas, and the sub-indices LDI and WEI were only slightly correlated. In other words, wetlands with a low LDI value did not necessarily have a low water environment index value. Due to wetland restoration and human management activities, integrating the LDI and WEI is increasingly necessary for wetlands in urbanized areas than for moderately urbanized areas. This method could guide the design of wetlands to optimize their qualities and benefits to residents and reinforce wetland conservation.

Keywords: water quality; landscape development intensity index; artificial wetland; wetland condition assessment

1. Introduction

Wetlands are known to be essential providers of valuable ecosystem services and functions, including the provision of habitat and biodiversity, water quality improvement, flood abatement, carbon sequestration, the source of food, and support of recreational activities [1–4]. Unfortunately, due to various natural and human factors, such as climate change, water pollution, and reclamation, wetlands have suffered severe losses and degradation around the world [5–8]. In order to protect wetlands, a large number of wetland condition assessment studies have been conducted to obtain wetland quality information [9–12].

Current wetland condition assessment methods can be classified into two main types according to different scales: the landscape scale (Scale-1) and the field scale (Scale-2) [13,14]. Scale-1 relies mostly on remote sensing data and geographic information systems (GIS) to obtain information about the land surface in wetland watersheds. The landscape development intensity index (LDI) [15–17] and watershed sustainability index [18] are commonly used for Scale-1 assessments. Such assessments are based on characterizing human disturbance gradients to predict wetland conditions. The advantages of the Scale-1 method are its cost efficiency and rapid assessment [19]. However, the Scale-1 method has obvious defects. The Scale-1 method presupposes that land surface in wetland watersheds can predict water quality or diatoms in wetlands [19–21]. Especially in artificial wetlands or urban wetlands, which are greatly affected by human interaction, use of the Scale-1 method has difficulty predicting wetland condition. For example, there are ditches in wetland watersheds that can change the natural patterns of runoff; therefore, runoff from the wetland watersheds will frequently not enter receiving wetlands [22]. Thus, the Scale-1 method has difficulty predicting wetland conditions for specific cases.

The Scale-2 method is the field-based method for which physicochemical and biochemical assessment procedures are employed to collect rigorous data about wetlands. The index of biotic integrity (IBI) [22] and the water quality index [23] require extensive fieldwork to complete a Scale-2 assessment. This method can directly assess wetland condition, but it ignores the influence of runoff from wetland watersheds for wetlands with poor water quality in high-density population watersheds. In order to quickly improve water quality, wetland restoration activities, such as mechanical dredging, water exchange, and the introduction of aquatic plants are used to improve water quality and ecosystem structure. If the Scale-2 method is used to assess wetland conditions, a higher index (good condition) will be included in the result. Many studies concluded that wetland restoration could change the wetland condition within a short period, but suitable wetland conditions may not persist because of poor watershed conditions [24,25]. Thus, the Scale-2 method may not accurately predict the wetland condition.

The use of Scale-1 or Scale-2 methods individually cannot accurately assess wetland conditions. Integration of both Scale-1 and Scale-2 methods may be a suitable approach under these conditions. Several studies have suggested that it is essential to develop an integrated index based on Scale-1 and Scale-2 for wetland condition assessments [26,27], but few methods of integration are available. Martínez-López et al. [28] used indices that combine wetland plant indicators and landscape characteristics to assess wetland conditions, but their method applied only to semiarid wetlands under agricultural hydrological regimes, because its watershed hydrological condition index was developed under the characteristics of infrequent rains, low groundwater tables, and hydrological change by anthropic stress on irrigation.

The need for the integration of both Scale-1 and Scale-2 methods for artificial wetland condition assessment is now especially urgent in China. Although several wetland evaluation indicator systems have been developed [29,30], these methods can be difficult to meet the needs of wetland condition assessment and management, ignoring the coupling of two scales. As a result, at present, governmental environmental agencies still focus on monitoring and evaluating wetland water quality parameters. The main aim of this study was to develop a new wetland condition index based on integrating the Scale-1 and Scale-2 methods for comprehensively and accurately assessing the wetland condition in the humid regions of China, which can help to promote wetland sustainability.

2. Methodology

2.1. Basic Idea

It is important to consider the relationship between the parts and the whole when evaluating wetland condition [31]. If the quality of the whole is not good, then the quality of the part will be impacted [32]. Given that a wetland is a part of the watershed, e.g., the wetland condition depends critically on human activities that affect land use throughout the watershed [33], neither measurement of human activities in the watershed area nor the monitoring of wetland ecological factors can comprehensively and accurately assess the status of the wetland–watershed ecosystem. we developed the wetland condition index (WCI) to evaluate wetland condition combining the landscape development intensity index (LDI) and the water environment index (WEI). The procedure established for WCI is shown in Figure 1.

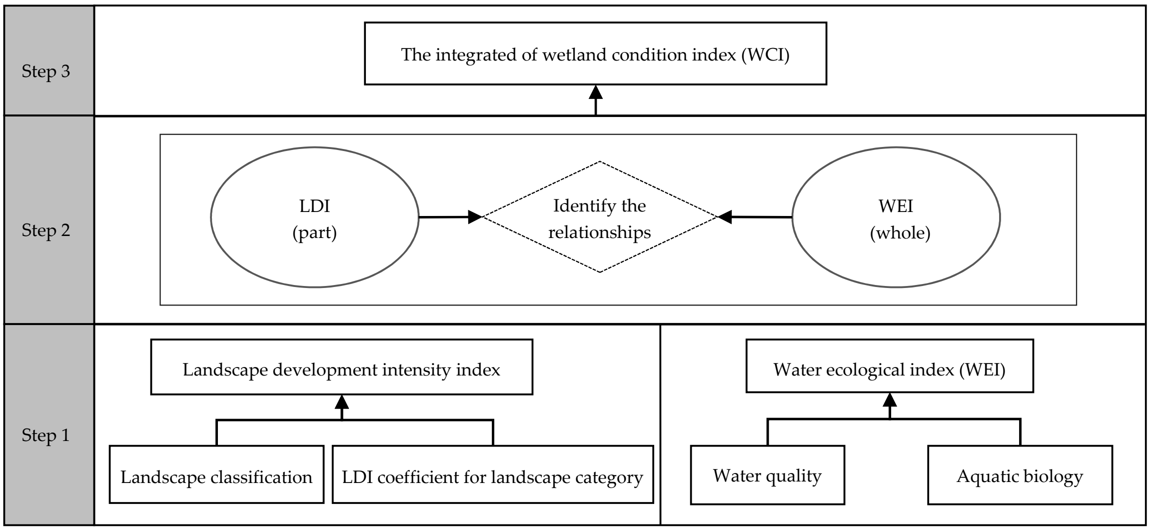

Figure 1. Methodological schema for forming the wetland condition index.

2.2. The Landscape Development Intensity Index (LDI)

The condition of a wetland is strongly related to the levels of human activity that occur within the surrounding watershed. Land-use data and a development-intensity measure that is derived from the energy use per unit area are included in the LDI, which is capable of quantifying the potential effects of a significant number of human activities that impact ecological systems within watersheds of varying sizes [15,34]. The LDI is calculated as shown in Equation (1) [15,26]:

$$\mathrm{LDI} = \sum \%\mathrm{LU_i} * \mathrm{LDI_i}, \tag{1}$$

where $\%\mathrm{LU_i}$ is the percent of the total area in land use/land cover i, and $\mathrm{LDI_i}$ is the LDI coefficient for land-use/land-cover category i (Appendix 1 in [17]). The LDI coefficient is calculated as the normalized natural log of the empower densities. Referred to as "empower density", energy use per area per time is calculated as average values for land-use categories from previous studies [15]. The LDI coefficient is normalized on a scale from 1 to 10, with the LDI coefficient for natural lands equal to 1.0, and an LDI coefficient of 10.0 for the highest intensity land use. Detailed methods on LDI are provided in Chen and Lin [17].

2.3. The Water Environment Index (WEI)

The water environment is characterized by chemical and biological parameters [35], and the WEI is developed from these two factors to identify the quality of surface water in wetlands. The water quality index and aquatic biological index were identified as a suite of key indicators that can be further evaluated for long-term water monitoring and wetland assessments [36].

Based on the "wetland ecological monitoring technology regulations" formulated by the Chinese wetland ecosystem research station alliance (SFBSS 2013), total nitrogen (TN, mg/L), total phosphorus (TP, mg/L), and phytoplankton biomass (PB, g/m^3) are considered indicators of nutrient enrichment, and are the metrics comprising the WEI. The monitoring period for the wetland assessment is designated at least for one year, and wetland sampling was conducted once per month [37,38]. The WEI can be written as follows [39,40]:

$$\mathrm{WEI} = \omega_{\mathrm{TN}} * \mathrm{WEI}(\mathrm{TN}) + \omega_{\mathrm{TP}} * \mathrm{WEI}(\mathrm{TP}) + \omega_{\mathrm{BP}} * \mathrm{WEI}(\mathrm{PB}), \tag{2}$$

WEI(TN), WEI(TP), and WEI(PB) can be calculated by Equation (3); ω_{TN}, ω_{TP}, and ω_{BP} can be calculated using Equation (4):

$$\mathrm{WEI}(\mathrm{X}) = 10 * \frac{\mathrm{C_X} - \mathrm{C_{Xmin}}}{\mathrm{C_{Xmax}} - \mathrm{C_{Xmin}}}, \tag{3}$$

$$\omega_{\mathrm{i}} = 0.5 * \left(\frac{\mathrm{r}_{\mathrm{iTN}}^2}{\sum_1^n \mathrm{r}_{\mathrm{iTN}}^2} + \frac{\mathrm{r}_{\mathrm{iTP}}^2}{\sum_1^n \mathrm{r}_{\mathrm{iTP}}^2} \right), \tag{4}$$

where X represents TN (Total Nitrogen), TP (Total Phosphorus), and PB (Phytoplankton Biomass); WEI(X) represent the partial indices of X; $\mathrm{C_X}$ is the value of X for the wetland; $\mathrm{C_{Xmax}}$ and $\mathrm{C_{Xmin}}$ are the maximum and minimum values of X for the wetland during the monitoring period; ω_{i} is the weighting factor of the *i*th WEI index (e.g., WEI(TN), WEI(TP), and WEI(PB)); $\mathrm{r_{iTN}}$ is the correlation coefficient between the *i*th indicator concentration and the TN concentration; and $\mathrm{r_{iTP}}$ is the correlation coefficient between the *i*th indicator concentration and the TN concentration. In most wetlands, TN and TP are the most essential elements for the wetland ecosystem, and they have a close relationship with ecosystem health status [41,42]. For example, elevated concentrations of TN and TP trigger eutrophication, the known consequences of which include blooms of noxious phytoplankton, hypoxia, and the degradation of recreational opportunities [43]. As the most important nutrient-related indicator in the Chinese Surface Water Quality Standard (GB3838-2002), concentrations of TN and TP are divided into five levels (Class I–Class VI), in which the lower TN and TP values indicate higher water quality [44]. Thus, TN and TP were selected as the basic indicators to calculate the correlation coefficient. The WEI ranges from 0 to 10, and lower values of WEI correspond to better ecological conditions in the wetland. Detailed methods on WEI are provided in Xu et al. [40].

2.4. Construction of the Wetland Condition Index (WCI)

There are two main steps involved in calculating the WCI. The first step is to calculate the LDI* and WEI*. The second step is to identify the relationship between the LDI* and WEI*. After that, the WCI can be calculated according to the requirements about the LDI* paired with WEI* in Table 1.

Table 1. The equations of the wetland condition index (WCI) for different conditions. LDI: landscape development intensity index, WEI: water environment index.

Equations	Requirements about LDI* Paired with WEI*	Illustration
$\mathrm{WCI} = \mathrm{LDI}^*$	L1W2 L1W3 L1W1 and LDI* < WEI*	L*i* and W*i* represent the ranges of LDI* and WEI* respectively, as described in Figure 2.
$\mathrm{WCI} = \mathrm{WEI}^*$	W1L2 W1L3 W1L1 and WEI* < LDI*	
$\mathrm{WCI} = (1 - 0.5\alpha) * (\mathrm{LDI}^* + \mathrm{WEI}^*)$	L2W2 L2W3 L3W2	
$\mathrm{WCI} = (1 - 0.5\alpha + \beta) * (\mathrm{LDI}^* + \mathrm{WEI}^*)$	L3W3	

In Table 1, where the LDI* and WEI* are determined by subtracting the LDI and WEI from 10 (Equations (5) and (6)), considering that the LDI and WEI are inversely proportional to the wetland conditions (i.e., higher values of the LDI and WEI correspond to lower WCI); α is the Pearson correlation coefficient between the LDI* and WEI*, which is used for elimination of the impact of collinearity between them [45]; β is the cumulative function (Equation (7)).

$$\mathrm{LDI}^* = 10 - \mathrm{LDI}, \tag{5}$$

$$\mathrm{WEI}^* = 10 - \mathrm{WEI}, \tag{6}$$

$$\beta = \frac{\mathrm{LDI}^* - \mathrm{LDI}^*_{\mathrm{com}}}{\mathrm{LDI}^*_{\mathrm{com}} - \mathrm{LDI}^*_{\mathrm{res}}} + \frac{\mathrm{WEI}^* - \mathrm{WEI}^*_{\mathrm{com}}}{\mathrm{WEI}^*_{\mathrm{com}} - \mathrm{WEI}^*_{\mathrm{res}}}, \tag{7}$$

In Equation (7), the restriction ($\mathrm{LDI}^*_{\mathrm{res}}$ and $\mathrm{WEI}^*_{\mathrm{res}}$) and compensation threshold ($\mathrm{LDI}^*_{\mathrm{com}}$ and $\mathrm{WEI}^*_{\mathrm{com}}$) have special meanings, which can identify wetlands in poor and good conditions (Figure 2). Especially, the compensation threshold emphasizes an ecological concept that high-quality wetlands can mitigate the loss of ecological functions caused by the decline of other wetland conditions. This concept is supported by numbers of ecological theories (including but not limited to landscape ecology, metapopulation, source-sink dynamics, and river continuum concept) and wetland ecological restoration practice [46–48]. For example, water diversion from high-quality wetland might decrease the contents of nutrients and organic pollutants in a low-quality wetland, thereby improving the ecological function [49]. The threshold values applied to the LDI*, TN, TP, and PB parameters in this study and their sources are summarized in Table 2. It should be noted that given the requirements of government wetland management, we determined the TN, TP, and PB parameters' threshold according to GB3838-2002, which is the guidance manual for wetland water quality management by Chinese governmental environmental agencies. The standard value of Class IV is selected as the restriction threshold because it is the red line of water quality management, and the standard value of Class I is selected as the compensation threshold due to the requirement of wetland ecological protection in China [44]. In the end, the $\mathrm{WEI}^*_{\mathrm{com}}$ and $\mathrm{WEI}^*_{\mathrm{res}}$ are 8.8 and 5.6, respectively, using Equation (2).

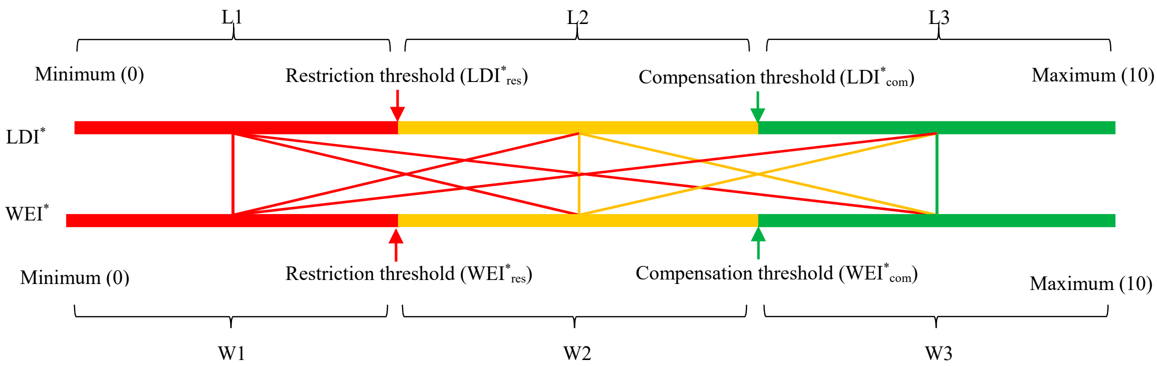

Figure 2. The nine situations (connecting line) about LDI* paired with WEI* (the red line represents L1W1, L1W2, L1W3, W1L2, and W1L3; the yellow line represents L2W2, L2W3, and L3W2, and the green line represents L3W3). L1 (red rectangle above), L2 (yellow rectangle above), and L3 (green rectangle above) represent the value of LDI* ranged from 0 to $\mathrm{LDI^*}_{\mathrm{res}}$, $\mathrm{LDI^*}_{\mathrm{res}}$ to $\mathrm{LDI^*}_{\mathrm{com}}$, and $\mathrm{LDI^*}_{\mathrm{com}}$ to 10, respectively, while W1 (red rectangle below), W2 (yellow rectangle below), and W3 (green rectangle below) are the same. The WCI calculated formulas from different pairs of LDI* and WEI* are listed in Table 1.

Table 2. Summary of threshold limits for constituents.

WCI Constituent		Good Condition (Compensation Threshold)	Poor Condition (Restriction Threshold)	Source
LDI*		8	5	[15]
WEI*	TN (mg/L)	0.2	1.5	[44]
	TP (mg/L)	0.02	0.3	[44]
	PB (g/m^3)	0.04	4.10	[44]

We assumed the value of the LDI* has three ranges (0–LDI^*_{res}, LDI^*_{res}–LDI^*_{com}, and LDI^*_{com}–10), while the value of WEI* also had three ranges (0–WEI^*_{res}, WEI^*_{res}–WEI^*_{com}, and WEI^*_{com}–10). So, in the end, the LDI* and WEI* have nine paired relationships (Figure 2). The corresponding equations were listed in when they met the following conditions:

- When the LDI* is less than the restriction threshold, the LDI* is the restricting factor of the WCI regardless of the value of the WEI*, and the WCI will be equal to the LDI*.
- If the WEI* is less than the restriction threshold, the WEI* is the restricting factor of WCI regardless of the value of the LDI*; then, the WCI will be equal to the WEI*. For example, if a wetland is downstream of livestock farms, the landscape in the wetland watershed is in a natural state with no buildings or agriculture, but the water quality of the wetland is poor because of the livestock wastewater, not the landscape structure or quality. In this situation, the WCI is determined by the water quality, and is equal to WEI*.
- If the LDI* is between the restriction and compensation thresholds, the WEI* is between the restriction and compensation threshold, and the WCI will be equal to the sum of the LDI* and WEI* with the same weights.
- If the LDI* and WEI* are both higher than the compensation threshold, then the WCI will be higher than the sum of the LDI* and WEI*. In this case, the quality of the wetland is high enough to provide compensatory ecological functions.

3. Case Study

3.1. Xianlin Sub-City

The Xianlin sub-city covers an area of 75 km^2 and is located east of the city of Nanjing in China's Jiangsu Province (Figure 3). The sub-city has a current population of 300,000, although the population is expected to double to 600,000 by 2030. Nanjing is the capital city of Jiangsu Province, and is a typical developing city in the Yangtze River Delta (YRD). A northern subtropical monsoon climate prevails in the area with a mean annual rainfall of 1100 mm. The Xianlin region is one of the three sub-cities of Nanjing, and has been divided into four sub-regions: Xianhe, Baixiang, Qinglong, and Qilin. Xianhe and Baixiang are urbanized regions, whereas Qinglong and Qilin are moderately urbanized regions [50] (Table 3).

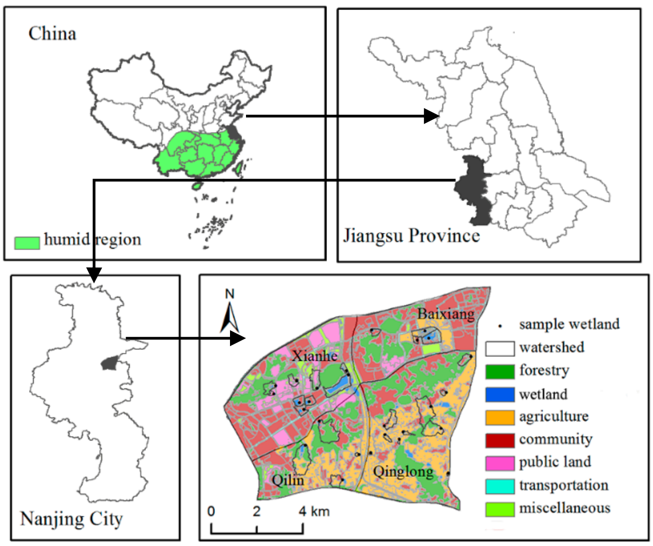

Figure 3. Location of the study area, land-use categories, and sample locations in the Xianlin sub-city.

Table 3. Area of total wetlands and selected sampling points in the four sub-regions.

Sub-Region	Development Stage	Total Wetland Rate (%)	Total Area (km^2)	Sampled Wetland	Average Area of the Sampled Watershed (km^2)	Average Area of Sampled Wetland (km^2)
Xianhe	urbanization	4.08	21.2	9	0.19	0.05
Baixiang	urbanization	3.35	15.0	4	0.20	0.05
Qinglong	moderate urbanization	4.41	24.7	10	0.16	0.01
Qilin	Moderate urbanization	3.86	13.9	4	0.40	0.04

3.2. Data Collection and Analysis

A land-cover/use map was derived from our previous work [51], in which remotely sensed QuickBird data were used to obtain land-cover/use information in 2009 (Figure 4), and the accuracy approached 96%. Seven major land-cover/use categories are considered in this study, namely, forestry, wetland, agriculture, community, public land, transportation, and miscellaneous. It is based on the land-use classification of China (GBT 21010-2007) (China's national standard, 2007), but differs slightly. Community use includes residential and commercial use, and public land is composed of government, institutions, and schools. Especially, we distinguish the wetland from the others. A high-quality digital elevation map (DEM) with a resolution of 5 m and a map of the municipal pipe networks were used to extract the watersheds for the wetlands.

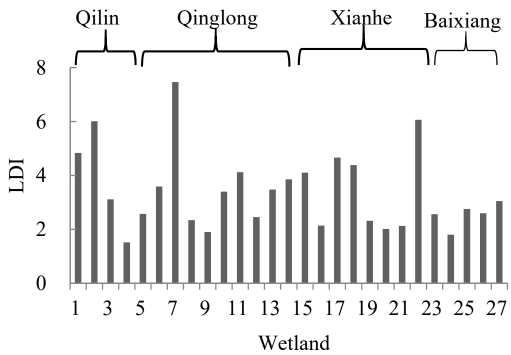

Figure 4. LDI of different wetland watersheds.

Water quality data were collected from 27 wetlands (Figure 3) at the end of each month from 2009 to 2010, and the sampled wetland was randomly selected. Water samples were analyzed for TN, TP, and PB after collection in 1000-mL low-density polyethylene sample containers. Each sampling collection event was repeated three times. The TN, TP, and PB were measured three times in the laboratory according to procedures for the monitoring and analysis of water and wastewater [44].

3.3. Landscape Development Intensity of the Xianlin Sub-City

The LDI of each wetland was calculated to identify the human disturbance gradient in the wetland watershed. Figure 4 shows the LDI values of 27 sampled wetlands in the Xianlin sub-city. The resulting values range from 1.52 to 7.46. Of the 27 wetlands, only three (11% of the total number of wetlands) had LDI values <2. More than 48% of the area of these wetlands was covered with forest and/or grassland, which indicates relatively low anthropogenic disturbance. Three wetlands were completely human-made, and each had LDI values >5. These constructed wetlands were surrounded by roads, houses, and schools, which suggests significant anthropogenic disturbance. The remaining watersheds had LDI values between two and five, which are typically associated with mixed landscapes (i.e., natural, agricultural, and urban). Also, the averages of the LDI in the urbanized area (Xianhe and Baixiang) and moderately urbanized areas (Qilin and Qinglong) are 3.12 and 3.51, respectively.

3.4. Water Environment Index of the Xianlin Sub-City

Table 3 shows the overall water quality and the WEI for different seasons. The average wetland depth was 992 mm. As expected, the summer values were significantly higher than the winter values because of the large amount of rainfall during the summer. The average seasonal values showed a decrease in TP from summer to winter. The TN ranged from 1.01 to 2.65 mg/L, with lower values during the spring and higher values during the summer. The average seasonal concentrations of TN increased from spring to summer, and subsequently decreased gradually to autumn. An analysis of variance (ANOVA) showed that the TP and TN were significantly higher in the summer than in the other seasons (lowercase letters in the rows in Table 4). The PB ranged from 4.50 to 11.73 g/m^3 with the lowest values in the winter and highest in the summer. The WEI was calculated based on the water quality index, and it was lower during the winter and higher during the summer, with values ranging from 2.53 to 4.51.

Table 4. Seasonal variation in water quality and the WEI in the Xianlin sub-city (average ± SD).

Water Index	Spring (n = 27)	Summer (n = 27)	Autumn (n = 27)	Winter (n = 27)	Average
D (Depth) (mm)	953 b ± 346	1158 a ± 336	1039 ab ± 381	817 b ± 405	992 ± 362
TP (mg/L)	0.26 ab ± 0.24	0.39 a ± 0.37	0.27 ab ± 0.22	0.13 b ± 0.15	0.26 ± 0.27
TN (mg/L)	1.01 b ± 1.42	2.65 a ± 1.98	1.30 b ± 0.12	1.86 ab ± 2.14	1.71 ± 1.80
PB (g/m^3)	8.76 ab ± 8.02	11.73 a ± 9.43	8.90 a ± 6.80	4.50 b ± 3.60	8.47 ± 6.96
WEI	3.05 a ± 0.85	4.51 b ± 0.79	3.75 a ± 0.81	2.52 a ± 1.11	3.56 ± 0.87

Note: An analysis of variance (ANOVA) showed mean values (lowercase letters) in rows that are significantly different ($p < 0.05$).

Figure 5 shows the variation of the WEI in the four regions. The average values and standard deviations of the WEI in Qilin, Qinglong, Xianhe, and Baixiang were 4.19 ± 3.08, 4.04 ± 0.98, 3.61 ± 2.56, and 1.62 ± 1.16, respectively. The values for Qilin and Qinglong showed more considerable seasonal variation than Xianhe and Baixiang (Figure 5), which indicates that the ecological conditions of wetlands in urbanized areas fluctuate less than wetlands in moderately urbanized areas. The averages of the WEI in urbanized areas (Xianhe and Baixiang) and moderately urbanized areas (Qilin and Qinglong) were 3.00 and 4.08, respectively.

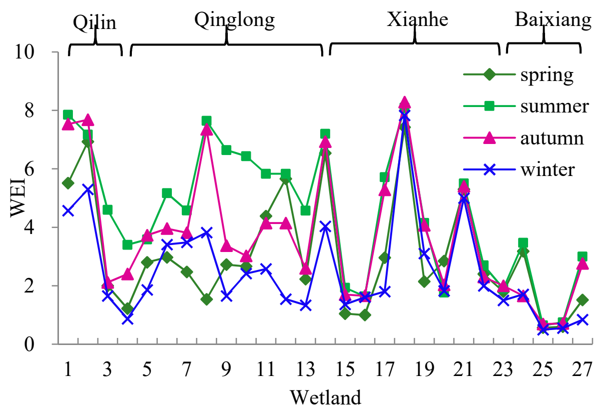

Figure 5. WEI seasonal values in different watersheds in different seasons.

3.5. Wetland Condition Index of the Xianlin Sub-City

The Pearson correlation coefficient (0.31) showed that the LDI* and WEI* were not correlated with each other. Thus, it was necessary to remove the overlap in the equation. The integrated values of the LDI* and WEI* and the WCI in 27 wetlands are shown in Figure 6. The resulting values of the WCI ranged from 0.53 to 13.64, and the average value of the 27 wetlands was 9.17. The wetlands in the best condition were located in Baixiang, where the WCI values were higher than 10. Qilin had the lowest WCI values in the study area. The WCI values indicated that 17 of the 27 wetlands, including those located in Qilin (2/7), Qinglong (6/10), Xianhe (5/9), and Baixiang (4/4), had WCI values >10. The remaining 10 wetlands had WCI values less than 10. The average WCI values in Qilin, Qinglong, Xianlin, and Baixiang were 8.04, 8.63, 8.73, and 12.65, respectively. The WCI value of the urbanized regions (9.93) was higher than that of moderately urbanized areas (8.46), which indicates that the nutrient levels in urbanized regions were better than in moderately urbanized areas. The reason may be that the moderately urbanized areas face more serious agricultural non-point source pollution and less capital investment for water environmental protection [52,53].

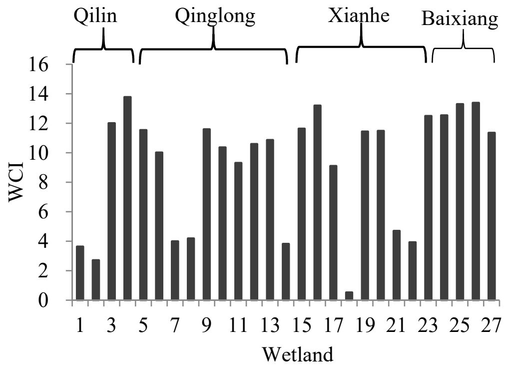

Figure 6. WCI of different wetland watersheds.

4. Discussion

4.1. Comparison of the WEI, LDI, and WCI

Assessments of the ecological conditions of wetlands are frequently required for purposes such as ecological reserve determinations, wetland management, and restoration planning. Indices of the ecological conditions of wetlands must be tested and validated to increase the reliability and reduce the uncertainty of such methods [54]. In this study, the LDI and WEI were integrated into the WCI. The relationships between these indices and the reasons that the LDI or WEI cannot be used alone to assess wetland conditions in areas with significant human management need explanation. Besides, the appropriate times and conditions for applying the LDI or WEI alone should be considered.

The Xianlin sub-city was used as a case study to apply the integrated method for determining wetland conditions. The differences between the WCI, LDI, and WEI were revealed in an urbanized region and a moderately urbanized region. The urbanized region is a recently designed urban area in which the balance between wetland conditions and human disturbance was considered during the design process. To maintain the wetland conditions, wetland restoration efforts, such as water exchange, silt clearance, and aquatic plant cultivation, were frequently applied. Therefore, a relationship between the LDI and WEI was not observed (Figure 7a, $R^2 = 0.035$, $p = 0.543$), and using only the LDI or the WEI (Figure 7b,c), and especially the LDI alone (Figure 7b), is not suitable for determining wetland conditions in this case. The moderately urbanized region in the Xianlin sub-city is mainly composed of farmland. The function of wetlands in moderately urbanized regions is to provide irrigated water and collect drainage from farmlands; thus, wetland restoration was not observed in the moderately urbanized regions, and the WEI and LDI values of these wetland watersheds were more significantly correlated (Figure 8a) than those in the urbanized regions. The proposed WCI showed a robust relationship with the WEI values (Figure 8c). The R^2 value in Figure 8c is higher than that in Figure 8b. In such cases, using the WEI alone can more accurately predict the WCI than using the LDI alone.

The uncertainty that is introduced by various wetland restoration and land management limits the usefulness of rapid assessments at the landscape scale (Scale-1), such as the LDI. Thus, detailed assessments at the ecosystem scale (Scale-2), such as the WEI, must be included to attain accurate results. In wetlands with lower levels of restoration or management effects, the LDI can be used to forecast wetland conditions with fewer deviations. However, to more accurately represent the conditions, the LDI and WEI should be integrated because it reduces uncertainty and increases the reliability when assessing wetland conditions.

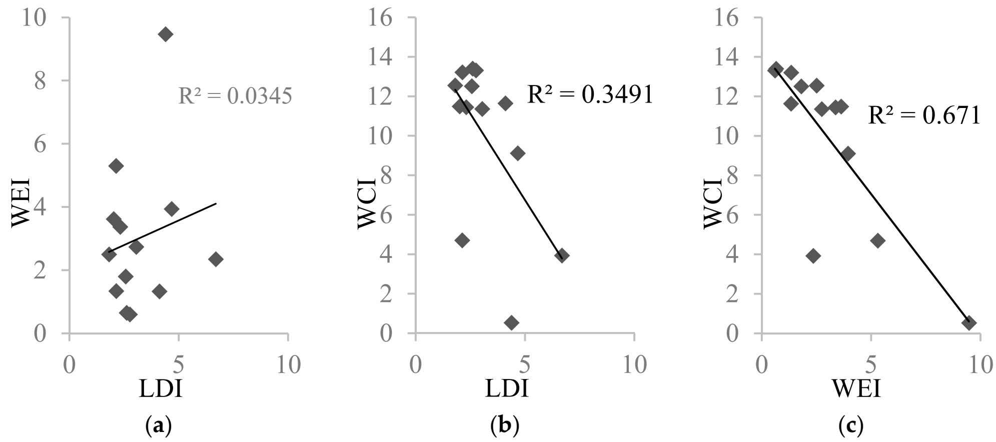

Figure 7. Linear regressions between the wetland condition index (WCI) and the values of the sub-indices in urbanized regions (Xianhe and Baixiang). Panel A shows the relationship between the LDI and WEI (n = 13). Panels (**a**–**c**) show the relationships between the WEI and LDI, the WCI and LDI, and the WCI and WEI (n = 13), respectively.

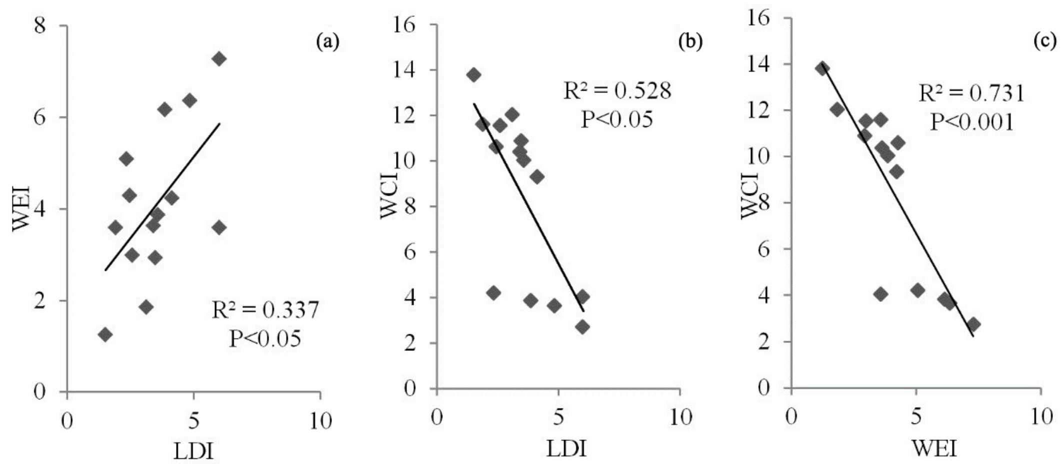

Figure 8. Linear regressions between the wetland condition index (WCI) and the values of the sub-indices in moderately urbanized regions (Qinglong and Qilin). Panel (**a**) shows the relationship between the LDI and WEI (n = 14). Panels (**b**,**c**) show the relationships between the WCI and LDI and the WCI and WEI (n = 14), respectively.

4.2. Comparing WCI to IBI and HGM

Current wetland condition assessment methods such as the IBI or hydrogeomorphic method HGM generally focus on either the biotic or abiotic components of wetlands [55]. The IBI was developed to use biological indicators to detect wetland conditions, coupled with ongoing use of this approach to assess water quality in streams, lakes, estuaries, etc. The HGM functional assessment method is predicated on the ability of hydrogeomorphic wetland classification and the visual assessment of alteration to provide reference standards against which functions in individual wetlands can be evaluated [56]. The IBI focuses on the wetland ecosystem itself, while the HGM mainly focuses on the characteristic hydrological and geomorphology in wetlands. These two methods emphasize different attributes and scales. WCI is a comparative method that combines both the water processes and landscape characteristics of wetland watersheds.

The HGM [57] and the index of biologic integrity (IBI) [58], which have gained the most notoriety and acceptance, utilize reference systems in their analysis. Biotic and abiotic parameters in the IBI or HGM are compared to those of reference communities. However, in the HGM, hydrological alterations, resulting in consistently low or high water table levels, were not correlated with a priori designations as reference and non-reference sites. Current practices for designating reference standard sites to assess wetland functions, at least in urbanized regions, are ineffective and potentially misleading [56]. Inherent to these comparisons is the assumption that functions change linearly through time. If 10 hydrophytic herbaceous plant species occur in the reference wetland and the assessed wetland has five species, an index of 0.5 would be calculated, signifying that the assessed wetland has 50% for that index. However, if the natural dispersion of hydrophytic herbaceous plant species follows a logarithmic relationship over time, we may only observe 10% for that index [55]. The key point is that the changing relationship (linear, logarithmic, or other relationship) of hydrophytic herbaceous plant species (or other biotic or abiotic parameters) is uncertain and difficult to define. Finally, most methods ultimately develop indices so that scores across functions can be accumulated with no reference, such as the WCI.

Wetland assessment in the Xianlin sub-city was also conducted by using the hydrogeomorphic method (HGM) [50]. Eight wetlands are appearing in this study, and also appear in [50] (Figure 9). The number of wetlands is three, 15, 16, 17, 20, 24, 25, and 27. The results of the HGM and WCI seem to indicate low significant relationships, according to Figure 9. This result may be connected to more variables being considered by the HGM than the WCI, and fewer wetland samples (only eight wetlands).

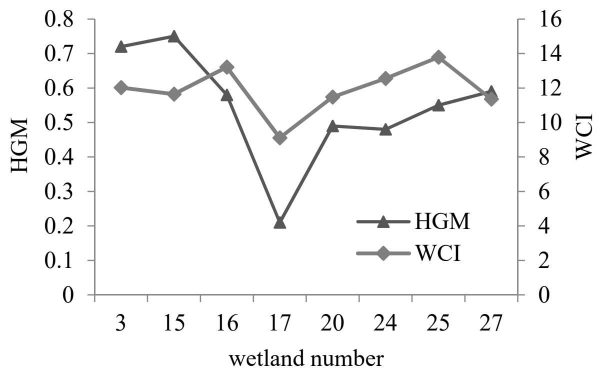

Figure 9. The values of WCI compared with the HGM in the wetland in Xianlin sub-city.

4.3. Evaluation of the WCI

There has been a large increase in interest in studying the impact of human activity on wetlands and their watersheds. Human impacts may be positive (e.g., wetland restoration) or negative (e.g., discharge sewage into a wetland) [59]. The uncertain nature of human impacts requires a comprehensive method of wetland assessment. The WCI is an integrated method that combines the LDI and the WEI, which express human disturbance in wetland watersheds and the ecological characteristics of wetlands, respectively. Although the WCI method is accurate and feasible, it needs to be refined further. First, the WEI sub-index is based on the wetlands where water samples can be collected (such as ponds and reservoirs near roads); however, other wetlands where water samples cannot be collected easily are common. Second, to integrate the LDI and WEI, the relationship between them must be identified. The Pearson correlation coefficient (*PCC*) was used to remove the overlap between the LDI and WEI. A population of LDI and WEI values is needed to determine the Pearson correlation, because it is not possible to correlate the LDI and WEI values for one watershed. Thus, the WCI is suitable for assessing several wetlands at a time. The WCI could be used for one wetland if the *PCC* of the LDI and WEI of its wetland type could be confirmed by establishing *PCC* reference standards. Third, the WEI is based on the total nitrogen, total phosphorus, and phytoplankton biomass, and does not include a broad range of toxicants, including xenobiotic chemicals, hydrocarbons, and heavy metals, the incidences of which are probably higher in urban areas [60,61]. Thus, the WEI can be improved for use in urban wetland assessments.

5. Conclusions

The WCI indicator offers a new perspective on assessing wetland conditions by combining two indicator scales. The following conclusions referring to the new indicator can be provided:

- To more accurately represent the conditions, the LDI and WEI should be integrated. Combining the WEI and LDI should consider the relationship between them. We developed a threshold weighting method to reduce the uncertainty and increase the reliability when assessing wetland conditions.
- The LDI is not suitable for artificial wetland conditions, especially in the urbanized regions in China. The WCI can identify and assess the wetland conditions, regarding the restoration and management of wetland.
- As the WCI has some advantages, we recommend the WCI as an alternative or complementary tool to assess the wetland conditions in the humid regions of China. However, there are several limitations of the WCI. First, the WEI is more about wetland water quality than ecological attributes. Thus, more ecological variables, such as aquatic vegetative and habitat variables, should be considered to calculate the WCI in the future. Second, more comparative studies, such as the IBI and HGM, should be conducted to improve the performance of the WCI.

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References

1. Nahlik, A.M.; Fennessy, M.S. Carbon storage in US wetlands. *Nat. Commun.* **2016**, *7*, 13835. [CrossRef]
2. Marazzi, L.; Gaiser, E.E.; Eppinga, M.B.; Sah, J.P.; Zhai, L.; Castañeda-Moya, E.; Angelini, C. Why Do We Need to Document and Conserve Foundation Species in Freshwater Wetlands? *Water* **2019**, *11*, 265. [CrossRef]
3. Jiang, H.; He, C.; Luo, W.; Yang, H.; Sheng, L.; Bian, H.; Zou, C. Hydrological Restoration and Water Resource Management of Siberian Crane (*Grus leucogeranus*) Stopover Wetlands. *Water* **2018**, *10*, 1714. [CrossRef]
4. Costanza, R.; de Groot, R.; Sutton, P.; van der Ploeg, S.; Anderson, S.J.; Kubiszewski, I.; Farber, S.; Turner, R.K. Changes in the global value of ecosystem services. *Glob. Environ. Chang.* **2014**, *26*, 152–158. [CrossRef]
5. Davidson, N.C. How much wetland has the world lost? Long-term and recent trends in global wetland area. *Mar. Freshw. Res.* **2014**, *65*, 936–941. [CrossRef]
6. Hu, S.; Niu, Z.; Chen, Y.; Li, L.; Zhang, H. Global wetlands: Potential distribution, wetland loss, and status. *Sci. Total Environ.* **2017**, *586*, 319–327. [CrossRef] [PubMed]
7. Max Finlayson, C. Forty years of wetland conservation and wise use. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2012**, *22*, 139–143. [CrossRef]
8. Smardon, R. Wetlands and Sustainability. *Water* **2014**, *6*, 3724–3726. [CrossRef]
9. McLaughlin, D.L.; Cohen, M.J. Realizing ecosystem services: Wetland hydrologic function along a gradient of ecosystem condition. *Ecol. Appl.* **2013**, *23*, 1619–1631. [CrossRef] [PubMed]
10. Hargiss, C.L.M.; DeKeyser, E.S.; Norland, J.E.; Ell, M.J. Comparing tiers of a multi-tiered wetland assessment in the Prairie Pothole Region. *Wetl. Ecol. Manag.* **2017**, *25*, 639–647. [CrossRef]

11. Chen, H.S. Establishment and Applied Research on a Wetland Ecosystem Evaluation Model in Taiwan. *Sustainability* **2015**, *7*, 15785–15793. [CrossRef]
12. De Troyer, N.; Mereta, S.T.; Goethals, P.L.M.; Boets, P. Water Quality Assessment of Streams and Wetlands in a Fast Growing East African City. *Water* **2016**, *8*, 123. [CrossRef]
13. Ndayisaba, F.; Nahayo, L.; Guo, H.; Bao, A.; Kayiranga, A.; Karamage, F.; Nyesheja, E.M. Mapping and Monitoring the Akagera Wetland in Rwanda. *Sustainability* **2017**, *9*, 174. [CrossRef]
14. Kachroud, M.; Trolard, F.; Kefi, M.; Jebari, S.; Bourrié, G. Water Quality Indices: Challenges and Application Limits in the Literature. *Water* **2019**, *11*, 361. [CrossRef]
15. Brown, M.T.; Vivas, M.B. Landscape development intensity index. *Environ. Monit. Assess.* **2005**, *101*, 289–309. [CrossRef]
16. Chen, T.-S.; Lin, H.-J. Application of a landscape development intensity index for assessing wetlands in Taiwan. *Wetlands* **2011**, *31*, 745–756. [CrossRef]
17. Chen, T.-S.; Lin, H.-J. Development of a framework for landscape assessment of Taiwanese wetlands. *Ecol. Indic.* **2013**, *25*, 121–132. [CrossRef]
18. Chaves, H.M.; Alipaz, S. An integrated indicator based on basin hydrology, environment, life, and policy: The watershed sustainability index. *Water Resour. Manag.* **2007**, *21*, 883–895. [CrossRef]
19. Lane, C.R.; Brown, M.T. Diatoms as indicators of isolated herbaceous wetland condition in Florida, USA. *Ecol. Indic.* **2007**, *7*, 521–540. [CrossRef]
20. Pratt, B.; Chang, H. Effects of land cover, topography, and built structure on seasonal water quality at multiple spatial scales. *J. Hazard. Mater.* **2012**, *209*, 48–58. [CrossRef] [PubMed]
21. Mack, J.J. Landscape as a predictor of wetland condition: An evaluation of the landscape development index (LDI) with a large reference wetland dataset from Ohio. *Environ. Monit. Assess.* **2006**, *120*, 221–241. [CrossRef]
22. Shuster, W.D.; Bonta, J.; Thurston, H.; Warnemuende, E.; Smith, D. Impacts of impervious surface on watershed hydrology: A review. *Urban Water J.* **2005**, *2*, 263–275. [CrossRef]
23. Nikoo, M.R.; Kerachian, R.; Malakpour-Estalaki, S.; Bashi-Azghadi, S.N.; Azimi-Ghadikolaee, M.M. A probabilistic water quality index for river water quality assessment: A case study. *Environ. Monit. Assess.* **2011**, *181*, 465–478. [CrossRef]
24. Kotze, D. The application of a framework for assessing ecological condition and sustainability of use to three wetlands in Malawi. *Wetl. Ecol. Manag.* **2011**, *19*, 507–520. [CrossRef]
25. Rooney, R.C.; Bayley, S.E.; Creed, I.F.; Wilson, M.J. The accuracy of land cover-based wetland assessments is influenced by landscape extent. *Landsc. Ecol.* **2012**, *27*, 1321–1335. [CrossRef]
26. Margriter, S.C.; Bruland, G.L.; Kudray, G.M.; Lepczyk, C.A. Using indicators of land-use development intensity to assess the condition of coastal wetlands in Hawai 'i. *Landsc. Ecol.* **2014**, *29*, 517–528. [CrossRef]
27. Faber-Langendoen, D.; Kudray, G.; Nordman, C.; Sneddon, L.; Vance, L.; Byers, E.; Rocchio, J.; Gawler, S.; Kittel, G.; Menard, S. *Ecological Performance Standards for Wetland Mitigation: An Approach Based on Ecological Integrity Assessments*; NatureServe: Arlington, VA, USA, 2008.
28. Martínez-López, J.; Carreño, M.; Martínez-Fernández, J.; Esteve, M. Wetland and landscape indices for assessing the condition of semiarid Mediterranean saline wetlands under agricultural hydrological pressures. *Ecol. Indic.* **2014**, *36*, 400–408. [CrossRef]
29. Chen, W.; Cao, C.; Liu, D.; Tian, R.; Wu, C.; Wang, Y.; Qian, Y.; Ma, G.; Bao, D. An evaluating system for wetland ecological health: Case study on nineteen major wetlands in Beijing-Tianjin-Hebei region, China. *Sci. Total Environ.* **2019**, *666*, 1080–1088. [CrossRef]
30. Sun, T.; Lin, W.; Chen, G.; Guo, P.; Zeng, Y. Wetland ecosystem health assessment through integrating remote sensing and inventory data with an assessment model for the Hangzhou Bay, China. *Sci. Total Envoron.* **2016**, *566–567*, 627–640. [CrossRef]
31. Proctor, J.D.; Larson, B.M.H. Ecology, Complexity, and Metaphor. *BioScience* **2005**, *55*, 1065–1068. [CrossRef]
32. Fischer, C.; Preonas, L. Combining policies for renewable energy: Is the whole less than the sum of its parts? *Resour. Future Discuss. Pap.* **2010**. [CrossRef]
33. Zhang, F.; Wang, J.; Wang, X. Recognizing the Relationship between Spatial Patterns in Water Quality and Land-Use/Cover Types: A Case Study of the Jinghe Oasis in Xinjiang, China. *Water* **2018**, *10*, 646. [CrossRef]
34. Reiss, K.C.; Hernandez, E.; Brown, M.T. Application of the landscape development intensity (LDI) index in wetland mitigation banking. *Ecol. Model.* **2014**, *271*, 83–89. [CrossRef]

35. Boyacioglu, H.; Boyacioglu, H. Surface water quality assessment by environmetric methods. *Environ. Monit. Assess.* **2007**, *131*, 371–376. [CrossRef]
36. Pinto, U.; Maheshwari, B. A framework for assessing river health in peri-urban landscapes. *Ecohydrol. Hydrobiol.* **2014**, *14*, 121–131. [CrossRef]
37. Poe, A.C.; Piehler, M.F.; Thompson, S.P.; Paerl, H.W. Denitrification in a constructed wetland receiving agricultural runoff. *Wetlands* **2003**, *23*, 817–826. [CrossRef]
38. Davidson, N.; Finlayson, C. Earth observation for wetland inventory, assessment and monitoring. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2007**, *17*, 219–228. [CrossRef]
39. Li, Y.; Liu, H.; Hao, J.; Zheng, N.; Cao, X. A quantitative method and case analysis for assessing water health. *Huan Jing Ke Xue* **2012**, *33*, 346–351. [PubMed]
40. Xu, F.-L.; Zhao, Z.-Y.; Zhan, W.; Zhao, S.-S.; Dawson, R.W.; Tao, S. An ecosystem health index methodology (EHIM) for lake ecosystem health assessment. *Ecol. Model.* **2005**, *188*, 327–339. [CrossRef]
41. Tan, E.; Hsu, T.-C.; Huang, X.; Lin, H.-J.; Kao, S.-J. Nitrogen transformations and removal efficiency enhancement of a constructed wetland in subtropical Taiwan. *Sci. Total Environ.* **2017**, *601–602*, 1378–1388. [CrossRef] [PubMed]
42. Müller, S.; Mitrovic, S.M. Phytoplankton co-limitation by nitrogen and phosphorus in a shallow reservoir: Progressing from the phosphorus limitation paradigm. *Hydrobiologia* **2015**, *744*, 255–269. [CrossRef]
43. Chislock, M.F.; Doster, E.; Zitomer, R.A.; Wilson, A. Eutrophication: Causes, consequences, and controls in aquatic ecosystems. *Nat. Educ. Knowl.* **2013**, *4*, 10.
44. Ministry of Ecology and Environment (MEE). *Environmental Quality Standards for Surface Water (GB 3838-2002)*; China Environmental Science Press: Beijing, China, 2002; p. 2. (In Chinese)
45. Graham, M.H. Confronting multicollinearity in ecological multiple regression. *Ecology* **2003**, *84*, 2809–2815. [CrossRef]
46. Heard, G.W.; Scroggie, M.P.; Malone, B.S. Classical metapopulation theory as a useful paradigm for the conservation of an endangered amphibian. *Biol. Conserv.* **2012**, *148*, 156–166. [CrossRef]
47. Tornwall, B.; Sokol, E.; Skelton, J.; Brown, B.L. Trends in stream biodiversity research since the river continuum concept. *Diversity* **2015**, *7*, 16. [CrossRef]
48. Murphy, M.T. Source-sink dynamics of a declining eastern kingbird population and the value of sink habitats. *Conserv. Biol.* **2001**, *15*, 737–748. [CrossRef]
49. Dai, J.; Wu, S.; Wu, X.; Xue, W.; Yang, Q.; Zhu, S.; Wang, F.; Chen, D. Effects of water diversion from yangtze river to lake taihu on the phytoplankton habitat of the wangyu river channel. *Water* **2018**, *10*, 759. [CrossRef]
50. Sun, Y.; Liu, H.; Li, Y.; Cai, C.; Li, Y. Assessment of water environment functions in urban wetlands by using the hydrogeomorphic model: A case study of Nanjing Xianlin. *Acta Ecol. Sin.* **2016**, *36*, 3032–3041.
51. Jingfeng, H.; Hongyu, L.; Hebing, H.; Jing, A. A study of the urban wetland water quality heterogeneity at differing scales. *Energy Procedia* **2011**, *11*, 4377–4383.
52. Ongley, E.D.; Xiaolan, Z.; Tao, Y. Current status of agricultural and rural non-point source pollution assessment in china. *Environ. Pollut.* **2010**, *158*, 1159–1168. [CrossRef] [PubMed]
53. Lu, H.; Xie, H.L. Impact of changes in labor resources and transfers of land use rights on agricultural non-point source pollution in Jiangsu Province, China. *J. Environ. Manag.* **2018**, *207*, 134–140. [CrossRef]
54. Sutula, M.A.; Stein, E.D.; Collins, J.N.; Fetscher, A.E.; Clark, R. A practical guide for the development of a wetland assessment method: The California experience 1. *J. Am. Water Resour. Assoc.* **2006**, *42*, 157–175. [CrossRef]
55. Kolka, R.K.; Nelson, E.; Trettin, C. Conceptual assessment framework for forested wetland restoration: The Pen Branch experience. *Ecol. Eng.* **2000**, *15*, S17–S21. [CrossRef]
56. Stander, E.K.; Ehrenfeld, J.G. Rapid assessment of urban wetlands: Do hydrogeomorphic classification and reference criteria work? *Environ. Manag.* **2009**, *43*, 725–742. [CrossRef]
57. Brinson, M.M. Changes in the functioning of wetlands along environmental gradients. *Wetlands* **1993**, *13*, 65–74. [CrossRef]
58. Karr, J.R. Biological integrity: A long-neglected aspect of water resource management. *Ecol. Appl.* **1991**, *1*, 66–84. [CrossRef] [PubMed]
59. Whigham, D.F. Ecological issues related to wetland preservation, restoration, creation and assessment. *Sci. Total Environ.* **1999**, *240*, 31–40. [CrossRef]

60. Jumbe, A.S.; Nandini, N. Heavy metals analysis and sediment quality values in urban lakes. *Am. J. Environ. Sci.* **2009**, *5*, 678. [CrossRef]
61. Brown, J.S.; Sutula, M.; Stransky, C.; Rudolph, J.; Byron, E. Sediment contaminant chemistry and toxicity of freshwater urban wetlands in southern California 1. *J. Am. Water Resour. Assoc.* **2010**, *46*, 367–385. [CrossRef]