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Relationship between hydroclimatic variables and reservoir wetland landscape pattern indices: A case study of the Sanmenxia Reservoir wetland on the Yellow River, China

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Reservoir construction has led to the development of numerous wetlands, and these wetlands play an important role in global environmental change. In this paper, we investigate the relationship between reservoir wetlands and hydroclimatic variables. We used the MODIS land cover product to extract the wetland area of the Sanmenxia Reservoir, China. Then, various indices of reservoir wetland landscape patterns were calculated. Principal component analysis was performed to build the Sanmenxia Reservoir wetland comprehensive landscape pattern index (CLPI) to depict the changes in Sanmenxia Reservoir wetlands from 2001 to 2013. Pearson correlation analysis was used to assess their relationship. The following results were obtained. Firstly, the Sanmenxia Reservoir wetland area considerably declined and the landscape heterogeneity decreased from 2001 to 2013, especially in 2004. Secondly, the CLPI is significantly negatively correlated with annual runoff and significantly positively correlated with annual sediment discharge, annual average water level and annual shallow groundwater table in Sanmenxia Reservoir regions. Additionally, due to the decline in the reservoir wetland area, the values of Shannon's diversity index and Simpson's diversity index decreased in the study area. Therefore, the study suggests that maintaining a stable and healthy reservoir wetland area should be the focus of ecological reservoir management.

Keywords. Sanmenxia Reservoir wetland landscape patterns; hydroclimatic variables; landscape pattern indices; principal component analysis.

1. Introduction

Wetlands support unique biota and provide important ecosystem services related to the interactions between land and hydrological processes (Straka *et al.* 2016). As key parts of the global ecological system and carbon pool, wetlands perform many valuable services, such as mitigating pollution, providing habitat for wildlife, regulating climate and preserving biodiversity; however, many of these important ecosystems are at risk because of current trends in climate change (Ouyang *et al.* 2014). For example, warmer temperatures and decreased precipitation in the 21st century could severely deplete

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wetlands in the prairie pothole region of western Canada (Withey and van Kooten 2011). Furthermore, shifting precipitation patterns associated with climate change may alter future distributions of wetlands (Garris *et al.* 2015). The hydrology of wetland ecosystems is a key driver of mercury (Hg) methylation as well as the foraging behaviour of water birds; thus, hydrological factors may play a fundamental role in the exposure of water birds to Hg contamination and the associated risks (Herring *et al.* 2013). To maintain the essential ecosystem services provided by wetlands, it is crucial to protect and restore wetlands that have been threatened or destroyed by degradation and pollution.

Research to better understand and support the protection of wetlands includes the development of wetland classification systems, wetland vulnerability assessment, wetland restoration, wetland construction, long-term wetland monitoring (Cui *et al.* 2009), sensitivity analyses of wetland hydrology in the context of external climate forcing (Lammertsma *et al.* 2015) and wetland modelling. The Ramsar Convention Bureau defines riverine wetlands as a typical type of wetland that are included in reservoir basins (Matthews 1993). Such wetlands provide important habitats as well as travel corridors for resident and transient species, which play a key role in maintaining the diversity of the landscape (Sui *et al.* 2015). Wetland ecosystems are influenced by many factors that affect the biodiversity and ecological balance (Chatterjee *et al.* 2015). Water and sediments play important roles in the formation and maintenance of estuarine wetlands (Li *et al.* 2009). Generally, the most common threats to wetlands are water scarcity, climate change, biodiversity change and human activities (Chatterjee *et al.* 2015).

Previous studies have focused on estuarine wetlands, wetlands in source and delta areas, constructed wetlands, plateau wetlands and wetlands in arid zones (Liu *et al.* 2014). According to statistics from the International Commission on Large Dams (ICLD), there were 68,000 dams in the world in 2011, including those constructed and under construction. Additionally, 4218 dams combined for a total storage capacity of greater than 3,000,000 m^3. The reservoirs formed by these dams created many reservoir wetlands. In these reservoir wetlands, studies mainly focus on the ecological water requirements, whereas little attention has been given to the hydroclimatic changes, which can impact the associated ecosystems.

Wetland landscape patterns are critical for understanding ecosystem health and sustainability (Lin *et al.* 2018). The relationships between the wetland landscape patterns and flood regimes were investigated in Dongting Lake (Hu *et al.* 2015). Changes in land-cover and landscape patterns were studied in the two national nature reserves of Ebinur Lake Watershed, Xinjiang, China (Zhang *et al.* 2017). Landscape pattern indices characterize various aspects of the composition and configuration of categorical variables and have become increasingly popular for quantifying and characterizing various aspects of spatial patterns (Remmel and Csillag 2003). There are several categories of landscape pattern indices, including area, shape, edge, contagion, interspersion, connectivity and diversity indices. Diversity indices, such as Shannon's diversity index (SHDI) and Simpson's diversity index (SIDI), are classic scalar ecological indicators, and their application is common in ecological analysis.

The spatial and temporal dynamics of wetland landscape patterns in the Yellow River delta were investigated, and the results showed that wetland coverage decreased by approximately 2.27% (Liu *et al.* 2014); however, few studies have examined the reservoir wetland landscape patterns. In contrast, many scholars have investigated wetland landscape indices and their transformation probabilities based on the wetland type. Wang (2008) used the landscape index to reveal changes in urban wetland landscape patterns (Wang *et al.* 2008). Yuan *et al.* (2015) linked metrics of landscape patterns to hydrological processes in a lotic wetland. However, little research has focused on the natural driving forces underlying changes in reservoir wetland landscape patterns. Landscape pattern indices can reflect changes of wetland landscape and land cover and have a range of applications, but little research has focused on the influence of dam operation on reservoir wetlands. The Sanmenxia Reservoir, which is located in the middle reach of the Yellow River, is a typical reservoir wetland (Wang *et al.* 2005). Based on its sediment load, the Yellow River has been the second largest river in the world over the past few thousand years (Milliman and Meade 1983). The Sanmenxia Dam was the first dam built on the Yellow River in China. The dam controls an area of 688,000 km^2 in the river basin, thus accounting for 91.5% of the total area of the Yellow River basin. After operations began on September 15, 1960, the dam experienced sediment deposition issues; thus, changes were made to the dam operational strategy. Since the 1980s, several dams have been built in the Yellow River basin, including the

Wanjiazhai and Xiaolangdi dams. During the same period, rainfall has gradually decreased (Liang *et al.* 2016). In comparison, the operation of the Sanmenxia Reservoir has rapidly changed, and those changes have affected the wetland landscape. The operation of the Sanmenxia Reservoir has experienced three main periods. The first stage, from 1960 to 1962, was the water storage period. The second stage, from 1962 to 1973, was the flood detention and sanding period. The final stage, from 1973 to the present, was the clearing and draining period. Moreover, the reservoir is influenced by interannual variability. During these stages, the annual highest average water level was 327.81 m and the annual lowest average water level was 303.49 m (Wu *et al.* 2004). Notably, beach wetlands rapidly disappeared. Coastal wetland ecosystems are among the most productive yet highly threatened systems in the world (Mcleod *et al.* 2011). Population growth and increasing economic development have resulted in extremely rapid losses of coastal wetlands (Xie *et al.* 2015). Considering the variations in reservoir operation, climate change, and hydrological processes, wetland landscape changes and the associated driving factors must be analyzed. Generally, methods are available to investigate the relationships between wetland landscape indices and the influencing factors. Multiple regressions were performed to analyze the local and landscape-level influences on wetland bird communities (Fairbairn and Dinsmore 2001) and the influence of hydrology processes on wetland landscape patterns in the Yellow River delta (Chatterjee *et al.* 2015). Panel data were used to examine the relationships between carbon emissions and urban forms (Ou *et al.* 2013). Principal component analysis was performed to investigate the landscape pattern and structure metrics (Riitters *et al.* 1995).

The objectives of this paper are as follows: (1) to calculate the indices of wetland landscape patterns in the Sanmenxia Reservoir area and assess the reservoir wetland changes; (2) to analyze the relationship between hydroclimatic variables and Sanmenxia Reservoir wetland comprehensive landscape pattern index.

2. Materials and methods

2.1 *Study area*

The Sanmenxia Dam (111°20′4.86″E, 34°49′45.54″N) is located in the middle reach of the Yellow River at the junction between the city of Sanmenxia (Henan Province, China) and the county of Pinglu (Shanxi Province, China). The reservoir area includes Longmen on the Yellow River, Lintong on the Weihe River, Hejin on the Fenhe River, and Beiluohe near the dam (figure 1) (Yang *et al.* 2008).

The Sanmenxia Reservoir is situated in the mid-latitudes in a region characterized as an inland mountain basin with a warm temperate continental monsoon climate. In the Sanmenxia Reservoir area, the annual precipitation is 587 mm. Summer precipitation accounts for approximately 48% of the annual total and is mainly concentrated from July to September; autumn precipitation accounts for 30% of the annual total; and winter precipitation from January to December accounts for only 1% of the total precipitation. The annual evaporation is 1,430 mm, and the land surface evaporation is 525 mm. The annual runoff (1960–2001) into the reservoir is 34.83 billion m^3. The annual flow out of the Sanmenxia Reservoir is 34.3 billion m^3, and the annual sediment discharge is 1.06 billion tons. During the flood season, sediment discharge totals 0.91 billion tons, or 85.7% of the annual total. There are a variety of wetland vegetation types in the reservoir. It is a complete wetland vegetation ecological system that mainly includes brush swamp, marsh grass, shallow wetland plant communities and salt marshes. Notably, marsh grass is widely distributed.

2.2 *Data sets*

2.2.1 *MODIS land cover datasets*

The MCD12Q1 MODIS land cover datasets are based on observed values from the Terra and Aqua satellites. These data denote and describe the land cover types. The data set includes seventeen main land cover types, eleven natural vegetation types and one wetland type according to the International Geosphere Biosphere Program (IGBP) (Friedl *et al.* 2010). The data set has been developed to support studies of seasonal phenology and interannual variations in land surface and ecosystem properties (Ou *et al.* 2013). Scholars have applied the data to map irrigated areas and estimate the heterogeneous source area of the Yellow River (Thenkabail *et al.* 2005). The data precision is 500 m, and there are five classes of land cover. The original data were obtained from https://ladsweb.modaps.eosdis.nasa.gov/. The MODIS Reprojection Tool (MRT) was used to convert the

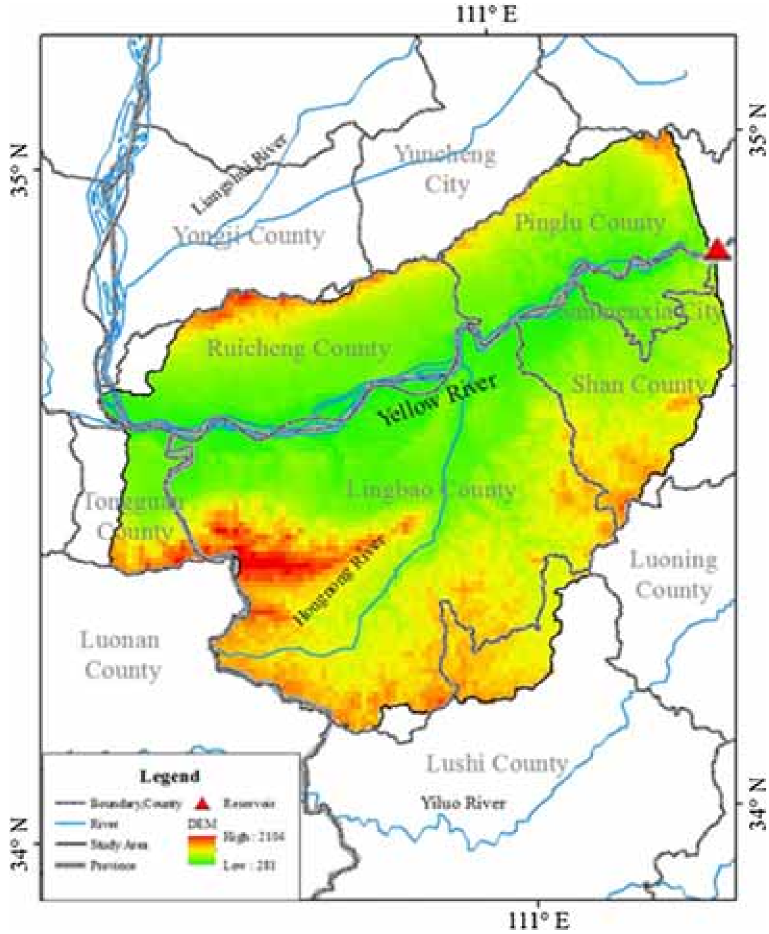

Figure 1. Location maps of the study area. This map shows the location of the Sanmenxia Dam, the Sanmenxia Reservoir Area, the main river (Yellow River) and the digital elevation (Unit: m).

MCD12Q1 product from a sinusoidal projection in HDF format to a geographic projection in GeoTiff format (Duan *et al.* 2017). IGBP global vegetation classifications were used to extract the land cover in the Sanmenxia Reservoir area. There are 17 land cover types, including water, evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, mixed forests, closed shrublands, open shrublands, woody savannas, savannas, grasslands, permanent wetlands, croplands, urban and built-up areas, snow and ice, and mixed cropland/natural vegetation. In our research, we considered water and permanent wetlands as reservoir wetlands.

2.2.2 *Hydrological and climate data*

Hydrological and climate data, including annual precipitation (AP), annual runoff (AR), annual sediment discharge (ASD) and annual average air temperature (AAT) data, were obtained from Sanmenxia station, which is located in the middle reach of the Yellow River. To investigate the relationship between the wetland landscape and water levels, annual average water level (AWL) data were collected. The collected data from 2001 to 2013 are shown in table 1. The ASD data are from 1980 to 2013.

2.3 *Methods*

2.3.1 *Landscape pattern indices*

Landscape pattern indices are the key method to analyze landscape spatial characteristics; however, landscape metrics are correlated to each other (Uuemaa *et al.* 2009). In this paper, we select area metrics, density metrics, edge metrics, shape metrics, contagion metrics, interspersion metrics, connectivity metrics, and diversity metrics, respectively, to investigate the changes in wetland landscape patterns from the patch, class, and landscape levels.

Table 1. *Hydrological and climate data from the Sanmenxia station (2001–2013).*

Year	Precipitation (mm)	Temperature (°C)	Runoff (10^8 m^3)	Sediment discharge (10^8 t)	Water level (m)
2001	332.60	14.70	158.90	3.42	327.39
2002	440.40	15.00	174.72	4.50	327.44
2003	899.40	13.47	261.13	6.18	327.38
2004	588.30	14.46	197.33	2.99	327.31
2005	455.10	14.24	230.75	3.28	327.24
2006	414.30	15.03	212.11	3.22	327.11
2007	533.70	14.96	242.56	2.46	327.10
2008	438.00	14.33	210.56	2.52	327.06
2009	552.70	14.22	220.42	1.29	327.05
2010	587.40	14.15	250.04	1.11	327.16
2011	740.25	13.84	259.60	2.25	327.14
2012	552.80	13.77	351.40	2.06	326.90
2013	339.35	15.17	304.50	3.05	326.95

Percentage of landscape (PLAND) and largest patch index (LPI) belong to the area metrics. Number of patches (NP) represents the density metrics. Total edge (TE) reflects the edge metrics. Landscape shape index (LSI) and normal landscape shape index (NLSI) are the classical shape metrics. Percentage of like adjacencies (PLADJ) and aggregation index (AI) are important contagion metrics. Splitting index (SPLIT) is one of the interspersion metrics. SHDI and SIDI are the typical diversity metrics. Patch cohesion index (COHESION) is the representative for the connectivity metrics. There are 11 indices in total, and these metrics are calculated in FRAGSTATS 4.2 software. The specific information of landscape metrics is presented in table 2.

2.3.2 *Statistical methods*

In SPSS 22, we used principal component analysis (PCA) to build the comprehensive landscape pattern index (CLI) to reflect the changes in the Sanmenxia Reservoir landscape patterns and prevent the highly related indices from being eliminated. The following steps represented the processing of the CLI.

Step 1: normalizing the reservoir wetland landscape pattern indices by equation (1).

$$x_i^{'} = \frac{(x_i - \bar{x})}{\delta_i}, \quad (1)$$

where $\bar{x}$ is the average of x_i and δ_i is the standard deviation of x_i.

Step 2: Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity. According to these two tests, we can determine whether the data are available for PCA.

Step 3: Calculating the correlation coefficient matrix among the landscape pattern indices.

Step 4: Calculating the eigenvalue and contribution rate of PCA and then obtaining the factor load matrix after orthogonal rotation.

Step 5: According to the first contribution rate of PCA and the load matrix, building the comprehensive landscape pattern indices.

When finishing the CLPI, we used Pearson correlation analysis to check the relationship between hydroclimatic and CLPI.

3. Results

3.1 *The Sanmenxia Reservoir wetland landscape pattern indices from 2001 to 2013*

The wetland landscape pattern indices declined rapidly from 2001 to 2013 (table 3) because the wetland area declined by 36.19% (figures 2 and 3). The number of patches (NP) decreased by 289. The percentage of the landscape (PLAND) decreased by 7.47%. The total edge (TE) index decreased by 20.31 m. The landscape shape index (LSI) decreased by 11.89. The patch cohesion index (COHESION) decreased by 20.71%. The splitting index (SPLIT) value in 2013 was 10 times larger than that in 2001.

3.2 *Wetland comprehensive landscape pattern index (CLPI)*

Table 4 represents the data after normalization. The KMO test value is 0.81, which is greater than 0.8, and the p value of Bartlett's test is less than 0.05. Table 5 shows the correlation coefficient

Table 2. *Basic information on the landscape pattern indices.*

Metric	Abbreviation	Description	Category
Largest patch index	LPI	Percentage of the landscape in the largest patch (units: percent)	Area
Landscape shape index	LSI	Reflects the landscape shape and integrates the landscape (units: none)	Shape
Percentage of landscape	PLAND	The percentage of a patch in the holistic landscape (units: percent)	Edge
Number of patches	NP	Reflects the number of patches (units: number)	Edge
Total edge	TE	Reflects the total edge length (units: m)	Edge
Normalize landscape shape index	NLSI	Reflects the landscape shape, and the land surface temperature (LST) is normalized (units: none)	Edge
Percentage of like adjacencies	PLADJ	The number of like adjacencies involving the focal class (units: percent)	Contagion
Splitting index	SPLIT	Reflects the degree of the splitting of different patches (units: percent)	Contagion
Aggregation index	AI	Number of similar adjacencies involving the corresponding class divided by the maximum possible number of like adjacencies involving the corresponding land use type (units: percent)	Interspersion
Patch cohesion index	COHESION	Measures the physical connectedness of the corresponding patch type (units: none)	Connectivity
Shannon's diversity index	SHDI	Based on information theory; indicates the patch diversity in a landscape (units: none)	Diversity
Simpson's diversity index	SIDI	Reflects the species diversity (units: none)	Diversity

Table 3. *Wetland landscape pattern indices in the Sanmenxia Reservoir area.*

Year	PLAND	NP	LPI	TE	LSI	PLADJ	COHESION	SPLIT/10^4	AI	NLSI
2001	11.73	647.00	0.44	33.83	34.79	29.25	69.74	0.89	29.86	0.70
2002	12.09	589.00	0.49	34.38	34.52	30.54	70.94	0.85	31.16	0.69
2003	10.93	521.00	0.43	31.12	32.79	30.60	70.30	0.96	31.26	0.69
2004	7.55	405.00	0.26	21.77	27.46	29.90	64.58	2.28	30.68	0.69
2005	5.39	382.00	0.10	16.47	24.79	25.45	53.27	6.10	26.24	0.74
2006	5.12	374.00	0.17	16.15	24.68	23.31	53.01	6.12	24.05	0.76
2007	5.85	374.00	0.17	18.08	26.11	24.65	59.10	4.11	25.38	0.75
2008	5.15	409.00	0.11	16.39	25.11	22.43	50.65	7.29	23.14	0.77
2009	5.67	397.00	0.15	17.54	25.71	24.57	58.14	4.21	25.32	0.75
2010	3.92	347.00	0.21	12.95	23.05	19.09	49.22	8.27	19.78	0.80
2011	4.59	343.00	0.13	14.75	24.08	21.42	53.98	6.68	22.14	0.78
2012	3.68	322.00	0.10	12.10	21.88	19.62	47.22	11.32	20.37	0.80
2013	4.26	358.00	0.09	13.52	22.90	22.02	49.03	9.23	22.80	0.77

*This table represents the landscape indices calculated by FRAGSTATS 4.2 for the Sanmenxia Reservoir wetlands.

matrix of LPIs. From the result of the significance test and the correlation coefficient matrix, we can use PCA to perform the factor analysis. Table 6 shows that the eigenvalue is 9.205, which is greater than 1.0, and the contribution of the first principal component (PC1) is 92.05%. Thus, the PC1 almost covers the original Sanmenxia Reservoir wetland landscape pattern indices. Table 6 shows the factor load matrix after orthogonal rotation, and we build the comprehensive landscape pattern index for Sanmenxia Reservoir wetlands, which is shown in equation (2). Table 7 presents the Sanmenxia Reservoir wetland comprehensive landscape pattern indices from 2001 to 2013.

$$F = 0.9205 \times (0.107 \times \mathrm{PLADN} + 0.1\mathrm{NP} + 0.101\mathrm{LPI} + 0.107\mathrm{TE} + 0.107\mathrm{LSI} + 0.104\mathrm{PLADJ} + 0.107\mathrm{COHESION} - 0.103\mathrm{SPLIT} + 0.103\mathrm{AI} - 0.103\mathrm{NLSI}). \tag{2}$$

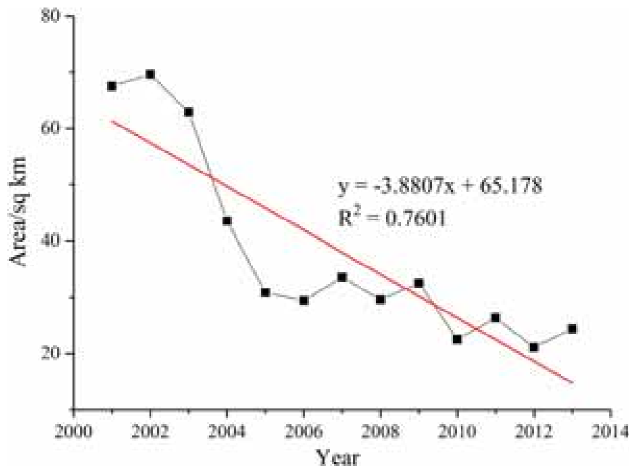

Figure 2. Changes in the wetland area in Sanmenxia Reservoir from 2003 to 2013, which shows a decreasing trend.

3.3 *Relationship between CLPI and hydrological and climate variables*

In SPSS (Statistical Package for Social Sciences) 19.0, Pearson correlation analysis was performed to analyze the relationship between the CLPI and hydroclimatic variables. The results showed that CLPI was significantly negatively correlated with annual runoff (AR), and the correlation coefficient was −0.669 ($P < 0.01$). There was a significant positive correlation with annual sediment transport (ASD) and annual average water level (AWL); the correlation coefficients were 0.728 ($P < 0.01$) and 0.896 ($P < 0.01$), respectively.

3.4 *Ecological significance of the landscape indices in the Sanmenxia Reservoir area*

Generally, the SHDI and SIDI are closely connected with landscape diversity changes. Due to the changes in the wetland area, patch area, and fractal dimension, the SHDI and SIDI also changed. The SHDI and SIDI declined by 26.57% from 2001 to 2013. The Pearson correlation analysis was performed between the diversity indices and the reservoir wetland area for the period 2001–2013. Significant correlations were observed. The correlation coefficient was 0.791 ($P < 0.01$) for SHDI and wetland area. And the correlation coefficient for SIDI and wetland area was 0.854 ($P < 0.01$). Therefore, the decline in the reservoir wetland area is related to the decreasing of the SHDI and SIDI, which may influence the ecological structure.

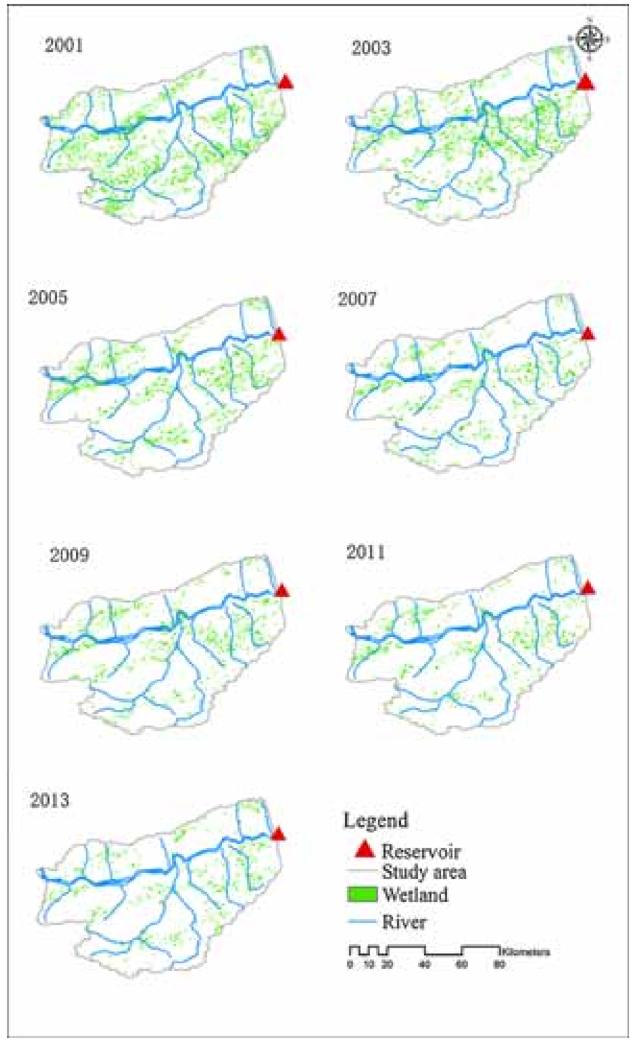

Figure 3. Mapping mainly shows the spatial and temporal changes in Sanmenxia Reservoir wetland area.

4. Discussion

4.1 *Water level effects on the reservoir wetland landscape*

Results show that CLPI is significantly positive with annual water level. Changes in the water level of Sanmenxia Reservoir directly influence the attached wetlands. However, surface water can influence the groundwater indirectly. Ludwig and Hession (2015) found that wetland storage was fully connected with the groundwater table and that fluctuations in surface water storage were not fully explained by precipitation and evapotranspiration, suggesting that storage was highly influenced by groundwater inputs. Figure 4 shows the trend of the shallow groundwater table and water

Table 4. *The Sanmenxia Reservoir wetland landscape pattern indices after normalization.*

Year	PLAND	NP	LPI	TE	LSI	PLADJ	COHESION	SPLIT	AI	NLSI
2001	1.70	2.25	1.55	1.75	1.82	1.08	1.41	−1.29	1.06	−1.11
2002	1.82	1.67	1.90	1.82	1.76	1.40	1.55	−1.30	1.38	−1.36
2003	1.44	1.00	1.48	1.41	1.37	1.41	1.47	−1.27	1.41	−1.36
2004	0.31	−0.16	0.29	0.23	0.16	1.24	0.81	−0.88	1.27	−1.36
2005	−0.41	−0.38	−0.84	−0.44	−0.45	0.15	−0.51	0.25	0.17	−0.13
2006	−0.50	−0.46	−0.35	−0.48	−0.47	−0.37	−0.54	0.26	−0.37	0.36
2007	−0.25	−0.46	−0.35	−0.23	−0.15	−0.05	0.17	−0.34	−0.04	0.11
2008	−0.49	−0.12	−0.77	−0.45	−0.37	−0.59	−0.81	0.60	−0.60	0.60
2009	−0.31	−0.23	−0.49	−0.30	−0.24	−0.06	0.06	−0.31	−0.06	0.11
2010	−0.89	−0.73	−0.06	−0.88	−0.84	−1.41	−0.98	0.89	−1.43	1.34
2011	−0.67	−0.77	−0.63	−0.65	−0.61	−0.84	−0.42	0.42	−0.84	0.85
2012	−0.97	−0.98	−0.84	−0.99	−1.11	−1.28	−1.21	1.79	−1.28	1.34
2013	−0.78	−0.62	−0.91	−0.81	−0.87	−0.69	−1.00	1.17	−0.68	0.60

Table 5. *The correlation coefficient matrix of landscape pattern indices.*

Index	PLAND	NP	LPI	TE	LSI	PLADJ	COHESION	SPLIT	AI	NLSI
PLAND	1.000	0.959	0.955	0.999	0.995	0.906	0.958	−0.896	0.900	−0.898
NP	0.959	1.000	0.906	0.965	0.970	0.798	0.865	−0.811	0.791	−0.793
LPI	0.955	0.906	1.000	0.955	0.949	0.801	0.910	−0.833	0.794	−0.798
TE	0.999	0.965	0.955	1.000	0.998	0.895	0.954	−0.893	0.889	−0.887
LSI	0.995	0.970	0.949	0.998	1.000	0.886	0.954	−0.905	0.880	−0.877
PLADI	0.906	0.798	0.801	0.895	0.886	1.000	0.944	−0.933	1.000	−0.998
COHESION	0.958	0.865	0.910	0.954	0.954	0.944	1.000	−0.968	0.940	−0.937
SPLIT	−0.896	−0.811	−0.833	−0.893	−0.905	−0.933	−0.968	1.000	−0.931	0.928
AI	0.900	0.791	0.794	0.889	0.880	1.000	0.940	−0.931	1.000	−0.998
NLSI	−0.898	−0.793	−0.798	−0.887	−0.877	−0.998	−0.937	0.928	−0.998	1.000

Table 6. *Factor load matrix after orthogonal rotation.*

Indices	PLAND	NP	LPI	TE	LSI	PLADJ	COHESION	SPLIT	AI	NLSI
PC1	0.107	0.1	0.101	0.107	0.107	0.104	0.107	−0.103	0.103	−0.103

Table 7. *The Sanmenxia Reservoir wetland comprehensive landscape pattern indices from 2001 to 2013.*

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
CLPI	1.57	1.67	1.42	0.67	−0.29	−0.43	−0.12	−0.56	−0.15	−0.99	−0.70	−1.23	−0.85

level in Sanmenxia Reservoir regions. Both of the shallow groundwater table and water level present decreasing trends. The shallow groundwater table decreases by 45.1% from 2001 to 2013. The Pearson correlation analysis indicates that the shallow groundwater table is positively related to CLPI and the correlation coefficient is 0.576 ($P < 0.05$). Additionally, low water levels in fluvial systems increase the vulnerability of wetlands to the spread of invaders, such as the common reed (Tougas-Tellier *et al.* 2015). The shallow groundwater table and water level in reservoirs jointly affect the reservoir wetland landscape in semi-arid plain regions. Therefore, future studies should evaluate the relationships among the water level, groundwater characteristics and different species to determine the optimal level of groundwater storage in reservoir wetlands.

4.2 *Effects of the sediment transport rate on the reservoir wetland landscape*

We find that the CLPI is positive with annual sediment discharge; however, it is negative with annual runoff. Figure 5 shows that the runoff and sediment transport rates declined from 1980 to 2003. However, from 2004 to 2013, runoff exhibited an increasing trend and the sediment transport rate displayed a decreasing trend. Because the reservoir water level is controlled by reservoir operations, runoff is no longer a natural process. However, water and soil conservation practices have been implemented to decrease the sediment content. Scholars have found that reducing sediment discharge can decrease the area or lead to habitat loss in coastal wetlands. Notably, wetlands in the prairie pothole region of North America have exhibited the most dramatic effects. Short hydroperiods and less dynamic vegetation cycles may have reduced the productivity of hundreds of wetland-dependent species (Werner *et al.* 2013). Thus, mitigation measures should be considered, including the management of sedimentation, rehabilitation and creation of wetland habitat, and reclamation (Wang *et al.* 2014).

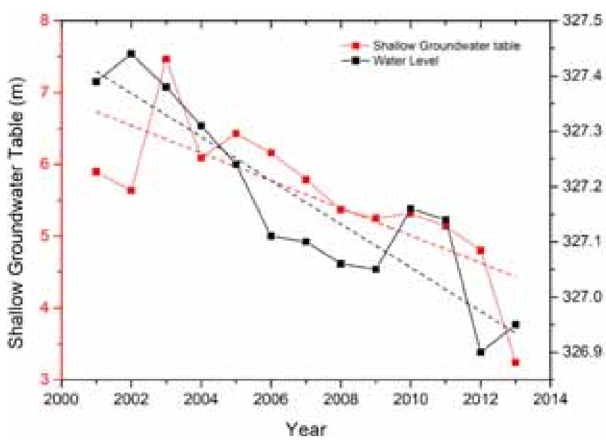

Figure 4. Changes in shallow groundwater table and water level in Sanmenxia Reservoir regions.

4.3 *Temperature effects on the reservoir wetland landscape*

Wetland vegetation is sensitive to temperature. Studies have shown that high temperatures may affect the competitiveness of submerged macrophytes relative to that of phytoplankton (Søndergaard and Moss 1998). In nutrient-rich lakes, warming tends can enhance eutrophication problems, trigger a wide range of changes in community interactions, and hamper macrophyte growth (Short *et al.* 2016). In the Sanmenxia Reservoir area, there are numerous submerged wetlands. The fifth Intergovernmental Panel on Climate Change (IPCC) reported that the atmospheric temperature during the last century has increased by approximately 0.74°C and is projected to increase another 1.8–4°C in the coming century (Pachauri *et al.* 2014). Therefore, to monitor the health of wetland vegetation, models of wetland vegetation growth and temperature should be constructed to determine the optimal temperatures for reservoir wetlands.

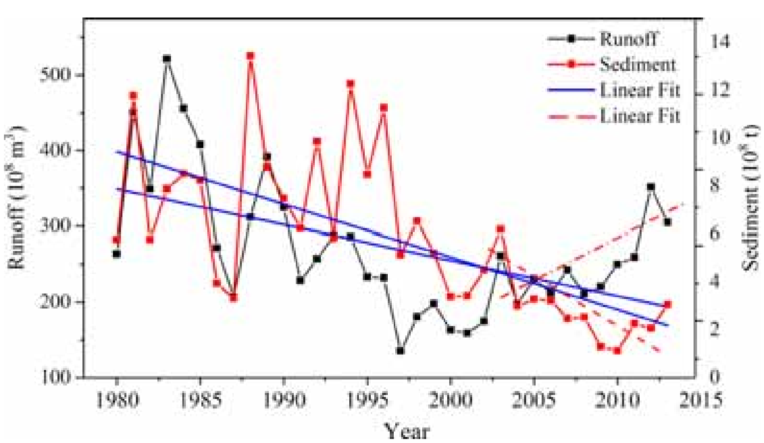

Figure 5. Trends of runoff and sedimentation in Sanmenxia Reservoir.

5. Conclusions

We applied MODIS data, landscape pattern indices, PCA and Pearson correlation to analyze the relationship between hydroclimatic variables and Sanmenxia Reservoir wetland comprehensive landscape pattern index. The results led to the following conclusions.

Firstly, the Sanmenxia Reservoir wetland area is considerably decreased by 36.19%. Additionally, the shape, area, edge, contagion, connection and diversity indices changed. Other than the SPLIT index, the landscape indices all decreased.

Secondly, many scholars have analyzed the effects of human activities, particularly reclamation, on the loss of wetlands. In this paper, we mainly investigated the natural factors (not including reclamation, urban expansion, and large-scale agricultural development) that have impacted the Sanmenxia Reservoir wetlands due to environmental changes. We used PCA to build the Sanmenxia Reservoir wetland comprehensive landscape pattern index and checked the relationship between CLPI and hydroclimatic factors. Of the five factors tested, CLPI is significantly negatively correlated with annual runoff and significantly positively correlated with annual sediment transport and annual average water level.

Finally, the SHDI and SIDI values rapidly decreased in the Sanmenxia Reservoir area during the study period. The correlation results showed that the decrease in the wetland area led to a decline in the species diversity index. Thus, to maintain the wetland landscape diversity of the Sanmenxia Reservoir, we should control the water level and sediment discharge to reasonable degrees. In future studies, we will investigate appropriate water level and sediment regulation programs to ensure that the wetland landscape pattern in the Sanmenxia Reservoir area is stable.

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