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Article

Wetland Changes and Their Responses to Climate Change in the "Three-River Headwaters" Region of China since the 1990s

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Abstract: The wetland ecosystem in the "Three-River Headwaters" (TRH) region plays an irreplaceable role in water source conservation, run-off adjustment and biodiversity maintenance. In recent years, assessment of wetland resources affected by climate changes has aroused enormous attention, since it can further protect wetland resources and provide a scientific basis for decision makers. In this study, wetland changes and its response to climate changes in the TRH region from the early 1990s to 2012 were analyzed by remote sensing (RS) image interpretation and climate change trend analysis. The results showed that wetlands occupied 6.3% of the total land area in 2012, and swamps, streams & rivers and lakes were the dominant wetland types in the TRH region. Since the early 1990s, wetlands have undergone great changes, and total wetland area increased by 260.57 km^2 (1.17%). Lakes, reservoir & ponds took on continuous increasing trend, but swamps, streams & rivers had a continuous decreasing trend. On the other hand, the wetland area in the Yangtze River basin showed an overall increasing trend, while in the Yellow River and Langcang River basins, it decreased in general. The climate turned from Warm-Dry to Warm-Wet. The average temperature and precipitation increased by 0.91 °C and 101.99 mm, respectively, from 1990 to 2012, and the average humidity index (*HI*) increased by 0.06 and showing an upward trend and a shifting of the dividing line towards the northwest in both the areas of semi-humid and semi-arid zone. The correlation analysis of wetland changes with meteorological factors from 1990 to 2012 indicated that the regional humidity differences and the interannual variation trend, caused by the change of precipitation and evaporation, was the main driving factor for the dynamic variation of wetland change in the TRH region. In the general, the increase of *HI* in the THR region since the 1990s, especially in the western TRH region, contributed to wetland increase continuously. The conclusions of this study will provide some scientific references for the management and protection of wetlands in the TRH region, especially for restoration, reconstruction and conservation of degradation wetland.

Keywords: wetland; "Three-River Headwaters" (THR) region; climate change; remote sensing (RS); trend analysis

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1. Introduction

Wetland is one of the most important ecosystems in the world. It has prominent significance not only in maintaining the regional and global ecological balances, but also providing a living environment for wild animals and plants [1]. Climate change is considered as one of the most important natural factors which affect wetland landscape patterns [2]. A better understanding of wetland changes and their response to climate changes will help in interpreting current environmental problems and developing sustainable wetland planning and decision-making.

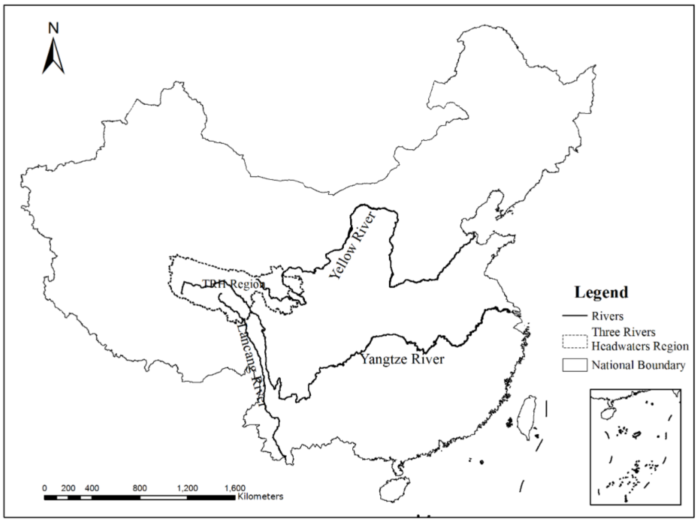
The "Three-River Headwaters" (TRH) region, as the headwaters of the Yellow River, the Yangtze River and the Lancang River, is located in southern Qinghai, the hinterland of the Qinghai-Tibet Plateau, which is highly sensitive to climate change because of its fragile natural ecosystems [3]. Since the 1970s, the inter-annual variation of temperature has taken on an obvious ascending trend in the TRH region [4–6]. The rapid climate change in this region has brought serious disturbances to the ecosystem structure and function, and poses a threat to ecosystem security. During the last decade, the wetland ecosystem has continuously degraded in the TRH region due to global warming. The swamp area in the Yellow River source region was 3895.2 km^2 in the 1980s and this was reduced to 3247.45 km^2 in the 1990s, at an annual average decrease rate of 58.89 km^2 [7]. In the Yangtze River source region, many wetlands at the foot of mountains and on the piedmont are shrinking and drying up [8]. Zhuang *et al.* [9] analyzed the interpretation results of multi-temporal land use/cover based on remote sensing (RS) images, and found that the area of wetlands in the Yellow River source region declined sharply during the recent 10 years, and converse succession occurred on some parts of the wetlands, *i.e.*, swamp-swamp meadow-meadow-desertification land-desert. Liu *et al.* [3] and Xu *et al.* [10] analyzed the grassland degradation and dynamic variation of ecosystem patterns in the TRH region from the late 1970s to 2004, and found that wetland degradation became increasingly serious, and the changes of wetland mainly occurred in the west and north TRH region, with transformation from water bodies to bottom land of rivers and from wetlands to grasslands. Through satellite observation, Qin and Huang [11] found that the total wetland area in the TRH region decreased by 15% from 1990 to 2000. Cai *et al.* [12] used multi-temporal Landsat images to monitor the Maqu wetland in the Yellow River source region, and they found that the wetland area decreased by 102.38 km^2 at an annual average rate of 0.74% from 1990 to 2001. Climate warming and drying was the major reason for the shrinkage of the Maqu wetland, which was exacerbated by human activities. Pan *et al.* [13] analyzed the spatial-temporal characteristics of alpine wetland changes from 1986 to 2000 using GIS techniques, and found that the wetland area declined by 2744.77 km^2 during 15 years, mainly as a result of climate warming, drying and human activities.

Wetlands in the TRH region have seriously degraded due to integrated influence of natural events and human activities since the 1990s, which have greatly changed the spatial distribution pattern of wetlands, accelerated peat decomposition and carbon loss, and led to such ecological problems as dry regional climate, desertification and drought of wetlands, decrease in river runoff, and sharp decline of wetland biodiversity [14]. Therefore, the present study is an attempt to understand the wetland changes and its response to climate changes in the TRH region since the 1990s by RS image interpretation, climate change trend analysis, which could provide valuable and scientific basis for the management and protection of wetlands and for the contribution to the studies on global climate changes.

2. Study Area

The TRH region (Figure 1), as the headwaters of the Yellow River, the Yangtze River and the Lancang River, is located in southern Qinghai, the hinterland of the Qinghai-Tibet Plateau. The total land area is more than 350,000 km^2 and it is also known as China's "Water Tower". Owing to its average elevation of more than 4000 m, annual temperature of −5.6 °C to −3.8 °C, and annual precipitation between 262.2 mm and 772.8 mm from west to southeast, the TRH region has a developed river system with numerous tributaries and plume or fan-shaped structures. Due to the flat terrain, slow water flow and developed meandering streams, oxbow lakes and divarication channels, a landscape of numerous rivers, lakes and swamps was formed in the THR region [8]. As China's major region with an extensive wetland distribution, the TRH region has abundant resources of rivers, lakes, snow mountains and glaciers. It is also the site of the world's largest alpine wetland ecosystem. On the other hand, as one of the regions with the world's highest elevation and the most extensive and concentrated distribution of wetlands, the TRH region also belongs to one of the most sensitive and fragile regions in the world.

Figure 1. Location of Three Rivers Headwaters Region, Qinghai, China.



The TRH region has distinctive swamp types and the primary type is the *Kobresia Tibetica* Maxim swamp, most of which are peat swamps, mainly distributed in the middle and western parts of Zaduo County, middle and south parts of Zhiduo County, eastern parts of Qumalai County, as well as

Maduo County and Chengduo County. Wetlands, glaciers and permanent ice and snow on mountains are not only distinctive ecosystems in the TRH region, but also play an important role in the water supply in this region.

3. Materials and Methods

3.1. Wetland Classification

The scientific classification of wetlands is not only one of the core problems in wetland science theory, but also the important marks of wetland science development level [15]. However, there are no unified criteria for wetland classification. Many classification systems have been proposed based on different perspectives and various purposes. For the purpose of wetland mapping and classification extraction based on the Landsat Thematic Mapper (TM) imagery, Bronge and Näslund-Landenmark [16] classified wetlands into inland swamps, wet peat swamps, developed peat swamps, other peat swamps and salt swamps. Philips *et al.* [17] used Landsat Enhanced Thematic Mapper Plus (ETM+) and Satellites Pour l'Observation de la Terre or Earth-observing Satellites (SPOT) 5 satellite images to monitor and assess wetlands in Missouri, USA, and they classified wetlands into permanent water bodies, seasonal water bodies, deep swamps, shallow swamps and wet meadows. Chinese researchers have also conducted many studies and proposed some practical wetland classification systems according to China's wetland features, actual conditions and research objectives. In 1995–2001, the Chinese State Forestry Administration organized the first investigation of national wetland resources, and classified wetlands into 5 first level classes and 28 second level classes, including coastal wetlands, rivers, lakes, swamps, reservoirs & ponds [18]. Du *et al.* [19] classified wetlands into lakes (perennial and seasonal), swamps (reed and sedge), salt swamps (saline-alkaline land, alluvial land), paddy fields, reservoirs & ponds, when extracting wetlands in the Zhalong Nature Reserve using ETM+ satellite images.

In our research, a RS classification system of wetlands was drafted (Table 1). Wetlands in the TRH region are classified into two first categories, which include water bodies and swamps, and then the two first categories can be further classified into four categories, which include streams & rivers, lakes, reservoirs & ponds, and swamps. Detailed information of the classification and the description for each category are shown in Table 1.

Table 1. Wetland classification and code based on remote sensing (RS) images.

First level categories	Second level categories		Descriptions
Name	**Code**	**Name**	
Water body	-	-	Lands covered by natural water bodies or lands with facilities for irrigation and water reservation.
	41	Stream & rivers	Lands covered by rivers including canals.
	42	Lake	Lands covered by lakes.
	43	Reservoir & ponds	Man-made facilities for water reservation.
Swamp	64	Swamp	Lands with a permanent mixture of water and herbaceous or woody vegetation that cover extensive areas.

3.2. Data Sources

The main data sources were Landsat TM digital images (28 scenes) in the early 1990s and in 2004 and HJ-1 images (mini-satellite constellation for environment and disaster monitoring) (15 scenes) in 2012 covering the whole THR region (Appendix Table A1), which were used to acquire wetland spatial data. In order to reflect wetland vegetation growth, RS images acquired concentrating on July and August were used. A series of image processing steps were done in three time periods, such as single band extraction, false color composition, geometric correction, histogram equalization, images mosaic and segmentation. Images were geo-referenced using 1:50,000 topographic maps and a polynomial method. The root mean squared error (RMSE) of geometric rectification was less than 1.5 pixels (or 45 m). Finally, standard false color image data set was built based on county administration unit and using the false color band combination (*i.e.*, RGB: 432 for all sensors) method.

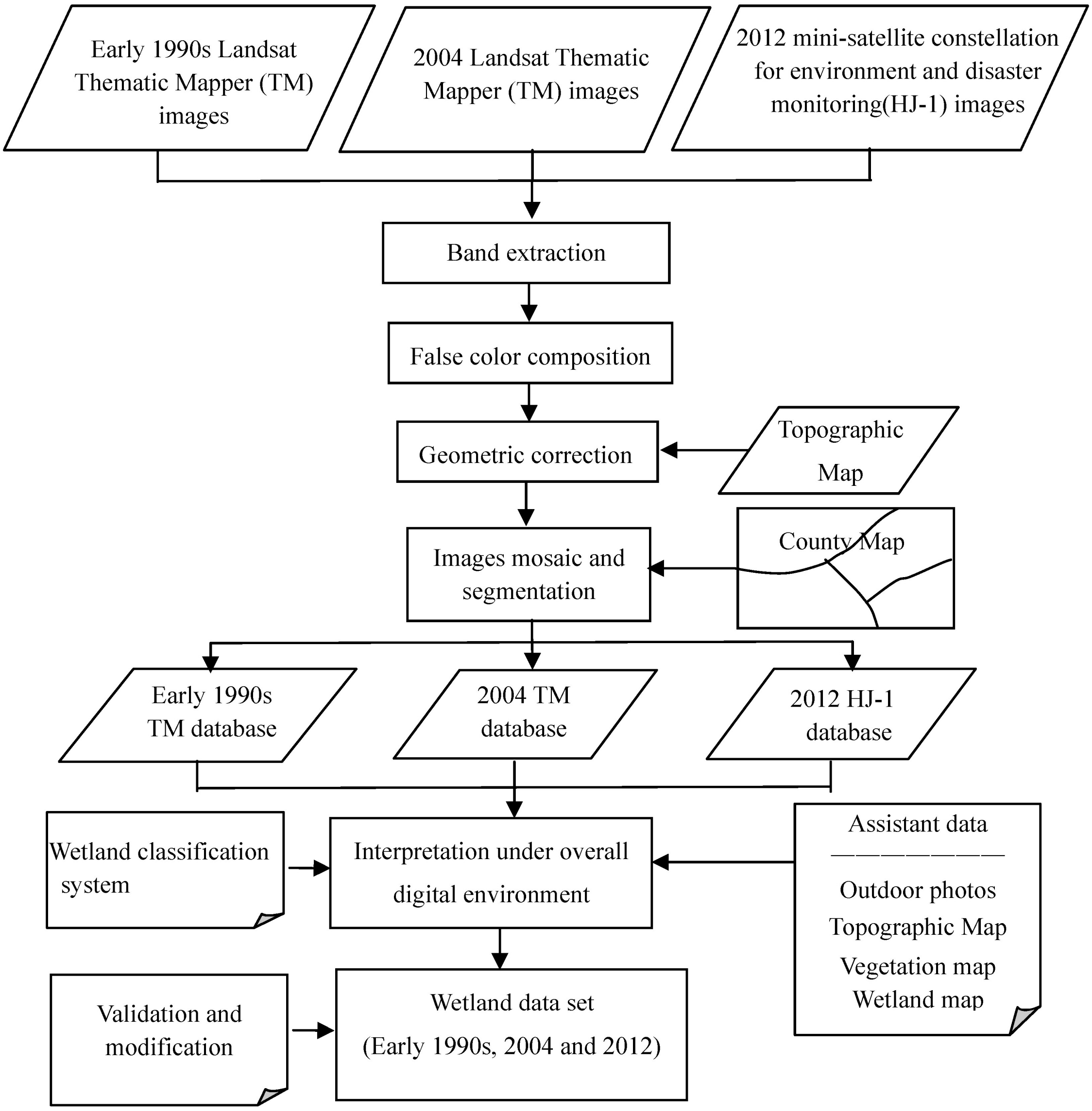
The other data source was meteorological data, including the monthly maximum air temperature, minimum air temperature, precipitation, relative humidity, wind speed at 10 m height and sunshine hours from 1970 to 2012. It was obtained from 43 national meteorological stations in China, including 18 stations located in the TRH region and 25 stations around the TRH region, all maintained by the Chinese Meteorological Administration (CMA) [20]. These measured monthly data were interpolated to individual 1 km resolution grid. Because of the rough terrain in the TRH region, the impact of topographic conditions in the interpolation of the meteorological data had to be considered. The ANUSPLIN version 4.2 software [21–23], proven to be appropriate for spatial interpolation of climate, was used to interpolate the meteorological data with the terrain elevation dataset. The terrain elevation dataset derived from the Shuttle Radar Topography Mission (SRTM) C-band is the world's first publicly available near-global, high resolution raster digital elevation model (DEM) [24]. Through using some meteorological station data, which are not used in the interpolation to assess the accuracy, the overall accuracy of the interpolation is more than 86% for all meteorological variables.

3.3. Wetland Interpretation Method

Quantitative and accurate extraction of wetland spatial information is the main prerequisite for wetland research. There are two kinds of methods to extract wetland information from RS data: (i) a computerized automatic classification method; and (ii) a manual interpretation method based on RS images. The former, which includes the unsupervised and supervised classification method, regression tree method and cellular automaton method, is widely applied in analyzing wetland changes based on RS data [25–30]. The latter not only has rigorous requirements for the selection of RS data sources and accurate data handling, but also needs interpretation staff having an integrated understanding of wetland distribution in the study region. However, the precision and efficiency of wetland information extraction is relatively high [31–34]. This method is used in the wetland changes study in the TRH region in Qinghai Province.

In order to build a temporal-spatial distribution data set of wetland, an effective research team was organized to work on remotely sensed data through human-machine interactive interpretation to guarantee classification consistency and accuracy. The workflow of this integration is displayed at Figure 2.

Figure 2. The technical process of wetland data interpretation by RS in the "Three-River Headwaters" (TRH) region.



The outline of wetland changes was delimited by comparison of RS images in different time periods, with the references from the former. Finally, wetland type thematic maps were completed in three time periods, including in the early 1990s, 2004 and 2012. The interpretation of RS images and wetland classifications was validated against 1:100,000 topographic maps in the early 1990s and extensive field surveys in 2004 and 2012. For example, in 2004, we conducted ground truth checking for more than 3500 km of transects across the TRH region and more than 2000 field photos were taken using global positioning system (GPS)-equipped cameras. The results showed that the overall accuracy of the wetland classification is 92.43% in the early 1990s, 94.5% in 2004 and 95.2% in 2012.

3.4. Climate Change Analysis Method

The meteorological factors, which were analyzed in this study, include temperature, precipitation and humidity index (*HI*). *HI* could be used to measure the humidity degree in the TRH region. *HI* can be calculated by the following equation:

$$HI = \left(\frac{P}{ET_0} - 1\right) \times 100\% \quad (1)$$

where *HI* is humidity index; *P* is annual precipitation (mm/year); and ET_0 is annual evapotranspiration (mm/year). ET_0 can be calculated using the modified Penman-Monteith equation in 1998 [35].

In order to estimate the long-term climate change trend, statistical and gridding methods are used. In the present study, the widely applied statistical methods of long-term time series analyses (linear trend analysis and least-squares method) are used for the computation of trend analyses [36]. A simple linear regression analysis, namely the least square method or linear regression was used to detect climatic trends over time series. The least-square method (y) is a linear function of (x)$y = ax + b$. where the slope (trend rate) of the line is given by a and the intercept of the y axis is given as b. For N data pairs, the equations used to find the slope a is:

$$a = \frac{N\sum xy - \sum x \sum y}{N\sum x^2 - (\sum x)^2} \quad (2)$$

The sign denotes an increase or decrease trend, $a < 0$ represents a decrease trend, and $a > 0$ represents an increase trend. On the other hand, the absolute value of a can be used to measure the degree of change trend. Trend analysis based on time-series data was carried out by applying above linear model. The slope of the regression line, which is calculated using the least squares method, was used to obtain the magnitude of trends. These slopes were also utilized to generate the spatial distribution maps of temperature, precipitation and *HI* change trends. ARCGIS 9.3 software was employed to generate climate trend contour maps.

4. Results and Analysis

4.1. The Current Situation and Characteristic of Wetland

The wetland monitoring results of 2012 (Table 2) show that the total wetland area is 22,481 km^2, accounting for 6.3% of the total land. Swamps, streams & rivers, and lakes are the dominant wetland types. Swamps cover an area of 7791 km^2, occupying 34.7% of the total wetlands, followed by streams & rivers and lakes, of which the area was 7511.4 km^2, occupying 33.4% and 7151.2 km^2, occupying 31.8%, respectively. On the other hand, reservoirs & ponds covered an area of 27.3 km^2, accounting for 0.1% of the total wetlands in this region.

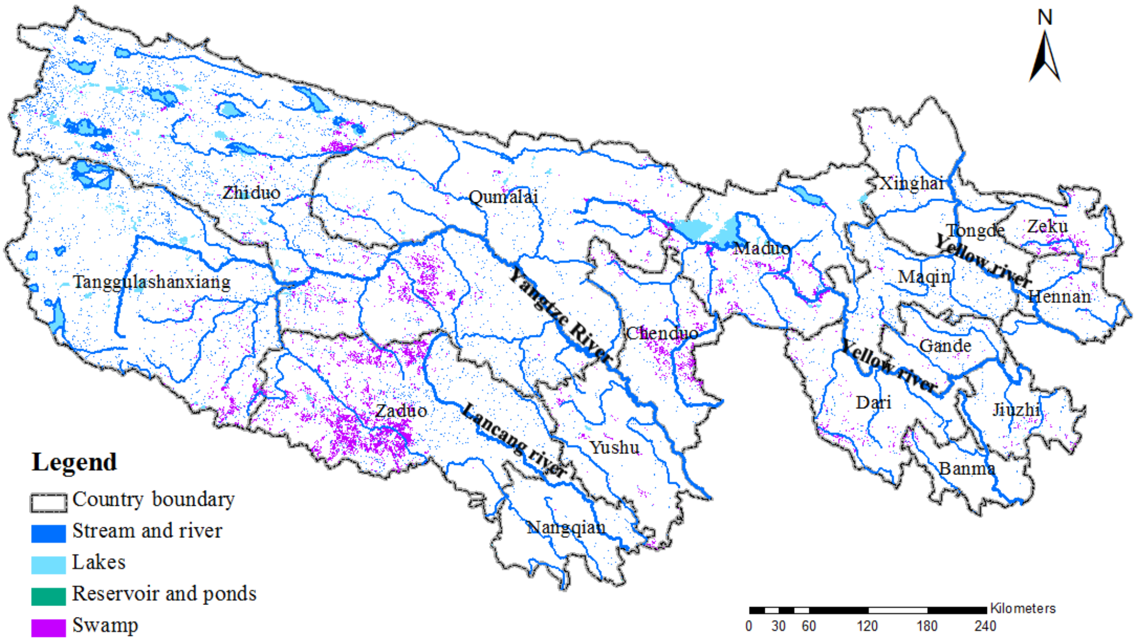
Table 2. Wetland area changes since early 1990s in the TRH region.

Wetland category	Early 1990s		2004		2012	
	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)
Streams and rivers	7,549.7	34.0	7,541.2	34.2	7,511.4	33.4
Lakes	6,595.6	29.7	6,664.5	30.2	7,151.2	31.8
Reservoirs and ponds	15.4	0.1	26.9	0.1	27.3	0.1
Swamps	8059.8	36.3	7,817.7	35.5	7,791.1	34.7
Total wetlands	22,220.4	6.2	22,050.3	6.2	22,481.0	6.3

Note: The percent of each wetland category is the proportion of its area in total wetland. The percent of total wetland is the proportion of total wetland in the total land.

Figure 3 shows the spatial distribution of different wetland types in the TRH region. Swamps were concentrated at the Yellow River source region and Yangtze River source region (including the Tuotuo River, Chumaer River and Dangqu River) and Lancang River source region, which were the dominant one in Yangtze River basin, covering an area of 5368.3 km^2, occupying 49.8%. With a dense river network, developed river system and numerous tributaries, streams & rivers were extensively distributed in the TRH region. In the Yangtze River basin, the area of streams & rivers was 3442.8 km^2, occupying 31.9%. Lakes were concentrated in the northwestern parts of Maduo County in the Yellow River source region and the northwestern parts of Tanggulashan County in the Yangtze River source region and northwestern parts of Zhiduo County.

Figure 3. Wetlands distribution in the TRH region in 2012.



4.2. The Spatial-Temporal Characteristics of Wetland Changes

From the early 1990s to 2012, the wetland structure in the TRH region has undergone great changes, and the total wetland area increased by 260.6 km^2 or 1.2% (Table 3). Lakes, reservoirs & ponds displayed a continuously increasing trend, but swamps, streams & rivers had a continuously decreasing trend. The area of reservoirs & ponds increased the most, while swamps decreased the most, which was 12 km^2 (77.9%) and 268.6 km^2 (3.3%), respectively. From the early 1990s to 2004, the total wetland area decreased by 170.1 km^2 (0.8%). Among all wetland types, swamps decreased by 242.1 km^2 (3%), which was the largest decrease, while reservoirs & ponds increased by 11.6 km^2 (75.3%), which was the largest increase. From 2004 to 2012, the total wetland area increased by 430.7 km^2 (2%), and lakes increased by 484.6 km^2 (7.3%). From the early 1990s to 2012, the wetland area in the Yangtze River basin showed an overall increasing trend, while in the Yellow River and Langcang River basins, the wetland area decreased in general.

In the Yangtze River basin, from the early 1990s to 2012, wetlands increased by 9.8 km^2 (0.1%). The increase of lakes (by 197.5 km^2, 11.8%) was the most obvious, whereas the swamps decreased by 165.4 km^2 (3%). In the temporal change process, lakes continuously increased with an intensive trend, swamps and streams & rivers sustained a decline and the swamp decrease has slowed down, while reservoirs & ponds showed little changes. The change of lakes from 2004 to 2012, which increased by 162.2 km^2 (9.5%), was the most obvious increase. From the early 1990s to 2004, swamps decreased by 135.1 km^2 (2.4%), which was most obvious decrease among all wetland types.

Table 3. The area changes of different wetland categories from the early 1990s to 2012.

Wetland category	The early 1990s–2004		2004–2012		The early 1990s–2012	
	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)
Streams and rivers	−8.6	−0.1	−29.8	−0.4	−38.3	−0.5
Lakes	68.9	1.1	486.6	7.3	555.6	8.4
Reservoirs and ponds	11.6	75.3	0.4	1.5	12.0	77.9
Swamps	−242.1	−3.0	−26.6	−0.3	−268.6	−3.3
Total wetlands	−170.1	−0.8	430.7	2.0	260.6	1.2

Note: The percent of each wetland category is the proportion of its area in total wetland. The percent of total wetland is the proportion of total wetland in total land.

In the Yellow River basin, from the early 1990s to 2012, the wetland area decreased by 30.7 km^2 (0.6%). The decrease of swamps, which decreased by 82.8 km^2 (4.6%), was the most obvious, and was consistent with the research result of Zhuang *et al.* [9], while reservoirs & ponds increased by 15.8 km^2 (494.1%), which was the most obvious. In the temporal change process, swamps and lakes first decreased and later increased, while streams & rivers and reservoirs & ponds increased continuously. For example, from the early 1990s to 2004, swamps and lakes decreased, and reservoirs & ponds obviously increased. The area of swamps and lakes decreased by 94.1 km^2 (5.2%) and 101.4 km^2 (6.5%), respectively, while in 2004–2012, the reservoirs & ponds showed the most dramatic increase (4.2 km^2, 28.6%).

In the Langcang River basin, from the early 1990s to 2012, wetland area decreased by 9.5 km^2 (0.9%). Lakes experienced the most significant reduction, declining 0.3 km^2 (4.3%), followed by swamps which were reduced 9.2 km^2 (2.4%). In the temporal change process, swamps decreased first and then increased, lakes decreased at first and then kept constant, while reservoirs & ponds remained basically unchanged. For example, from the early 1990s to 2004, swamps and lakes were most significantly decreased by 9.7 km^2 (2.5%) and 0.3 km^2 (4.3%), respectively.

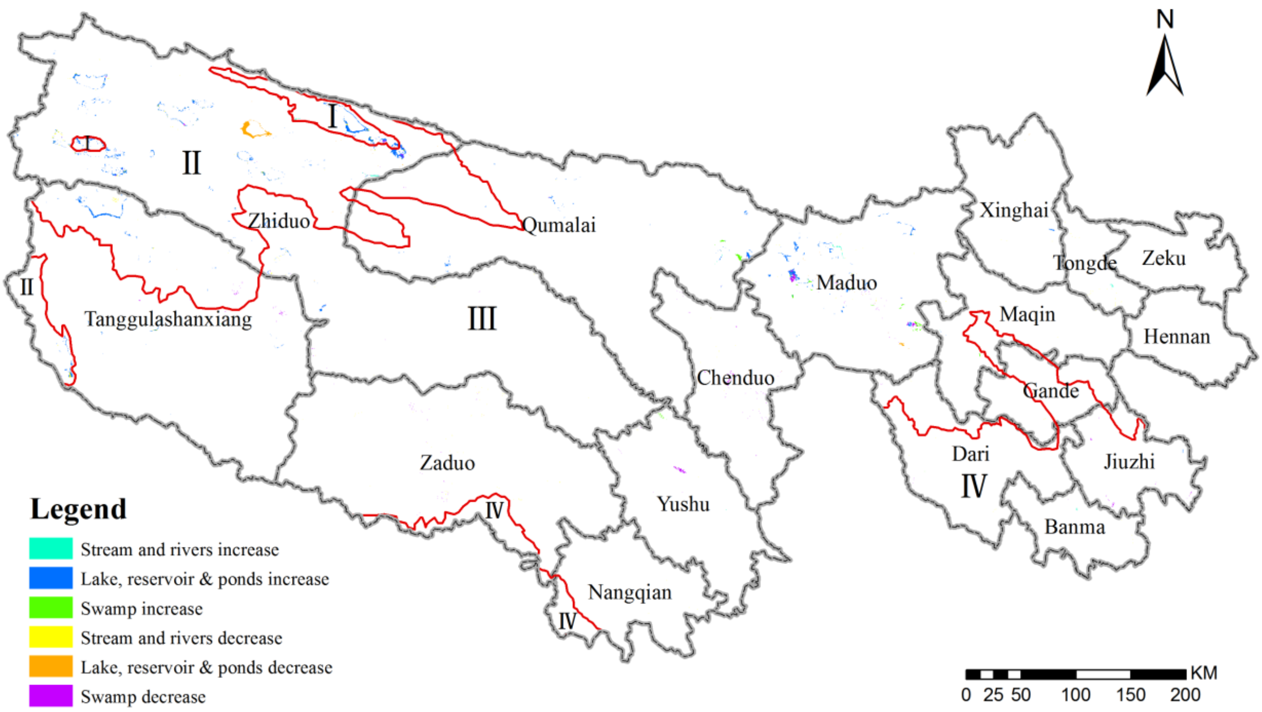
Figures 4 and 5 show the spatial pattern of wetland changes. From the early 1990s to 2012, the wetland changes experienced a shift from the middle parts to the western parts in the TRH region. Wetlands in the middle and western parts varied significantly during these years.

From the early 1990s to 2004, the decrease of swamps was mainly concentrated in Maduo County in the Yellow River source region, Yushu, Qumalai and Zhiduo counties in the Yangtze River source region, as well as Zaduo County in the Langcang River source region, while the decrease of lakes, reservoirs & ponds mainly occurred in Maduo County in the Yellow River source region; and the expansion of lakes, reservoirs & ponds mainly occurred in western parts of Zhiduo County and northern parts of Tanggulashan County.

From 2004 to 2012, the changes (including expansion and shrinkage) of all kinds of wetlands was concentrated in Maduo County in the Yellow River source region, the western parts of Zhiduo County and the northern parts of Tanggulashan county.

Figure 4. The distribution of wetland changes in the TRH region from the early 1990s to 2004 (humidity Region I: 0.3–0.4; II: 0.4–0.5; III: 0.5–1; and IV: >1).

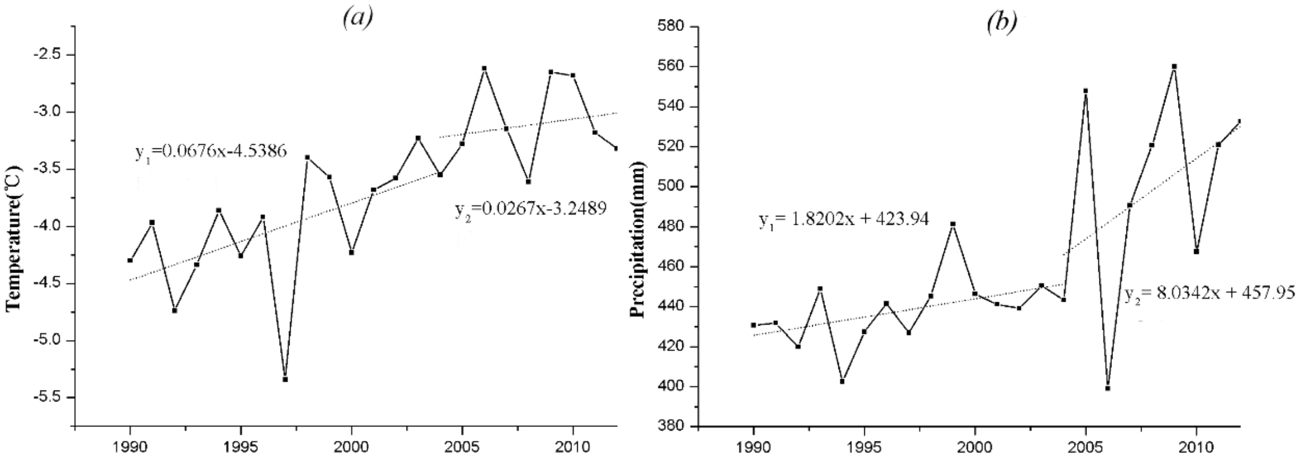
Figure 5. The distribution of wetland changes in the TRH region from 2004 to the early 2012 (humidity Region I: 0.3–0.4; II: 0.4–0.5; III: 0.5–1; and IV: >1).



4.3. Climate Change since 1990 in the TRH Region

According to the variations of annual average temperature in the TRH region (Figure 6a), the average temperature had shown an obvious upward trend since 1990, from −4.2 °C in 1990 to −3.3 °C in 2012, an increase of 0.9 °C in total. The annualized growth rate of temperature varied in different time periods. The warming rate was 0.68 °C/10 years from 1990 to 2004, faster than that during 2004–2012, when it decreased to 0.27 °C/10 years. As the temperature increased, the change of annual precipitation (Figure 6b) also showed an increasing trend from 1990 to 2012 in the TRH region. Annual precipitation was 430.63 mm in 1990 and 532.6 mm in 2012 respectively, an increase by 102.0 mm. On the other hand, the increase of annual precipitation also showed significant periodic differences. The annual precipitation grew slowly during 1990–2004 at 1.8 mm/year, while the growth rate increased to 8.0 mm/year during 2004–2012 with significant fluctuations. For example, the annual precipitation shrank to 399.2 mm in 2006 due to a severe drought.

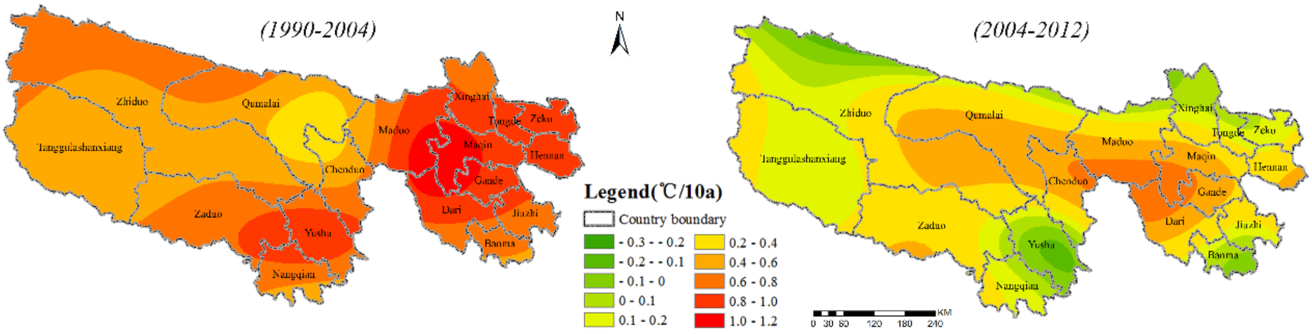
Figure 6. Change of average annual (**a**) temperature and (**b**) precipitation in the TRH region.



In conclusion, the temperature and precipitation showed a general upward trend from 1990 to 2012. During 1990–2004, the temperature rose fast while precipitation grew slowly. During 2004–2012, the temperature growth trend slowed down and the upward trend of precipitation became more obvious.

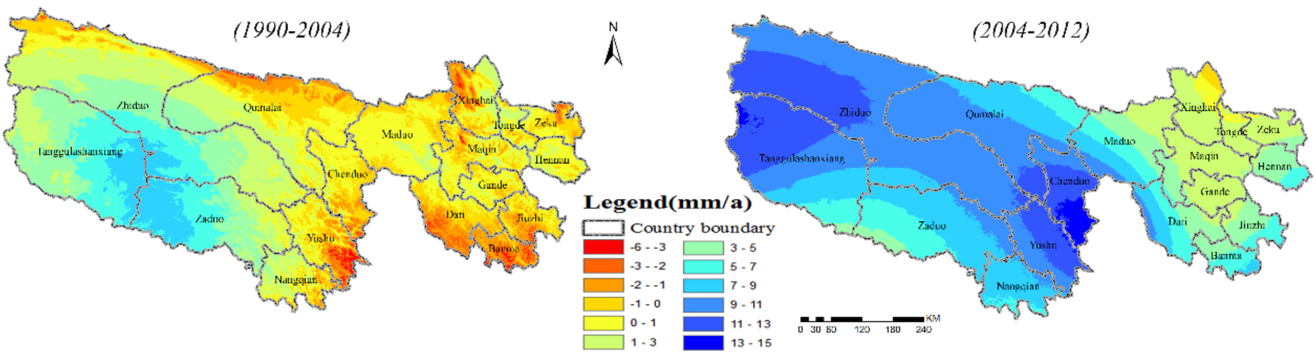
Based on the general upward trend of temperature and precipitation, the change trend of temperature and precipitation also showed spatial differences (Figure 7). During 1990–2004, the spatial distribution of annual average temperature trend rate showed an increasing trend in all over the TRH region. The average temperature trend rate was 0.82 °C/10 years in the Yellow River basin which was the most significant in the three major source areas. In particular, the temperature of the eight counties in the eastern Yellow River basin had a greater growth rate between 0.6 °C/10 years and 1.2 °C/10 years. In addition, the temperature increased relatively significantly in Yushu, between 0.8 °C/10 years and 1.0 °C/10 years, and gradually decreased from Yushu to the periphery. The temperature growth in the extensive region of western Tuotuohe in the Yangtze River basin was relatively low, under 0.6 °C/10 years. From 2004 to 2012, the variation tendencies of temperature had evident regional differences. The temperature growth rate in the central TRH was the most significant, between 0.6 °C/10 years and 0.8 °C/10 years, and decreased gradually from the center to the periphery. On the contrary, the temperature had decreasing tendency in Yushu in southern TRH, Banma and Xinghai in eastern TRH, and Zhiduo in northwestern TRH. During 2004–2012, the average temperature trend rate was 0.38 °C/10 years in the Yellow River basin, which was the most obvious warming basin, while it was only 0.16 °C/10 years in the Lancang River basin.

Figure 7. Spatial distribution of annual average temperature tendency rate in the TRH region.



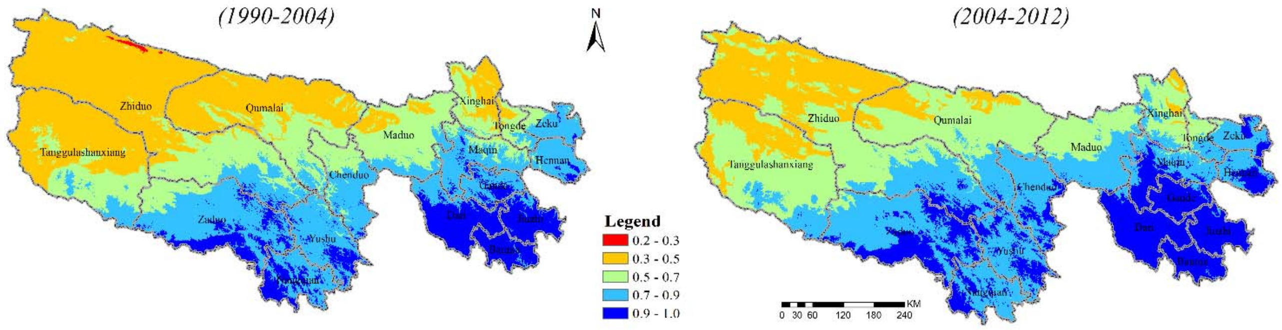
The annual trend rate of precipitation (Figure 8), during 1990–2004, in Tanggulashanxiang, Zhiduo, and Zaduo counties in the southwestern TRH region presented an obvious increasing tendency, with a trend rate of 5–11 mm/year. While the range of change in vast areas of central TRH is relatively small, with trend rate was between −1 mm/year and 1 mm/year. Precipitation declines occurred in the northern part of Xinghai, Maduo, Qumalai counties; Yushu, Nangqian counties in central TRH, and Banma, Dari, Jiuzhi counties in the southeastern TRH. During 2004–2012, the precipitation increase trend was more obvious than that in previous time periods, especially the precipitation increased most significantly in Chengduo-Qumalai-Zhiduo, with an average growth rate of 9–15 mm/year. Precipitation changes of each river basin showed that the precipitation tendency in the Yangtze River basin increased most significantly, with an of average 3.48 mm/year during 1990–2004 and 9.8 mm/year during 2004–2012. By contrast, the precipitation in the Yellow River basin raised slowly, merely 4.4 mm/year during 2004–2012.

Figure 8. Spatial distribution of annual average precipitation trend rate in the TRH region.



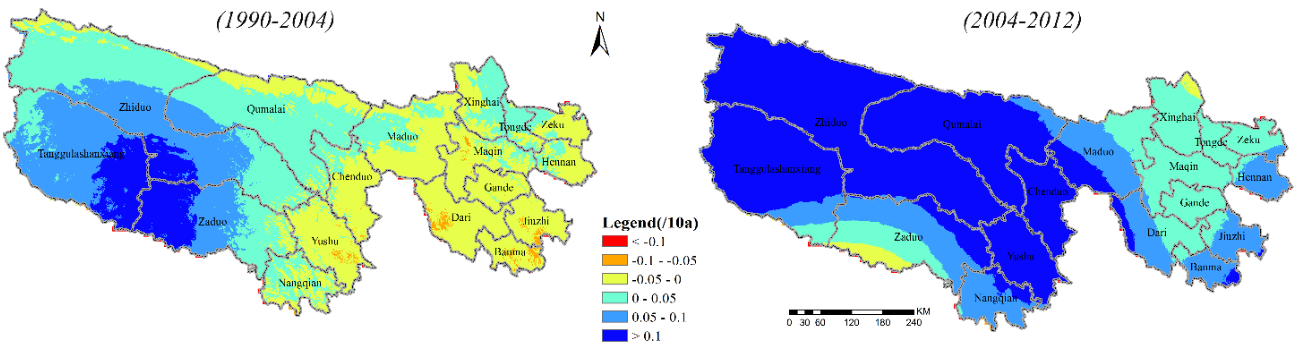
The change of temperature and precipitation directly resulted in the change of humidity conditions in the THR region. The humidity conditions were divided by the Tanggulashanxiang-Zhiduo-Qumalai-Maduo-Xinghai line, showing a semi-arid zone to the north of the line and a semi-humid zone to the south of the line. The *HI* decreased gradually from southeast to northwest and reached the lowest value (lower than 0.3) in the northwest of Zhiduo. The average *HI* was 0.5 in 1990–2004 and it increased to 0.6 in 2004–2012, increased by 0.06 and showed an upward trend and a shift of the dividing line towards the northwest in both the semi-humid and semi-arid zone areas (Figure 9).

Figure 9. Spatial distribution of annual humidity index (*HI*) in the TRH region.



The spatial pattern of annual *HI* change rate showed that during 1990–2004, the humidity tendency was slow, and the average change rate of annual *HI* was only 0.025/10 years in the TRH region. Especially, the change rate was only −0.05/10 years to −0.05/10 years in most areas, and only Tanggulashanxiang, Zhiduo and parts of Zaduo in the southwest areas were higher than 0.05/10 years. During 2004–2012, the average annual *HI* change rate was 0.121/10 years, showing a significant increase of humidification compared to the former period. However, the change of *HI* showed great spatial heterogeneity. It presented a *HI* that was higher than 0.1/10 years in Tanggulashanxiang, Zhiduo, Qumalai, Yushu and Chengduo but an obviously lower rate of −0.1/10 years in the eastern TRH regions (Figure 10).

Figure 10. Spatial distribution of annual *HI* change rate in the TRH region.



4.4. Impact of Climate Change on Wetland Changes

The statistic results of wetland changes in the TRH region during 1990 to 2012 show that wetland changes over two periods had different characteristics (Table 4). During 1990–2004, wetland changes took place mainly in the semi-arid and semi-humid regions ($0.3 < HI < 1.0$), accounting for 68.5% of the total wetland changes. In the Region I, the wetland changes were dominated by increases in lakes, reservoirs and ponds, those accounted for 90% of the regional wetland changes and 28.8% of the total wetland changes in the TRH region. In the Regions II, III and IV, wetlands obviously shrank, with the decrease in area accounting for 12% and 27.8% of the total wetland changes in the Regions II and III, respectively. According to the climate change during 1990–2012, generally the temperature went up and precipitation rose slightly in the whole region, but the trend showed spatial heterogeneity. Comparing the climate changes in the Regions I and II, we discovered that annual temperature trend rate almost stayed at the same level, and precipitation tendency trend differed significantly in that the rate increase tendency in the Region I was higher than that in the Region II. Taking climate change into account, the wetland change responses in Regions I and II were totally different, with wetland expanding in the Region I, but drying up in the Region II. Compared to the climate changes in the Regions II and III, the temperature rate tendency had a little discrepancy and the annual precipitation trend in the Region III was higher than that in the Region II. However, wetland changes in the two regions displayed a different response magnitude, in that the wetland decrease in the Region II was 15.8% less than that in the Region III.

Table 4. The relativity statistics between wetland and climate changes in the TRH region from 1990 to 2012.

Period	Region	Major change	Local area ratio (%)	Total area ratio (%)	Precipitation (mm/year)	Temperature (°C/10 years)	Humidity (10^{-3}/year)
1990–2004	I	Lakes, reservoir & ponds increase	90.0	28.6	2.6	0.06	4.3
	II	Swamp decrease	44.6	12.0	1.1	0.05	2.1
	III	Swamp decrease	68.0	27.8	1.9	0.08	1.8
	IV	Swamp decrease	50.0	0.2	−1.0	0.07	−3.6
2004–2012	I	Lakes, reservoir & ponds increase	92.1	11.5	10.0	0.01	17.3
	II	Lakes, reservoir & ponds increase	69.7	33.2	11.1	0.01	20.4
	III	Lakes, reservoir & ponds increase	49.1	19.3	7.1	0.04	10.4
	IV	Swamp decrease	83.3	0.5	5.0	0.02	6.2

Note: humidity Region: I: 0.3–0.4, II: 0.4–0.5, III: 0.5–1.0, and IV: >1.0; local area ratio = area of major wetland change/area of each humidity region; and total area ratio = area of major wetland change/area of wetland changes in whole region.

The above phenomenon suggested that wetland changes might be not directly related to temperature and precipitation changes. As was shown by the spatial distribution of the *HI* tendency, the Region I had the maximum humidity trend rate as well as biggest wetland changes, therefore, the increase of lakes, reservoirs and ponds in this region was consistent with the climate humidification tendency. In addition, the *HI* value in the Region II was higher than that in the Region III, accordingly, the magnitude of wetland decrease was smaller than in the Region III. Additionally, in the Region IV, the *HI* showed a negative growth rate, which contributed to wetland decrease. Consequently, *HI*, reflecting drought and wetness condition, were the direct factor resulting in wetland changes in the whole region.

During 2004–2012, the *HI* increased in the THR region. Regions with *HI* of 0.3–0.4 had largely disappeared, but the area of the humid region increased considerably (Table 4). Wetland changes were mainly distributed in the semi-arid region ($0.2 < HI < 0.5$) during this period, accounting for nearly half of the total wetland change area. Wetland changes mainly happened with the increase of lakes, reservoir & ponds in the Regions I, II and III, which accounted for 64% of the total wetland change area, double that in the former period.

During 2004–2012, precipitation increased significantly while the rate of temperature increase slowed; therefore, wetland changes were tightly associated with climate humidification. Among these regions, the maximum wetland area increase was in the Region II, accounting for one third of the total change of area. Meanwhile, the *HI* growth rate was also the maximum in this region, reaching 20.4×10^{-3}/year. In the Region IV, the *HI* also showed an increasing trend, however, the annual growth rate was the minimum among regions. Wetland changes mainly presented as swamp decreases, accounting for merely 0.5% of total wetland area change.

Therefore, the regional humidity differences and the interannual variation trend, caused by the change of precipitation and evaporation, were the main driving factors for the dynamic variation of wetland change in the TRH region. In general, the increase of *HI* in the THR region since the 1990s, especially in the western TRH region, has continuously contributed to wetland increases.

5. Conclusions and Discussion

The TRH region is one of China's most important regions with concentrated wetland distribution. As an ecosystem with distinctive features, wetlands in the TRH region play an irreplaceable role in water source conservation, run-off adjustment and biodiversity maintenance. The wetland changes and its response to climate in the TRH region were analyzed based on climate data and remote image data from the early 1990s to 2012. The main conclusions can be summarized as follows:

(1) In the TRH region, wetlands occupied 6.3% of total land area in 2012. Swamps, streams & rivers and lakes were the dominant wetland types in the region. The Yangtze and Yellow River basins had the most extensive distribution of swamps, which accounted for 49.8% and 36.8% of the total wetland area in each basin, respectively. Streams & rivers were most extensively distributed in the Langcang River basin, accounting for 63% of total wetland area in this basin.

(2) Wetlands have undergone great changes since the early 1990s. The total wetland area increased by 260.6 km^2 (1.2%). Lakes, reservoirs & ponds displayed a continuous increasing trend, but swamps, streams & rivers show a continuously decreasing trend. The wetland area in the Yangtze River basin showed an overall increasing trend, while in the Yellow River and Langcang River basins, the wetland areas decreased in general. From the early 1990s to 2012, the wetland changes showed a shifting trend from the middle parts to the western parts. Wetlands in the middle and western parts varied significantly during these years.

(3) In the past 20 years, the climate in the TRH region has turned from Warm-Dry to Warm-Wet. The average temperature and precipitation increased by 0.9 °C and 102 mm, respectively, from 1990 to 2012, and the average *HI* increased by 0.1, showing an upward trend and a shift of the dividing line towards the northwest in both the areas of the semi-humid and semi-arid zones.

(4) By correlation analysis of wetland changes with meteorological factors from 1990 to 2012, the results indicated that wetland changes might be not directly related to temperature and precipitation changes. The regional humidity differences and the interannual variation trend, caused by the change of precipitation and evaporation, was the main driving factors for the dynamic variation of wetland changes in the TRH region. In the general, the increase of *HI* in the THR region since the 1990s, especially in the western TRH region, has contributed continuously to the wetland increases.

Wetland dynamics are the consequence of the interactions among various factors, such as geological structure, climatic conditions and supplement patterns. Climate change, especially temperature, precipitation and humidity, observably impacts the wetland changes. Generally, in the TRH region *HI*, which changes with precipitation and evaporation, is the primary climatic factor affected wetland changes, and the good consistency between the regional *HI* and the change trends of wetland are presented as controls on the wetland balance during the last 20 years. We can see that the obviously increasing *HI* in the northwestern TRH region (4.3/year in region I during 1990–2004 and 17.3/year, 20.4/year and 10.4/year in the Regions I, II and III, respectively, during 2004–2012). This trend was directly related to the expanding lakes, reservoirs and ponds in this region. However, although the *HI* (2.1/year and 1.8/year, respectively, during 1990–2004) in the Regions II and III increased, swamps mainly showed shrinking trends. Therefore, swamp changes in these regions were primarily controlled by other factors, and the increasing *HI* was not obviously related to the decrease of swamp area, but rather the degree of increase of the *HI* affected the degree of decrease of swamp area in these regions.

Against the background of warming, hydrological regime changes, such as increased runoff, ice and snow melt water, accelerated permafrost thawing, land use/cover changes and anthropic activity, would synthetically have complicated effects of wetland variation in arid regions [37]. Ice and snow melt, released soil moisture of permafrost, caused by the temperature increasing, vary the water supplies of wetlands. For example, in the origin of the Yangtze River such as Tuotuo River, Dangqu, Gaerqu and Buqu, *etc.* wetlands are primarily supplied by melt water originating from the large glaciers of the Tanggula Mountain. The wetland changes may be more affected by temperature change. Geophysical surveys in the TRH region have suggested that warming temperatures lead to thinning and eventual breaching of permafrost, which may be the reason for the shrinkage of most large wetland patches. For example, as mentioned by Smith *et al.* [38] and Riordan *et al.* [39], initial warming leads to lake expansion followed by drainage as the permafrost degrades still further. The influence of anthropic activity on wetland change always takes effect together with climate change. In 2005, the State Council [40] approved the *Ecological Protection and Construction Master Plan of Qinghai Sanjiangyuan Nature Reserve*. The 22 projects, such as forbidding grazing, combating desertification, controlling rodent pests and human-induced rainfall, were instigated to recuperate the grassland. The human-induced rainfall, which increased the water supplies of wetland, has an important influence on wetland changes. For example, the lakes, reservoirs & ponds increased (Figure 5) in the source region of the Yellow River (the Qumalai and Maduo counties), which was directly related to the human-induced rainfall and *HI* increase. Therefore, understanding the wetland changes and their response to climate change under anthropic disturbance is more complicated.

Wetland study is a hot research field in modern ecology and environmental science. The study of wetland changes and its responses to climate changes in the TRH region, which is relatively weak in the field of research on land use/cover change process in Qinghai-Tibet Plateau, occupies an important position among global environmental changes. Therefore, this study could provide a valuable and scientific basis for understanding the correlation of wetland changes with climate factors. Wetland dynamics would greatly affect the structure, function and process of the landscape, as well as population dynamics, biodiversity and ecosystem processes [14,31,32,41]. The conclusions of this study will provide some scientific references for the management and protection of wetlands in the TRH region, especially for restoration, reconstruction and conservation of degraded wetlands. The study on the correlation of the wetland change process and global climate changes is one of the prospective priority research fields in the future. The changes of wetland landscape patterns will produce profound impacts on regional and global climate changes, for example, it will accelerate climate change. Climate warming and drying will cause the shrinkage of wetland and accelerate peat decomposition. Therefore, there is an interaction and mutual influence between dynamic changes of wetland landscape patterns and global climate changes. This study is an attempt to understand the wetland changes and its response to climate changes, and it is also an important contribution to the studies on global climate change.

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Author Contributions

Xinliang Xu conceived and designed the study. Laga Tong wrote the paper. Ying Fu, Shuang Li and Laga Tong performed the data analysis. Laga Tong, Xinliang Xu, Ying Fu and Shuang Li reviewed and edited the manuscript. All authors read and approved the manuscript.

Appendix

Table A1. The satellite images used to acquire wetland in the TRH region. TM: Thematic Mapper.

TM images in the early 1990s		TM images in 2004		HJ-1 images in 2012	
Path/row	**Acquired time**	**Path/row**	**Acquired time**	**Path/row**	**Acquired time**
131/36	8 July 1990	131/36	14 September 2003	816/844	29 July 2012
132/35	15 July 1990	132/35	10 September 2005	829/439	19 August 2012
132/36	18 July 1991	132/36	10 September 2005	833/458	25 August 2012
132/37	4 September 1991	132/37	6 August 2004	834/168	26 August 2012
133/35	4 August 1992	133/35	29 June 2005	839/177	2 September 2012
133/36	6 July 1990	133/36	14 September 2004	840/899	4 September 2012
133/37	6 July 1990	133/37	14 September 2004	841/345	5 September 2012
134/35	30 August 1990	134/35	23 August 2005	841/347	5 September 2012
134/36	30 August 1990	134/36	17 July 2003	846/276	12 September 2012
134/37	30 August 1992	134/37	17 July 2003	846/731	13 September 2012
134/38	30 August 1992	134/38	8 September 2005	846/899	13 September 2012
135/35	21 August 1990	135/35	10 July 2004	847/381	14 September 2012
135/36	21 August 1990	135/36	10 September 2003	847/388	14 September 2012
135/37	26 August 1992	135/37	10 July 2004	847/401	14 September 2012
135/38	10 August 1992	135/38	24 July 2003	848/016	15 September 2012

Table A1. *Cont.*

TM images in the early 1990s		TM images in 2004		HJ-1 images in 2012	
Path/row	**Acquired time**	**Path/row**	**Acquired time**	**Path/row**	**Acquired time**
136/35	28 August 1990	136/35	17 July 2004	-	-
136/36	28 August 1990	136/36	17 July 2004	-	-
136/37	2 September 1992	136/37	22 December 2003	-	-
137/35	4 September 1990	137/35	10 October 2003	-	-
137/36	4 September 1990	137/36	10 October 2003	-	-
137/37	2 July 1990	137/37	25 June 2005	-	-
138/35	14 September 1991	138/35	16 August 2004	-	-
138/36	15 August 1992	138/36	16 August 2004	-	-
138/37	31 August 1992	138/37	24 June 2002	-	-
139/35	17 August 1990	139/35	22 September 2003	-	-
139/36	5 September 1991	139/36	22 September 2003	-	-
139/37	29 May1990	139/37	22 September 2003	-	-
14//35	12 September 1991	14//35	15 September 2004	-	-

Conflicts of Interest

The authors declare no conflict of interest.

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