Changes in alpine wetland ecosystems of the Qinghai–Tibetan plateau from 1967 to 2004

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Abstract Spatiotemporal shifts in the extent and distribution of alpine wetland ecosystems in China's Qinghai–Tibet plateau were investigated for the period 1967–2004. Using aerial photographs for 1967, and satellite remote sensing data for 1986, 2000, and 2004/5, the main components and distribution of alpine wetland ecosystems in the headwaters regions of the Yangtze and Yellow Rivers, as well as those of the nearby Zoige region, were analyzed. Widespread degradation of the Qinghai–Tibet plateau's alpine wetlands occurred between 1967 and 2004, with over 10% of their area being lost. The greatest such degradation occurred in the headwaters region of Yangtze River, where wetland areas shrank by 29%, and the area of dried-up lakes rose by 17.5%. In the Yellow River's headwaters region as well as the Zoige region, wetland ecosystems clearly underwent accelerated fragmentation and isolation in their spatial distribution. The wetlands' degradation was closely correlated to the

rise in air temperature, which from 1982–2004 was over 2-fold faster than from 1965–1982.

Keywords Alpine wetland · Dynamical change · Spatial pattern · Hydro-ecological function · Qinghai–Tibetan plateau

Introduction

Wetlands ecosystems, bearing traits of both terrestrial and aquatic ecosystems, have important global ecological functions. Their abundant biodiversity and large water conservation and storage capacities distinguish them from other terrestrial and aquatic ecosystems (Bullock and Acreman 2003). Hydrological conditions determine a wetland's attributes and spatial layout, while conversely, wetlands influence a region's water cycle and a basin's hydrological processes (Price and Schlotzhauer 1999; Price and Waddington 2000; Reeve et al. 2000). The mechanisms by which wetland ecosystems and hydrological processes mutually interact have long attracted the attention of ecologists and hydrologists. The response mechanisms of wetland ecosystems to hydrological changes at different scales has been established (Wassen and Grootjans 1996; Rodriguez-Iturbe 2000; Price et al. 2005).

Global climate change has significantly affected natural ecosystems around the world, particularly

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wetland ecosystems, whose sensitivity to global climate changes has accelerated their degradation (Wassen and Grootjans 1996; Rodriguez-Iturbe 2000; Bullock and Acreman 2003). Studies of Arctic frost wetland ecosystems have shown the cryosphere to be highly sensitive to global temperature changes and their effects on permafrost (Conly and Van Der Kamp 2001; Quinton and Marsh 1999). The changes in frost wetland ecosystems under such conditions have led to dramatic shifts in such regions' soil properties, water cycle, and soil CO₂ emissions, as well as profoundly affecting other regional systems (Quinton and Marsh 1999; Jorgenson et al. 2001; McGuire et al. 2003; DeFries and Eshleman 2004).

Located in the hinterland of the Qinghai–Tibetan plateau, the headwaters regions of the Yangtze and Yellow Rivers house the largest frost wetlands in China. The Zoige wetland, located in the northeastern portion of the Qinghai–Tibetan plateau, represents the largest peatland in China (Lang 1999). These three wetlands represent over 85% of alpine wetland areas in the Qinghai–Tibetan plateau region and form the largest lower latitude alpine wetland in the world. As with Arctic permafrost wetlands, alpine wetlands are quite sensitive to global climate changes (Jorgenson et al. 2001; Wang et al. 2001; An 2003; McGuire et al. 2003). Making up the majority of China's swamp wetland, alpine wetland systems are dominated by alpine swamp wetland and frost lake wetland types (Lang 1999; An 2003; Gong et al. 2010). Given the push to protect the plateau's biodiversity and implement water conservation measures in the headwaters region of the Yangtze and Yellow Rivers, what has happened to alpine wetland ecosystems under the last 40 years' climatic changes and how such ecological changes have impacted upon the headwaters' hydrological processes are important considerations.

Over the last 50 years, climate change in the Qinghai–Tibetan plateau has largely paralleled that of the whole country, where air temperatures have risen by 0.4–0.6°C decade⁻¹ (Qin 2002). However, within the Qinghai–Tibetan plateau, air temperatures have risen somewhat more sharply, particularly in the headwaters regions of the Yangtze and Yellow rivers (Wang et al. 2001; Li and Wu 2005). Consequently, changes in the

plateau's unique alpine wetland ecosystems have become a matter of common concern to both ecologists and hydrologists. However, few studies have documented the change in extent and distribution of alpine wetland ecosystems under climatic changes and its influence on hydrological processes (He and Zhao 2000; Zhou 2001; Wang et al. 2007a, b). While the spatial pattern of wetland ecosystems is known to have an important effect on hydrological and biological processes (Price et al. 2005; Cui and Yang 2006), the link between changes in wetland ecosystems and river hydrological processes has not been adequately quantified. Consequently, the main purpose of this study was to explore changes (1967–2004) in both the Qinghai–Tibetan plateau's alpine wetland ecosystems and their influence on surface hydrological processes. More specifically, we sought to address the following questions: (1) what spatiotemporal shifts in alpine wetland ecosystem extent, distribution, and condition have occurred under the climatic changes? (2) how do these changes correlate with climatic change? and (3) how do these changes affect the hydrological processes of the region's rivers?

Data and methods

Study area

The headwaters portion of the Yangtze River watershed has an area of 13.78×10^4 km² and lies between 90°43'–96°45' E and 32°30'–35°35' N, while that of the Yellow River at 6.48×10^4 km² lies between 33°00'–35°35' N and 96°00'–99°45' E (Fig. 1). The region's landforms are dominated by tall hills and a well-developed network of watercourses. The region's main naturally occurring alpine ecosystems are grassland, meadow, and swamp-wetland. Sparse alpine *Myricaria* shrub cover occurs locally in river valleys and provides sparse anti-erosive cover on upper mountain and scree slopes (Li and Zhou 1998; Wang et al. 2001). The Yangtze and Yellow rivers' headwaters, located in a transitional region between alpine semiarid and subhumid climatic zones, are characterized by a mean annual temperature of –1.3°C to –5.5°C and a mean annual precipitation of

Fig. 1 Location of study

270–540 mm (Wang et al. 2001, 2006a, b). The Zoige wetland, listed among China’s “important wetlands,” is located between 102°8′–103°36′48″ E and 33°3′12″–34°12′ N (Fig. 1), on the upper reaches of the Yellow River in the southeastern portion of the Qinghai–Tibetan plateau. Its main types of vegetation are alpine meadow and swamp meadow. The mean annual temperature is 0.9°C and the mean annual precipitation 656.8 mm (Yang 1999).

In all three of the Qinghai–Tibetan plateau’s regions, alpine wetland ecosystems constitute important sites for water conservation and the building of biodiversity, particularly in the headwaters regions of the Yangtze and Yellow rivers. Such ecosystems also represent a key ecological type in the China National Nature Reserve region of the Qinghai–Tibetan plateau (He and Zhao 2000; An 2003). Three main types of wetlands have been inventoried, namely “alpine swamp,” “alpine lake,” and “river” (Table 1). Alpine swamp wetlands, dominated by alpine swamp meadows, are most

concentrated in the headwaters region of Yangtze River, whereas alpine lake wetlands mainly occur in Yellow River’s headwaters region. The ratio of swamp and lake areas to the total area (swamp ratio) is greatest in the Zoige region (23%), being only 5.1% and 5.5%, respectively, in the headwaters regions of the Yangtze and Yellow Rivers. The similarly calculated wetland ratio [(swamp + lake + river)/total] is 8.6% and 8.2% for the headwaters of the Yangtze and Yellow Rivers, respectively.

The vegetation of these wetlands has some similarities: aquatic plant species include communities of *Potamogeton distinctus* A. Benn. and *Hippuris vulgaris* L. The dominant swamp vegetation species in the two headwaters regions include *Kobresia tibetica* Maxim. and *Carex tibetica* Franch (Li and Zhou 1998; Wang et al. 2001), while in the Zoige region, the dominant species include *K. tibetica* and *Carex muliensis* Tang. (Yang 1999; He and Zhao 2000). The soil types in the study region were mainly classified into Cryic

Table 1 Typical alpine wetlands status and distribution of the Qinghai–Tibetan plateau

Region and time	Swamp (km ²)	Lake (km ²)	River (km ²)	SR (%)	WR/EWR (%)	PR (%)	Main wetland river
Yangtze R. headwaters (2000)	5191.85	964.21	4289.07	5.1	8.6/10.6	87.4	Tongtian river (Yangtze)
Yellow R. head-waters (2000)	2141.71	1465.44	1733.53	5.5	8.2/10.0	56.7	Yellow River
Zoige (2004)	2302.89	17.97	93.79	22.6	23.6/26.8	Seasonal	Hei River

WR wetland ratio: wetland area/total land area; EWR effective wetland ratio: wetland area/total land area excluding upper mountain bare rock areas; SR swamp ratio: swamp area/total land area; PR permafrost ratio: permafrost area/total land area

Calcic Aridisols (Alpine steppe soil, as Cambisols in FAO/UNESCO taxonomy) and Mattic Cryic Cambisols (Alpine meadow soil, as Cambisols in FAO/UNESCO taxonomy).

Methods and datasets

Data sets

In the Yangtze and Yellow river headwaters areas, supported by a remote sensing interpretation marker database established on the basis of transect surveys, three sets of remote data, including 1967 aerophotographic data, as well as 1986 and 2000 satellite TM image data, were processed using ERDAS IMAGE and ARC/INFO softwares (with ArcView 3.1, ESRI Ltd.). Based on a 1:100,000 topographic base map, raw data was run through a series of treatments including TM[ETM] radiation calibration, geometric rectification, UTM geographical coordinate image rectification, and topographic map (1:100,000) rectification. A remote sensing interpretation mark database consisting of 246 mark points of 11 types was established on the basis of transect surveys. so as to attain an accuracy of RMS < 1 pixel.

Little intentional human disturbance of the Zoige region's wetlands has occurred since 1982; however, prior to 1985, the Zoige region's wetlands had been degraded by peat extraction and artificial drainage of wetlands to improve pasturelands (<1982) (He and Zhao 2000). Consequently, the wetlands changes since 1982 in the Zoige region were reasonably caused by climate change as similar as the Yangtze and Yellow River headwaters regions. The combination of remote sensing data (acquired in 1987, 1997, and 2004) and the field investigation data in 1967 and 1982

could be reasonably compared through time or across the region (i.e., with similar data from the Yangtze and Yellow River headwaters regions).

Six meteorological stations were located in the Yangtze and Yellow river headwaters areas and two in the Zoige region. These provided complete precipitation and air temperature data for the period of 1960–2005. Stream runoff depth at the outlet of the Yangtze and Yellow river headwaters' wetland areas was available for the period of 1960–2005, but for the Zoige wetland's outlet, runoff data were limited to the period of 1980–2005.

Analysis of within-wetland spatial pattern changes

Used to compare and analyze spatiotemporal shifts in wetland types, the variation in extent of land cover attributable to a specific wetland type, P_i , its rate of variation in time, R_i and its extent of variation across subregions (Yellow, Yangtze, Zoige), P_k , were defined as (Liu et al. 2003; Wang et al. 2006a, b):

$$P_i = 100 \times [(LU_{it1} - LU_{it0}) / LU_{it0}] \quad (1)$$

$$R_i = \frac{(LU_{it1} - LU_{it0})}{LU_i} \times \frac{1}{T} \times 100\% = P_i \times \frac{1}{T} \quad (2)$$

$$P_k = \frac{\sum_{i=1}^n |LU_{kit1} - LU_{kit0}|}{LU_{kit0}} \times 100\% \quad (3)$$

where,

i subscript represents wetland type,
 k subscript represents the sub-region,

t_0, t_1 subscript represents time of onset and end, respectively, of the time interval, T , under study,
 LU_{it0} and LU_{it1} represent the area of the i th wetland type in the study region at the start and end of the study period, respectively, and
 LU_{kit0} and LU_{kit1} represent the area of the i th wetland type in the k th sub-region at the start and end of the study period, respectively.

For assessing the discrete degree of spatial fragmentation of the wetland ecosystem, one can calculate the landscape fragmentation index and the degree of patch isolation, which can be viewed as potential influences on biodiversity. A wetland ecosystem's fragmentation index is calculated based on the landscape fragmentation formula of Wang et al. (2005, 2006a, b):

$$C_{ki} = n_{ki} / LU_{ki} \quad (4)$$

where,

n_{ki} is the area of the patch number corresponding to i th wetland type in the k th sub-region,
 C_{ki} is the fragmentation of the i th wetland type in the k th sub-region, and
 LU_{ki} is the area of i th wetland type in the k th sub-region.

The wetland's degree of patch isolation within the spatial distribution, S_{ki} , can be determined according to the method developed in landscape ecology (Wang et al. 2005, 2006a, b).

$$S_{ki} = \left(0.5 \sqrt{\frac{n_{ki}}{LU_{ki}}} \right) / (LU_{ki} / LU_k) \quad (5)$$

Relationship between climatic factors and changes in wetland area

For the Yangtze and Yellow rivers' headwaters regions, analysis of remote sensing data and historical records yielded vegetative cover distribu-

tions for the years 1967, 1986, 2000, whereas for the Zoige region cover distributions were developed for 1967, 1982, 1989, 1997, and 2004. The period of 1967 to 2004 was divided into two interpolation intervals for the headwater regions of the Yangtze and Yellow rivers (1967–1986, 1987–2000; $j = 1-2$), and four such intervals for the Zoige region (1967–1982, 1983–1987, 1988–1997, and 1997–2004; $j = 1-4$). The extent of cover provided by each of two wetland types, alpine swamp and alpine lake, was correlated against climate change parameters to obtain a relationship extending between 1967 and 2004. Regional changes in wetland area on the Qinghai–Tibetan plateau were mainly driven by population dynamics, economic policies, and their interactions (He and Zhao 2000; Wang et al. 2001). In this study, a population-based piecewise linear interpolation method was developed to simulate the dynamics of wetland area change, using a 3-year moving average as the weight of the linear interpolation:

$$LU_{it} = LU_{i,t-1} + r_{jt} \Delta LU_{ij} \quad (6)$$

where,

j is the date interval number,
 r_{jt} is the mean population growth/economic policy weighing factor at year t within the j th interval.
 ΔLU_{ij} is the difference in wetland area of the i th region between the beginning and end of the j th interval;
 $LU_{it}, LU_{i,t-1}$ are the areas of the i th wetland type in the study region, at times t and $t - 1$, respectively.

Results and discussion

Changes in the spatial distribution of alpine wetland ecosystems

A plot of the changes in the spatial distribution of wetland ecosystems in the source region of the Yangtze River between 1967 and 2000 (Fig. 2a) shows that prior to the mid-1980s, changes in the headwaters regions' wetland ecosystems, mainly limited to the northeastern portion of the region,

Fig. 2 Variation in the spatial pattern of typical alpine wetlands in the Qinghai–Tibetan plateau region

were minor. From 1989 to 2000, dramatic changes in the spatial distribution of wetland ecosystems took place, such that by the year 2000, a large area of wetlands had disappeared from the central and southeastern portions of the region. The situation was similar in the Yellow River headwaters region (Fig. 2b), where the small changes in wetland distribution were mainly limited to the northern and middle mountain regions between 1967 and 1986, whereas between 1986 and 2000, the wetland distribution changed significantly over almost the entire region. This change was particularly evident in the wetlands of Maduo county, including the region to the north where two lakes disappeared. As for the Zoige region's wetland, shifts in its spatial distribution were investigated for the period of

1989 to 2004, when no large-scale anthropogenic disturbances occurred. Shifts in wetland distribution were far smaller between 1989 and 1997 than between 1997 and 2004 period (Fig. 2c), when the loss of wetlands occurred both in the western and southern portions of the region.

Changes in spatial distribution of alpine swamp wetland

The area of alpine swamp wetlands typical of the Qinghai–Tibetan plateau and predominantly located in the Yangtze River's headwaters region, decreased by 29% ($0.93\% \text{ year}^{-1}$) between 1967 and 2000 (Table 2). Roughly 96% of this loss took place between 1986 and 2000 period, occurring

Table 2 Changes in spatial distribution characteristics of alpine wetland systems of the Qinghai–Tibetan plateau

Index		P_i			R_i			Area Km ²	P_k
		Swamp	River	Lake	Swamp	River	Lake		
Yangtze source region	1967–1986	−1.05	−0.37	−0.82	−0.06	−0.02	−0.05	−101.54	0.80
	1986–2000	−28.11	−0.33	−10.64	−1.87	−0.02	−0.71	−2159.28	17.13
	1967–2000	−28.87	−0.70	−11.37	−0.93	−0.02	−0.37	−2260.82	17.79
Yellow source region	1967–1986	−0.17	−0.44	−1.44	−0.01	−0.03	−0.08	−35.11	0.59
	1986–2000	−13.41	−9.03	−5.28	−0.89	−0.60	−0.35	−585.47	9.88
	1967–2000	−13.55	−9.43	−6.64	−0.44	−0.30	−0.21	−620.58	10.41
Zoige region	1987–1997	−2.93	−17.29	−11.55	−0.16	−0.96	−0.64	−97.53	3.51
	1997–2004	−10.46	13.27	−9.82	−1.49	1.90	−1.40	−260.38	9.72
	1987–2004	−13.08	−6.31	−20.24	−0.87	−0.42	−1.35	−357.91	12.89

at a rate of 1.87% year^{−1}. The area of swamp wetland in the Yellow River's headwaters decreased by 13.55% between 1967 and 2000 (0.44% year^{−1}, i.e. roughly half the rate of the Yangtze headwaters region), with the majority of the drop occurring between 1986 and 2000 period.

The changes in wetland distribution in the Zoige region since 1967 can be divided into two stages: the period before 1982 when the region was submitted to intense human disturbance and the period from 1982 onwards when, besides grazing, disturbance from human activities was minimal, or at worst controlled. In the earlier period (1970s), swamp wetlands were drained to increase grazing pasture, their area decreasing by about 52%, while the area of lake wetlands decreased by 80% between 1967 and 1982 (Fig. 3; Yang 1999; Wang et al. 2005). After 1982, changes in the area of wetland ecosystems were comparable to those occurring in the headwaters regions of the Yangtze and Yellow Rivers. Between 1982

and 2004 period the area of swamp wetland in the Zoige region decreased by 15.8%, split roughly 60:40 between the periods of 1997–2004 and 1982–1997, respectively (Table 2).

Changes in lake and river areas

Between 1967 and 2000, the area of wetland lakes in the Yangtze and Yellow River headwaters regions decreased by 11.4% and 6.6%, respectively, 93% and 78% of which decline occurred after 1986 (Fig. 4b). Between 1982 and 2004, the area of wetland lakes in the Zoige region decreased by 24% (0.26 km² year^{−1}), 84% of which decline occurred after 1987 (Table 2).

Within the Yangtze and Yellow River headwaters regions, losses in lake area were distinctly different between interior and exterior lakes (Fig. 4a), the latter of which accounted for 62.3% and 84.7%, respectively, of each region's total lake area (1967). Between 1967 and 2000, the area of interior and exterior lakes within the Yangtze River headwaters region decreased by 54.6 and 66.5 km², respectively, representing decreases of 13.3% and 9.8% in the respective lakes' areas. This resulted in the loss of 360 lakes or 17.5% of those existing in 1967. Between 1967 and 2000, the area of interior and exterior lakes in the Yellow River headwaters region decreased by 34.1 and 70.2 km², respectively, representing decreases of 14.2% and 5.3% in the respective lakes' areas. The loss of interior lake wetlands by areas was significantly greater than that of exterior lake wetlands. The effects of wetland variation on hydrology regimes were led to an alteration in hy-

Fig. 3 Wetland area decrease from 1967–2004 in the Zoige region Qinghai–Tibetan plateau

Fig. 4 The interior and exterior lakes' distribution **a** and changes **b** in the Yangtze and Yellow Rivers headwaters regions within the Qinghai–Tibetan plateau

drological process in alpine wetland-bearing river basins, the severer the degree of degradation of swamp wetlands, and the more significant the changes in associated hydrological processes. Under conditions of an evident increase in precipitation during the January–February drought period, the Qinghai–Tibetan plateau's alpine wetland ecosystems runoff for the same period showed a decreasing trend.

The area of river wetlands in the Yangtze River headwaters region decreased by only 0.7% over

the period of 1967–2000, while that of the Zoige region showed no clear trend (Table 2, Fig. 3). The situation was quite different in the Yellow River headwaters region, where the area of river wetlands decreased continuously between 1967 and 2000, reaching a total decline of 9.4% or 180.6 km², which exceeded that of lake wetlands for the region.

Changes in spatial patterns of wetland ecosystems

Swamp wetlands' fragmentation and patch isolation indexes were greatest for the Yellow River headwaters region and least for the Zoige region, indicating such wetlands' distribution to be relatively concentrated in the Zoige region and relatively scattered in the Yellow River headwaters region (Table 3). For lake wetlands, the fragmentation index was greatest for the Yangtze River headwaters region, and patch isolation greatest in the Zoige region, indicating that in the former case wetland lakes were well scattered in small lake groups, while in the latter case they consisted of a few widely scattered large lakes. In the Yellow River headwaters region, wetland lakes were closely spaced and relatively concentrated. Such a distribution pattern occurring for the Yellow River headwaters' swamp wetlands and Yangtze River headwater's lake wetlands rendered them more sensitive and fragile to disturbance by environmental changes.

The level of patch isolation for the Yellow River headwaters and Zoige regions' alpine swamps increased continuously from 1967 onwards, particularly after the mid-1980s (Table 3). The trend in lake wetlands was towards large lakes, especially after the mid-1980s when many scattered small lakes dried up or disappeared; therefore, lake wetlands' levels of fragmentation

Table 3 Indexes of spatial pattern changes for typical alpine wetlands of the Qinghai–Tibetan plateau

Parameter/wetland type		Region/Year								
		Yangtze headwaters			Yellow headwaters			Zoige region		
		1967	1986	2000	1967	1986	2000	1987	1997	2004
Fragmentation	Swamp	0.15	0.15	0.11	0.86	0.87	0.94	0.10	0.11	0.15
	Lake	1.89	1.91	1.76	0.52	0.52	0.32	0.49	0.45	0.45
Patch isolation	Swamp	0.25	0.25	0.23	0.72	0.72	0.76	0.16	0.17	0.2
	Lake	2.35	2.37	2.18	0.70	0.71	0.54	3.88	3.90	3.87

and patch isolation tended to decrease. Unlike the changes in these regions, swamp and lake ecosystems in the Yangtze River headwaters region showed decreases in both fragmentation index and patch isolation index, suggesting that the degradation of wetlands led to the disappearance of some small scattered lakes.

In summary, (1) while, from 1967–2004, the Qinghai–Tibetan plateau witnessed the degradation of alpine wetland ecosystems, close to two thirds of this degradation occurred after 1985, when the rate of degradation began to climb, (2) the degradation of alpine wetland ecosystems was dominated by that of alpine swamps, which accounted for 93%, 54%, and 97% of the total decrease in wetland area in the Yangtze River headwaters, Yellow River headwaters, and in the Zoige region, respectively. The dwindling of interior wetland lakes was severest in the Yangtze and Yellow River headwaters regions, (3) the degradation of wetland ecosystems led to changes in their pattern of spatial distribution. In the Yellow River headwaters and Zoige regions, the extent of fragmentation and patch isolation of swamp wetland increased continuously, whereas in the Yangtze River headwaters region, wetland ecosystem degradation manifested itself in the disappearance of scattered small wetland patches and the spatial concentration of wetland ecosystems.

Correlations between wetland degradation and climate variables

Alpine wetland ecosystems are sensitive to climate change. To explore the correlation between wetland area and climate change, the climate variables of the mean annual air temperature, annual precipitation, mean air temperature, and precipitation during the growing season (April–Sept.) were selected.

In the Yangtze River headwaters region, wetland area correlated strongly with growing season air temperature ($R = 0.73$, $P \leq 0.001$; Fig. 5a) and relatively weakly with mean annual air temperature ($R = 0.43$, $P = 0.044$). In contrast, wetland area was more weakly correlated with annual precipitation ($R = 0.25$, $P = 0.38$) and mean

Fig. 5 Correlative relationships between alpine wetland area and climate variables

growing season precipitation ($R = 0.32$, $P = 0.19$). In the Yellow river headwaters region, wetland area closely correlated with growing season air temperature ($R = 0.67$, $P < 0.001$; Fig. 5b) and to a lesser extent with mean annual air temperature ($R = 0.47$, $P = 0.021$). Wetland area was more weakly correlated with annual precipitation ($R = 0.21$, $P = 0.48$) and mean growing season precipitation ($R = 0.30$, $P = 0.23$). For the Zoige region, wetland area was strongly correlated with both growing season air temperature ($R = 0.82$, $P < 0.001$) and the mean annual air temperature ($R = 0.71$, $P < 0.001$; Fig. 5c), but no significant correlation occurred with precipitation. However, the nature of the relationship between the area of alpine wetlands and air temperature differed according to region: in the Yangtze and Yellow River headwaters regions, the relationship was

quadratic, while it was linear for the Zoige region (Fig. 5).

These strong wetland area–air temperature relationships demonstrate that the Qinghai–Tibetan plateau’s alpine wetlands were strongly influenced by air temperature changes, particularly during the vegetation’s growing season. Alpine wetland degradation (loss of area) was strongly linked to the rise in growing season air temperature over the past 40 years. The fact that the degree of inverse correlation between alpine wetland area and air temperature in the Yangtze and Yellow Rivers headwaters regions was less than that in the Zoige region suggests that the permafrost present in the former regions, but largely absent in the latter, had a great influence on the growth and development of alpine swamp and meadow ecosystems (Zhao et al. 2000; Wang et al. 2006a, b). The permafrost layer can effectively prevent surface water and soil water from downward seepage, leading to greater root zone soil moisture. Numerous observations and studies (Wang et al. 2006a, b; Zhou 2001; Zhao et al. 2000) showed that there is a significant statistical correlation between vegetative cover and thickness of the active soil layer of permafrost in alpine meadow and alpine swamp meadow ecosystems. As the thickness of the active layer increases, the vegetative cover of alpine swamp (including alpine meadows) decreases. Over the last 30 years, the warming climate has raised the temperature of the upper 0–0.40-m layer of the Qinghai–Tibetan plateau’s permafrost soils by 0.2–0.3°C, on average (Wang 1998; Wu et al. 2001). Raising of the topsoil’s temperature has expanded the thawed soil area, thickened the seasonal thawing layer, or even led to complete disappearance of permafrost (Zhao et al. 2000; Wang et al. 2001). This degradation of the permafrost has, in turn, significantly impacted alpine wetland ecosystems in the Yangtze and Yellow River headwaters regions.

Conclusion and discussion

Degradation of alpine wetlands in the Qinghai–Tibetan plateau has progressed since the 1960s to become a widespread phenomenon. Since the 1960s, wetlands area had decreased by over 10%,

particularly swamp wetland in the Yangtze River headwaters region, which declined by 18% between 1986 and 2000. Degradation of alpine wetland ecosystems in the Yellow River headwaters and Zoige regions led to fragmentation in their spatial distribution and a continuous increase their degree of patch isolation, resulting in their greater sensitivity and fragility in the face of climate-change-induced disturbances. The fragmentation and isolation of habitats poses a severe and potential threat to the biodiversity of the alpine wetland.

The widespread degradation of the alpine wetland system on the Qinghai–Tibetan plateau is closely linked to regional climate warming. Between 1960 and 2000, the region’s mean annual air temperature rose by 0.19–0.23°C decade^{−1} and after 1982 by 0.46–0.53°C decade^{−1}; however, over the latter period, the precipitation was stable or increased only slightly. Given the presence of permafrost in the Yangtze River headwaters region, the temperature increase and corresponding permafrost changes had a synergetic degrading influence on alpine wetland ecosystems.

Changes in alpine wetland’s hydrological functionality directly led to an alteration in hydrological process in alpine wetland-bearing river basins. The greater a basin’s wetland ratio, the severer the degree of degradation of swamp wetlands, and the more significant the changes in associated hydrological processes. The impacts of alpine wetland systems’ degradation on the runoff from the Yangtze and Yellow rivers are the key science issue required to deeper research in future.

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