Analysis of landscape fragmentation processes and driving forces in wetlands in arid areas: A case study of the middle reaches of the Heihe River, China

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\textbf{A R T I C L E I N F O}

\textit{Article history:}
Received 3 September 2013
Received in revised form 30 April 2014
Accepted 18 June 2014

\textbf{Keywords:}
Wetlands
Fragmentation
Driving forces
Heihe River
Landscape indices

\textbf{A B S T R A C T}

Landscape fragmentation in wetlands usually implies degradation of its ecological functions. Landscape fragmentation divides wetlands into isolated islands, which disturbs the energy flow and nutrient cycling within the wetland. Research into the development and causes of landscape fragmentation in wetlands is urgently needed for effective monitoring and protection of wetlands. We use a combination of techniques including remote sensing, a landscape index model, and redundancy analysis to analyze landscape fragmentation and its driving forces in the middle reaches of the Heihe River from both temporal and spatial perspectives. A new mathematic morphological method that enhances the credibility of landscape fragmentation analysis without changing the original pixel size of the interpreted data is proposed for the calculation of landscape indices. The combination of this new mathematic morphological method and traditional landscape pattern indices enhances the evaluation strategy for landscape fragmentation. Our results demonstrate that the fragmentation processes that affect the wetland landscape of the study area are primarily represented as the shrinking of core wetland area and decrease in mean size of wetland patches. Our results also show an increase in the fragmentation index (\textit{FS}) of the landscape in recent decades. The impacts of natural factors on wetland landscape fragmentation processes are typically reflected in changes in climate and hydrology. In the study area, temperature, which is more important than precipitation in driving wetland landscape fragmentation processes, cannot be omitted. In addition, our analysis proves that unnecessary human activity is a major threat for sustainable development and maintenance of wetlands.

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1. \textbf{Introduction}

Wetlands are unique ecosystems formed as a result of interactions between the forces affecting land and water (Zhang et al., 2010). As key parts of the global ecological system and carbon pool, wetlands offer important ecological functions and effects that cannot be replaced: they mitigate pollution, provide habitats for wildlife, regulate climate, and preserve biodiversity, among other things (Mander and Mitsch, 2009; Copeland et al., 2010; Sulman et al., 2013). However, the Organization of Economic Cooperation and Development has estimated that approximately 50% of global wetlands could have been lost since 1900, with the remainder experiencing increased fragmentation in recent years (Lienert et al., 2002; Erwin, 2008; Khaznadar et al., 2009; Zhang et al., 2010; Wang et al., 2011). Similarly, incomplete statistics suggest that two-thirds of wetlands in France were lost during 1900–1993 (Westergaard et al., 2010). In general, climatic change accompanied by increased disturbance caused by human activity has placed wetlands at greater risk, particularly in arid zones (Zhao et al., 2009). Wetlands in arid zones are key nodes and represent critical areas in the landscape patterning that is crucial to the functioning of arid environments; they also play a key role in providing water, energy, and other resources to sustain human life (Zhou, 2005;
Mwakaje, 2009). However, owing to a lack of consideration of their role in sustainable resource use, wetlands in arid areas continue to fragment, resulting in decreased wetland biodiversity (Soomers et al., 2013; Walz and Syrbe, 2013).

Wetland landscape fragmentation plays a major role in the degradation of ecological systems (Liu et al., 2014) and the reduction of wetland biodiversity; in particular, this fragmentation results in complex spatial distributions of vegetation and reduced functioning of wetlands (Alexandridis et al., 2009; Liu et al., 2009; Song et al., 2012). As such, 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 affects cycles of material and energy directly (Wiens, 1994; Cerian and Keys, 2009). As a key factor exerting pressure on biodiversity, wetland fragmentation also has a negative effect on the functioning of wetland ecosystems (Opdam and Wascher, 2004). In most cases, fragmentation represents the first step in the process of wetland degradation. Accordingly, research into the processes underlying wetland landscape fragmentation should improve our understanding of typical wetland evolution and help advance techniques to protect wetlands. The underlying processes and driving forces of wetland landscapes are core research topics in current wetland science (Liu et al., 2009).

The wetlands distributed along the middle reaches of the Heihe River have great significance for the eco-environmental protection of northwestern China. In particular, as the primary westward route for migratory birds of China, the wetlands in the middle reaches of the Heihe River also act as a staging point along the East Asia–India section of the eight global migratory channels. Additionally, these wetlands act as an environmental barrier that prevents the southward invasion of the Badain Jaran desert and play a key role in maintaining the ecosystem balance of the Heihe River basin. However, the wetlands have been partially destroyed by human activity and climate change in recent years, with fragmentation and ecosystem degeneration of these wetlands becoming increasingly pronounced over time. Such degeneration has induced the southward expansion of the Badain Jaran desert, exposing large expanses of grassland and oasis to the threat of desertification, and endangering the survival and development of the Heihe River basin. At worst, such changes could have a profound influence on the ecological security of the Hexi Corridor and northwestern China as a whole. Consequently, research into the wetlands of the Heihe River basin is urgently required. Previous studies of the Heihe River focused on various aspects of the environment, including landscape evolution, hydrological change and its ecological effects, water consumption, evapotranspiration, vegetation cover, and carbon sequestration (Lu et al., 2003; Kang et al., 2007; Kong et al., 2009; Wang et al., 2009; Zhao et al., 2010; Li et al., 2012; Wang et al., 2012; Li et al., 2013). However, many features of these wetlands remain unknown; in particular, knowledge of landscape fragmentation in the region remains insufficient (Li and Zhao, 2010).

Here, we adopt remote sensing (RS), geographical information system (GIS), redundancy analysis (RDA), and techniques of morphological image processing to explore the processes and driving forces of wetland landscape fragmentation in the Heihe River basin. The primary aims of this study are: (1) to characterize the processes of wetland fragmentation in the middle reaches of the Heihe River during 1975–2010 at the landscape and pixel levels; and (2) to analyze the driving forces that promote wetland landscape fragmentation, distinguishing between the effects of human activity and natural environmental changes in the middle reaches of the Heihe River.

2. Study area

The middle reaches of the Heihe River (98°57′–100°52′E, 38°39′–39°59′N) are located in the western part of Gansu Province, northwestern China, spanning three counties (Ganzhou, Gaotai, and Linze) and covering an area of 10,753 km² (Fig. 1). The climate of the region is characterized by cold winters, hot summers, and
generally dry weather. The mean annual precipitation and evaporation are 50–250 mm and 2000–3500 mm, respectively. The terrain of the study area can be divided primarily into mountain and plain areas and includes the Hexi Corridor plain and the Qilian and Heli mountains that are located to the south and north of the Heihe River, respectively. The study area lies at altitudes of 1234–3633 m above sea level, with maximum altitudes in the Qilian Mountains. As a result of human activity and the presence of the Heihe River, cropland and forest cover much of the piedmont alluvial fan and floodplain, with farmland, grassland, and the Gobi desert constituting the primary land use types. The vegetation in the middle reaches of the Heihe River consists primarily of temperate shrubs and desert vegetation.

In recent decades, the social and economic landscapes of Ganzhou, Gaotai, and Linze have changed considerably. Grain output and the income of farmers have continued to rise, resulting in corresponding increases in gross domestic product and the total population of the study area (to $1.7 	imes 10^6$ yuan and $8.255 	imes 10^6$, respectively, by 2010).

In the study area, wetlands are distributed mainly along the Heihe River and occur as marshes, lakes, and bottomlands, among others. Wetland flora and fauna such as Elsholtzia ciliata, Scirpus validus, and the black stork occur extensively in these wetlands. To protect these wetland resources and ensure that this unique ecosystem is protected from disturbance by desertification or climate change, the Chinese State Council established the Heihe River Basin Nature Reserve in 2011. The reserve covers a total area of 41,164.56 ha.

3. Materials and methods

3.1. Data sources and processing

We extracted all data relating to the wetlands in the middle reaches of the Heihe River for the period from 1975 to 2010 from remote sensing images (Table 1). We combined the extracted data with land use/land cover data for the study area (acquired at a scale of 1:100,000 for 1985; and 1996) obtained from the Chinese Academy of Science (http://westdc.westgis.ac.cn/) and a topographic map at the 1:50,000 scale (obtained by a field study in 1972). The selection of yearly images was conducted based on historical events (e.g., the initiation of reform and openness in the 1980s, the influx of western development in the 1990s), policy changes (e.g., water diversion work in the middle reaches of the Heihe River that began in 2001), and image availability. Conversely, the selection of monthly images was conducted based on the occurrence of major changes in vegetation, such as that in summer and at the beginning of autumn.

Image processing was performed using EDRAS Imagine (version 9.2), and data preprocessing involved several steps, including image adjustment, image enhancement, and image cutting. Moreover, MSS (58 m), TM (30 m), and ETM+ (30 m) images were resampled to a 60 m × 60 m pixel size using the nearest-neighbor resampling method. Then, the wetland areas were categorized into rivers, lakes, marshes, bottomlands, reservoirs, and ponds based on the China Wetland Classification System (Zhao et al., 2009) and the landscape characteristics of the study area (Fig. 2). Five land use/land cover types were also identified according to the classification criteria of Liu et al. (2010).

The extraction of wetlands and other land use and land cover information for 1975, 1987, and 1992 required the use of the topographic map at scale 1:50,000 (produced in 1972) and land use
and land cover data from 1985 to 1996 acquired from the Chinese Academy of Science (http://westdc.westgis.ac.cn/); all these products have high accuracy. Therefore, the present study focuses primarily on assessing the accuracy of the classification of the 2001 and 2010 data based on field surveys and high-resolution images. We calculated the kappa coefficient as follows:

\[
K = \frac{N \sum_{i=1}^{m} P_{ii} - \sum_{i=1}^{m} (P_{pi} \times P_{i1})}{N^2 - \sum_{i=1}^{m} (P_{pi} \times P_{i1})}
\]  

(1)

where \( K \) is the kappa coefficient, \( N \) is the total number of samples, and \( P_{pi} \) and \( P_{i1} \) are the total number of samples in the row and rank, respectively, of a given land use/land cover type. Our results show that the accuracies of the classified images for 2001 and 2010 are 84.06% and 81.18%, respectively (Table 2).

To increase our understanding of the dynamics of wetland landscape fragmentation, we considered land use and land cover change, socioeconomic development, hydrology, and climate change in our analysis of the driving forces of fragmentation. We adopted ten socioeconomic indices: gross domestic product, primary industrial output, secondary industrial output, revenue, expenditure, total population, grain yield, total investment, total retail sales, and rural per capita net income. The data for these indices were obtained from the 1984–2011 yearbooks from Gansu Province, and we selected data from a 60-year period (1949–2008) to illustrate the effects of socioeconomic development on wetland fragmentation. Similarly, we used annual precipitation and annual temperature data for 1967–2010 obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/) to investigate the effects of climate change on fragmentation. Finally, we used runoff data acquired from monitoring at the Yingluoxia and Zhenyixia stations between 1956 and 2005 to investigate the effects of changes in hydrology on wetland landscape fragmentation.

3.2. Analysis

3.2.1. Fragmentation processes at landscape level

Landscape fragmentation studies typically adopt a selection of landscape indices. In this study, we selected the mean patch size (MPS), patch density (PD), mean patch shape fragmentation index (FS1), and area-weighted mean shape fragmentation index (FS2) for use in quantitative analysis of the processes involved in wetland landscape fragmentation. Further details of these indices can be found in previous studies (Lu et al., 2003; Zhao et al., 2009; Wang et al., 2011). MPS and PD were calculated using FRAGSTATS version 3.3 and ArcGIS version 9.3. FS1 and FS2 were calculated according to Eqs. (2)–(4).

\[
FS_1 = 1 - \frac{1}{MSI}
\]

(2)

\[
FS_2 = 1 - \frac{1}{ASI}
\]

(3)

\[
MSI = \frac{\sum_{i=1}^{N} S_i(i)/N}{\sum_{i=1}^{N} S(i)} = \frac{P(i)}{\sqrt[4]{A(i)}}
\]

(4)

\[
ASI = \sum_{i=1}^{N} A(i) S_i(i)/A ; A = \sum_{i=1}^{N} A(i)
\]

(4)

Here, MSI is the mean shape index, ASI is the area-weighted shape index, and \( S_i \) (i), \( A(i) \), and \( P(i) \) are the shape index, area, and perimeter, respectively, of the patch i. \( S(i) \) (i) is typically calculated for a square shape index; accordingly, the square patch shape index is 1 and other shape indices are greater than 1.

3.2.2. Fragmentation processes at pixel level

We developed four area indices using morphological image processing to explore the process of wetland fragmentation. First, two 3 × 3 SEs were defined according to the research of Vogt et al. (2006) and Ritters et al. (2009). Then, four wetland types (Core, Edge, Patch, and perforated wetlands) were obtained from the binary images (Fig. 3). 'Core wetland' is the wetland that is separated from non-wetlands by a buffer zone. Spatially, they are generally expressed as wetlands with a large area and high concentration. 'Patch wetland' refers to wetlands that are much smaller than 'core wetlands' and they are surrounded by non-wetlands. 'Edge wetlands' and 'perforated wetlands' are the buffer zones between 'core wetlands' and non-wetlands. 'Perforated wetlands' are located in the interior of core wetlands and 'edge wetlands' in the exterior. In most cases, increases in 'patch wetland' and 'perforated wetland' indicate an increase in fragmentation. The specific steps undertaken for extraction of the different wetlands from the binary image are as follows (Fig. 4):

Step 1: The extraction of core wetland: SE1 was used to perform an operation of erosion on wetland pixels. If all the neighbors are wetlands, we define the center pixel as the core wetland. The other pixels are then taken to be different from core wetlands and non-wetlands and they are the patch, edge, and perforated wetlands, which are distinguished by the following operations.

Step 2: The extraction of patch wetland: SE2 was used to perform an operation of dilation on core wetlands. Since patch

| Table 2 |

Error matrix for the interpretation of 2010/2001 data.

<table>
<thead>
<tr>
<th>GPS and google earth samples</th>
<th>Classification</th>
</tr>
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<tbody>
<tr>
<td>A1</td>
<td>A2</td>
</tr>
<tr>
<td>21/1</td>
<td>2/1</td>
</tr>
<tr>
<td>1/0</td>
<td>61/8</td>
</tr>
<tr>
<td>2/0</td>
<td>7/1</td>
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<td>1/0</td>
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<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>26/1</td>
</tr>
</tbody>
</table>

Notes: A1: farmland; A2: grassland; A3: forest; A4: desert; A5: construction; A6: river; A7: bottomland; A8: lake; A9: marsh; A10: reservoir and pond. The left number is the sample number of 2010 and the right is the sample number of 2001.
wetland pixels are indirectly connected with the core wetland, we applied a repeated dilation on core wetlands with SE2. Only when all indirectly connected wetland pixels are identified can the dilation be stopped.

Step 3: The extraction of edge wetland: In contrast to the extraction of core and patch wetlands, edge wetlands were identified by set non-wetland pixels to perform the dilation operation.

Step 4: The extraction of perforated wetland: Since the core, patch, and edge wetlands were subtracted, the remaining undefined wetland pixels were classified as perforated wetlands.

3.2.3. Driving forces of wetland landscape fragmentation

The forces driving wetland landscape fragmentation can be divided into two groups: factors related to human activity and natural factors. We selected annual temperature and annual precipitation as primary variables to investigate the effects of natural factors on fragmentation based on the characteristics of the study area. In addition, factors such as total population, rural per capita net income, gross domestic product, primary industrial output, secondary industrial output, total investment, total retail sales, and grain yield, were chosen to explore the effects of socioeconomic development on fragmentation. Then, we performed redundancy analysis (RDA) to calculate the cumulative

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**Fig. 3.** Four classes of wetland patterns defined in this study.

**Fig. 4.** Extraction process of the four classes of wetland patterns defined in this study.
contribution ratio of socioeconomic development and climate change. In this manner, the effects of socioeconomic development and natural variations on wetland landscape fragmentation could be assessed quantitatively.

Furthermore, we conducted other, more qualitative, analyses to derive the relationship between landscape fragmentation and changes in hydrology and land use/cover, which are detailed in the discussion section. In this manner, we identified and quantified the effects of human activity and natural changes on wetland landscape fragmentation.

4. Results

4.1. Fragmentation processes in wetland landscapes

4.1.1. Fragmentation processes at landscape level

Our results demonstrate that the MPS of the wetlands in the study area decreased each year during 1975–2010 (Fig. 5a and b), with particularly marked reductions during 1975–1987 and 2001–2010 (reductions of 22.56% and 19.35%, respectively). Conversely, PD, FS1, and FS2 in the study area increased considerably in recent years, particularly during 1975–1987 and 1992–2010. PD increased from 0.008 Ind/ha to 0.111 Ind/ha and from 0.012 Ind/ha to 0.014 Ind/ha during 1975–1987 and 1992–2010, respectively. During these same intervals, FS1 increased from 0.565 to 0.575 and from 0.270 to 0.275, and FS2 increased from 0.524 to 0.556 and from 0.269 to 0.276, respectively.

In general, the indices used here suggest increased fragmentation of the wetland landscape, particularly in the 1990s and 2000s. The Ninth Five-Year Program was implemented during 1996–2000 and the Western Development Program and a water diversion project in the middle reaches of the Heihe River were initiated in 2001. The resulting high-density human activity in the study area likely resulted in accelerated fragmentation of the wetland landscape; this fragmentation would have been exacerbated by factors such as the expansion of farmland, excessive use of water resources, and wetland reclamation. Therefore, our results suggest that, even with different evolutionary pathways or components, landscape fragmentation is the primary manifestation of landscape pattern changes in the study area and will likely persist over relatively long periods.

4.1.2. Fragmentation processes at pixel level

The change in area of the core, patch, edge, and perforated wetlands shows a significant process of fragmentation of the wetland landscape in the past decades. The area of core wetlands decreased by 42.54% from 1975 to 2010 (Fig. 5c, Fig. 5d). Correspondingly, the proportion of its pixels in the total wetland pixels reduced from 49.17% to 36.83% during 1975–2010 (Fig. 5d). Along with the reduction of core wetlands, edge wetlands also decreased. However, the area of patch and perforated wetlands increased by 586.8 ha and 34.20 ha, respectively (Fig. 5c). Thus, the core wetlands in the study area are observed to have gradually fragmented into patch and perforated wetlands.

Furthermore, we can directly observe that the spatial pattern of wetlands in the Heihe River basin is characterized by fragmentation. As Fig. 6 shows, core wetlands were the dominant landscape in 1975. Patch and perforated wetlands were scattered and only covered a small area in the wetland landscape. However, in 2010, this situation had gradually changed. In this period, the area of perforated wetlands had enlarged significantly and large numbers of core wetlands had been replaced by patch and edge wetlands.

Fig. 5. Landscape indices of wetlands in the middle reaches of the Heihe River.
4.2. Driving forces of wetland landscape fragmentation

When performing RDA analysis, landscape indices, such as $FS_1$, $FS_2$, $MPS$, $PD$, and area of core, patch, edge, and perforated wetlands, were selected as dependent variables, and factors reflecting socioeconomic and natural change were selected as independent variables (Fig. 7). Prior to the RDA analysis, a significant test (Monte Carlo Permutation Tests, Number of permutation: 499) for each variable was performed to primarily screen the important factors. As the results in Table 3 show, the PIO (primary industrial output), T (annual temperature) and GDP (gross domestic product) passed the hypothetical testing under the 0.05 significance level. Therefore, only the PIO, T, and GDP were selected for the RDA analysis.

According to the results of RDA analysis, the first three eigenvalues reported above are canonical and the fourth is not since only three independent constraints can be formed from the environmental variables. As Table 4 and Table 5 show, the cumulative percentage variance of species data and species-environment relations are high, at 84.6% and 100%, in the first three axes. This demonstrates that the environmental variables we selected interpret the process of wetland landscape fragmentation appropriately. Based on the angles between the landscape indices and environmental variables, we found that the PIO and GDP have a significant positive correlation with PD and perforated wetlands, but a significant negative correlation with MPS and core wetlands (Fig. 8). Furthermore, T also has a significant positive correlation with $FS_1$, $FS_2$, PD, and patch wetlands, but a significant negative correlation with MPS and core and edge wetlands. Moreover, T-test results for the influence of T, PIO, and GDP on the landscape indices of wetlands also show that $FS_2$ and patch wetlands have a significant positive correlation with T, PIO, and GDP (Fig. 8). However, it is obvious that PIO and GDP contribute more to wetland landscape fragmentation than T according to the length of the arrow. This further demonstrates that human activities are the most important driving forces in our study area as compared with natural changes.

5. Discussion

5.1. Extraction of wetland information

Accurate extraction of wetland information is the most critical step in the analysis of long time series of wetland landscapes.
(Wang et al., 2011). However, in the present study, the selected landscape pattern indices were all calculated from data obtained from remote sensing images; this technique often results in considerable errors relating to incorrect classification during the calculation of landscape pattern indices (Langford et al., 2006).

Using the topographic maps and land use data described above, we were able to extract precise wetland information for 1975, 1987, and 1992. Therefore, we considered only the accuracy of information extracted for 2001 and 2010 explicitly in the present study, placing more importance on the collection of historical atlas data, high-resolution Google Earth images, and field survey data for these periods. Moreover, wetlands can be distinguished more easily than other land cover types in arid regions on TM and ETM+ images, and the primary error in our technique arises from classification. However, by selecting different band combinations and collecting data from different channels, we were able to confirm the high quality of our results through accuracy assessment.

5.2. High-density human activity as a primary cause of wetland landscape fragmentation

The relationship between wetland landscape pattern evolution and human activity is currently the subject of considerable debate in the field of landscape ecology. Many previous studies have posited that high-density human activity is the primary factor controlling the evolution of wetland landscape pattern (Khaznadar et al., 2009; Li and Zhao, 2010; He et al., 2011; Song et al., 2012). Based on our results, we believe this to be the case in the middle reaches of the Heihe River.

Known for their oasis agriculture, reclaimed wetlands (Fig. 9b) have long been considered an important means by which to increase available arable land (Table 6). During recent decades, 5410.82 ha of wetland has been transferred into farmland (Table 6). Moreover, agricultural activities such as flood irrigation and application of insecticide and chemical fertilizers can also damage wetland ecosystems and alter their pattern. Statistical data have shown that agriculture accounts for 95% of the total consumption in the study area (Wang et al., 2009), although various forms of construction engineering (such as artificial sand excavation: Fig. 9a), the Binhe New Zone, and the Second Railway between Lanzhou and Urumqi in Ganzhou, are likely to place additional stress on the wetland landscape as the economy of the region develops further. Throughout the study period, 434.24 ha of wetlands were developed for construction and used as residential land (Table 6); as the population in the study areas continues to increase, yet more land will be required to meet demand.

<table>
<thead>
<tr>
<th>Table 3</th>
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<tr>
<th>P-value and F-value of the environmental variables</th>
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<table>
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<th>TRS</th>
<th>PIO</th>
<th>GDP</th>
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<th>SIO</th>
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<td>0.076</td>
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<td>2.698</td>
<td>2.607</td>
<td>2.536</td>
<td>0.440</td>
</tr>
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</table>

Notes: GY (grain yield), TRS (total retail sales), PIO (primary industrial output), GDP (gross domestic product), T (annual temperature), SIO (secondary industrial output), RPCIN (rural per capita net income), TI (total investment), TP (total population), P (annual precipitation).

* P < 0.05.
since the implementation of the water diversion policy in 2001. Ignorance of the dwindling water helped increase the farmland area in the study area by 7798.14 ha during 1975–2010. Accordingly, increasingly small amounts of water were available for the wetlands, causing those without adequate water to degenerate and be replaced by desert or grassland. Accordingly, wetlands with a sufficient water supply have formed vegetation mosaics within grassland and desert landscapes.

### 5.4. Key of water diversion in the middle reaches of the Heihe River in wetland fragmentation during 2001–2010

Water is a critical factor controlling the formation and development of wetland vegetation and soil, particularly in arid environments (Kong et al., 2009). Accordingly, in most cases, changes in hydrology have direct effects on the energy cycle and material flow in wetland systems; such systems are particularly sensitive to hydrological changes such as variations in the quantity and quality of their water sources (Wang et al., 2011).

Water diversion (Fig. 7f) 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 (Table 7). This water diversion also had a profound effect on the processes involved in the maintenance of the wetland landscape pattern. Wetlands are particularly sensitive to changes in water supply; in our study area, such changes affected the productivity of aquatic plants and animals and disrupted the regional water balance. Our results show that these intervals with decreased water availability coincided with periods of obvious landscape fragmentation. For example, the water surplus during 1975–1987 was less than that at any other time, and FS1 and FS2 for wetlands as a whole increased from 0.565 to 0.575 and from 0.270 to 0.275 (Fig. 5), respectively, during this period. Similarly, the water surplus in 2001–2005 was only $6.50 \times 10^8$ m$^3$ (Table 7) owing to the influence of water diversion; this period of low surplus corresponded to decreases in MPS (19.35%) and PD (from 0.0121 ind/ha to 0.0151 ind/ha) but increases in FS1 and FS2 (from 0.272 to 0.276 and from 0.539 to 0.556, respectively) (Fig. 5). Thus, our results demonstrate a direct relationship between hydrology and wetland landscape fragmentation.

Water demand in the region will continue to increase with increases in industrialization and urbanization, resulting in tension as competition grows for the available resources. Such human intervention has altered the hydrological cycle in the wetland ecosystem, reducing the supply of water from upstream and endangering the balance between supply and demand and disrupting the wetlands in the middle reaches of the Heihe River. Moreover, because the area requiring irrigation in the study area
has been maintained since the water diversion, farmers have begun to develop groundwater resources to meet irrigation needs (Table 8), resulting in reductions in exploitable groundwater and overall groundwater level described above (Wei et al., 2007).

Groundwater flow has a considerable influence on the chemical properties of groundwater in the aquifer that feeds the study area, and it has been shown that river water is preferable for irrigation (Qin et al., 2011). Therefore, high-density exploitation of the groundwater will likely induce soil salinization without maximizing the potential of the regional water balance and may have a considerable negative effect on plant life and soil characteristics. Accordingly, we believe that decreasing groundwater levels may be primarily responsible for the degradation of wetland landscape patterning and that the wetlands in the middle reaches of the Heihe River will continue to fragment and even disappear without intervention.

5.5. Effects of climate change on wetlands

Climate is the primary factor controlling the dynamics of wetland formation and material exchange (Sutula et al., 2003), and the influence of climate change on wetlands is expressed primarily through changes in precipitation and temperature, which determine wetland plant physiology (Dawson et al., 2003). Accordingly, changes in precipitation and temperature can induce changes in wetland hydrology (Milzow et al., 2010), causing wetlands to expand or contract. Furthermore, as previous studies have shown, temperature is the most fundamental factor controlling the dynamics of wetland landscape patterning (Song et al., 2012).

Wetland systems are particularly vulnerable to changes in climate and water supply, particularly in arid regions, where such changes threaten the continued existence of wetlands. In particular, climate change often affects the landscape pattern of wetlands through its effects on wetland hydrology, and fluctuations in precipitation or temperature are known to affect water availability and stream flow (Dawson et al., 2003).

Throughout our study period, a significant increase in temperature and fluctuations in precipitation occurred in the middle reaches of the Heihe River: temperature increased from 7.53 °C to 8.72 °C in recent decades, whereas precipitation decreased from 121.78 mm to 118.74 mm between 1992–2001 and 2001–2010 (Fig. 7e). Generally speaking, the region has

Fig. 8. T-test results for GDP (a), PIO (b), and T (c) influencing landscape indices (red circle means negative correlation and grey circle means positive correlation); Redundancy analysis results for landscape indices and environmental variables (d).
Mean surplus of water during different time periods ($\times 10^6$ m$^3$).

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Notes: Water surplus = influx from Yingluoxia valley – outflow from Zhengyixia valley.
Laws for the protection of wetlands must be enacted and improved in a timely manner in order for wetlands to come under the unfailling aegis of law.

6. Conclusions

The results of our study show that the indices we choose reveal the process of landscape fragmentation in wetlands at landscape and pixel levels well. A new mathematic morphological method was proposed for the calculation of four indices. Compared with the landscape pattern index, the indices based on this new method can better support the analysis of landscape fragmentation without changing the original pixel size of the interpreted data; this enhances the credibility of the analysis. In addition, this new method is useful for researchers to evaluate landscape fragmentation not only for wetlands but also for forests, farmlands, and other land types.

Redundancy analysis was performed to analyze the driving forces of landscape fragmentation in wetlands. In addition, qualitative analyses were also performed to explore the effects of changes in hydrology and land use/cover on the landscape fragmentation in wetlands. By combining quantitative analysis with qualitative analysis, we were able to comprehensively analyze the cause of the landscape fragmentation in the wetlands of our study area. The results show that PSI (primary industrial output), T (annual temperature), and GDP (gross domestic product) were the major factors causing wetland fragmentation in our study area. Our results indirectly show that human activities are not the sole reason for landscape fragmentation of wetlands in arid zones. Natural changes, such as increases in temperature, also play a key role and cannot be ignored. In addition, the driving forces analysis that we propose in this study provides a reference for related studies.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant No. 41371017, 41001238), the National Key Technology R&D Program of China (Grant No. 2012BAH28B02). Sincere thanks are given for the comments and contributions of anonymous reviewers and members of the editorial team.

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