Spatiotemporal Evolution of Wetland Landscape and Its Driving Factors in the Middle Reaches of the Shule River (Postprint)

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Abstract

Wetland landscape patterns can reflect the area changes and spatial distribution characteristics of wetland types, and their spatiotemporal evolution facilitates understanding of the interaction relationships between disturbance factors and wetland ecological processes. This study selected five wetland types in the middle reaches of the Shule River, including reservoir and pond wetlands, permanent river wetlands, and inland salt marshes, and employed landscape pattern analysis and principal component analysis methods to investigate the spatiotemporal evolution of wetland type areas, landscape indices, and their influencing factors. The results indicated that: (1) From 1987 to 2017, the total wetland area in the middle reaches of the Shule River decreased by 477.24 km^2, with reservoir and pond wetlands, permanent river wetlands, and inland salt marshes decreasing by 50.99%, 53.28%, and 35.78%, respectively, while herbaceous marshes and marshy meadows increased by 175.26% and 21.89%. (2) At both the landscape and class levels, patch density and landscape shape index exhibited a fluctuating increasing trend, with wetland landscape patches tending toward fragmentation and scattered distribution. (3) In 2017, population and cultivated land increased by 1.2 times and 1.5 times compared to 1987, respectively; the explanatory power of main socioeconomic development indicators for wetland area change was 68.89%, while that of climate factors was 22.09%. Over the past 30 years, population growth, farmland expansion, and water conservancy project construction have led to wetland area reduction and landscape fragmentation in the middle reaches of the Shule River.

Full Text

Abstract

Wetland landscape patterns can reflect the area variations and spatial distribution characteristics of wetland types, and their spatio-temporal evolution helps to understand the relationship between disturbance factors and wetland ecological processes. This study selected five wetland types in the middle reaches of the Shule River, including reservoir wetlands, permanent river wetlands, and inland salt marshes. Using landscape pattern analysis and principal component analysis, we examined the spatio-temporal evolution of wetland type areas and landscape indices and their influencing factors. The results show that: (1) From 1987 to 2017, the total wetland area in the middle reaches of the Shule River decreased by 477.24 km^2, with reservoir wetlands, permanent river wetlands, and inland salt marshes decreasing by 50.99%, 53.28%, and 35.78%, respectively, while herbaceous marshes and swamp meadows increased by 175.26% and 21.89%, respectively. (2) At both landscape and class levels, patch density and landscape shape index showed fluctuating increasing trends, with wetland landscape patches becoming increasingly fragmented and scattered. (3) In 2017, population and cultivated land increased by 1.2-fold and 1.5-fold, respectively, compared with 1987. The explanatory power of major socioeconomic development indicators on wetland area change was 68.89%, while that of climatic factors was 22.09%. Population growth, farmland expansion, and water conservancy projects over the past 30 years led to wetland area reduction and landscape fragmentation in the middle reaches of the Shule River.

Keywords: wetland; landscape pattern; influencing factors; principal component analysis; middle reaches of the Shule River

1. Study Area and Methods

1.1 Study Area Overview

The Shule River is located at the westernmost end of the Hexi Corridor in China, originating from the western section of the Qilian Mountains. The study area is situated in Guazhou County (formerly Anxi County) in the middle reaches of the Shule River [Figure 1: see original paper], geographically located at 39°52 –41°53 N, 94°45 –97°00 E. The region has a temperate continental climate with an average temperature of 6.98–9.82 °C, average annual precipitation of 47–63 mm, and annual evaporation of 1109–2901 mm. Precipitation is concentrated in summer. The dominant soil types are irrigation-silt soil, aeolian sandy soil, meadow soil, and swamp soil. Vegetation consists mainly of desert, psammophyte, hygrophyte, swamp, and halophyte communities, with key species including *Phragmites australis*, *Typha orientalis*, *Achnatherum splendens*, *Tamarix chinensis*, *Calamagrostis pseudophragmites*, *Karelinia caspia*, *Leymus secalinus*, *Carex lasiocarpa*, and *Kobresia myosuroides*. Wetlands in the middle reaches primarily develop on the Changma alluvial fan and the middle-lower alluvial plain, with water supply mainly dependent on surface runoff and groundwater springs from the Shule River.

1.2 Data Sources and Methods

1.2.1 Data Sources and Processing Following the *National Wetland Resources Survey and Monitoring Technical Regulations* and considering the hydrological and geomorphological conditions and wetland vegetation community characteristics of the middle Shule River, we classified the study area wetlands into three categories: river wetlands, artificial wetlands, and marsh wetlands, including five types: permanent river wetland, reservoir wetland, herbaceous marsh, swamp meadow, and inland salt marsh. Wetland type data were extracted from Landsat TM and Landsat OLI imagery. Remote sensing images were preprocessed through image enhancement and geometric correction, with standard false-color composites using bands 4, 3, and 2. Based on 2017 field survey data of wetland types, we established interpretation keys for wetland types according to vegetation types and image texture and color features in the study area . Using ENVI 5.3 software, we obtained wetland type data through a combination of supervised classification and visual interpretation. To improve accuracy, 120 of 150 field sampling points containing various wetland types were used to establish interpretation keys, and 30 sampling points were used for accuracy verification of wetland classification. The classification results were edited and corrected, with misclassified or omitted objects manually assigned correct attributes. The final overall classification accuracy exceeded 85%, meeting the requirements of this study. Temperature and precipitation data were obtained from the China Meteorological Data Sharing Network (http://data.cma.cn/), while socioeconomic data were sourced from the *New China 60-Year National Economic and Social Development Statistical Bulletin*, *Gansu Development Yearbook*, *Guazhou County (Ninth and Tenth Five-Year) Statistical Yearbooks*, and existing literature.

1.2.2 Landscape Pattern Analysis Methods Among the numerous methods for analyzing landscape pattern evolution—such as qualitative description, landscape pattern quantitative analysis, and landscape ecological map overlay—landscape pattern indices are widely applied for quantitative description of landscape patterns. This study selected patch density (PD) and landscape shape index (LSI) to characterize the fragmentation process of wetland landscapes in the study area, considering both landscape density and shape differences. A higher PD value indicates greater landscape fragmentation, while a smaller LSI indicates more regular landscape shapes and a larger LSI indicates increasingly complex shapes.

1.2.3 Principal Component Analysis Principal component analysis has been widely applied in ecology and geography for quantitatively identifying factors influencing ecosystem degradation. Factors affecting wetland type changes include climate and human economic activities. Climate impacts on wetland resources are mainly manifested in temperature and precipitation, while human activity disturbances represented by population growth and economic development have become increasingly prominent. We selected six impact indicators: average annual temperature, annual precipitation, total population, gross domestic product, cultivated land area, and primary industry value. Using SPSS 22.0 software, we performed principal component analysis on these selected indicators to explore the main factors influencing wetland landscape evolution in the middle reaches of the Shule River.

2. Results

2.1 Analysis of Wetland Type Area Changes

Wetlands in the study area are mainly distributed along both banks of the Shule River channel and in the Tashi Basin [Figure 2: see original paper]. Permanent river wetlands are widely distributed in the main channel of the middle Shule River. Reservoir wetlands are primarily constructed beside the main channel or at the edges of cultivated land and villages within oases. Herbaceous marshes are mainly distributed in the floodplains of the Shule River, around reservoir wetlands, and in areas where groundwater and springs emerge. Swamp meadows are mainly distributed on the periphery of herbaceous marshes. Inland salt marshes are mostly distributed at the outer ends of alluvial fans and on the periphery of river beaches.

From 1987 to 2017, the wetland area in the middle reaches of the Shule River showed a decreasing trend [Figure 3: see original paper], with the total area decreasing by 477.24 km^2 (28.30%). Area changes varied among wetland types: reservoir wetlands, permanent river wetlands, and inland salt marsh wetlands showed fluctuating decreasing trends, decreasing from 23.26 km^2, 1271.02 km^2, and 11.4 km^2 to 188.38 km^2, 88.22 km^2, and 816.68 km^2, respectively, with reductions of 50.99%, 53.28%, and 35.78%. In contrast, herbaceous marsh and swamp meadow areas increased by 175.26% (50.93 km^2) and 21.89% (38.19 km^2), respectively, in 2017 compared with 1987.

2.2 Changes in Wetland Landscape Pattern Indices

2.2.1 Changes in Landscape-Level Pattern Indices From 1987 to 2017, patch density (PD) at the landscape level showed an overall trend of first decreasing and then increasing [Figure 4: see original paper]. PD reached its minimum value of 0.002 in 1995, remained relatively stable from 1995 to 2002, and increased sharply after 2002, mainly due to intensified human activities and increased landscape fragmentation. Landscape shape index (LSI) showed a fluctuating pattern of first increasing, then decreasing, and then increasing again, with the minimum value appearing at the beginning of the study period (23.4) and the maximum at the end (107.7). The LSI increased by 5.81 times, indicating that wetland landscape edges became increasingly complex due to human interference throughout the study period.

2.2.2 Changes in Class-Level Pattern Indices Changes in landscape pattern indices for each wetland type in the middle reaches of the Shule River are shown in [Figure 5: see original paper]. Patch density (PD) for all wetlands showed an increasing trend, with patches becoming more fragmented and scattered. Reservoir wetland PD was the smallest, remaining stable at 0.002–0.030. Permanent river wetland PD increased from 0.002 in 1987 to a maximum of 0.030 in 2017. Herbaceous marsh PD showed a fluctuating decline before significantly increasing, reaching its highest value in 2017. Swamp meadow PD showed a fluctuating decreasing trend before significantly increasing, reaching its highest value of 0.028 in 2017. Inland salt marsh PD showed a trend of first decreasing and then increasing, reaching a maximum of 0.026 in 2017.

All wetland landscape shape indices (LSI) showed increasing trends, indicating that wetland boundaries were severely damaged and shapes became increasingly complex. Reservoir wetland LSI showed a pattern of first decreasing and then increasing, reaching a maximum of 50.99 in 2017. Permanent river wetland LSI showed a fluctuating increasing trend, reaching a maximum of 53.28 in 2017. Herbaceous marsh LSI showed a trend of decreasing and then increasing, reaching its highest value of 35.78 in 2017. Swamp meadow LSI showed large fluctuations, with the maximum appearing in 2017. Inland salt marsh LSI reached its lowest value of 21.89 in 1995 before showing a fluctuating increasing trend, reaching its maximum in 2017.

2.3 Analysis of Influencing Factors

2.3.1 Interannual Variation of Temperature and Precipitation Analysis of annual precipitation and average temperature changes in Guazhou County within the middle reaches from 1987 to 2017 shows that both annual precipitation and average temperature showed overall upward trends. The multi-year average temperature was 6.7 °C, with a temperature increase rate of 0.04 °C · a^{-1} and a fluctuation range of 5.81-7.6 °C. The multi-year average precipitation was 68.9 mm, with a precipitation increase rate of 0.18 mm · a^{-1} and a fluctuation range of 23.4-107.7 mm. Compared with precipitation changes, the interannual variation of average temperature in this region was greater, with the maximum value appearing in 2017. Precipitation in 2017 was 5.81% higher than the average.

2.3.2 Socioeconomic Development Major socioeconomic development indicators in Guazhou County from 1987 to 2017 are shown in . The total population in 2017 increased by 72.21% compared with 1987, with the fastest growth rate occurring during 1995-2002. Gross domestic product increased from 0.67$×10^{8}$ yuan to 72.41$×10^{8}$ yuan, an increase of 107.7 times. Cultivated land area and primary industry value increased by 25.70% and 1.5 times, respectively. The expansion of cultivated land mainly relied on reclamation of wetland resources and grassland resources following the implementation of the "Two Wests Project," Shule River immigration project, and Jiudianxia immigration project.

2.3.3 Principal Component Analysis of Wetland Influencing Factors

The principal component factor load matrix shows that in the first principal component, the loadings of total population, gross domestic product, cultivated land area, and primary industry value were all high, while the loadings of average temperature and precipitation on wetland changes were relatively low. This indicates that human economic activities had a much greater impact on wetland area changes than climatic factors in the first principal component. In the second principal component, average temperature had a relatively high loading on wetland changes, while the loadings of population, gross domestic product, and agricultural development were all below 0.5. Unlike the first principal component, the loading of average temperature increased to 0.68 in the second principal component, while precipitation loading remained low, indicating that precipitation changes had a minor ecological role in middle-reach wetlands. Overall, the first principal component representing socioeconomic activities explained 68.89% of the total variance, while the second principal component representing climatic factors explained 22.09%. Socioeconomic activities were the dominant factor in wetland type changes in the study area, with climatic factors having a lower loading in the first principal component and their influence being masked by human economic activities.

3. Discussion

3.1 Analysis of Factors Influencing Wetland Type Changes

Hydrological processes play a crucial role throughout the entire process of wetland development, succession, and eventual disappearance. Climate change and human activities jointly affect wetland changes. Given the limited study area and relatively short time span, human-dominated socioeconomic activities are the most direct and intense driving factors of wetland area changes, often masking the contribution of climate change to wetland area variations. This study found that the total wetland area in the middle reaches of the Shule River showed an overall decreasing trend over the past 30 years, with different changes among wetland types. Reservoir wetlands, permanent river wetlands, and inland salt marshes decreased, while herbaceous marshes and swamp meadows increased [Figure 3: see original paper]. The loadings of precipitation on wetland changes were low in both principal components, indicating that socioeconomic activities had a far greater impact on wetland area changes than climatic factors. In the second principal component, although the loading of average temperature increased to 0.68, precipitation loading remained low, suggesting that precipitation changes had minimal ecological effects on middle-reach wetlands. Overall, the first principal component (socioeconomic activities) explained 68.89% of total variance, while the second principal component (climatic factors) explained 22.09%. Wetland type changes in the study area were dominated by human economic activities, with climate change contributions being masked.

Guazhou County is rich in light, heat, and land resources, making it easy and inexpensive to reclaim. Since 1987, three major immigration projects have been implemented: the "Two Wests" immigration project, the Shule River agricultural irrigation and resettlement project, and the Jiudianxia Reservoir immigration project. The population increased by 72.21% from 1987 to 2017. To solve livelihood and income problems for immigrants, large areas of sandy wasteland and forest-grass land were reclaimed as farmland and resettlement bases. Rapid economic development, continuous growth in gross domestic product, and simultaneous increases in cultivated land and primary industry value intensified the contradiction between limited water resources and agricultural irrigation. To address water shortages for irrigation and daily life, the Changma Reservoir was completed and began storing water in 2002, reducing flood peak expansion along the Shule River and weakening water exchange between the river channel and wetlands. Field canal system projects consolidated scattered surface water while reducing water volume in the middle reaches, causing river channel changes and affecting ecological water use for wetlands. Rising temperatures increased evaporation, and under low precipitation conditions, the ecological role of precipitation could not be manifested. Water conservancy facilities caused wetland area to shrink by nearly 13.47% in the early 21st century. The water-saving society construction project implemented in the early 2000s promoted efficient agricultural water-saving technologies such as ridge-furrow irrigation, adjusted high water-consumption crop structures, and effectively improved water use efficiency, alleviating water supply-demand contradictions. With surplus irrigation water and under comprehensive land development policies, a second wave of land development emerged, causing large-scale reclamation of salt marsh wetlands on oasis peripheries and a declining trend in total wetland area after 2002.

3.2 Analysis of Factors Influencing Wetland Landscape Fragmentation

Wetland landscape fragmentation is the process of landscapes transitioning from simple and continuous to complex and dispersed, sensitively responding to human activity interference through wetland ecological and hydrological processes. This is mainly manifested by increased patch numbers leading to higher density, increasingly irregular patch shapes, reduced interior habitat area, and patch separation. This study found that human economic activity interference on wetland area is closely related to landscape fragmentation, with all wetland types showing increased patch density, shape complexity, and fragmentation trends [FIGURE:4, FIGURE:5].

The factors influencing fragmentation of each wetland type in the middle reaches of the Shule River are as follows: (1) Reservoir wetland fragmentation was mainly due to water scarcity limitations that prompted extensive water conservancy facilities construction, directly increasing reservoir wetland patch density. As oases expanded, natural river channels disappeared, water supply sources decreased, and reservoir wetlands shrank and transformed into other wetland types, with wetland edges becoming increasingly complex. (2) River wetlands were mainly affected by reservoir interception and extensive water diversion for irrigation through field canal facilities, drastically reducing river flow, increasing river branches, raising patch density, and shrinking wetland area. As river water surfaces contracted and water levels shallowed, conversion to herbaceous marshes and swamp meadows resulted in increasingly complex landscape shapes. River wetland area decreased by 53.28% due to reduced water volume. (3) Herbaceous marshes developed as water levels dropped and surfaces contracted after overall water supply from reservoirs and rivers decreased. Edges became exposed due to sediment deposition, and under waterlogged and anaerobic conditions, plant residues and roots were not easily decomposed, developing smaller herbaceous marshes that increased patch numbers and area while strengthening patch density. However, because these small patches were scattered without connectivity, landscape shapes became complex. (4) Swamp meadows are distributed in poorly drained areas inundated by surface and groundwater around reservoirs and rivers. As reservoir construction and canal facilities improved, water supply to reservoirs decreased, local areas in the center and periphery were slightly elevated by sediment retention, water levels shallowed, and river development formed oxbow lakes, providing conditions for hygrophytic herbaceous plants and causing swamp meadow area to increase by 21.89%. However, as swamp meadows are premium grazing areas in this region, overgrazing by increasing immigrant populations caused vegetation degradation, breaking connections between large meadow areas, increasing small patch numbers, raising patch density, and complicating meadow edges. (5) Inland salt marshes were severely damaged by cutting of halophytic plants such as tamarisk, saxaul, and nitre bush to meet living needs after immigration projects, increasing edge shape complexity and reducing connectivity. Reclamation of salt marsh land and field canal system construction isolated concentrated wetlands, leaving unsuitable reclaimed salt marshes as small, fragmented patches, increasing patch density.

Population increase, uncontrolled farmland expansion, field canal engineering, and human destruction intensified fragmentation of all wetland types while also causing overall spatial dispersion of middle-reach wetlands, with wetland shapes becoming increasingly complex and internal fragmentation increasing.

4. Conclusions

From 1987 to 2017, wetland area in the middle reaches of the Shule River decreased by 28.30% (477.24 km^2). Influenced by wetland hydrological processes, herbaceous marshes and swamp meadows increased by 175.26% (50.93 km^2) and 21.89% (38.19 km^2), respectively, as reduced reservoir and water surfaces and ecological water delivery provided favorable resource conditions. Reservoir wetlands, permanent river wetlands, and inland salt marsh wetlands decreased by 50.99% (100.16 km^2), 53.28% (454.34 km^2), and 35.78% (11.86 km^2), respectively, under disturbances from population surge, water conservancy project construction, and agricultural development. Landscape pattern indices at both landscape and class levels showed increasing trends due to interference from human socioeconomic activities, with serious wetland landscape fragmentation. Agricultural socioeconomic activities were the main factor causing wetland area shrinkage and fragmentation in the middle reaches, with a contribution of 68.89%, while climate change contributed 22.09%, masked by human economic activity impacts. The area changes and landscape fragmentation of inland river middle-reach wetland types represent a complex and chaotic eco-hydrological process, requiring further investigation of factors such as groundwater depth, soil salinity, and aridity indices on wetland area and landscape changes.

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Note: Figure translations are in progress. See original paper for figures.