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Spatial and Temporal Changes of Wetlands on the Qinghai-Tibetan Plateau from the 1970s to 2010s

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Abstract: Wetlands on the Qinghai-Tibetan Plateau (QTP) perform a dazzling array of vital ecological functions and are one of the most fragile ecosystems in the world. Timely and accurate information describing wetland resources and their changes over time is becoming more important in their protection and conservation. By using remote sensing data, this study intended to investigate spatial distribution and temporal variations of wetlands on the QTP at different watershed scales from 1970s to 2010s. Results show that wetlands on the QTP have undergone widespread degradation from 1970s to 2010s, with nearly 6.4% of their area being lost. Areas of freshwater marsh, salt marsh and wet meadow declined by 46.6%, 53.9% and 15.6%, respectively, while lake area increased by 14.6%. The most extensive losses of natural wetlands have occurred in endorheic basins, such as in the Kunlun-Altun-Qilian Drainage Basin and Qiangtang Basin, which shrank by 44.5% and 33.1%, respectively. A pronounced increase in temperature tends to facilitate the evaporation process and reduce water availability for wetlands. One-third of the wetlands on the QTP are under threat of being submerged due to lakes rising in recent years. More research is needed to gain insight into the interaction mechanisms behind observed variations and potential impacts from further warming in the future.

Keywords: wetland; spatial and temporal change; climate change; Qinghai-Tibetan Plateau (QTP)

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1 Introduction

Wetland ecosystem is a unique mixture of species, conditions, and interactions produced by a combination of aquatic and terrestrial conditions (Brinson and Malvarez, 2002). As the most diverse and varied habitats in the world, wetlands perform vital functions such as water filtration, water storage, biological productivity, and providing habitat for wildlife (Hruby, 1999; Woodward and Wui, 2001). However, wetlands, with their fragility and sensitivity to climatic changes and anthropogenic activities, are among the most vulnerable ecosystems in the world (Foti et al., 2013). The Qinghai-Tibetan Plateau (QTP), also known as 'the third pole', is the highest (average elevation of 4000 m above sea level) plateau in the world (Wu, 2001). It is also a

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major region with a large amount of wetlands (Zhao, 1999). However, most wetlands on the QTP have experienced major changes during the past several decades.

Earth observation technologies have met spatial information needs for the inventory, assessment, and monitoring of wetlands (Seto and Fragkias, 2007; MacKay et al., 2009). Remote sensing technology provides a useful approach for wetland monitoring at different scales (Prigent et al., 2001; Ozesmi and Bauer, 2002). Compared to ground survey, the main advantage of satellite remote sensing is that it offers repeated large-scale coverage of landscapes. Many remote sensing images at various resolutions are currently used in wetland monitoring, principally including: high resolution multispectral images (Ikonos, Quickbird), middle resolution multispectral images (Landsat series, Spot series), low resolution multispectral images (MODIS (the Moderate Resolution Imaging Spectroradiometer), AVHRR (Advanced Very High Resolution Radiometer)), synthetic aperture radar and airborne light detection and ranging (SAR (Synthetic Aperture Radar), Lidar) (Dechka et al., 2002; Zoffoli et al., 2008; Cook et al., 2009; Kayastha et al., 2012; Michishita et al., 2012; Reschke et al., 2012). Remote sensing and Geographical Information Systems (GIS) can provide cost-effective detection for large-scale monitoring on wetlands.

Recently, the importance of wetlands on the QTP has been increasingly recognized by scientists. Many researchers have focused their efforts on spatial and temporal changes, structure and function of wetlands on the QTP (Lu, 2008; Zhang, et al., 2011). However, because of the absence of reliable data on wetlands within the entire area, most studies focus on source areas of the Yangtze River, Huang (Yellow) River, Lancang (Mekong) River, the Lhasa River Basin and Zoige Plateau (Wang et al., 2007; Fan et al., 2010; Zhang et al., 2010). Research concerning all wetlands on the QTP is still sparse. By combining wetland maps from Landsat images and meteorological measurements, we studied long-term changes of wetlands on the QTP, with the following two goals: 1) to document major wetland changes on the QTP from 1970s to 2010s; 2) and to improve the understanding of the relationship between changes to wetlands due to climate warming and human activities.

2 Data and Methods

2.1 Study area

The QTP is the highest and largest plateau in the world, and is located in the southwest of China (26°10′N–39°30′N, 73°20′E–104°20′E) (Chen et al., 1996; Zheng et al., 2002) (Fig. 1a). It stretches about 1532 km from north to south and 2945 km from east to west, and mainly covers the Tibet Autonomous Region, Qinghai Province of China (Zhang et al., 2002). The QTP is surrounded by massive mountains such as Himalayan, Kunlun, Qilian and Hengduan Mountains and is home to many widespread lakes, large glaciers and wetlands, a major source of rivers and regulators of water storage (Gujja et al., 2003; Yang and Zheng, 2004). Primarily, climate of the plateau is characterized by intense solar radiation, low air temperature, and significant spatial difference of precipitation. The average annual temperature is around 3.39 ℃ and gradually drops off from the outside edge to the inner of the plateau. The annual precipitation of the plateau is 482.8 mm which is lower than the corresponding evaporation of 756.8 mm (Wu et al., 2005). Wet meadow is dominant on the QTP, which occupies 35% of the Qinghai Tibet Plateau and extends more than 2.5×10^6 km^2 (Zheng et al., 2000). The primeval forest is mainly distributed in the southeastern plateau and the southern flanks of the Himalayan Mountain with an area of nearly 0.2×10^6 km^2 (Deng, 2000). According to the sixth national population census of China, the QTP has China's lowest population density, with about 4.5 people/km^2. Tibetans make up over 47% of the local population, most of them engage in stock raising and farming.

2.2 Materials and processing

Due to the massive, high altitude area the QTP covers, with rough terrains and depopulated zones, it is difficult to conduct large scale field surveys on the plateau. In order to obtain precise spatial data of wetlands, we chose 561 cloudless Landsat MSS/TM images acquired primarily in the growing season from May to September, 1970s to 2010s (Figs. 1b and 1c) as source data, the 5, 4 and 3 bands of the acquired images were enhanced, rectified to Albers Equal Area Conic projection and mosaicked using ENVI 4.3 and ArcMAP 9.1.

Considering errors from shadows of mountains and clouds, automatic classification methods such as super vised, unsupervised classification algorithms and object-

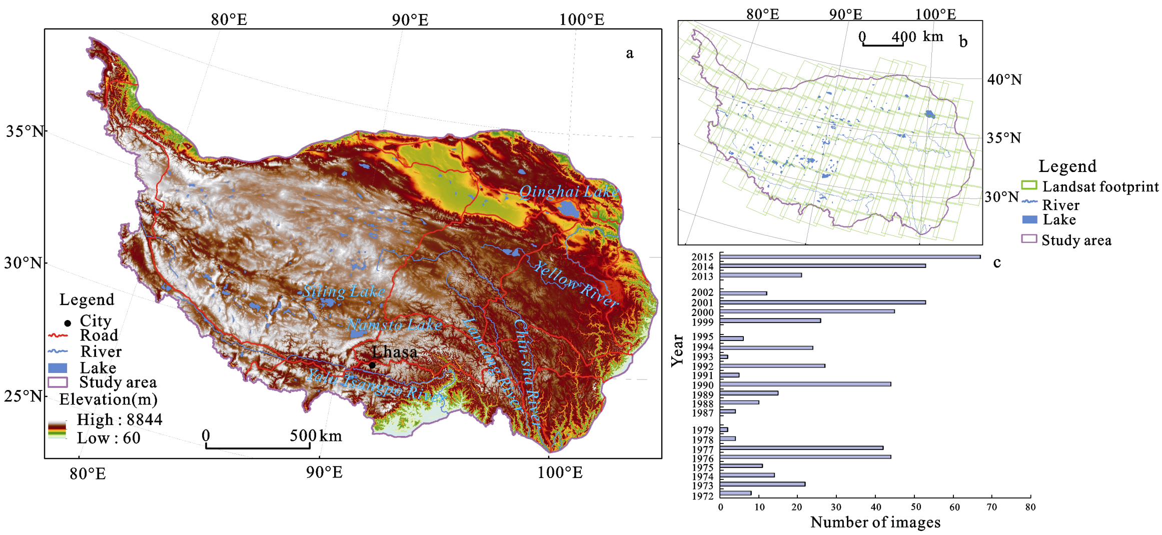

Fig. 1 Location of the QTP and details of images for this study

oriented classification, *etc*., were not applied in this study. We employed the visual interpretation method to extract wetland information from Landsat TM images. The classification system contains five types, including lake, freshwater marsh, salt marsh, wet meadow, and constructed wetland (Fig. 2). Freshwater marsh and salt marsh types are defined as wetlands that are submerged with permanent fresh or salt water and dominated by plants that are adapted to saturated soils. Wet meadows differ from marshes because they have no standing water. Constructed wetland types include reservoirs and salt fields. Subsequently, according to field survey data of 2015–2016 and the Mire Map of China, the wetland dataset was revised and modified.

A confusion or error matrix was used to accurately estimate the overall and individual category classification accuracy (Rooney et al., 2012). In this study, a total of 547 test sample plots, from two field surveys carried out in 2015 and 2016, were used for accuracy assessment. User's accuracy was high for the constructed wetland at 100%, lake at 98.62%, as well as for wet meadow at 95.60%. Freshwater marsh and salt marsh had relatively low user's accuracy, 87.01% and 85.71% respectively (Table 1). On the whole, mapping accuracy of the wetland dataset was 89.00%, and overall Kappa statistics was 0.82 which is acceptable for change analysis.

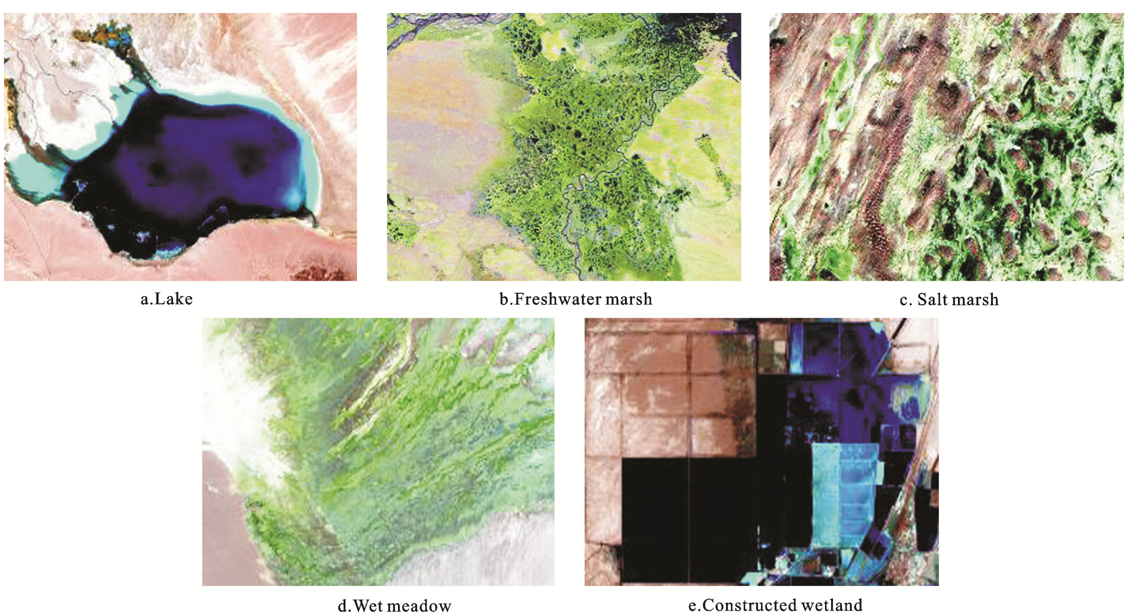

Fig. 2 The classification of wetlands over the Qinghai-Tibetan Plateau

Table 1 Confusion matrix for image classification

Wetland categories	Number of samples	Product accuracy (%)	User accuracy (%)	Kappa for each Category
Lake	185	98.13	98.62	0.98
Freshwater marsh	80	81.71	87.01	0.86
Salt marsh	52	69.23	85.71	0.85
Wet meadow	191	83.24	95.6	0.91
Constructed wetland	39	100.00	100.00	1.00
Overall accuracy		89.0%		
Overall Kappa statistics		0.82		

2.3 Ancillary data

Ancillary data used in this study included Shuttle Radar Topography Mission (SRTM) data distributed by USGS EROS Data Center (EDC), data of monthly precipitation, monthly average temperature and monthly average ground temperature downloaded from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/) and the Mire Map of China (1∶4 000 000) (Wang, 2004). Air temperature for future scenarios were from Global Climate Data (http://worldclim.org/). Future scenarios were downscaled global climate model (GCM) data from Coupled Model Intercomparison Project Phase 5 (CMIP5) for four representative concentration pathways (RCPs) (IPCC, 2007; Sillmann et al., 2013). The Mire Map of China classified wetland into 79 categories according to vegetation and topography. In this study, the wetland maps of 1970s was digitized and simplified into five categories for contrastive analysis. To improve the comparability, all lake data and most wetland data were modified according to Landsat 1–3 MSS images acquired in the 1970s. Boundaries of drainage basin and gradient (in degrees) were derived from the Shuttle Radar Topography Mission (SRTM) data using hydrologic and spatial analysis tools of ArcGIS. Based on drainage system, the whole study area was sub-divided into 10 drainage basins, including Qaidam Basin (QDB), Qiangtang Basin (QTB) and Kunlun-Altun-Qilian drainage Basin (KAQDB) which are endorheic basins. The remaining 7 basins are exorheic basins and include Indus River Basin (IRB), Lancang River Basin (LRB), Nujiang River Basin (NRB), Yalu Tsangpo River Basin (YTRB), Yangtze River Basin (YZRB), Yellow River Basin (YLRB) and Dulong River Basin (DLRB).

3 Results

3.1 Distributive characteristics of wetlands

Wetland maps of the QTP for the 1970s, 1990s, 2000s and 2010s are displayed in Fig. 3. Most wetlands are located in Qinghai, in the western Tibet and the Zoige Plateau. At the drainage basin scale, wetlands are mainly located in the QTB, the YRB, the QDB and the YZRB, accounting for 36.1%, 17.6%, 13.3% and 13.0% of the total, respectively. Nearly 60% of freshwater marsh and 50% of wet meadow are concentrated in the upper reaches of the YLRB and the YZRB. Yet, salt marshes are only distributed in endorheic basins, 60.0%, 23.1% and 13.8% was in the QDB, QTB and the KAQDB, respectively. Over 70% of lakes are scattered around the QTB and 12.7% are in the KAQDB.

3.2 Topography and wetlands distribution

Topographical features are intimately linked to wetlands distribution (Gao et al., 2012). Most wetlands appear at elevations between 800–5800 m, of which over 74.2% occurred at elevations between 4200–5200 m (Fig. 4). For freshwater marsh and salt marsh, distribution demonstrated approximate double-peaked curves, and the valley between peaks was around 3800 m. Roughly 54.1% and 33.3% of salt marsh occurred between 2800–3200 m and 4200–5200 m. Over 20.1% and 77.4% of freshwater marsh occurred between 3400–3800 m and 4200–5200 m. Nearly 70.0% of wet meadow occurred between 4200–5200 m. Topography and water supply are the two most important features in determining distribution of wetlands (Zedler and Kercher, 2005). Wetlands usually develop in areas with low gradients and poor drainage outlets. In the study area, about 73.8% of wetlands were located on areas with a gentle slope (< 2°). Nevertheless, there were a fair amount of wetlands distributed on sloped surfaces (Fig. 5). Nearly 17.2% of fresh marsh and 40.3% of wet meadow were distributed in areas with a gentle slope gradient (from 2° to 5°). Around 13.2% of wet meadow was located in areas with a certain slope gradient (> 6°), such as hillsides and valleys receiving melt water from

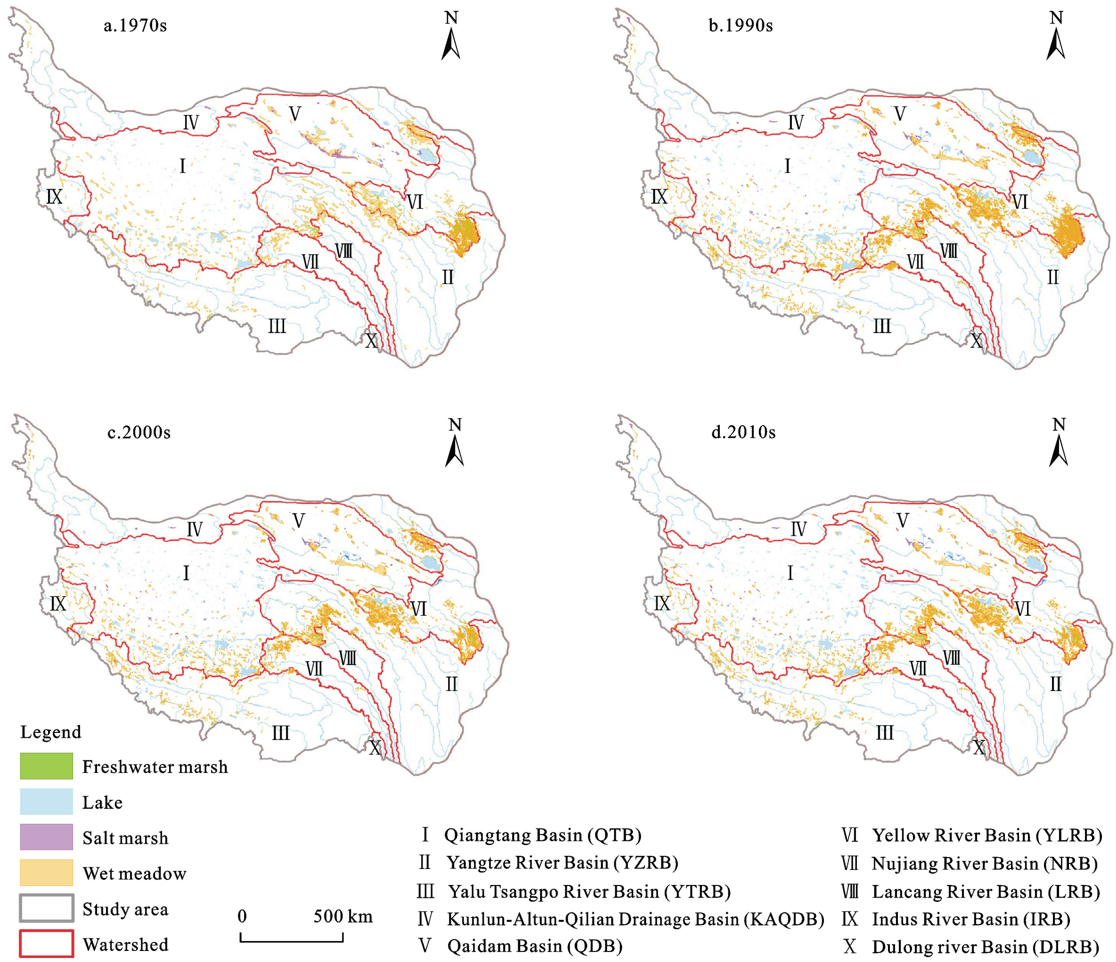

Fig. 3 Distribution of wetlands on the Qinghai-Tibetan Plateau from the 1970s to 2010s

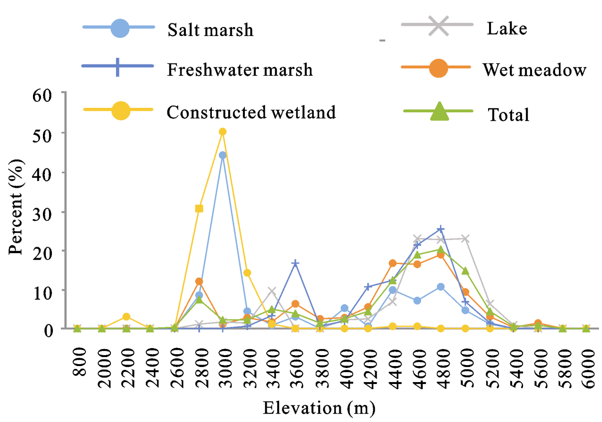

Fig. 4 Distribution of wetlands along altitude

permafrost and glaciers.

3.3 Changing trends of wetlands

The overall changes of wetlands from the 1970s to 2010s are shown in Table 2. Wetlands cover about 4.3% of the study area with an estimated total area of 11.47 × 10^4 km^2 in the 1970s. From the 1970s to 2010s, the total area of wetlands was reduced substantially by about 7.5% to 10.61 × 10^4 km^2 in the 2010s. Wet meadow was predominant in this region, with areas of 6.61 × 10^4 km^2 in 1970s, occupying more than half (57.6%) of the total wetlands. However, wet meadow decreased by 15.6% to 5.58 × 10^4 km^2 in the 2010s. The most remarkable change of wetlands on the QTP was the tendency of declining marshes and increasing lakes. In the 1970s, areas of freshwater marsh and salt marsh were 0.63 × 10^4 km^2

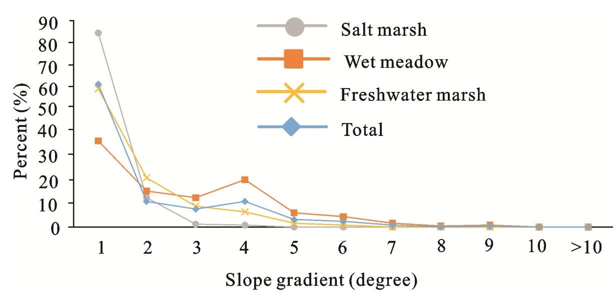

Fig. 5 Distribution of wetlands along the gradient of slope

and 0.39 × 10^4 km^2, taking up about 5.5% and 3.9% of the total, respectively. In the 2010s, areas of freshwater and salt marsh were 0.33 × 10^4 and 0.18 × 10^4 km^2, a dramatic decline of 46.6% and 53.9% compared to those in the 1970s, respectively. In contrast, areas of lake increased by 14.6% from 3.84 × 10^4 km^2 in the 1970s to 4.4 × 10^4 km^2 in the 2010s. Areas of constructed wetland increased to 0.12 × 10^4 km^2 in the 2010s.

From the 1970s to 2010s, areas of wetlands in IRB declined by 28.1%, followed by 22.7% in the KAQDB and the NRB (Fig. 6). Due to lake areas increasing, areas of wetlands in the QTB grew by 4.6%. In the 2010s, there were 474 new lakes with a total area of 1055.5 km^2 on the QTP, and 75.3% of them were located in the QTB. Salt marshes in the QDB have declined by 67.5%. The freshwater marsh and wet meadow decreased by 26.3% and 4.9% in the YZRB, and by 53.5% and 6.0% in the YLRB during the period of the 1970s–2010s.

4 Discussion

Climate change and anthropogenic activities are major driving factors for wetland change (Yan et al., 2015). Our another study showed that anthropogenic impacts accounted for 75.7% and climatic impacts accounted for 24.3% of wetland loss in China during the past 30 years. Regional differences of proportion of impacts are obvious. In the QTP, the proportion of anthropogenic and climatic impacts is 1.3% and 98.3%, respectively (Lyu et al., 2018). Thus, we mainly discuss on the impacts and potential threats of climate change to wetlands on the QTP in the following section.

4.1 Climate warming and impacts on wetlands

Wetlands degradation and loss of the QTP were mainly attributed to both human interference and climate changes (Nie and Li, 2011). Wetlands in alpine areas are usually fragile and sensitive to natural climate variations and changes (Mihuc and Toetz, 1996). The QTP experienced significant climate changes during the period from 1970 to 2010. Annual air temperature and annual precipitation on the QTP have risen at the rate of 0.51℃/10yr and 11.1 mm/10yr, respectively. Most significantly warming occurred in the QDB by 0.76 ℃/10yr.

Table 2 Area of wetlands on the Qinghai-Tibetan Plateau from the 1970s to 2010s (10^4 km^2)

Type	1970s	Percent (%)	1990s	Percent (%)	2000s	Percent (%)	2010s	Percent (%)	Rate of change (%)
Freshwater marsh	0.63	5.5	0.52	4.9	0.39	3.8	0.33	3.2	–46.6
Lake	3.84	33.5	3.96	37.2	3.99	39.0	4.40	41.5	14.6
Salt marsh	0.39	3.4	0.24	2.3	0.19	1.8	0.18	1.7	–53.9
Wet meadow	6.61	57.6	5.89	55.4	5.62	54.9	5.58	52.6	–15.6
Constructed wetland	0.00	0.0	0.03	0.2	0.05	0.5	0.12	1.1	–
Total	11.47	100.0	10.64	100.0	10.24	100.0	10.61	100.0	–7.5

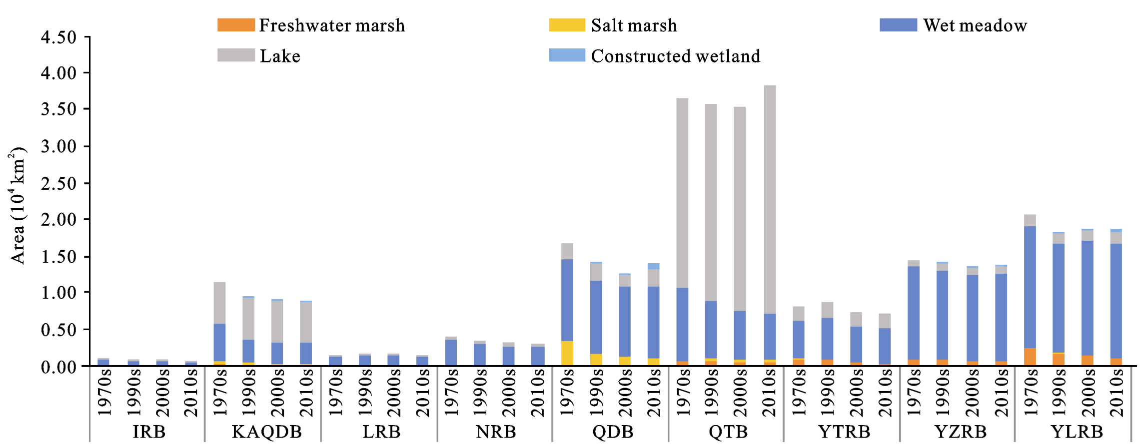

Fig. 6 Changes of wetlands in basins from the 1970s to 2010s (Indus River Basin, IRB; Kunlun-Altun-Qilian drainage Basin, KAQDB; Lancang River Basin, LRB; Nujiang River Basin, NRB; Qaidam Basin, QDB; Qiangtang Basin, QTB; Yalu Tsangpo River Basin, YTRB; Yangtze River Basin, YZRB; Yellow River Basin , YLRB)

However, variations of precipitation in drain age basins were not the same as those of temperature. The annual precipitation in YLRB increased by the rate of 49.1 mm/10yr while it only increased by the rate of 3.4 mm/10yr in YZRB (Fig. 7). Unequal changes of precipitation and temperature patterns impaired water balance on the QTP. Increases in temperature tends to increase evaporation and reduce water level of wetlands, especially in endorheic basins and arid regions.

Previous studies have projected that climate warming on the QTP would continue and even become greater in the future (Liu et al., 2009; Guo et al., 2016). The annual average temperature projections from CMIP5 under RCP scenarios for drainage basins of the QTP are shown in Fig. 8. All projections indicated a general warming trend and the magnitude increased from the 2000s to 2100s. The projected greatest warming occurs in the KAQDB, increasing to 3.6 ℃ and 6.2 ℃ from the 2000s to 2100s under the RCP 2.6 and 8.5 scenario (Sillmann et al., 2013). The annual average temperature of QDB, YLRB, NRB and LRB are projected to be higher than 0 ℃ in the future. Climate warming promoted additional ET- related water losses, particularly in wetland-dominated areas of the QTP (Zhang W J, Ren Z P, Yao L et al., 2016). Changes of water balance due to enhanced evaporation will not only put wetlands at risk of degradation and type conversion or even loss, but will also affect wetland capacity for regulating river flows and reducing downstream flooding.

4.2 Potential threats to wetlands

On the QTP, wetlands are generally restricted to the narrow lowlands along river valleys and lake edges. According to our data, nearly one-third of wetlands are located within a 2-km radius of lakes. These wetlands can be directly affected by the lake level fluctuations. It is widely recognized that warming temperatures lead to the degradation of permafrost and glaciers on the QTP (Ye et al., 2008). Also, the melt water from permafrost and glaciers has resulted in widespread lake rising on the QTP. A recent case study showed that most lakes show a significant trend of increasing on the QTP during the period of 2003 to 2015 (Jiang et al., 2017). For example, Qinghai Lake, as the largest saline and alkaline lake on the QTP, has expanded 143.5 km^2 in area and risen in level over 1.6 m from 2004 to 2016 (Cui and Li, 2015; Luo et al., 2017). Nam Co Lake has increased about 25 km^2 in area and risen 2.5 m in water level from 2000 to 2010 (Lei et al., 2013; 2014). Fig. 9 shows the obviously increasing trends of air temperature and ground temperature from 1980 to 2011 at two weather stations near Qinghai Lake (37.2°N, 100.08°E) and Nam Co Lake (31.23°N, 90.01°E). In contrast, lakeside wetlands along the shores of the two lakes mentioned above reveal a decreasing trend from 1970s and 2010s, with areas of lakeside wetlands of Qinghai Lake decreasing

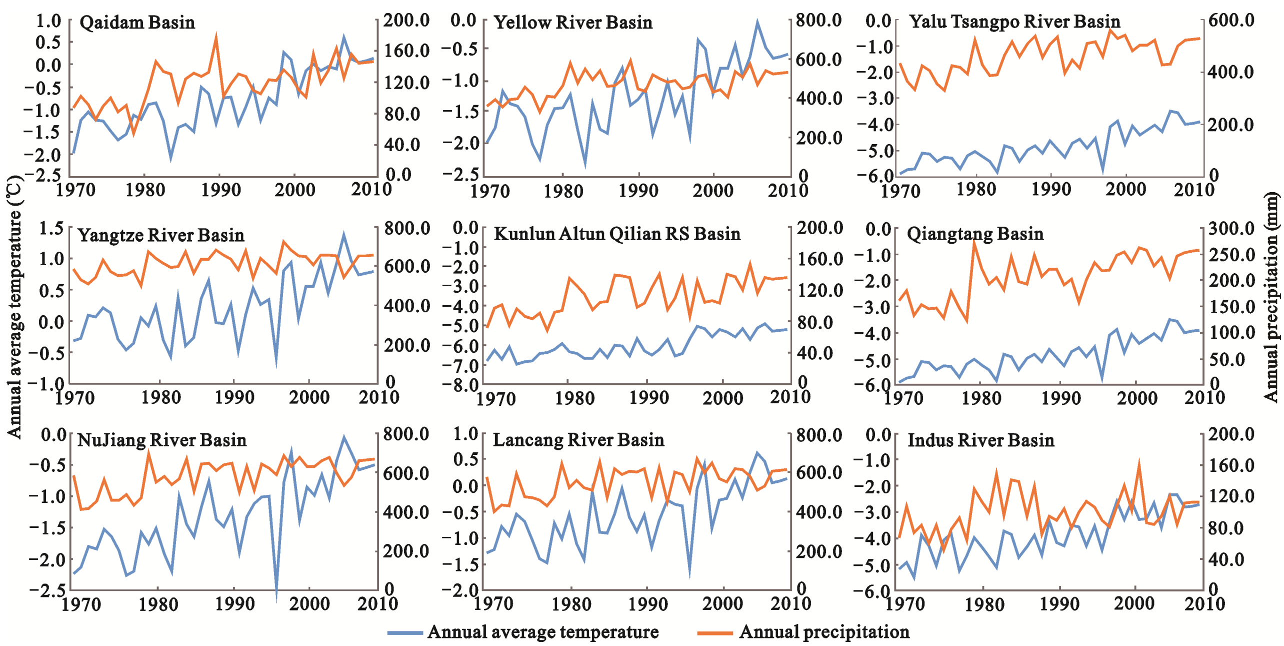

Fig. 7 Annual average temperature and annual precipitation in typical drainage basins from the 1970s to 2010s

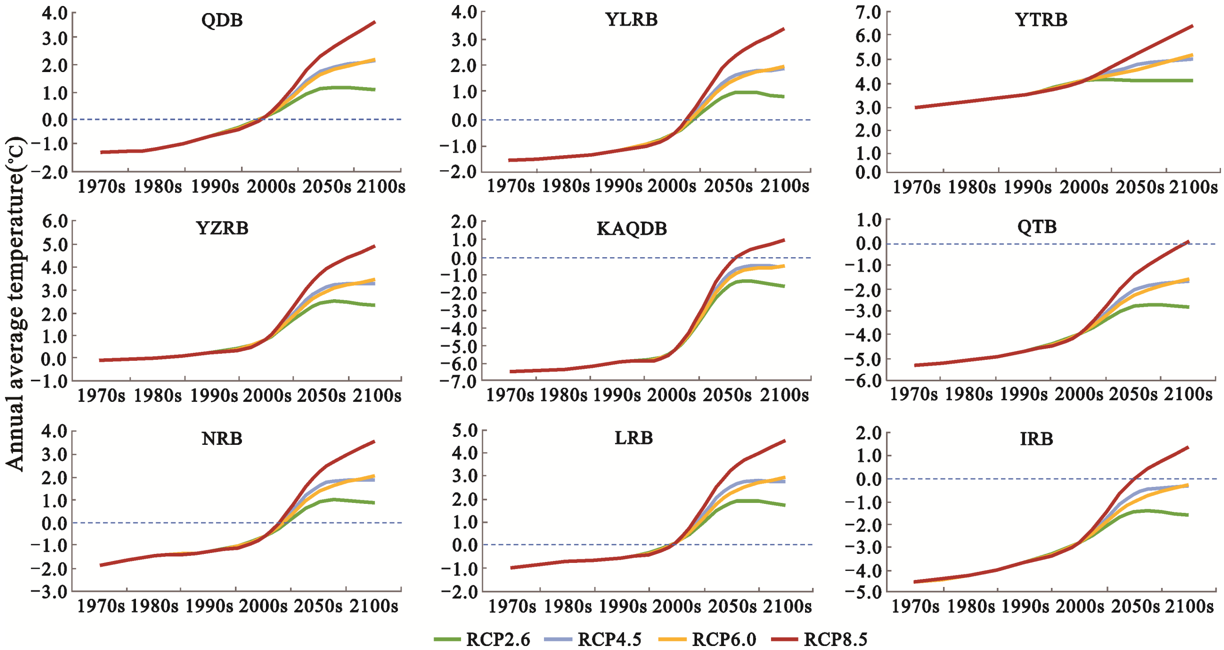

Fig. 8 Projected changes in annual average temperature in typical drainage basins under four Representative Concentration Pathways (RCPs) scenarios, RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 represent a radiative forcing of 2.6, 4.5, 6.0, and 8.5 W/m^2, respectively (Sillmann et al., 2013) (Indus River Basin, IRB; Kunlun-Altun-Qilian drainage Basin, KAQDB; Lancang River Basin, LRB; Nujiang River Basin, NRB; Qaidam Basin, QDB; Qiangtang Basin, QTB; Yalu Tsangpo River Basin, YTRB; Yangtze River Basin, YZRB; Yellow River Basin, YLRB)

from 3.00 × 10^2 km^2 to 1.47 × 10^2 km^2, a decline of 48.9%, and areas of lakeside wetlands of Nam Co Lake decreasing from 0.92 × 10^2 km^2 to 0.59 × 10^2 km^2, a decline of 35.6% (Fig. 10). Lakeside marshes may be submerged or forcibly pushed landward and revert to wet meadow in response to lake-level rise. The study of Jiang et al. (2017) shows that lakes in the north and northwest of the QTP had a significant level increase. Our results also found 474 new lakes within the same region in the 2010s (Fig. 10). Habitable low-lying lands for wetlands developing within this region have been submerged by those new lakes. Thawing of permafrost triggers an initial but transitory phase of arctic lake and wetland expansion, followed by their widespread disappearance (Smith et al., 2005). Zhang W J, Ren Z P, Yao L et al. (2016) projected that the permafrost on the QTP will experience different degrees of significant degradation under the four RCP scenarios. Xue et al. (2014) predicted the total area of wetland in the QTP could decline by 35.7% under the optimistic scenario by 2100. Although it is not clear whether the water supply from melting glaciers and permafrost is sustainable or not, wetlands on the QTP still face a variety of potential threats in the future.

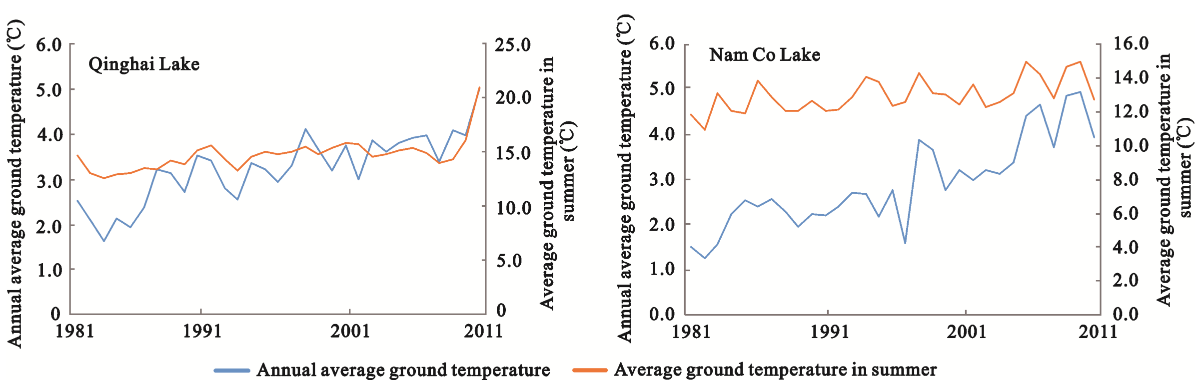

Fig. 9 Annual average temperature and annual average ground temperature of Qinghai Lake and Nam Co Lake during the period from 1981 to 2011

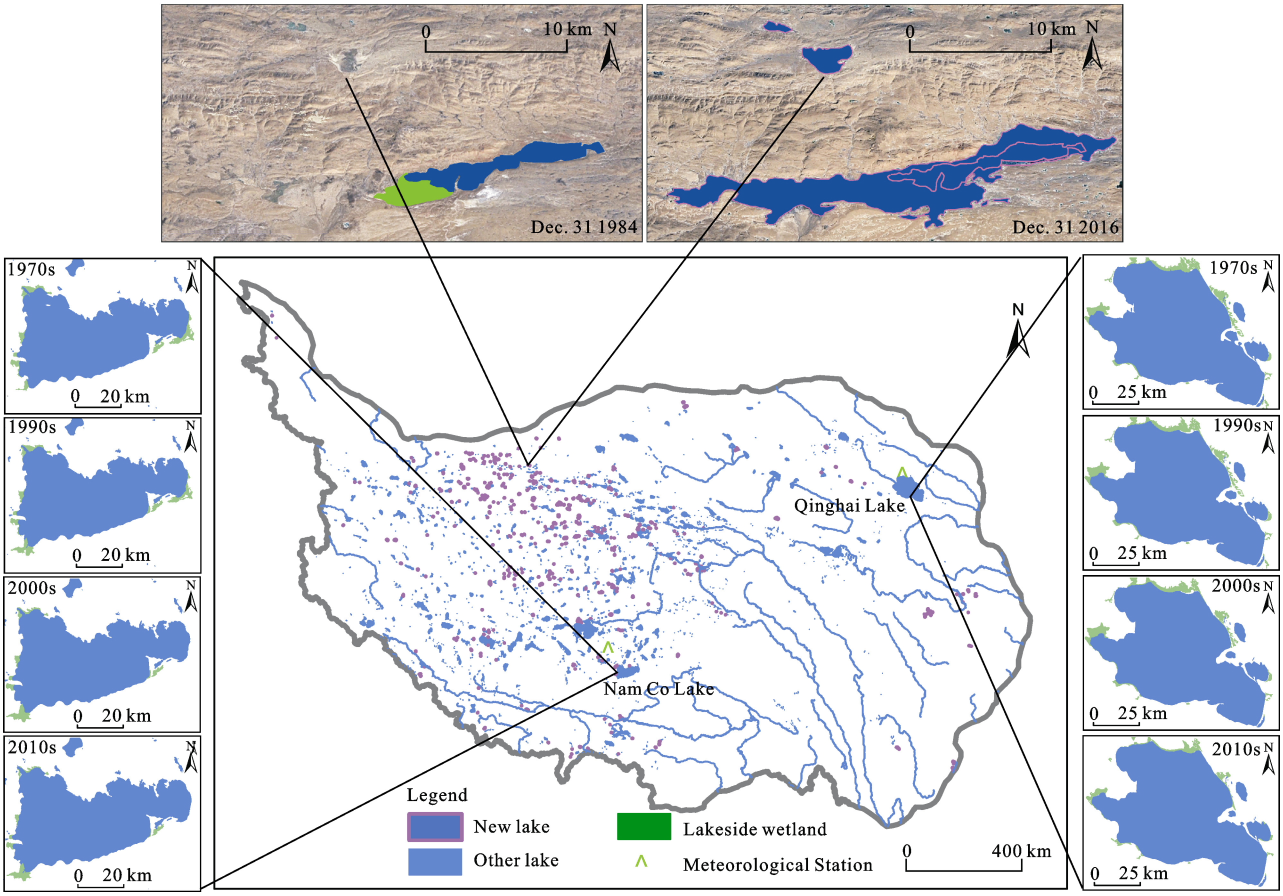

Fig. 10 Lake level fluctuations and shrinkage of lakeside wetlands from the 1970s to 2010s

5 Conclusions

This research attempts to map and analyze changes of wetlands on the QTP using remotely sensed satellite data. Results indicate that typical wetlands on the QTP have degraded extensively from the 1970s to 2010s. Significant climate change might contribute to the widespread and ongoing degradation and loss of wetlands on the QTP. Wetlands on the QTP still face a variety of potential threats following continuous climatic warming in the future. This study provides substantial evidence to indicate significant spatial and temporal variations of wetlands on the QTP. To effectively preserve and manage wetlands, more research such as investigating baseline relationships between climate warming and wetlands and developing scenario-based models to quantify impacts should be undertaken in the future. Meanwhile, due to lack of quantifiable data about human activity of the entire study area, this study only focused on impacts of climate change on wetlands. So it is necessary to comprehensively analysis impacts of directly or indirectly from human activities on wetlands within the QTP in further study.

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