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Keywords: land use and land cover change, anthropogenic activities, dynamic monitoring, vegetation dynamics, wetland restoration

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As an important part of the global ecosystem, wetlands and their dynamics greatly influence regional eco-environment systems. To understand the distributions, change processes and temporal-spatial characteristics of the wetlands of the inland river basin in an arid region (Heihe River Basin, HRB), this paper employed multi-source remote sensing data to facilitate multi-temporal monitoring of the HRB wetland using a wetland information extraction method. First, we performed monitoring of these wetlands for the years 2000, 2007, 2011 and 2014; then, we analyzed the variation characteristics of the spatial-temporal dynamics of the wetlands in the HRB over the last 15 years via the landscape dynamic change model and the transformation matrix. In addition, we studied the possible driving mechanisms of these changes. The research results showed that the total area of the HRB wetlands had decreased by 2959.13 hectares in the last 15 years (Since 2000), and the annual average loss was ?1.09%. The dynamics characterizing the HRB wetlands generally presented a trend of slow increase after an initial decrease, which can be classified into three stages. From 2000 to 2007, the total wetland area rapidly decreased; from 2007 to 2011, the area slowly decreased; and from 2011 to 2014, the area gradually increased. The dynamic changing processes characterizing the wetland resources were ascribed to a combination of natural processes and human activities. The main driving mechanisms of wetland dynamic changes include climatic conditions, upper reach water inflows, population, water resources, cultivated area, and policy. The findings of this study can served as reference and support for the conservation and management of wetland resources in the HRB.

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Article

Impacts of Climate Change and Anthropogenic Activities on the Ecological Restoration of Wetlands in the Arid Regions of China

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Keywords: wetland restoration; vegetation dynamics; dynamic monitoring; anthropogenic activities; land use and land cover change

1. Introduction

Wetlands cover approximately 5%–8% of the World's land surface (7–10 million km^2) and contain 10%–20% of the global terrestrial carbon [1]. Wetlands are unique ecosystems with important ecological functions. They are well known because they not only maintain regional and global ecological balances but also provide a living environment for wild animals and plants [2]. They represent one of the most important ecosystems in the World and cannot be replaced by other ecosystems. Healthy wetland ecosystems are a crucial component of ecological security systems and are a vital foundation for the sustainable development of economies and society. The protection of wetlands is of great significance to maintaining ecological balances, improving ecological conditions, and achieving harmony between man and nature.

Although wetlands are very important, it has been argued that wetlands continue to shrink globally at a fairly rapid rate, especially in developing countries. Studies have shown that the planet has lost approximately 50% of its wetlands since 1900 [3]. Recently, wetlands were found to be among the first of any ecosystem type to show loss rates worldwide [4]. For instance, in the U.S., 22 states had lost more than 50% of their wetland area between the 1780s and the 1980s [5], with losses continuing into the 21st century [6]. Similarly, statistics have suggested that two thirds of wetlands in France were lost during 1900–1993 [7]. Those phenomena were also observed existed in the West Songnen Plain [8] and the MulengeXingkai Plain [9] (Northeast China), which indicated a significant decrease in wetlands area in the last five decades.

Wetland protection schemes should first determine the distribution of wetland resources and then conduct continuous dynamic monitoring. Basic information on wetland status and trends is critical to evaluating the effectiveness of wetland management activities [10,11]. Remote sensing technology, with its advantages of rapid automatic acquisition and large-scale multi-temporal coverage, can play an important role in the detailed investigation and dynamic monitoring of wetland resources. Concerning studies on the dynamic monitoring of wetlands using remote sensing, Rebelo [12] and Niu [13] conducted remote-sensing-based mapping on a large regional scale based on typical wetlands found worldwide and in China, respectively. However, the mapping was restricted in its accuracy and timeliness due to the large-scale research with a wider scope. At the regional scale, many scholars have conducted numerous studies on wetland landscape mapping and dynamic analysis of wetland landscape patterns and on relevant driving factors for different areas, including the Australian Mumimbidgee River Wetland [14], the French Mediterranean region wetland [15], and the Gallatin basin in the United States [16]. Many studies have also implemented regional wetland monitoring in China such as for the northeast Sanjiang Plain [8,17], Dalian coastal wetland [18] and wetlands in Beijing [19]. However, changes in wetlands, including detailed mapping, are not well documented, particularly in developing countries [11]. Moreover, most of these studies have been concentrated in the humid regions of the middle eastern region of China, and relatively few such studies have focused on the changes in wetland landscapes in the arid regions of Western China. The lack of knowledge on long time scale of regional wetland dynamics is not conducive to the protection and management of wetlands [8].

A better understanding of wetland changes and their responses to climate change will help in interpreting current environmental problems, developing sustainable wetland planning and facilitating decision making [20]. Wetlands in aird zones are critical areas in the arid environments, they play an important role in providing water, energy, and other resources to human life. Climate change and anthropogenic activities have increased disturbances in the wetland enviroments, which places the wetlands at greater risk, especially in the arid regions [21].

The Heihe River Basin (HRB) is located at the intersection of the Qinghai Tibet Plateau, the Loess Plateau and the Inner Mongolia plateau; plays a role as an ecological security barrier in the northwest and throughout China; and holds an important strategic position in national ecological construction. The wetlands of the HRB are mainly located in Zhangye city, located in the arid inland region of the Hexi Corridor, which is classified as a typical arid region. This area is known to be sensitive to global environmental changes and as zone of the ecological environment that is vulnerable, with its dry climate, strong evaporation and scarce rainfall; thus, its limited wetland resources are precious.

To date, an increasing number of studies on the Heihe Wetland concerning, for example, landscape evolution during the last decade [22], the effects of landscape fragmentation resulting from land use change [23], and ecosystem service evaluation [24], have been conducted. However, research on land cover change and wetland surveys after 2000 have rarely examined the HRB. In particular, a series of water management and wetland protection policies have been conducted in the HRB since 2000 and have greatly impacted the wetland dynamics.

Therefore, this study selected the HRB wetlands, a type of wetland located in an arid region, as the study area. The main objectives of this study are as follows: (1) to assess the spatial and temporal characteristics of wetlands in the HRB in the past 15 years by employing multi-source remote sensing data; (2) to characterize the landscape fragmentation and vegetation dynamics of the study area; (3) to analyze the factors influencing wetland shrinkage and fragmentation in the region; and (4) to explore the general effects and implications for wetland protection and water resource management. By analyzing the variation characteristics of the spatial-temporal dynamics of wetland resources and their driving mechanisms for the last 15 years in the HRB wetland, this paper can serve as a reference for supporting decision making in relevant government departments for the protection and management of wetland resources.

2. Study Area

The main study area, *i.e.*, the Heihe wetlands, is located in the middle part of the Hexi Corridor, which is also located in the middle reaches of the Heihe River Basin (Figure 1), crossing three counties (Ganzhou, Linze and Gaotai) in Zhangye city. The area ranges between 99°17′24″–100°30′15″E and 38°56′39″–39°52′30″N. The HRB is a typical inland river basin in the arid region of Northwestern China. In 2011, the government approved the establishment of the State Reserve of Heihe Wetland in Zhangye to protect the wetland resources in the HRB. Our study area is mainly focused on the region of the reserve. The HRB wetland, as a typical type of inland wetland and aquatic ecosystem in the arid region, with rare, endangered and representative natural features, is a type of natural ecological reserve that provides the integrated functions of ecological protection, scientific research and monitoring, resource management, eco-tourism, publicity and education, and biodiversity protection. The reserve experiences a temperate continental arid climate with large differences in diurnal temperature, little rainfall, drought, large evaporation, and long hours of sunshine. The study area is a typical irrigated agricultural district, which mainly uses water from the Heihe River. The mean annual precipitation is approximately 150 mm, and the potential evaporation is 1000–2000 mm. The study area served as an irrigated agricultural district in the HRB.

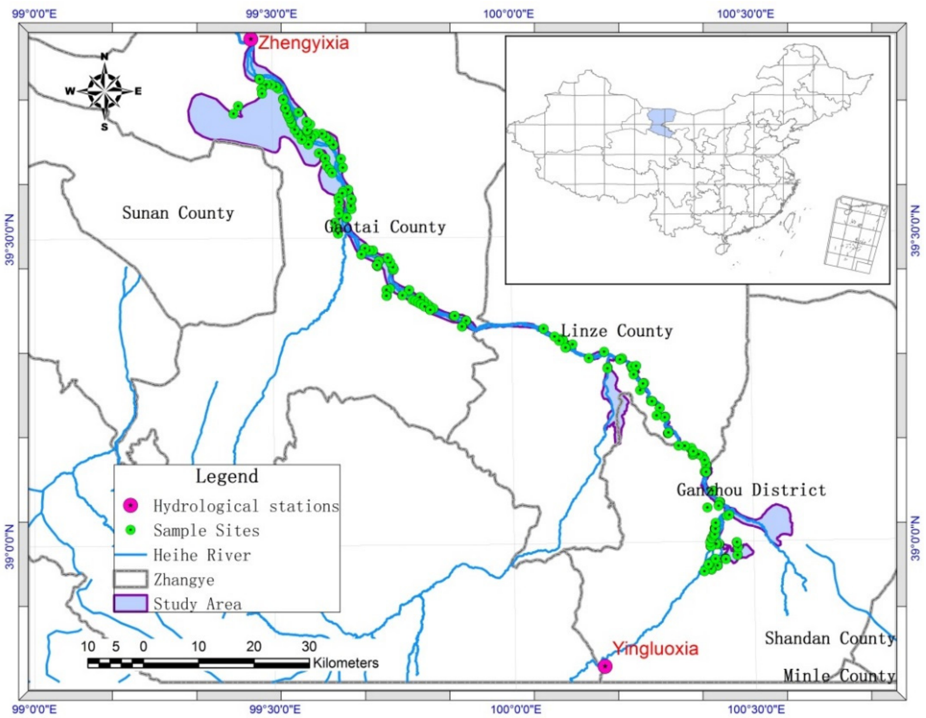

Figure 1. Study area and the verification points in the Heihe River Basin in northwest China.

3. Materials and Methods

3.1. Data Sources

This research collected Landsat Thematic Mapper (TM) / Enhanced Thematic Mapper (ETM) images of the study region for the years 2000, 2007 and 2011. These images were downloaded from the U.S. Geological Survey (USGS) [25]. To maintain the consistency of wetland survey phases, we sorted the remote sensing images of the wet season from July to September when water quality was substantially better in the study area as reference images for extracting wetland information in the historical period. Moreover, we applied WorldView-2 satellite imagery provided by the Gansu Surveying and Mapping Geographic Information Bureau as the reference imagery for the wetland resource inventory in the study area for 2014. Additionally, we used a time series composed of 250 m reflectivity products of the Moderate Resolution Imaging Spectroradiometer (MODIS) images between 2001 and 2010 to monitor the dynamic variations in vegetation in the middle reaches of the HRB.

Meanwhile, the first national water census data of Zhangye (provided by Gansu surveying and mapping geographic information Bureau) and Zhangye land-use data (collected from "Cold and Arid Regions Science Data Center at Lanzhou" in Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences [26]) were adopted to extract wetlands remote sensing information, compare and verify the results of wetland investigation. Furthermore, gathering meteorological and hydrological data, population and socio-economic Statistical Yearbook data in the study area can be also used for analyzing the driving factors of wetland dynamic changes.

3.2. Wetland Classification Indicator System

There is substantial disagreement as to the definition of wetlands, and the various wetland classification systems were mainly established at a specific regional scale. By referring to the China Wetland Classification System [21] and based on the actual distribution of wetland resources in the Heihe wetland of Zhangye, this survey of wetland resources was divided into four categories (*i.e.*, river wetlands, lake wetlands, marsh wetlands and artificial wetlands) and 14 types, among which, the river wetland contains three wetland types, *i.e.*, permanent river (PR), seasonal river (SR), and flooding wetland (FW); the lake wetland contains permanent freshwater lake (PFL) and seasonal freshwater lake (SFL); the marsh wetland contains herbaceous marsh (HM), shrub marsh (SM), inland salt marsh (ISM) and seasonal salt water marsh (SSM); and the artificial wetland comtains reservoir (RV), farm pond (FP), freshwater aquaculture (FA), irrigation field (IF), urban artificial landscape and recreational wetland (UAL).

3.3. The Extraction Methods for Wetland Remote Sensing Information

The wetland resource information was extracted based on a combination of remote sensing information, geological data, field surveys, existing materials and expertise. By analyzing the soil and vegetation data in the monitoring region, we conducted field surveys, established corresponding relationships between each wetland type based on correspnding imagery in terms of color, texture and shape, and fanally determined the interpretation marks among different types of wetland landscapes. Using computer-based automatic interpretation integrated with human-machine interactive interpretation to abstract the wetland information, combined with field investigation points sampled using GPS (Figure 1), the status and history of wetland resources in the HRB were thoroughly surveyed. In addition, we superimposed, compared, inspected and rectified our interpreted results with the support of high-resolution remote sensing imagery obtained from Google Earth©. With the enhanced quality and accuracy obtained by the image interpretation, we obtained the distribution map of wetland resources in the reserve in 4 phases (2000, 2007, 2011 and 2014). Meanwhile, by applying a Geographic Information System (GIS) area statistical function, the areas of both wetland resource and land cover types in the reserve were obtained by measuring the wetland landscape areas in this region.

3.4. Dynamic Monitoring Methods of Wetland Landscape

Based on the remote sensing dynamic monitoring data sets for wetlands in the study area, using GIS software (*i.e.*, ArcGIS (a GIS software for working with maps and geographic information) and ENVI (The Environment for Visualizing Images)), the dynamic features of the spatial patterns of wetland resources in the study area, such as landscape change dynamics and transfer matrix of landscape types, were analyzed via spatial statistics analysis. With the introduction of a wetland landscape (Dynamic Change) model and the transfer matrix of landscape types, we can conduct a quantitative evaluation of the time-dependent dynamics of wetlands within the scope of the study area. The landscape type transfer matrix clearly reflects the circulation of various landscape types and is of great value for analyzing the dynamic changes and causes of ecological landscapes. The wetland dynamic change (DC) is calculated as [27]:

$$DC = \frac{\frac{Ua - Ub}{Ub}}{T} \times 100\% \quad (1)$$

where DC is dynamic rate of change (%) of wetland landscapes in T years; Ub stands for areas of landscape in the initial stage of the study (km^2); Ua is the area of landscape in the terminal stage of the study (km^2); T is time (years).

Landscape dynamic change is a reflection of the changes in amplitude and rates of variation rate for different land use types in unit time and cover type discrepancies in the change of regional land use [27]. The model can not only describe the variation intensity of the wetland itself, but also reflect the temporal characteristics of wetland changes.

3.5. Landscape Pattern Fragmentation of Wetland Resources

The wetland landscape pattern analysis approach is an important method for revealing the ecological situation and spatial heterogeneity of wetlands and their ecological processes. Analyzing the dynamic changes of wetland landscape patterns over time is conducive to revealing the laws and mechanisms of wetland landscape changes, the interrelationships among wetland landscape pattern, natural ecological processes, social economic activities, and the impacts of human activities on the landscape spatial pattern. Fragmentation can be considered as one of the most significant expressions of wetland degradation and has been recognized as a core component of landscape ecology and landscape conservation because it directly affects material and energy cycles [28]. Wetland landscape fragmentation plays a major role in the degradation of ecological systems and the reduction of wetland biodiversity [29].

Landscape fragmentation studies typically adopt a series of landscape indices. Landscape index is a quantitative index that can be highly condensed information about the landscape pattern and reflected the characteristics of its structural composition and spatial distribution. In this study, six indices were selected (Table S1): (1) number of patches (NumP); (2) mean patch size (MPS); (3) patch density (PD); (4) mean shape index (MSI); (5) area-weighted mean patch fractal dimension (AWMPFD); (6) species diversity index (SDI); (7) dominance index (DI); and (8) species evenness index (SEI). These landscape indices are widely implicated with more explicit ecological meaning, which can used to analyze the evolution law of the spatial structure of the wetland landscape pattern, and understand the structural composition of wetland landscape, relationships of spatial distribution and dynamic process. Further details of these indices can be found in the previous studies [8,18–22,30,31]. The landscape indices were calculated using FRAGSTATS version 3.3 [29] and ArcGIS version 10.2.

Among them, the patch number, average patch size, patch density can reflect the landscape fragmentation; the average shape index, fractal dimension index, diversity index reflect the degree of uniformity and complexity for the distribution of different landscape types, particularly on the non-equilibrium distribution of each patch types in the landscape. The dominance index is used to measure the degree of a certain landscape elements dominating the landscape during the composing of landscape structures, which reflects the position and importance of some landscape patches in the landscape.

3.6. Dynamics Monitoring Approach for Wetland Vegetation Covers

The change in vegetation coverage is a direct result of the change in the eco-environment, which, to a large extent, represents the general condition of the eco-environment. Temporal and spatial variations in vegetation coverage are the result of interactions between nature and human activities. The normalized difference vegetation index, which is closely related to vegetation coverage, leaf area index and biomass, is the most commonly used indicator for representing vegetation condition and is widely applied in, for example, the eco-environment monitoring of vegetation. This study adopted the internationally popular tendency analysis model to extract the green rate of change (GRC) of vegetation for each remote sensing pixel, and to monitor the dynamic changes in wetland vegetation coverage.

Trend analysis model uses slope from minimal power of the linear regression equation of the inter-annual variability to describe the normalized difference vegetation index (NDVI) or maximize normalized difference vegetation index (MNDVI), season synthesis normalized difference vegetation index (SINDVI) and other annual trend [32]. Among them, the green rate of change (GRC) is defined as a period of seasonal synthesis normalized difference vegetation index (SINDVI) [33,34].

4. Results and Analysis

4.1. Dynamic Changes in Wetland Resources in HRB Since 2000

4.1.1. Dynamics of the Area of the Wetland Landscape

After analyzing the dynamics characterizing wetland resources in the reserve for the past 15 years by applying 2000 as the benchmark year for the dynamic monitoring of wetlands in the reserve and by employing a total of four phases (2000, 2007, 2011 and 2014) of landscape type data in the Heihe wetland national nature reserve, it can be found that the wetland landscape in the HRB has changed tremendously since 2000 (Table 1, Figures 2 and 3). The results showed that the changing of wetland area generally presented a trend of slow increase after an initial decrease, and characteristics of the phases could be clearly observed (Figure 2). From 2000 to 2007, the wetland area sharply decreased, and the wetland degradation was very severe; from 2007 to 2011, the area continued exhibiting a decreasing tend, but the degradation had decelerated; and since 2011, the wetland area has tended to slowly increase, indicating a gradual restoration of the wetland area and the improving ecological environment. However, the total wetland area was still in decline relative to the benchmark year of 2000. From 2000 to 2014, the total wetland area decreased by 2959.13 ha, and the average annual dynamic change rate reached −1.09% (Table 1).

Figure 3 reflects the changes in the area of various types of landscapes in the Heihe Wetland. Concerning the various wetland landscape types, the areas containing herbaceous marshes, permanent river wetlands and flooding plain wetlands were larger, fundamentally representing the changes in the total wetlands areas. It can be observed that, in addition to the permanent river wetlands first increasing and then decreasing, the other two types of wetlands show a trend of first decreasing and then increasing. The increasing area of permanent rivers in 2007 was directly related to the volume of runoff during that year; however, the current floodplain wetlands are decreasing in area. The surface area of cultivated land and desert has been increasing over the years, indicating that the exploitation of farmland has increased, the degree of desertification has been aggravated year after year, the functions of wetlands have degenerated, the desertification of the reserve has been enhanced and the wetlands have severely degraded.

Table 1. Dynamic changes in the areas of wetland landscapes in the HRB.

Wetland Types	2000–2007 Year			2007–2011 Year			2011–2014 Year		
	2000 Area (ha)	Variation (ha)	Rate of change (%)	2007 Area (ha)	Variation (ha)	Rate of change (%)	2011 Area (ha)	Variation (ha)	Rate of change (%)
River wetland	10036.73	−2935.23	−4.18	7101.51	−593.48	−2.09	6508.03	−634.87	−13.51
Lake Wetland	83.01	−26.29	−4.52	56.73	−23.93	−10.55	32.79	55.63	56.55
Marsh Wetland	7823.94	−15.29	−0.03	7808.65	−132.70	−0.42	7675.95	1226.59	337.97
Constructed Wetlands	1422.65	−142.93	−1.44	1279.71	181.44	3.54	1461.16	81.92	221.39
Total area Wetland	19366.34	−3119.73	−2.30	16246.60	−568.67	−0.88	15677.93	729.27	602.39

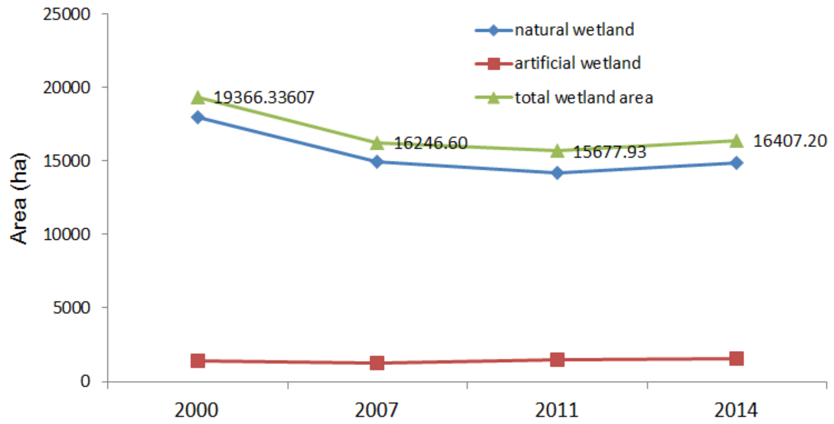

Figure 2. Dynamics of the wetland areas in the HRB.

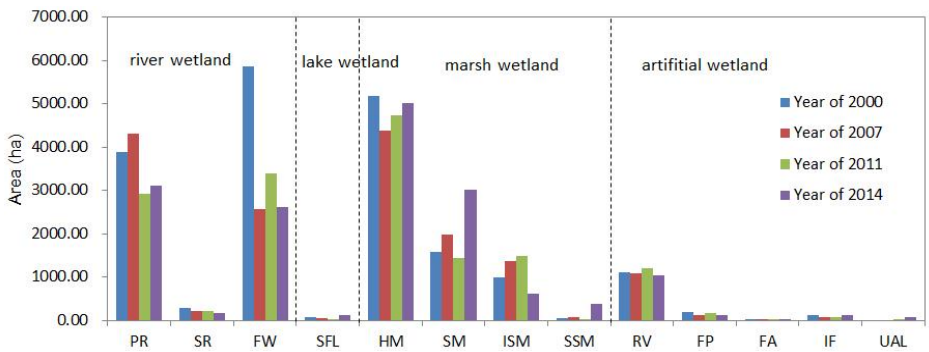

Figure 3. Dynamics of the wetland landscape area in the HRB. The abbreviation of the wetland types: permanent river (PR); seasonal river (SR); flooding wetland (FW); seasonal freshwater lake (SFL); herbaceous marsh (HM); shrub marsh (SM); inland salt marsh (ISM); seasonal salt water marsh (SSM); reservoir (RV); farm pond (FP); freshwater aquaculture (FA); irrigation field (IF); urban artificial landscape and recreational wetland (UAL).

The variation in the total wetland area in the reserve was strongly related to the changes in the natural wetland area, but was less relevant to the area of constructed wetlands. This was mainly because the constructed wetland area accounted for a smaller proportion of the total wetland area, and the former area generally tended to be slightly increased over the last 15 years. During these 15 years, the constructed wetland area increased by 120.43 hectares, with a dynamic degree of 0.60%. However, the changing trend characterizing the natural wetland area basically remained the same as that of the total wetland area, which was in an overall downward trend, first decreasing and subsequently increasing, and the wetland area rate of change and characteristics were consistent with the trend of the total wetland area. Between 2000 and 2014, the natural wetland area decreased by 3079.56 hectares, with a rate of change of −1.23%.

Considering the various types of wetlands, the river wetland accounted for a bigger proportion of the total wetland area ratio, and its change in area was also larger, e.g., the flooded wetland area decreased by 3257.81 hectares over the past 15 years, followed by permanent river wetlands, with an area loss of 783.63 hectares. The wetland types that saw increased wetland area mainly include natural wetlands, such as shrub marshes and seasonal salt water marshes, which saw increase of 1427.46 hectares and 318.28 hectares, respectively, and constructed wetlands, such as reservoir, and urban man-made water landscapes and recreational wetlands, increasing by 103.42 hectares and 82.38 hectares, respectively.

Between 2000 and 2007, due to implementation of water diversion policies of the lower reaches of the HRB and the impact of the "Water-saving project of HRB", the water consumption of the middle reaches of the Heihe River was strictly controlled, and the reduced water flow in the watercourse in addition to the repaired channel blocking the leakage of surface water, intensified the degradation, desertification and salinization of parts of the wetlands. Therefore, the flooded wetland area was significantly reduced during this period, with reductions of 2935.23 hectares over 7 years and a dynamic degree reaching −9.76%; in addition, herbal marsh area decreased by 796.24 hectares. The water areas of lakes, reservoirs and ponds decreased by 26.29 hectares, 24.58 hectares and 79.70 hectares, respectively. Meanwhile, the areas of inland salt marshes and seasonal saltwater marshes increased by 385.73 hectares and 16.49 hectares, respectively, with dynamic degrees of 5.54% and 4.37%; more land was found to often be subject to salinization.

From 2007 to 2011, the wetland areas changed relatively little compared to the previous stage, with a small total wetland area reduction of 598.37 hectares. Apparently, because the Zhangye government has gradually paid increasing attention to wetland protection in recent years, wetland degradation has eased, and parts of the wetlands have gradually been restored, in particular, the artificial wetland area slightly increased by 183 hectares over 4 years, with an average annual growth rate of 3.57%. This was mainly from renovations of reservoirs and ponds, and the construction of artificial lakes and reservoirs and artificial landscape with recreation wetland increased the area by 113.97 hectares and 11.85 hectares, respectively. Although wetland degeneration eased, parts of the wetlands continued decreasing in terms of area. Natural wetland area decreased by 781.36 hectares over 4 years, primarily result from the reduction of river wetland area. Due to a further decrease in the water volume of a river, the permanent river water surface was reduced by 1401.74 hectares, similar to shrub marshes, which suffered from a total decrease of 535.64 hectares.

From 2011 to 2014, wetland areas changed to a lesser extent, except that the areas of several wetlands continued to decline; generally, most of the wetland areas increased. It can be observed that, in recent years, with the implementation of wetland protection and construction in the reserve, wetland degradation in the protected areas had been effectively curbed; wetland landscapes were gradually restored. Over the past 3 years, the areas of wetlands increased by 729.27 hectares, among which natural wetland and artificial wetland increased in area by 647.35 hectares and 221.39 hectares, respectively. In natural wetlands, inland salt marshes and flooded wetlands further decreased in area by 864.99 hectares and 773.25 hectares, respectively, over the course of 3 years, whereas permanent rivers, herbaceous marshes and shrub swamps gradually increased in size, indicating gradual wetland recovery; moreover, land salinization had also been effectively controlled. Simultaneously, with the promotion of wetland restoration projects, the area of artificial wetlands gradually increased, mainly in the areas of reservoirs, urban man-made landscapes and recreational wetlands. However, the continued increasing of the areas of irrigation lands, urban man-made landscapes and recreation wetlands embodied the effects of construction on wetland park and water conservancy facilities in recent years.

4.1.2. Dynamic Changes in the Land Cover Types in the HRB Wetland Landscape

The transition matrix provides information on the magnitude and direction of land use changes in the study area, which is of great importance for the analysis of the dynamics of wetland landscapes and their mechanisms [35]. Table S2, S3 and S4 show the transfer matrix of wetland landscapes in the HRB from 2000 to 2007, from 2007 to 2011 and from 2011 to 2014. It can be found from the tables that, during these three periods, tremendous changes occurred in the HRB in addition to abundant conversions between types of wetlands and types of non-wetlands.

From 2000 to 2007, the types of wetlands converted to types of non-wetlands primarily included flooded wetlands and herbal marshes, with conversions of 3779.68 hectares and 1216.98 hectares, followed by permanent rivers and shrub marshes. This was mainly because the water flow in the middle reaches of the Heihe River decreased after implementing the water diversion scheme; consequently, the water coverage of the Heihe River decreased, and its surrounding flooded wetland area was correspondingly reduced, simultaneously generating degradation and shrinkage of the herbal and shrub marsh wetlands around the river. Non-wetland types converted mainly into herbal wetlands and floodplain wetlands, 1093.54 hectares and 579.17 hectares in total, respectively, second to shrub marshes and inland salt marshes, 548.86 hectares and 130.12 hectares in total, respectively. This was caused by the "returning farmland to wetland, returning grazing to wetland" policy, the wetland restoration of the HRB, *etc*.

The variation in area of the landscape from 2007 to 2011 was relatively small compared to the former period. Conversion from wetland to non-wetland mainly occurred in floodplain wetlands, with a transition of 1220.63 hectares, second to marsh wetland types such as herb marshes, shrub marshes and inland salt marshes, with transitions of 969.93 hectares, 900.43 hectares and 233.38 hectares, respectively. Non-wetland types converted primarily to herb wetlands and floodplain wetlands, with conversions of 1273.06 hectares and 771.78 hectares, respectively, second to inland salt marshes and shrub marshes, with conversions of 557.85 hectares and 144.94 hectares, respectively. The result that wetland degradation eased and that the converted area of non-wetlands from their corresponding wetland types significantly decreased was caused by the later implementation of water diversion schemes in the HRB, whereby the Zhangye municipal government placed the "returning farmland to wetland and grazing to wetland" policy into effect. These results were also caused by a series of wetland restoration and engineering measures in the HRB, as well as the recent years increased water flow in the upper reaches in the Heihe River.

The changes in the landscape area from 2011 to 2014 decreased and basically became in accordance with previous phases. The conversion from wetlands to non-wetlands mainly occurred in inland salt marshes and floodplain wetlands, with transitions of 1173.17 hectares and 1106.51 hectares, respectively, second to herbal marshes and shrub marshes, with transitions of 920.11 hectares and 282.88 hectares, respectively. The transition from non-wetlands to wetlands mainly occurred for herb marshes and shrub marshes, with 1679.11 hectares and 1299.79 hectares, respectively, second to floodplain wetlands and inland salt marshes, with 985.69 hectares and 183.19 hectares, respectively. This demonstrates that, in recent years, the policy of "returning farmland to wetland, returning grazing to wetland" implemented by the Zhangye municipal government and the wetland restoration measures in the HRB had achieved remarkable results, with evidence showing that wetland degradation and shrinkage were effectively decreased, the corresponding area of wetland types converting to non-wetland types had obviously decreased, and the wetland ecological environment had been significantly restored.

4.1.3. Characteristics of Spatial Pattern Evolution of Wetland Landscape

Figure 4 shows the spatial distribution of the changes in the wetland landscape from 2000 to 2007 in the HRB. It can be observed that the wetland landscape in the HRB had changed significantly since the scheme of water diversion in the Heihe wetlands had been implemented in 2000. The major types of lands that did not experience changes were types of water bodies, such as river water surfaces, reservoirs and ponds, and types of unused lands such as deserts and bare grounds. Because they were influenced by the water diversion scheme, river water areas decreased, wetland areas around the river began to shrink, and consequently the primitive ecology of the wetland environment had been destroyed.

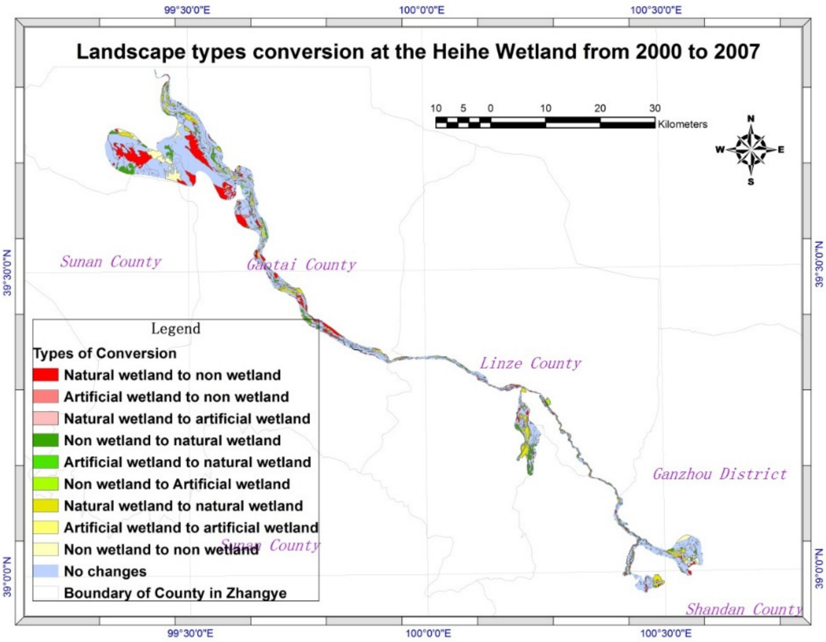

Figure 4. Transition of landscape types during 2000–2007 in the Heihe wetlands. The legend in the figure shows the conversion of different landscape types, such as the "natural wetland to natural wetland", which means that one type of natural wetland was transformed into another natural wetland type (e.g., from permanent river to shrub marsh).

Figure 5 reflects the spatial distribution of wetland landscape changes from 2007 to 2011 in the Heihe wetland in Zhangye. Compared with the previous periods, the wetland landscapes changed to a lesser extent, especially in the core area of the HRB. Meanwhile, after implementing the water diversion scheme in the HRB, the water volume was controlled and the water area decreased; therefore, the area of the wetland tended to be increased locally but decreased overall. As a result of the policy on wetland restoration and the planning project of National Wetland Park construction, wetland types such as urban man-made landscape water surfaces and recreational wetlands gradually emerged.

Figure 6 shows the spatial distribution of the changes in wetland landscapes from 2011 to 2014 in the Heihe Wetland National Nature Reserve. Because it was influenced by variations in the base map resolution of the reference image, the reference image of 2014 provided higher resolution and greater classification precision; therefore, non-wetland types increased in this period. Simultaneously, with the implementation of the water resource restoration efforts in the middle reaches of the Heihe River in Zhangye, wetland protection had achieved a certain amount of success. Because the planting structure for crops in Zhangye had been adjusted in recent years, the original rice-planting region basically became a corn-growing region, which provided substantial economic benefits, and the rice-growing areas decreased year over year, almost disappearing. In addition, a large number of urban man-made landscapes and recreational wetlands appeared.

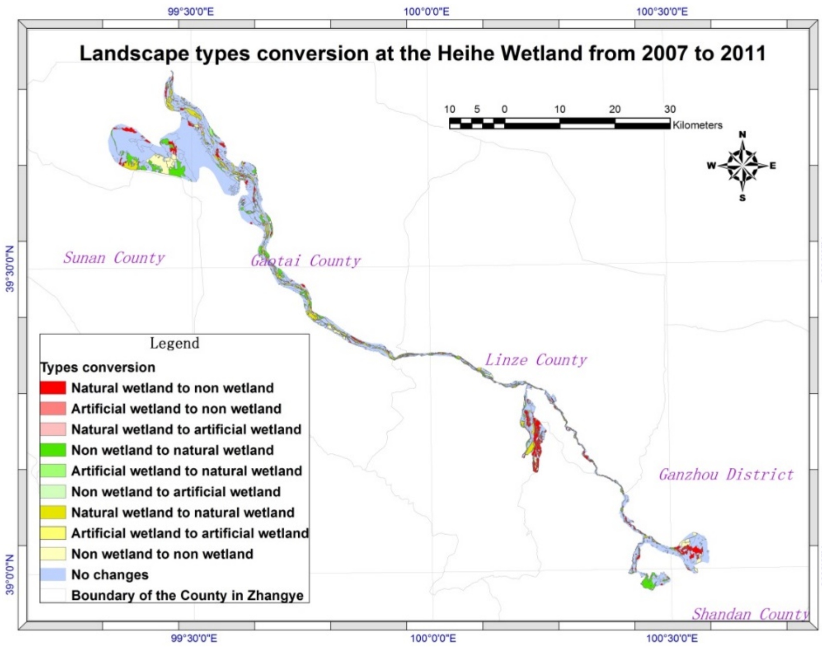

Figure 5. Transition of landscape types during 2007–2011 in the Heihe wetlands. The legend in the figure shows the conversion of different landscape types.

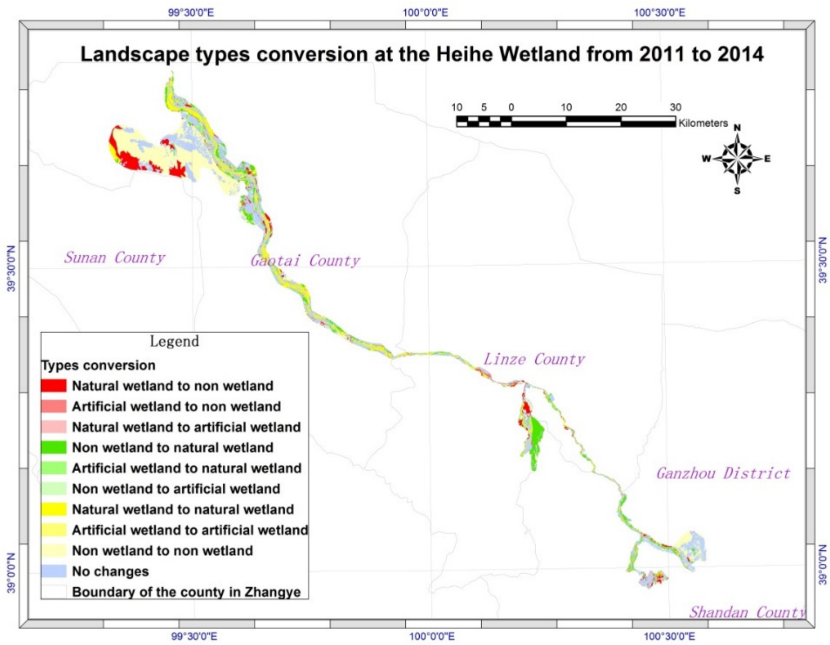

Figure 6. Transition of landscape types during 2011–2014 in the Heihe wetlands. The legend in the figure shows the conversion of different landscape types.

4.2. Dynamic Changing Process of Landscape Patterns in the HRB Since 2000s

Based on the extracted results of wetland resources from the four periods in 2000, 2007, 2011 and 2014 from the State Reserve of Heihe Wetland in Zhangye, by employing landscape pattern analysis software, we calculated the indexes of landscape patterns from these four periods for wetland resources in the HRB and analyzed the law of dynamic changes in wetland landscape patterns from 2000 to 2014 in the HRB.

4.2.1. The Patch Type Scale Status of Landscape Patterns and Its Variation Characteristics

Table S5 shows the characteristics of various types of wetland landscape pattern indexes in the HRB in 2014. A patch is the basic unit of a landscape, and the average difference in patch size and number can reflect the degree of fragmentation of each landscape type. Patch number (NumP) is an intuitive and simple measure of the degree of subdivision of a land use type. PD measures the density of patches for each land use, representing an aspect of fragmentation, which is the dissection of patches. MPS is a simple and commonly used metric in spatial pattern analysis [31]. AWMPFD reflects the shape complexity weighted by the areas of the patches [30]. As can be observed from Table S5, among the various types of wetland landscapes, the patch area of herbaceous marshes is the largest, followed by those of permanent rivers and shrub marsh wetlands; the patch area of arable land is the largest of the non-wetland types. The number of patches in the flood wetland is the largest; however, its large patch density and smaller average patch size indicate its high degree of fragmentation. The average patch size of artificial wetlands, such as farm ponds, freshwater farms, and irrigated land, is low, implying that the degree of fragmentation is relatively high compared to natural wetlands. The fractal dimension index of urban man-made landscapes, water recreational wetlands and river wetlands is higher, indicating a high degree of fragmentation in the landscape because of the high intensity of human interference. Overall, the fractal dimension of the artificial wetlands is smaller than that of natural wetlands, which shows that the greater the impact of human activities, the lower the self-similarity, and the smaller the fractal dimension.

Figures S1, S2 and S3 reflect the variation tendency of the patch numbers, patch densities and mean patch sizes of various types of landscapes in the HRB. In recent years, the patch number and density of the majority of wetland landscape types have been increasing while the mean patch size of landscapes has been decreasing, apparently indicating that landscape fragmentation has been increased overall. Permanent rivers suffered the largest variation in mean patch size, followed by seasonal rivers and inland salt marsh wetlands. The patch density of floodplain wetlands and freshwater wetlands strongly fluctuated compared with other wetland types. Among them, the sharp variation in 2011~2014, possibly related to the high-resolution data of the Reference Image Base in 2014, which was based on a more accurate and higher resolution base map of geographic conditions compared to TM/ETM images, obtains a more refined classification, this results in differences between the landscape index and calculations of images with moderate resolutions. However, it can reflect the underlying trends of variation on various types of landscape patterns.

Figure 7 reflects the variation tendencies of mean patch fractal dimensions over various types of landscapes in the HRB. In recent years, the patch fractal dimension index of most wetland landscape types has been increasing, therein showing an increase in overall landscape fragmentation and human interference year over year. Similar with the variations of patch densities in various types of landscapes in the HRB, the sharp variations in the stage of 2011~2014 were possibly related to the high-resolution data of the Reference Image Base in 2014. However, human interference could be one of the possible causes as well, since the overall tendencies of mean patch fractal dimensions from 2000 to 2014 in the HRB was increasing; besides, previous studies have showed that high-density human activity is the primary factor controlling the evolution of wetland landscape pattern [36,37]; in addition, the State Reserve of Heihe Wetland in Zhangye was constructed in 2011, a series of important measures of wetland protection and management has been adopted by the government, which greatly impacted the patch fractal dimensions as well.

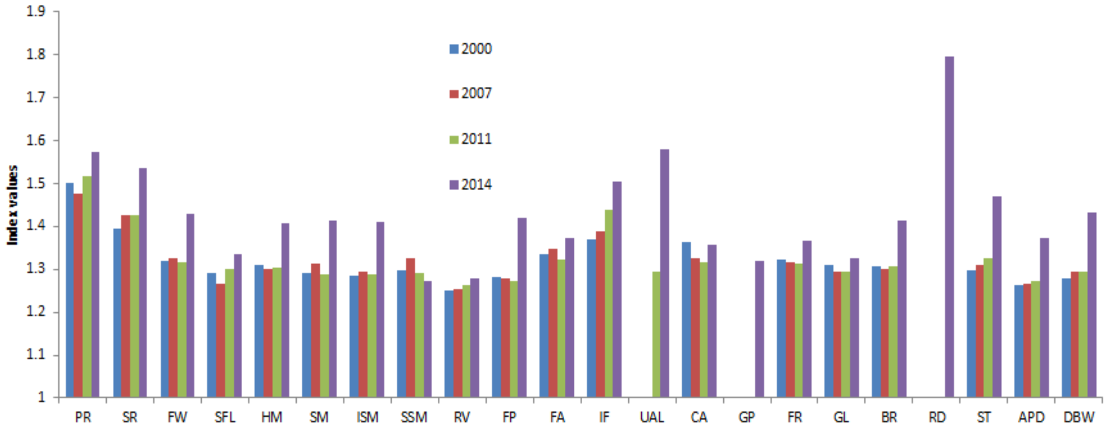

Figure 7. Mean patch fractal dimensions of landscapes in the HRB from 2000 to 2014.

4.2.2. The Variation Characteristics of Landscape Pattern and Scale

From Table 2 and Figure 8, it can be observed that the spatial patterns of wetland landscapes have changed significantly during the period of 2000~2014; their basic characteristics show that the NumP and PD of wetland landscapes increased year after year but that the MPS gradually decreased. Meanwhile, the AWMPFD, MSI, SDI and SEI tended to decrease after first increasing and generally tended to increase during 2000~2014; however, the DI trend was an initial increase and subsequent decrease. These changes in the landscape indices illustrated that wetland landscapes in the HRB as a whole tend to be fragmented and complicated. The increased NumP and PD of wetland landscapes and the decreased MPS denoted an increased degree of fragmentation, and the reduction in the DI demonstrated the decreasing differences in the proportions of the various wetland types within the landscape. The trends of the DI and SDI were opposite, and the evenness represented the differences in areas of each landscape. The increase in SEI represented an increase in heterogeneity within the landscape. The increased AWMPFD signified that the overall shape of the landscape tended to become more complicated, which is a manifestation of the enhanced impact of human activities in recent years on wetland landscapes within protected areas.

Table 2. The changes in landscape scale and pattern in the HRB.

Year	Area-Weighted Mean Patch Fractal Dimension (AWMPFD)	Patch Density (PD)	Dominance Index (DI)	Species Diversity Index (SDI)	Species Evenness Index (SEI)	Mean Shape Index (MSI)	Mean Shape Size (MPS)	Patch Number (NumP)
2000	1.333	0.016	0.758	2.187	0.743	2.562	63.250	660
2007	1.323	0.017	0.837	2.107	0.716	2.271	58.143	718
2011	1.319	0.021	0.835	2.161	0.721	2.015	47.212	883
2014	1.391	0.307	0.789	2.302	0.745	2.330	3.259	12797

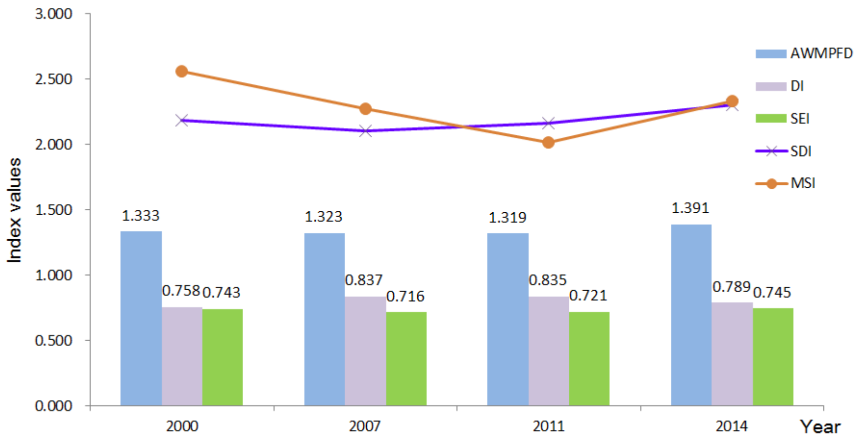

Figure 8. The changes in the landscape pattern index in the HRB from 2011 to 2014.

4.3. The Dynamics Trend Analysis on Wetland Vegetation Cover

We used a long time series of MODIS remote sensing data to monitor the dynamic variations in vegetation in the middle reaches of the HRB. Based on the 250 m reflectivity products of MODIS images between 2001 and 2010, the changing rates of seasonal ingredient normalized difference vegetation index (SINDVI) of the middle reaches of the Heihe River area in 2001–2010 have been determined (Figure 9). It can be found that, except for a few areas from Gaotao and Linze, which presented in red (indicating vegetation degradation), most areas were green (representing vegetation greening), which demonstrated that the basic characteristics of the vegetation coverage dynamic in the study area is "overall increasing and partly decreasing" and that the protection of vegetation has been significantly improved in most regions. However, vegetation degeneration is found in some sections, and an area with vegetation degradation is basically an area suffering from serious groundwater decline. As can be observed, in parts of Gaotai and Linze, due to the serious overexploitation of groundwater caused by frequent agricultural production activities, the degradation of aboveground vegetation has accelerated, resulting in a series of ecological and environmental problems such as desertification and salinization.

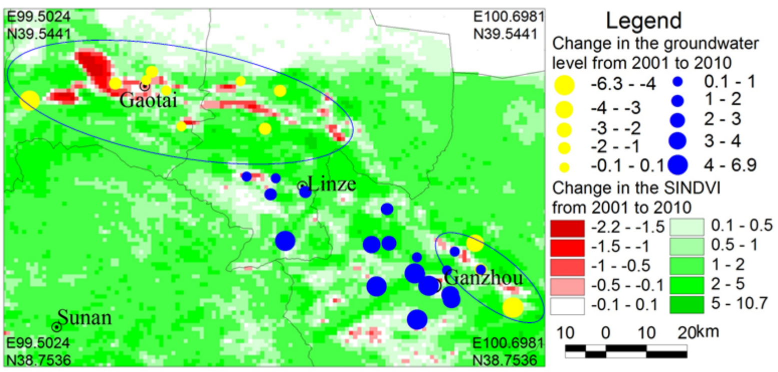

Figure 9. The dynamics of vegetation coverage and groundwater level change in the HRB.

Clearly, the increasing vegetation coverage in the HRB does not imply increased natural vegetation cover, but may indicate newly added cultivated land formed by reclamation in the low vegetation covered areas with sparse vegetation or bare land. This increased anthropogenic vegetation coverage resulting from agricultural activities, compared to natural vegetation, will consume more water, thereby increasing the exploitation velocity of groundwater, and thus increasing the vulnerability of the eco-environment in water-scarce arid regions. For these extremely sensitive ecological areas, the exploitation of groundwater and the expansion of cultivated land should be limited.

5. Discussion

The driving mechanisms of the dynamic changes in wetland resources were analyzed using the natural geographical factors and socio-economic factors in the HRB. The dynamic changing process of wetland resources in the HRB was the result of the combined action of nature and human activities. Natural factors influencing the variation in water resources affected the growth in wetland vegetation and natural distribution regularities of wetland landscape; however, human and social factors, such as water source management policies, engineering measures for wetland protection and wetland park construction, artificially alter the natural landscape of wetland by influencing landscape planning and layout in both the HRB and the wetland park.

5.1. The Impact of Natural Factors on the Dynamic Changes in Wetland Resources in the HRB

5.1.1. Climate Variation

Climate change is considered as one of the most important natural factors that affect wetland landscape patterns [38]. Climate impacts wetland resources mainly in two regards: precipitation and temperature. Adequate precipitation represents an important water supply of wetlands; therefore, a decrease in rainfall directly leads to insufficient replenishment of water resources into the wetland, and simultaneously affects the vegetation and soil of the wetland. However, on the one hand, the rising temperature enhances evapotranspiration, thereby reducing water content in the wetland; on the other hand, it accelerates the melting of glacier and further increases surface runoff. Based on the gathered data on average annual temperature and precipitation in the study area and its various surrounding meteorological stations between 2000 and 2011, using trend analysis, we analyzed the basic law of temperature and rainfall in the study area.

Figure 10 shows a larger inter-annual variation in rainfall in the study area. The rainfall overall tended to increased first and later decreased, finally reaching a peak in 2007. The increasing precipitation was conducive to the growth in wetland vegetation and the increase in river runoff. The expansion of the water surface of permanent rivers in the study area in 2007 was linked to the increased river runoff because of this year's increased precipitation. According to Figure 8, the temperature in the study area had generally presented a slight upward trend for more than a decade. Climate warming facilitated vegetation growth, which was a key factor in augmenting vegetation coverage in the HRB. Simultaneously, climate warming was also closely related to the change in water resources, which was reflected in two aspects: a warm and dry climate could enhance evaporation and thus impact on the reduction in water resources, and the rising temperature would result in accelerated melting of the Hexi Corridor region's most important water sources—the Qilian mountain glaciers. Studies have showed that climate change around the area of the Qilian mountain glaciers had resulted a shrinkage of 21.7% in the decades between 1956 and 2003, with an average reduction in the area of an individual glacier of 0.10 km^2 [39,40]. The increased glacier melting is contributing greater runoff into the Heihe River.

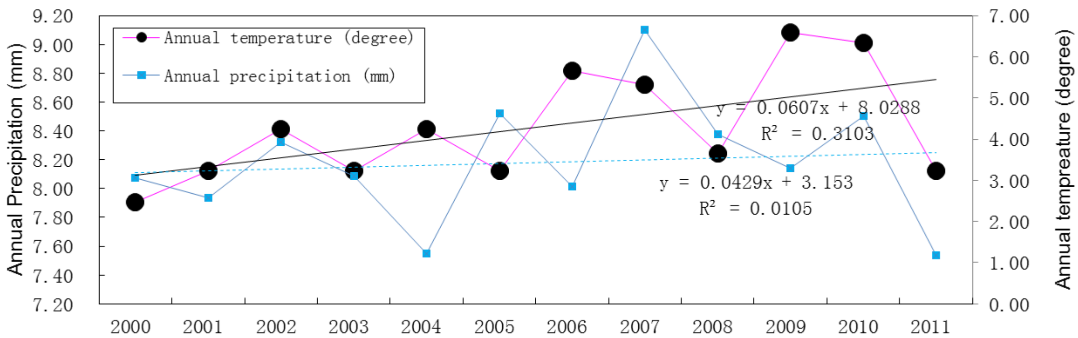

Figure 10. Changes in annual temperature and precipitation in the HRB.

5.1.2. The Change in Upstream Inflow and Midstream Consumption in the HRB

The hydrological condition of the wetland is a decisive factor; however, the influential factors of the hydrological conditions are complex because they are affected by rainfall, air temperature, water resource utilization *etc.* As observed from Figure 11, Yingluoxia and Zhangyexia stations are two hydrological stations that recorded runoff flow entering the middle reaches from the upper reaches of the HRB and entering the lower reaches from the middle reaches of the HRB, respectively (Figure 11). Figure 12 reveals that the annual runoff measured by Yingluoxia station, which is the water inflowing site of the middle stream from the upstream of HRB, increased significantly in recent years from 14.62×10^8 m^3 in 2000 to 22.73×10^8 m^3 in 2014 (Figure 12). In addition, the discharge water measured by Zhengyixia station, which is the transition station into the downstream of the HRB, also tended to increase from 6.59×10^8 m^3 in 2000 to 13.24×10^8 m^3 in 2014. Correspondingly, the constant change in water consumption by Zhangye from 8.03×10^8 m^3 in 2000 decreased to 6.88×10^8 m^3 in 2006 and then increased to 9.49×10^8 m^3 in 2014, showing a trend of first decreasing and then increasing.

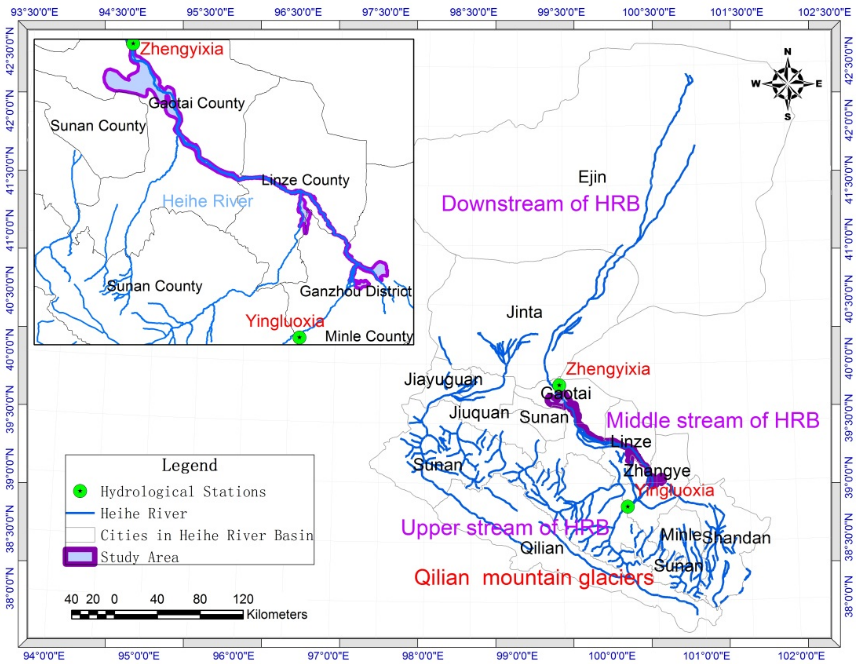

Figure 11. Diagram of hydrological observation sites and different parts of the HRB.

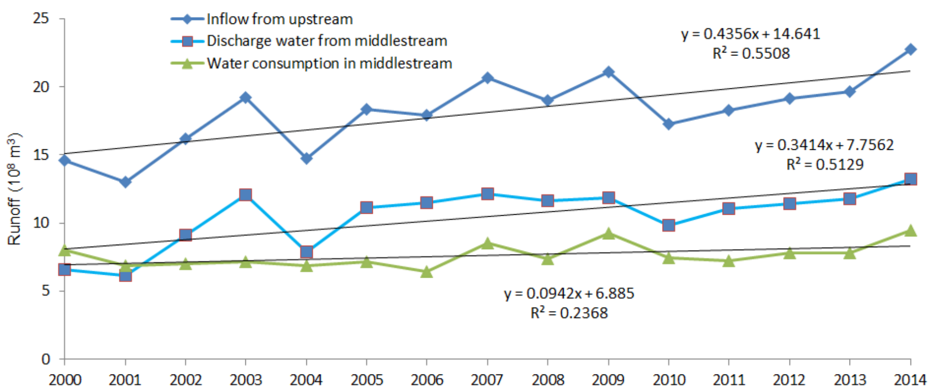

Figure 12. Changes in the upstream inflow and midstream consumption in the HRB.

According to the base flow separation method and a stepwise multiple regression model, the increased runoff in the HRB was due to the changes in precipitation and air temperature [40]. In spring, the dominant factor causing the increasing runoff was the air temperature, while in autumn, precipitation was the main factor. Changes of the glacier melt runoff from the Qilian Mountain glaciers were not significant, only contributed less than 10% to the runoff increase [38]. Thus, the possible reason for the increased runoff is caused by the climate warming thickened the active permafrost layers, which result in the increase of soil water storage capacity, and finally makes the increase of rainfall infiltration and base flow [40].

Theoretically speaking, the increased upstream inflow improved the hydrological situation of the wetland, which was conducive to the restoration of the natural eco-environment. However, the river runoff changed in response to the impoundment of the reservoirs and channels as well as the influence of water diversion policies targeting the lower reaches of the Heihe River from the midstream of the HRB. The water diversion in the middle reaches of the Heihe River was initiated in 2001 and was directly responsible for the decrease in the water surplus during 2001–2010. Statistics showed that, with the development of water conservancy constructions, in recent years, a number of reservoirs of the tributary from the HRB have gradually expanded [41]. The water inflow from the Heihe was effectively intercepted and consumed, resulting in decreased replenishment of water into the wetland of the Heihe main stream. In addition, the constructed hydropower dam intercepted part of the water resources; the repaired rivers and canals blocked the leakage of groundwater, thereby hindering the development of wetland landscapes. Meanwhile, since the implementation of water diversion plans in the lower reaches of Heihe in 2000, water consumption in the middle reaches has been controlled. In the past 15 years, the total water delivery from Zhengyi gorge to the lower reaches totaled 15.731 billion m^3 accounting for 57.86% of the water inflow of the upstream. The dynamics of the wetland distribution were also strongly influenced by large-scale expansion of irrigated farmland in the middle reaches. In addition, the cultivated land area of Zhangye continued to grow, which caused the available surface water resources to fail to satisfy the needs of agricultural production and residents' demands. Therefore, as a supplement, the limited groundwater had to be exploited and thus resulting in deterioration of the eco logical environment. However, in recent years, along with the increased of water inflow from the upstream and the emerging growth trend of surface water resources in the midstream, ecological deterioration tended to be gradually reduced and contained.

5.2. Influence of Human Factors on the Dynamic Changes in Wetland Resources in the HRB

5.2.1. Population Growth, Cultivated Land Increase and Planting Structure Adjustment

The increasing population caused large-scale land reclamation, which crowded out natural wetlands and consequently resulted in more cultivated land area. The accelerated urbanization led to a population explosion and urban construction land expansion, therein occupying part of the wetland area. From Figure 13 , it can be observed that, in the last 10 years, the population of Zhangye has been increasing, and agricultural acreage has seen rapid growth since 2007. It is thus clear that the contradiction between people and land was prominent; the increasing cultivated land area encroached on parts of wetlands and wastelands and also brought greater demands on water resources. In the context of the very limited wetland ecological carrying capacities, the increasing population and the continuous expansion of cultivated land were the main factors in the deterioration of wetland environments.

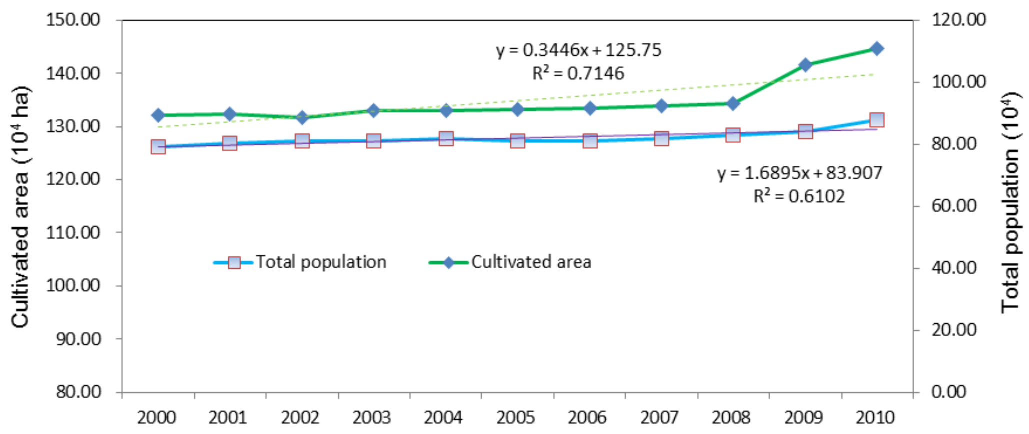

Figure 13. Changes in agricultural acreage and total population of Zhangye city.

Since the Heihe River comprehensive treatment project was launched, the cultivated land in the study area has greatly increased. The new cultivated land area was mainly concentrated in the artificial wetland and desert transitional zones, which were away from surface water supply sources; combining with the fact that there was no perfect system for water irrigation and conveyance and thus a reliance on groundwater for irrigation, groundwater exploitation was increased. By superimposing layers and groundwater level changes, it can be found that the area with increased cultivated land saw the greatest decrese in ground water levels. Therefore, the increased cultivated land area endangered the original fragile eco-environment in the study area, and the reclamation of wetland areas also led to further shrinkage.

In addition to the variation in agricultural acreage, the planting structure has also undergone huge changes. In recent years, Zhangye accelerated the adjustment of planting structures and vigorously developed special industries such as the cultivation of vegetables and seeded corn. After adjusting the planting structure, the production area of high-profit seeded corn planting accounted for a substantially greater proportion of the cultivated land compared to other traditional crop planting, the former increasing from 10.92% in 2000 to 53.95% in 2010 [42], whereas other crops gradually decreased. The change in planting structure significantly lowered the crop acreage, such as rice fields, which are more water intensive but that provide fewer economic benefits compared to the planting of seeded corn.

5.2.2. Variation in the Utilization of Water Resources

As an important wetland of the Hexi corridor, Zhangye city has relied on agriculture as its main subsistence. The HRB is located in an arid inland river basin; therefore, utilization of water resources acted as the basic driving force for wetland changes in the region. Since the Heihe River diversion program had been officially launched in 2000, the use of agricultural motor-driven wells has rapidly increased rapidly from 5547 wells in 2000 to 9297 wells in 2010 due to the increased cultivated areas and the decreased amount of surface water supply, and groundwater extraction had increased by 164 million m^3 [42]. The seriously overdrawn groundwater saw greatly decreased level in many areas, which consequently sped up the degradation of natural wetlands.

In addition, Figure 9 shows the relationship between the dynamic variation in vegetation in the middle reaches of the Heihe River and the groundwater level. The figure displays a very good relationship between vegetation dynamics and the underground water level, and the spatial differences are regular and evident. The underground water table in the middle reaches of the Heihe River tended to slightly decrease, and the water table was increasing in the Ganzhou district, except for two underground wells in its northeast corner; however, the levels in Linze and Gaotai counties showed an overall downward trend.

For the region with increased water table, its cultivated land around the wells did not significantly increase; however, its SINDVI was increasing. The conditions of those regions with decreased water tables were more complex, therein manifesting as an expansion of cultivated land that mainly relied on underground water and that was surrounded by wells, leading to a rapid decline in the water table. Other wells located in the areas with decreased SINDVI, which were strongly distributed either near the main channel of the Heihe River or in the ecological transition zone, were in areas that were primarily covered by natural vegetation and were mostly supplied by underground water; therefore, the decreased of water table caused the degradation of natural vegetation.

5.2.3. Policy Influences

The change in national political policies and systems has a great influence on the variation in regional land coverage. The implementation of the Heihe water diversion policy was the main factor affecting changes in the utilization of water resources in the HRB in recent years and was also essential to wetland changes. To curb the ecological deterioration of the lower reaches of Heihe, the Heihe water diversion plan has been formally applied since 2000 [43], adding water diversion to the downstream. The pilot program of the construction of the water-saving society in Zhangye district ("Heihe Water-Saving Project") was officially approved by the Ministry of Water Resources (MWR) in 2002, and one of its objectives was to improve the utilization of agricultural water in the middle reaches of Heihe through the construction of diversion channels in the middle reaches, the standardization of irrigation systems, increasing the efficiency of water resource management and the reduction in regional water disputes [44]. Studies have shown that, in the pilot program of the water-saving society in Zhangye, measures concerning establishing a water-saving society, such as building water rights systems, channel lining engineering and adjustments of agricultural structure, played an active role in implementing "total control" and guaranteeing smooth allocation in the HRB [45]. However, problems remained during the implementation such as the mechanism for and period of the water diversion, contradictions between the supply and demand of water resources, and efficient utilization patterns for water resources [46].

In recent years, the water transfer scheme in the HRB has achieved various results, but has also triggered a shortage of water in the middle reaches of the Zhangye region, resulting in a deteriorating ecological environment in the middle stream of the Hehei River. The improvement of the canal system resulting from "The Heihe Water-saving project" increased water efficiency but also blocked the leakage of groundwater such that water in part of wetland vegetation was not supplied. Figure S4 showed the negative side effect of constructing channels on the shrinkage of seasonal river in the Dasha River (*i.e.*, a tributary of Heihe River), which showed the shrinkage of the seasonal river area because of the construction of irrigated channels. During the irrigation season of the plants, the seasonal river was shrinking, even it was drive up. Such cases also existed in the Sanjiang Plain Wetland areas, where the irrigated channels almost blocked all parts of surface water in the wetland areas, leading to the interception of the surface water and the ground water in the Sanjiang Plain [46]. The excessive indicators of water transfer downstream did not satisfy water demands in the midstream, resulting in the widespread death of artificial eco-forests, continuous shrinkage of wetland areas and gradual expansion of desertification. The increasing cultivated land area required increasingly more water, and the available surface water resources were reduced following the transfer of water; therefore, the water requirements had to be met by exploiting the limited groundwater. Researchers showed that for the past 30 years, the groundwater depth in the middle reaches of the HRB had seen decreases year over year [47]. The decreased level of the groundwater made the ecological environment even more fragile.

For the long term, Zhangye has attached great importance to the protection and restoration of wetland resources in the HRB. The Zhangye municipal government effectively restored the wetland ecological environment through the development of a series of environmental protection and wetland protection policies, as well as a large number of engineering constructions.

In terms of policies on environmental protection and wetland conservation, the government in Zhangye city adopted many policies, such as "returning farmland to forest", returning farmland to marsh" and "returning grassland, returning wetland", which decreased the area of cultivated land while increasing the area of forest, grassland and wetland; moreover, the engineering of Three-North Shelterbelt increased the area of planted forests. Meanwhile, forest and grass lands, as well as wetlands were protected to a certain degree under the policies of closing hillsides to facilitate afforestation and closing gardens to facilitate grassland growth. By implementing the above policies, the trend of degrading wetland ecological environment was effectively restrained, and the restoration of the wetland ecosystem was promoted.

Moreover, urban development and wetland park construction significantly impacted the types of wetland variations observed in the HRB, especially the Wetland Park. The oasis distribution along both sides of the Heihe River in the Heihe Wetland National Nature Reserve of Zhangye was the ecological corridor zone of the Hexi Corridor, which was the congeries of population because of its abundant water resources facilitating agricultural production and life. In recent years, Zhangye has been advocated by ecological constructions as the focus for building an ecological civilization city and striving to create a golden livable and tourist-oriented Zhangye to harmoniously develop urban construction and ecological environments. Through construction and the implementation of planned projects such as the national wetland nature reserve and Zhangye National Wetland Park, numerous engineering facilities and infrastructure projects began to be established, and a significant change in the wetland types occurred within the wetland reserve and the wetland parks. Due to the intervention of engineering constructions and protection policies, natural wetlands, such as rivers and marshes, could be converted into non-wetland types, such as building lands, and some non-wetland types, such as cultivated lands, could also be transformed into natural wetlands such as herbal marshes, or artificial wetlands such as artificial lakes (urban man-made landscapes and recreation wetlands). Overall, the intervention of human activity will lead to gradually increasing areas of wetland types in wetland parks.

5.3. Implications of the Wetland Dynamics on Wetland Protection and Water Resource Managment

To improve the quality of wetland eco-environments in the HRB and curb wetland degradation processes, therein allowing wetlands to better play their ecological roles in regulating regional climate, conserving water, halting pollution degradation and providing biodiversity protection, it is indispensable to strengthen the protection of wetland ecosystems.

First, the disordered utilization and excessive exploitation of wetland resources will seriously damage the original eco-environments of wetlands, driving the wetland landscape to the verge of complication and fragmentation and affecting the stability of wetland landscape functions in HRB. Blindly exploiting agricultural land and occupying natural wetlands for the purposes of building urban constructions in the reserve zone directly resulted in the abatement of natural wetland areas of the HRB and their reduced ability to support ecological functions. Since the building of large reservoirs and canals in the late 1970s to the late 1990s in the Sanjiang Plain will altered the hydrological process of the study region and led to wetland degradation [48,49]. There are two sides to human interference in wetland; however, the key is to ensure a balance. The way of unreasonably and excessively interfering in wetlands should be avoided to the greatest extent possible; instead, reasonable planning and the protection and restoration of wetland resources should be encouraged, which will achieve the orderly development and utilization of wetland resources. Because of the low occupancy rates of wetlands within the core area of the reserve and eco-environment vulnerability, the direct interference of human activity is strictly prohibited. In the process of wetland ecological restoration, it is possible to take a project plan that is in favor of and in accord with the natural evolution process of wetland landscapes, attempt to ensure the natural environment of the wetland, and realize the self-recovery of the wetland ecosystem.

In recent years, sustained economic and social development and continued population growth, nourished a constantly increasing demand for water use in industrial, agricultural and domestic sectors, and due to the irrational use of water in some regions, the ecological functions of wetlands began to degenerate. There are two aspects for alleviating the contradiction between water supply and demand. The first aspect is changing the concept of water, developing water-saving agriculture and improving the utilization of water resources, which can be achieved through strengthening irrigation management, promoting water-saving irrigation techniques, reconstructing and consolidating the diversion entrance of surface water, and enhancing canal construction and integrated water utilization of channels as well as adjusting crop planting structures with a target of high economic benefits and low water consumption. The farmland area should thus be strictly controlled. We suggested that farmland in the transition zone between the wetland and the desert be gradually abandoned to control the farmland area [50]. The second aspect is co-coordinating the relationships concerning water usage among the upper, middle and lower reaches of the river basin to allow water resources to be rationally allocated and used in a highly efficient manner and to achieve the sustainability of its usage. The implementation of the Heihe River diversion provided remarkable achievements in oasis eco-environment restoration [51] but correspondingly brought about certain problems such as the reasonable choice in the manner of water transfer and its appropriate period, effectively overcoming disposal on the contradiction between water supply and demand, and the un-established pattern of utilizing water resources within the basin in a rational and highly efficient manner, issues that remain to be studied and resolved. Therefore, it is necessary to conduct research on the optimal allocation of water in the middle and lower reaches; to determine a water resource allocation scheme that meets the demands of coordinated and balanced development in the upper, middle and lower reaches of the basin; and to achieve sustainable development of eco-environments, economies and society.

The expansion of arable land and overgrazing severely damaged the ecosystem functions of wetlands. The unreasonable land use method will destroy the completeness of the structure for wetland landscape [52,53], making the complete and continuous wetland became dispersed; the shape of the wetland tends to be irregular; and reducing the connection degree and polymerization degree, finally result in fragmentation of the wetland landscape. It is critical to strictly control the expansion of cultivated land in protected areas, particularly the core areas of wetland reserve and ecologically fragile areas where more countermeasures are needed, therein banning occupation of natural wetlands, strictly limiting the exploitation of groundwater and the expansion of cultivated land, reducing interference by human activities, and prohibiting all types of acts that can damaged to the eco-environment. In addition, grazing should be restricted in desert steppe regions with less coverage to protect vegetation from livestock. For currently developed and less covered desert steppes surrounded by wetlands in the reserve, according to planning and construction, it is necessary to actively seek safe funding projects, execute wetland restoration projects such as "returning farmland to wetland, return grazing land to grassland", and recover the natural landscape of wetlands within the protected area. Meanwhile, the implementation of various policies should be strengthened, thereby firmly stopping all types of random acts of occupying and destroying wetlands and thoroughly inspecting activities that occupy wetlands, reclaiming landfills and polluted natural wetlands, and preventing and addressing all types of illegal destruction of wetlands.

Wetland protection requires broad participation and support from the community, through a series of public education activities and training seminars as well as activities for wetland protection with public participation to raise public awareness of the functions and benefits of wetland resources to strengthen the public's consciousness of voluntarily protecting wetland resources and proactively preventing ecological degradation. This would allow the creating an environment and atmosphere conducive to wetland conservation.

In addition, enhancing the standardized management of landfill sites of the villages around the protected areas and strictly forbidding citizens from indiscriminately dumping and disposing of garbage in wetland regions in the reserve should be realized to ensure the promotion of a low-energy, green and clean production mode. By regulating the discharge of municipal sewage and industrial wastewater, controlling the dosage of agricultural-use pesticides and the application of fertilizers, reducing the discharge of contaminated water from industrial and agricultural production, applying purification technologies to the wetland water and treating water pollution problems in the wetlands, the ecological environment of wetlands can be improved.

In addition, to ensure the protection and rational utilization of wetland resources, the state of the wetland ecological system evolution process must first be understand, and is inseparable from the technical support of wetland monitoring. Through cooperation with scientific research institutions, a communication platform should be established, and a number of cooperative research projects should be executed, therein fully utilizing the scientific research institutes, especially through the strengths of information technologies such as remote sensing and GIS [11–13]. In addition, the area, distribution and evolution processes of wetland resources in the reserve can be dynamically monitored; likewise, the quality of the eco-environment, and the security status of the ecology and ecological restoration effects of wetland ecosystems can be regularly assessed. Meanwhile, a database management information system can be established for monitoring wetland resources to improve the information level of wetland surveillance as well as regularly form monitoring reports on the wetland dynamics. Furthermore, by applying technical methodologies, such as wetland resource investigation and dynamic monitoring from a monitoring project, and establishing normalized and dynamic surveillance mechanisms for wetland resources, decision support concerning the protection, ecological restoration, comprehensive management and sustainable use of wetland resources can be enhanced.

6. Conclusions

This study was based on multi-source remote sensing data, combining with analysis of spatial and temporal dynamics on the wetland landscape, and conducted a dynamic monitoring using remote sensing data of the wetland resources, therein achieving results with higher accuracy and better up-to-date mapping of the status of wetland resources in the reserve. In addition, the study obtained data sets for the dynamic monitoring of the wetland resources in the last 15 years, attempted to understood the present situation and dynamic changing processes of wetland resources in the reserve, and analyzed the driving mechanism of dynamic changes in wetland resources. We present the main conclusions in the following paragraphs:

- We monitored the spatial-temporal dynamic changes in wetland resources for the last 15 years in the reserve by applying images of four phases (2000, 2007, 2011 and 2014) and using 2000 as the benchmark year. The results showed that the change in wetland area generally presented a trend of slow increasing after an initial decreasing, and the characteristics of the phase could be clearly observed. From 2000 to 2007, wetland areas greatly decreased, and wetland degradation was severe. From 2007 to 2011, the area was still decreasing; however, the degradation had slowed. Since 2011, wetland areas had tended to slowly increase, indicating that wetland restoration projects had achieved initial successes in Zhangye, the wetland ecological environment had been improved, and the wetland degradation had been relieved to some degree. However, compared to the benchmark year, *i.e.*, 2000, relatively speaking, the total wetland area continued to decrease. From 2000 to 2014, the total area of the wetland decreased by 2959.13 hectares during the last 15 years, with an average annual reduction rate as high as −1.09%.
- A detailed analysis of the driving forces of the wetland dynamic variations was conducted based on two aspects: natural factors and human factors. The main impact factors, including changes in climatic conditions, upper reach water inflow, population, water resources, and cultivated land, as well as policy influences were analyzed. Thus, it was found that the dynamic changing process of wetland resources was the result of concurrent activities between nature and human activities. The growth in wetland vegetation and the natural distribution of wetland landscapes have been affected by natural factors through water resource changes. However, the natural

landscape of wetlands had been significantly altered by human activities and social factors such as water source management policies, engineering measures for wetland protection and wetland park constructions, consequently influencing landscape planning and layout in both the reserve and the wetland park.

Supplementary Materials: The following are available online at www.mdpi.com/1996-1073/9/3/166/s1.

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