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Changing inland lakes responding to climate warming in Northeastern Tibetan Plateau

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Abstract The main portion of Tibetan Plateau has experienced statistically significant warming over the past 50 years, especially in cold seasons. This paper aims to identify and characterize the dynamics of inland lakes that located in the hinterland of Tibetan Plateau responding to climate change. We compared satellite imageries in late 1970s and early 1990s with recent to inventory and track changes in lakes after three decades of rising temperatures in the region. It showed warm and dry trend in climate with significant accelerated increasing annual mean temperature over the last 30 years, however, decreasing periodically annual precipitation and no obvious trend in potential evapotranspiration during the same period. Our analysis indicated widespread declines in inland lake's abundance and area in the whole origin of the Yellow River and southeastern origin of the Yangtze River. In contrast, the western and northern origin of the Yangtze River revealed completely reverse change. The regional lake surface area decreased by 11,499 ha or 1.72% from the late 1970s to the early 1990s, and increased by 6,866 ha or 1.04% from the early 1990s to 2004. Shrinking inland lakes may become a common feature in the discontinuous permafrost regions as a consequence of warming climate and thawing permafrost. Furthermore, obvious expanding were found in continuous permafrost regions due to climate warming and glacier retreating. The results may provide information for the scientific recognition of the responding events to the climate change recorded by the inland lakes.

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1 Introduction

The ecosystem in regions with higher elevation such as Tibetan Plateau, similar to the poles area with high latitudes, is more sensitive to global change (Sun and Zheng 1998; Feng et al. 1998; Zheng and Li 1999; Liu and Chen 2000; Yao et al. 2000). It could be used as a detection tool or a monitor for global warming (Giorgi et al. 1997; Liu and Chen 2000). The global average surface temperature has increased by $0.76 \pm 0.19°C$ over the last 100 years especially since about 1950, accompanied by increased average atmospheric water vapour content, wide spread reduced sunshine duration, and increased global land precipitation by about 2% (Jones and Hulme 1996; Hulme et al. 1998; Stanhill and Cohen 2001; IPCC 2007). The main portion of Tibetan Plateau especially the River Source Region has experienced statistically significant warming since the mid-1950s especially in cold seasons (Chen et al. 1991; Kang 1996; Liu and Chen 2000; Wang and Cheng 2000; Zhao et al. 2004; Feng et al. 2006), driving an array of complex physical, chemical and ecological changes in this region. Ice cores or tree-ring reconstructed climate of the Tibetan Plateau reflected this significant warming trend and drought stress (Thompson et al. 1993; Yao et al. 1994), which also related to retreats of most mountain glaciers (Oerlemans 1994; Ding 1996; Ding and Bing 1996; Pu et al. 1998; Su et al. 1999; Yang et al. 2003).

An orderly succession of hydrologic changes associated with climate warming are through changes in ground temperatures, precipitation, evaporation and runoffs in cold and arid regions (Kane et al. 1991; Lai and Ye 1991; Hinzman et al. 1991; Lai 1996; Cheng et al. 1997; Wang and Cheng 1999; Jin et al. 2000; Morison et al. 2000; Zhao et al. 2004), which includes drying up of wetlands (Ji 1996; Wang and Cheng 2000; Feng et al. 2006), increasing annual snow cover (Zwally et al. 1989; Robinson and Dewey 1990; Morgan et al. 1991; Ke et al. 1997; Li 1996, 1999; Ke and Li 1998; Gao et al. 2003), thawing of permafrost (Haeberli et al. 1993; Wang 1998; Li and Cheng 1999; Jin et al. 2000; Zhang et al. 2004a, b; Li et al. 2005), earlier spring river and lake ice break-up (Zhao et al. 2004; IPCC 2007), lowering of the regional groundwater table (Feng et al. 2006; Peng et al. 2006), disconnecting river (Tian 1990; Liu 1996; Xi 1997; Yang 1997) and shrinking lakes (Shi 1990; Wang et al. 1995; Qin 1999; Wu et al. 2001, 2008; Guo et al. 2003; Yoshikawa and Hinzman 2003; Bian et al. 2006; Ding et al. 2006; Riordan et al. 2006; Shao et al. 2007; Li et al. 2008; Ma et al. 2008; Niu et al. 2008).

Permafrost together with its water-heat processes are primary driving forces for ecosystem change in permafrost area next only to climate factors (Yoshikawa and Hinzman 2003; Wu et al. 2003). Widely dispersed permafrost has an important role for the regional water circulation system in the Tibetan Plateau especially the River Source Region. The permafrost degradation is occurring worldwide such as Alaska and Canada, Mongolia, Russia and China (Ding 1998; Yoshikawa and Hinzman 2003), and characterized by expanding thawed area, shortage of frozen duration, thickening seasonal thawing layer, increasing and expanding of taliks, deepening in thaw depths, vertical disconnection in unstable permafrost, disconnecting and even led to the entire disappearance (Zhao 1996; Wang 1998; Jin et al. 2000; Zhao et al. 2004). The degradation resulted to variations of ecological and hydrologic processes, such as decreased soil moisture in the root zone, increased surface temperature, intensified evapotranspiration, lowered water table, downwards of karst springs, dried up swamps, changed soil structure and composition, reduced water resources, decreased summer peak flows, disappeared lakes, etc. (Ji 1996; Cheng and Wang 1998; Wang 1998; Wang and Cheng 2000; Yoshikawa and Hinzman 2003; Zhang et al. 2004a, b; Peng et al. 2006). Numerous observations have shown that the ground temperature in the upper layer (0∼20 m) of the frozen soil on the Tibetan Plateau risen by 0.2∼0.3°C on average especially since the 1970s (Zhao 1996; Cheng et al. 1997; Li and Cheng 1999; Jin et al. 2000; Feng et al. 2006). Sallow soil temperature in permafrost area of River Source Region increased remarkably from 1980s to 1990s, with about 0.3∼0.7°C in the patchy permafrost zone of the southeastern origin of the Yangtze River and 0.4∼0.6°C in the seasonally frozen area of the northern origin of the Yellow River (Yang et al. 2004).

The inland lakes are sensitive to climate change, in the hydrological system consists of glacier, ice, lake, and river in cold and arid regions. Its disappearance, expansion and shrinkage are the synthetically consequences of water balance and thermal dynamics (Benson and Paillet 1989; Shi 1990; Riordan et al. 2006; Bian et al. 2006; Ding et al. 2006). Lakes in Tibetan Plateau under natural conditions with less human activities are capable of responding climate change factually. Several studies on the relationship between lake dynamics and climate change (Wang et al. 1995; Shi and Zhang 1995; Ding and Liu 1995; Qin 1999; Wu et al. 2001; Hu et al. 2002; Guo et al. 2003; Ma et al. 2003; Sun et al. 2005). Whereas, most focus on single lake or lake comparisons for narrow information, and lack of understanding the interdecadal variations in time-scales, regional variations in spatial-scales and change mechanism (Ding et al. 2006).

Changing surface area of lake may be consequences of warming climate, thawing permafrost, retreating glaciers and uplifting process (Shi et al. 2002; Hu et al. 2006). Some lakes have shown inward-flow and salinization phenomena with a decreasing water surface, and others shown expansion. It has been concluded that the major mechanism for drying water bodies in no-permafrost zone was decreased water balance in a warming climate (Klein et al. 2005). The shrunk and split of Gyaring Hu, Ngoring Hu, Xinxinhai, Xinsuhai, Duogcuorengiang, Mitijiangmuco, Rumchanco and Wupuemoco Lake in the Tibetan Plateau could be applied to validate the mechanism (Guo et al. 2003; Bian et al. 2006; Shao et al. 2007; Li et al. 2008; Wu et al. 2008; Niu et al. 2008). There also observed a spatially patchy process related to permafrost distribution rather than a direct climatic mechanism such as increased evaporation. Numerous studies have described increasing of total lake surface area and abundance in continuous permafrost environments, and a contrasting decrease in regions of discontinuous, sporadic, and isolated permafrost. In the contrary, climate change especially precipitation and temperature are major mechanism for water-level rise such as Aydin Lake, Sayram Lake, Manas Lake in Sinkiang, China (Yang et al. 1996; Hu et al. 2002; Ma et al. 2003, 2008) and Nam Co, Serling Co, Tong Co, Shin Co, Lonbasa Lake and glacial lakes in the Pumqu Basin of Tibet (Lu et al. 2005; Chen et al. 2005). And, Yoshikawa and Hinzman (2003) found the major mechanism for shrinking lake in the permafrost-dominated area was formation of taliks allowing internal drainage through the permafrost. It is difficult to determine the dominant driving mechanism behind the observed patterns of shrinking lakes in origin of the Yellow River and the expanding lakes in the origin of the Yangtze River since the 1970s, which may due to permafrost thawing, evapotranspiration and precipitation increasing, and glacier melting.

In this paper, as a typical representative of Tibetan Plateau, we compared satellite imageries in the late 1970s, early 1990s and recent to investigate the landscape-level change and spatial-temporal variations of inland lakes associated with recent climate warming in the River Source Region, which is regarded as the water tower of China and contains the largest marshland in the world. The lakes in the origin of the Yellow River and the Yangtze River were examined to determine how recent changes in climate have impacted their development or degradation. The objective of this research is to improve the understanding of the response characters and change mechanisms of lakes in Tibetan Plateau, and the role that climate change and permafrost degradation plays in affecting the surface water balance at regional scale in cold and arid region.

2 Materials and methods

2.1 Study area

The River Source Region (Fig. 1) is located in the hinterland of the Tibetan Plateau and southern of Qinghai Province, China. Glaciers, permafrost and snows are widespread here owing to its average elevation of more than 4,000 m, annual temperature of −5.6°C to −3.8°C, and annual precipitation between 262.2∼772.8 mm from west to southeast (BARE-RSR 2007). The average potential evapotranspiration appears to be in contrast to a predicted increased hydrological cycle under global warming scenarios and reduced by 13.1 mm/decade during 1961–2000 (Thomas 2000; Li et al. 2000; Chen et al. 2006). In the River Source Region, the climate regimes switched from a predominantly cold and dry to warm and dry (Shi et al. 2002; Wei et al. 2003; Wu et al. 2005; Ma and Hu 2005; Zhang et al. 2006; BARE-RSR 2007). Harsh and cold permafrost zone formed the peculiar hydrological processes, cryosols structure, fragile and sensitive environment. From a geomorphological point of view, with the Tangula Mountains, Kunlun Mountains, Bayan Har Mountains and Anyemaqen Mountains form as the outer rim, which tectonically among river valleys, mountain summits, down faulted high plains and flat wide-valley shoals, from where several major rivers such as the Yangtze River, the Yellow River and the Lancang River originate. Total number of lakes in River Source Region is 16,543, in which 11,037 locates in the source region of the Yangtze River and cover 2354.25 km^2, and 5,300 in the source region of the Yellow River and account for 1270.77 km^2 (The Editorial Board of the Sanjiangyuan Natural Reserve 2002).

2.2 Permafrost evidences

Permafrost distributed in the River Source Region can be classified into predominantly continuous permafrost, predominantly continuous and island permafrost, middle-thick seasonally frozen ground, mountain permafrost, thin seasonally frozen ground and short time frozen ground (Fig. 1). Literature reviews on permafrost in Tibetan Plateau showed obvious degradation as following:

Xidatan (35°43′ N, 94°11′ E) at the elevation of 4480-m along the Qinghai–Tibet Highway (QTH) is located in the island permafrost zone near the northern lower limit of permafrost distribution on the Tibetan Plateau (Fig. 1). The first observation

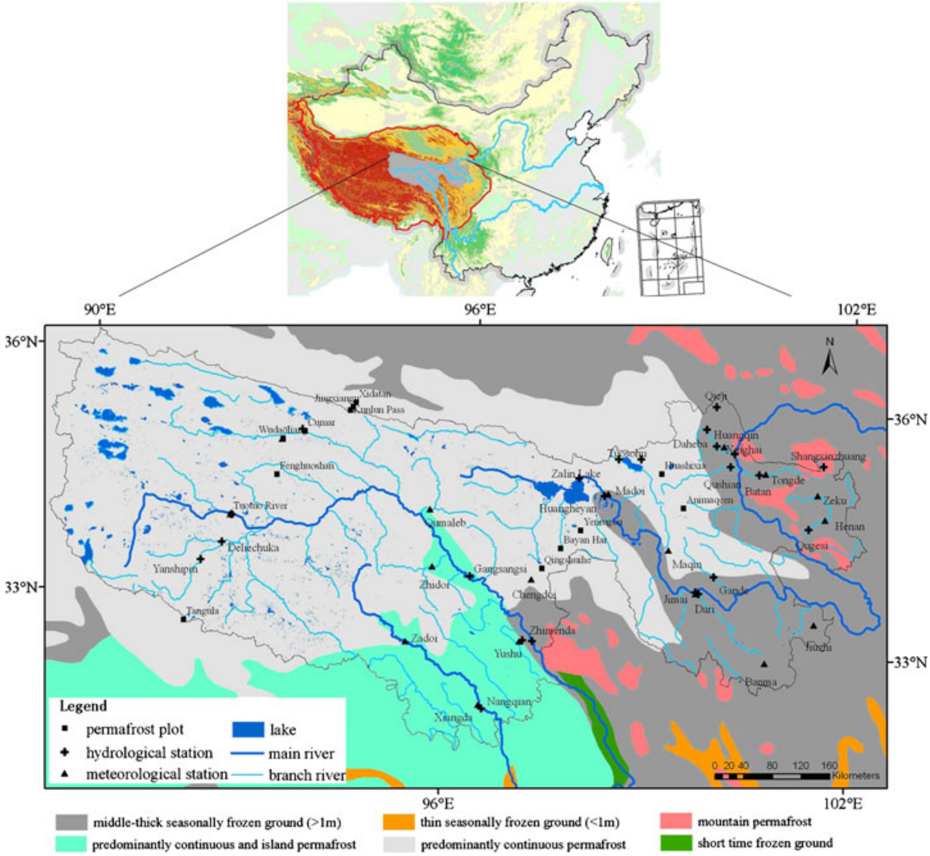


Fig. 1 The study area, station distribution, permafrost plots and distribution. The *black and blue line* presents respectively the boundary of the Tibetan Plateau and the rivers, and *blue surface* for the lakes. Meteorological stations marked with *triangle*, *crisscross* for hydrological stations and *square* for permafrost surveying plots

site is set on the first terrace of a brook, where the soils consist of fluvial sands and gravel, which surface is dry and barren vegetation. Permafrost has been degraded upwards. The maximum seasonal thaw depth at this position varies from 2.0 to 2.6 m. Drilling indicated a 4∼5 m rising of the permafrost bottom from 1983 to 1993. At the second site (4428 m) located 1 km distance from the first site at the direction of southeast, permafrost degraded both upward and downward rapidly, even disappeared. Drilling and temperature readings suggested a vertical decay of permafrost (at least 4 m) from 1975 to 1989 (Jin et al. 2000).

Jing Xiangu is also located at the northern lower limit along the QTH. The bottom of permafrost has risen about 10∼15 m in the past 20 years (Jin et al. 2000; Wang 1993).

Kunlun Pass is located at elevation of 4700 m, which is underlain by fluvial gravel and lacustrine sediments. Ground temperatures at a borehole increased by 0.2–0.4°C at depths of 6∼15 m in the past 15 years (from 1982 to 1997). The thaw depth reaches its maximum of 1.3∼1.4 m in summer (Jin et al. 2000).

At Borehole CK2956 on the Cumar High Plateau, ground temperatures have increased by about 0.3∼0.4°C at depths of 5∼10 m and 0.1∼0.3°C at depths of 12∼14 m (Jin et al. 2000).

The ground temperatures at depths of 15∼35 m at the Fenghuo Mountains have increased by 0.2∼0.3°C during the past 35 years (Jin et al. 2000; Wang 1993). Thawed nuclei have been detected widely at Anyemaqen Mountains, Qingshuihe and Huashixia along National Highway No.214 in Eastern Tibetan Plateau, indicating a vertical disconnection in unstable permafrost (Jin et al. 2000).

The exploration survey at the lakeshore of Xinxinhai and alluvial fan of Yeniugou pediment in 1991 showed that both had buried frozen-ground, but disappeared during the in-situ survey in 1998, which indicated the obvious permafrost degradation (Zhang et al. 2004a, b).

The lower bound of permafrost on the south slop of Bayan Har Mountains moves upward (about 70 m), and the borehole at Kailailonggeng on the north slop with altitude of 4,498 m do not found permafrost (Zhang et al. 2004a, b; Peng et al. 2006).

2.3 Remote sensing imagery

We had a time series of spatially aligned images including Landsat TM, ETM+ and MSS for whole River Source Region from the late 1970s, early 1990s to present. Images were used to investigate the water surface changes and to classify the landscapes according to the land-forming processes. Each image was collected during similar precipitation conditions in summer and autumn (June to September) except four based on weather records (Table 1). Clouds and cloud shadows covering the Earth's surface were major limitations in acquiring useful satellite imagery in summer months at high latitude area. Our selection of study regions in River Source Region was constrained by the availability of cloud-free satellite imagery. We abandoned automated spectral approaches commonly used in digital image processing to avoid the confusion with other bright targets such as meadows and cloud shadows and the differences in water quality. Vegetation cover on the lake surface is one of the problems for threshold in the image analyses. Some of the lake may still support the same water level, but appear different due to emergent vegetation cover.

To begin with, remote sensing images were geometrically corrected and georeferenced by using 1:50,000 or 1:100,000 relief maps. For each TM/ETM scene (showed as a combination of band 432 RGB), there are at least 20 evenly distributed sites served as Ground Control Points. The Root Mean Squared Error of geometric rectification was less than 0.5 pixels or 15 m for TM/ETM and 0.5 pixels or 40 m for MSS. The statewide coverage of relief maps and aerial photos depicted in 1970s were applied to relatively accuracy lake recognition from MSS in 1970s to avoid the spatial resolution difference. And then, image matching was applied through ENVI 4.0 to address the spectral band difference between MSS and TM. The threshold boundary of lake in 2004 was manually distinguished firstly at a spatial scale of 1:100,000 by visual interpretation and digitalization with technical support from Intergraph modular of Arc GIS 9.0 software. Interpreters identify the lakes on the computer screen and drew the boundaries, according to the understanding on the lake's texture, color, structure and other expert's information. Then, lake change patches in 1970s

Table 1 The total precipitation of ten days before the acquisition date

Row-column		1970s		1990s		2004		Station
MSS	TM/ETM+	Acquisition date	Prep. (mm)	Acquisition date	Prep. (mm)	Acquisition date	Prep. (mm)	
141036	131036	1977-07-14	40.9	1990-07-08	41.3	2003-09-14	35.1	Henan
142035	132035	1977-07-15	38.3	1990-07-15	27.4	2005-09-10	–	Zeku
142036	132036	1977-07-15	38.3	1991-07-18	21.6	2005-09-10	–	Henan
142037	132037	1977-06-09	19.7	1991-09-04	27.8	2004-08-06	23.8	Banma
143035	133035	1977-07-16	14.6	1992-08-28	17.6	2005-06-29	–	Xinghai
143036	133036	1977-07-16	19.6	1990-07-06	27	2004-09-14	18	Maqin
143037	133037	1977-07-16	30.9	1990-07-06	35.3	2004-09-14	21.3	Dari
144035	134035	1977-06-29	20.6	1990-08-30	28	2005-08-23	–	Madoi
144036	134036	1977-08-22	39.4	1990-08-30	28	2003-07-17	35.2	Madoi
144037	134037	1977-08-04	24.7	1992-08-03	36.9	2003-07-17	35.2	Yushu
144038	134038	1977-08-04	27.9	1992-08-03	24.8	2005-09-08	–	Nangqian
145035	135035	1977-06-30	19.9	1990-08-21	24.8	2004-07-10	29.4	Qumarleeb
145036	135036	1977-08-05	37.6	1990-08-21	24.8	2003-09-10	23.4	Qumarleeb
145037	135037	1977-08-05	27.5	1992-08-26	30.5	2004-07-10	24.5	Zadoi
145038	135038	1977-08-05	27.5	1992-08-10	27	2003-07-24	17.4	Nangqian
146035	136035	1977-06-06	12	1990-08-28	13.8	2004-07-17	14.2	Qumarleeb
146036	136036	1977-09-11	19.6	1990-08-28	13.8	2004-07-17	14.2	Qumarleeb
146037	136037	1977-09-11	18.7	1992-09-02	19.6	2003-12-22	10	Zadoi
147035	137035	1977-05-20	0.97	1990-09-04	2.61	2003-10-10	0.2	Wudaoliang
147036	137036	1977-07-02	0.35	1990-09-04	2.61	2003-10-10	0.2	Wudaoliang
147037	137037	1977-07-02	3.5	1990-07-02	1.5	2005-06-25	0	Tuotuo River
148035	138035	1977-07-03	3.5	1991-09-14	8.3	2004-08-16	5.46	Wudaoliang
148036	138036	1977-07-03	3.5	1992-08-15	3.13	2004-08-16	5.46	Tuotuo River
148037	138037	1977-07-03	3.5	1992-08-31	7.9	2002-06-24	3.55	Tuotuo River
149035	139035	1976-11-30	0	1990-08-17	1.58	2003-09-22	0.95	Wudaoliang
149036	139036	1973-07-16	1.9	1991-09-05	3	2003-09-22	0.95	Tuotuo River
149037	139037	1973-06-10	0.69	1990-05-29	1.08	2003-09-22	0.95	Tuotuo River
150035	140035	1973-06-29	2.5	1991-09-12	0	2004-09-15	0.34	Tuotuo River

and 1990s were depicted by comparing the images from 1970s and 1990s with those in 2004, which can be considered as real change instead of classification errors and the small location shift.

2.4 Meteorological data

The River Source Region has few national and local stations with weather records spanning 1960s to present, and therefore some stations used in the study are located hundreds of kilometers from the permafrost research plots and the lake observation area. For the closest long-term meteorological station, we obtained daily data sets of 13 national stations, including daily maximum and minimum air temperature, air pressure, daily total water equivalent precipitation, relative humidity, snow depth and evaporation from China Meteorological Bureau.

Evaporation shows the degree of water consumption, and the moisture index comprehensively consideration of precipitation and evaporation presents the advantage to reflect the dry and humidity conditions. The moisture index equals to the ratio of annual precipitation and annual potential evapotranspiration (PET). For each meteorological station, we estimated annual potential evapotranspiration and moisture index using ground meteorological measurement and DEM as input data, applying improved Penman-Monteith and Thornthwaite Moisture Index to fusion processes, then to estimated water balance of this region for each year. The improved Penman-Monteith recommended by FAO in 1998 present the PET and Thornthwaite Moisture Index as follows:

$$\mathrm{PET} = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34 u_2\right)} \tag{1}$$

$$I_m = 100\% \times \left(\frac{\text{precipitation}}{\mathrm{PET}} - 1\right) \tag{2}$$

Where, PET is the potential evapotranspiration (mm day^{-1}), R_n is canopy net radiation (MJ m^{-2} day^{-1}), G is soil heat fluxes (MJ m^{-2} day^{-1}), T is the air temperature at standard 2 m height (°C), u_2 is the wind velocity at 2 m height (m s^{-1}), e_s and e_a are saturation vapor pressure and actual water vapor pressure respectively (kPa), Δ is curve slope of saturation vapor pressure (kPa °C^{-1}), γ is constant of psychrometer (kPa °C^{-1}), and I_m is the Moisture Index (BARE-RSR 2007).

2.5 Hydrological data

In the River Source Region, several series of daily means of runoff are available since 1959. Unfortunately, measurements have been interrupted and most of the stations were abandoned except main hydrological control station. Therefore, the daily runoff data from the primary control stations (Fig. 1) of the Yellow River (Jimai station) and the Yangtze River (Tuotuo River station) were averaged and applied to analyze the variations of annual mean runoff from 1970 to 2004.

3 Results

3.1 Climate change analysis since the late 1970s

From 1970s to 1990s (Fig. 2), annual mean temperature of Wudaoliang (−0.004°C/a), Tuotuo River (−0.036°C/a) and Dari (−0.091°C/a) showed slightly decreasing trends and another four stations that close to main lake area increased obviously. The precipitation, except for Tuotuo River, almost presented as linear increasing trends. The annual PETs for seven stations close to main lake area were decreased significantly except Zadoi. And the Moisture indexes were primarily decreased, except Qingshuihe and Zadoi.

From 1990s to 2004 (Fig. 2), annual mean temperature of the seven stations were all increased rapidly. The precipitation of Wudaoliang, Tuotuo River, Zadoi and Qumarleeb showed increasing trends. The annual PETs for six stations were increased, except the slightly decreasing of Zadoi. And the Moisture indexes of Madoi, Qingshuihe and Dari were decreased.

During the last 30 years (Table 2, Fig. 2), we found a significant linear increasing trends in annual mean temperature for the seven weather stations close to main lake

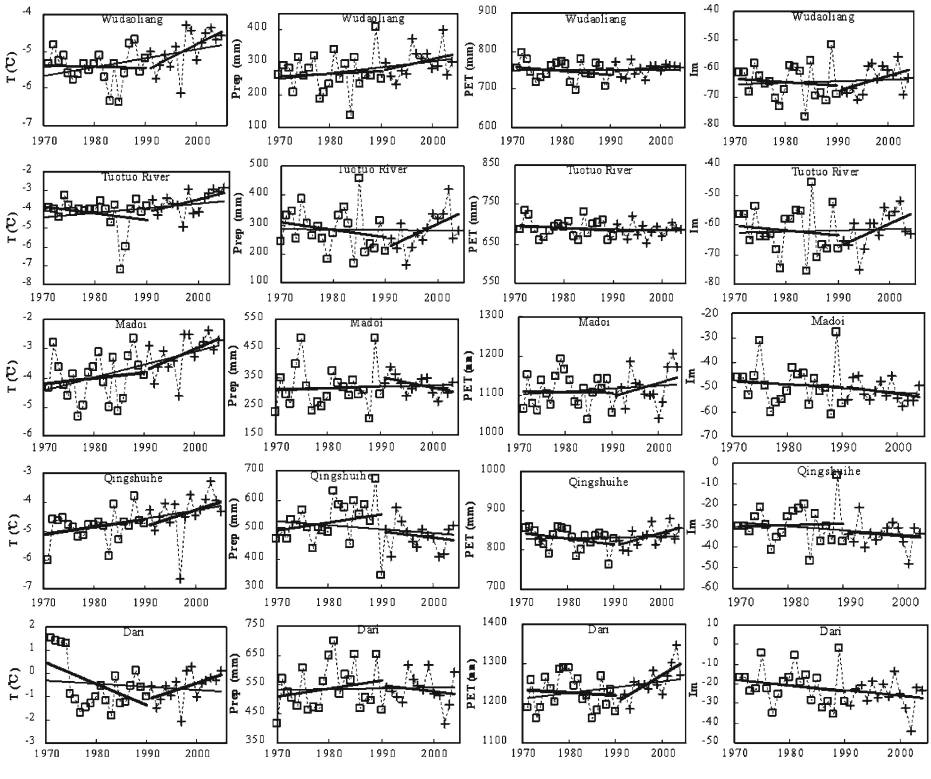


Fig. 2 Annual mean temperature (°C), annual total precipitation (mm), annual mean PET (mm) and moisture index for the seven long-term, national weather stations close to lake area in the origin of the Yellow River, the Yangtze River and River Source Region

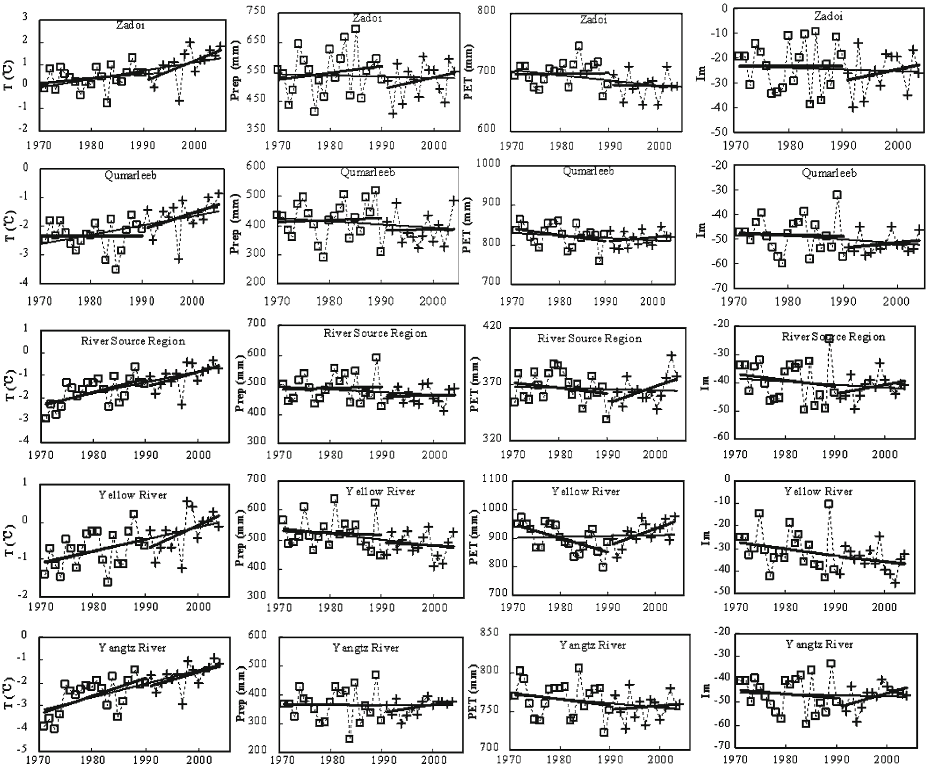


Fig. 2 (continued)

area, except for Dari. There were no obvious trends for annual total precipitation and annual total PET at these stations. Moisture index had a consistently negative trend for all stations except Wu Daoliang and Tuotuo River.

The variable trends of hydrothermal could be defined as warm and wet, warm and dry, cold and wet, cold and dry according to the variation of temperature and precipitation. Therefore, the Synthetic variation of water and heat condition

Table 2 Linear temporal trends in annual mean temperature (T, °C), annual total precipitation (Prep, mm), annual potential evapotranspiration (PET, mm) and mean Moisture index (Im) based on the seven long-term China Central Meteorological Station which close to lake area in study region

Station	T, °C		Prep, mm		PET, mm		Im	
	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2
Wu Daoliang (1969–2004)	0.024	0.218	1.835	0.114	0.201	0.059	0.099	0.121
Qumarleeb (1969–2004)	0.033	0.293	−1.132	0.036	−0.648	0.302	−0.152	0.321
Madoi (1960–2004)	0.045	0.300	0.909	0.038	0.753	0.029	−0.171	0.288
Tuotuo River (1960–2004)	0.025	0.091	−0.046	0.091	−0.380	0.155	0.04	0.057
Zadoi (1960–2004)	0.037	0.339	−0.718	0.070	−0.976	0.389	−0.066	0.018
Qingshuihe (1960–2004)	0.029	0.208	−2.082	0.291	0.297	0.048	−0.2044	0.362
Dari (1969–2004)	−0.015	0.028	0.243	0.013	1.487	0.118	−0.272	0.396

in study area during 1970s~1990s and 1990s~2004 were obtained through the tilt rate calculations of average temperature and annual total precipitation (Table 3). The stations in source origin of the Yellow River especially Madoi, as well as the Yushu and Chengdoi in the southeastern origin of the Yangtze River, presented as warm and dry both during 1970s–1990s and 1990s–2004,. However, stations in other regions of origin Yangtze River like Qumarleeb, Zadoi and Wu Daoliang, always showed warm and wet.

Generally, the Moisture Index of River Source Region during 1988~2004 were showed low levels, mainly ranging from −83 to 11, which higher in the southeastern and lower in northwestern part of study area (Fig. 3a). From the view of standard deviation in Moisture Index variation, the southeastern part was also the region with great changes. However, areas centered on Qumarleeb showed less variation (Fig. 3b).

Analysis of meteorological data from thirteen stations of River Source Region indicated warm and dry, warm and wet trends from west to east. The central Qumarleeb, eastern Zadoi and Nangqian were the ‘water divide’, with western part tended to be moist and eastern part tended to be dry. Over the last 30 years, annual average temperature in River Source Region (Fig. 2) showed accelerate increasing trend, with tendency rate of 0.33°C/10a ($R^2 = 0.485$), which were obvious in winter. Annual precipitation decreased at a rate of 13.879 mm/10a ($R^2 = 0.049$), which showed less in 1970s and 1990s, and more in 1980s. We can see that the periodicity characters of precipitation in River Source Region, presented as short at southern part (2~3 years), middle at central (5~6 years) and long at northeastern part (>7 years). PET decreased at a rate of 0.873 mm/10a. But the long-term trends do not show obvious differences that likely to cause drying of the lake. All three periods (1970s, 1990s and 2004) had similar rain and snowfall in previous winters. For the source region of Yellow River, the temperature (0.33°C/10a) and PET (3.05 mm/10a) were increased, the precipitation decreased (−19.477 mm/10a) and moisture index showed warm and dry. For the source region of the Yangtze River, the temperature (0.582°C/10a) was increased, the precipitation (−0.36 mm/10a) and PET (−5.46 mm/10a) were decreased, and moisture index showed warm and wet.

3.2 Changing inland lakes compared in 1970s with 1990s and 2004

Our analysis revealed interesting spatial heterogeneous patterns of changing lakes and apparent discrepancies between these opposing sets of observations within River

Table 3 Synthetic variable trends of temperature and precipitation for all weather stations in River Source Region during 1970s, 1990s and 2004

Station	1970s–1990s	1990s–2004	Station	1970s–1990s	1990s–2004
Source region of the Yellow River			Source region of the Yangtze River		
Xinghai	Warm and wet	Warm and dry	Qumarleeb	Warm and wet	Warm and wet
Henan	Cold and dry	Warm and wet	Zadoi	Warm and wet	Warm and wet
Jiuzhi	Warm and dry	Warm and wet	Wu Daoliang	Warm and wet	Warm and wet
Banma	Warm and dry	Warm and dry	Tuotuo River	Cold and dry	Warm and wet
Dari	Warm and dry	Warm and wet	Nangqian	Warm and wet	Warm and dry
Madoi	Warm and dry	Warm and dry	Yushu	Warm and dry	Warm and dry
			Chengdoi	Warm and wet	Warm and dry

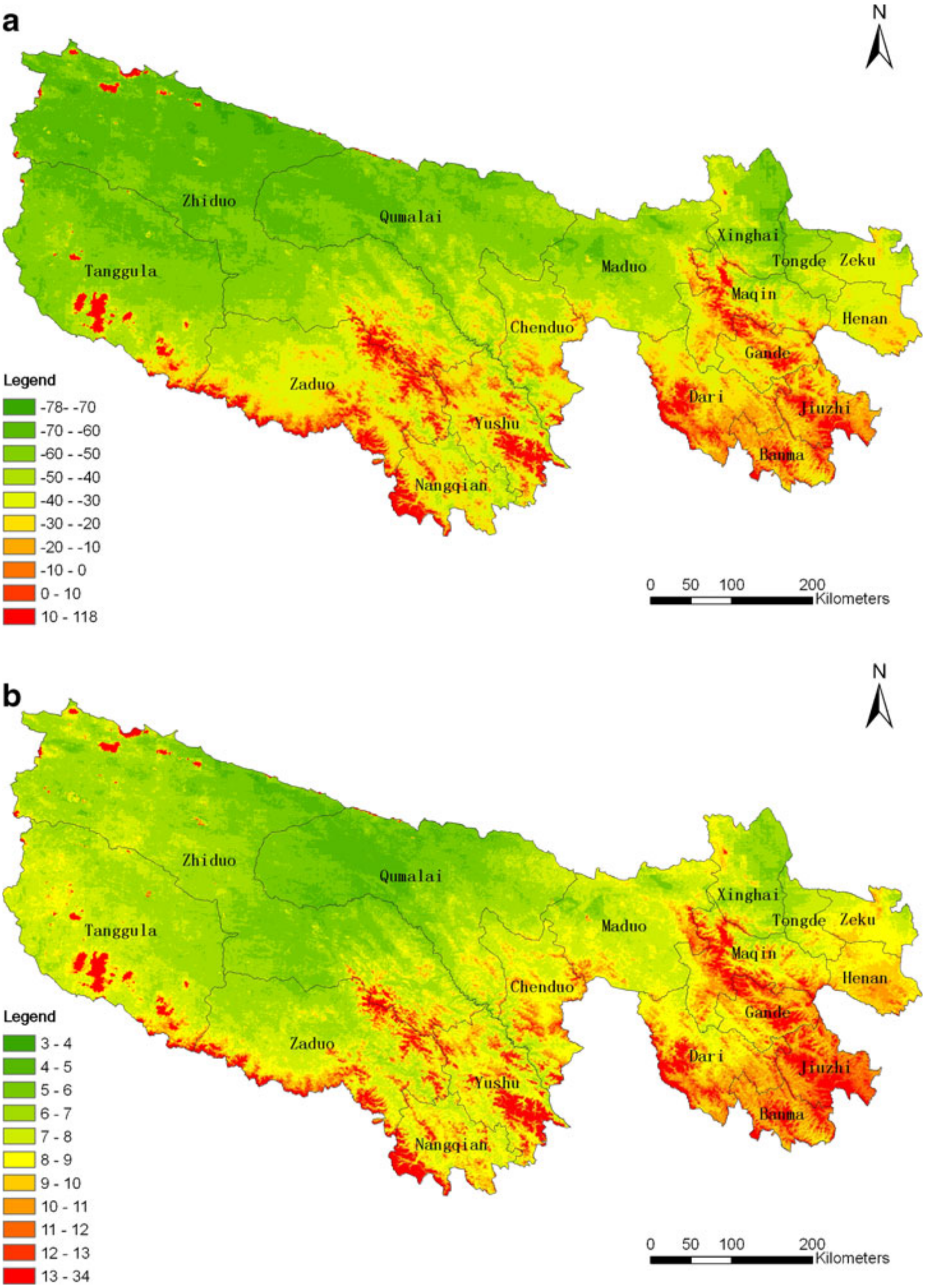


Fig. 3 The spatial variations (**a**) and standard deviation (**b**) of Moisture Index

Source Region. Between the late 1970s and the early 1990s, the regional lake surface area were decreased from 668,892 to 657,393 ha, a decline of 11,499 ha or 1.72%. And it increased from 657,393 to 664,259 ha between the early 1990s and 2004, a rise of 6,866 ha or 1.04%. Compared the late 1970s with the early 1990s, the expanding and shrinking area of lake surface were 4,404 ha (0.66%) and 17,100 ha (2.56%) respectively. And, the expanding and shrinking area showed 21,468 ha (3.27%) and 13,319 ha (2.03%) from the early 1990s to 2004. Furthermore, 11,899 ha (1.78%) and 16,121 ha (2.41%) compared the late 1970s to 2004.

Between 1970s and 2004, the source region of the Yellow River had a widespread decline in the area and abundance of lake, as well as the southeastern part of the origin Yangtze River (Figs. 4, 5). It also validated by other researches that the surface area of lake decreased at a rate of 0.54% from 1970s to 1980s and 9.25% from 1980s to 1990s, and the water height descended and lakeshore line retrograded in the origin of the Yellow River (Cheng and Wang 1998; Wang and Cheng 2000; Feng et al. 2006). Some lakes shrank to sizes and disappeared altogether, or some vanished

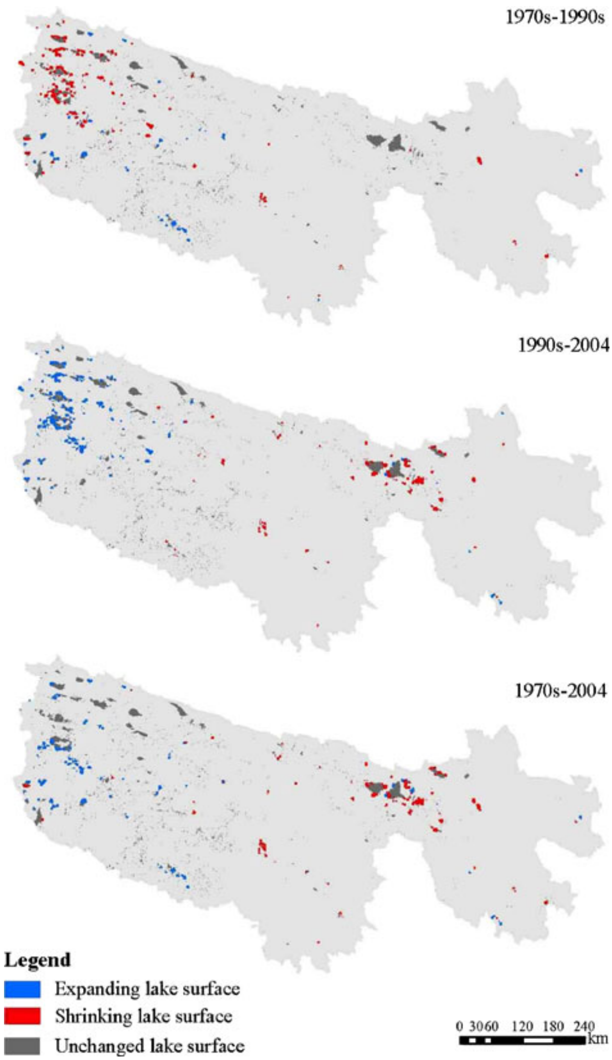


Fig. 4 The spatial patterns of variable and stable lake surface in River Source Region during 1970s~1990s, 1990s~2004 and 1970s~2004

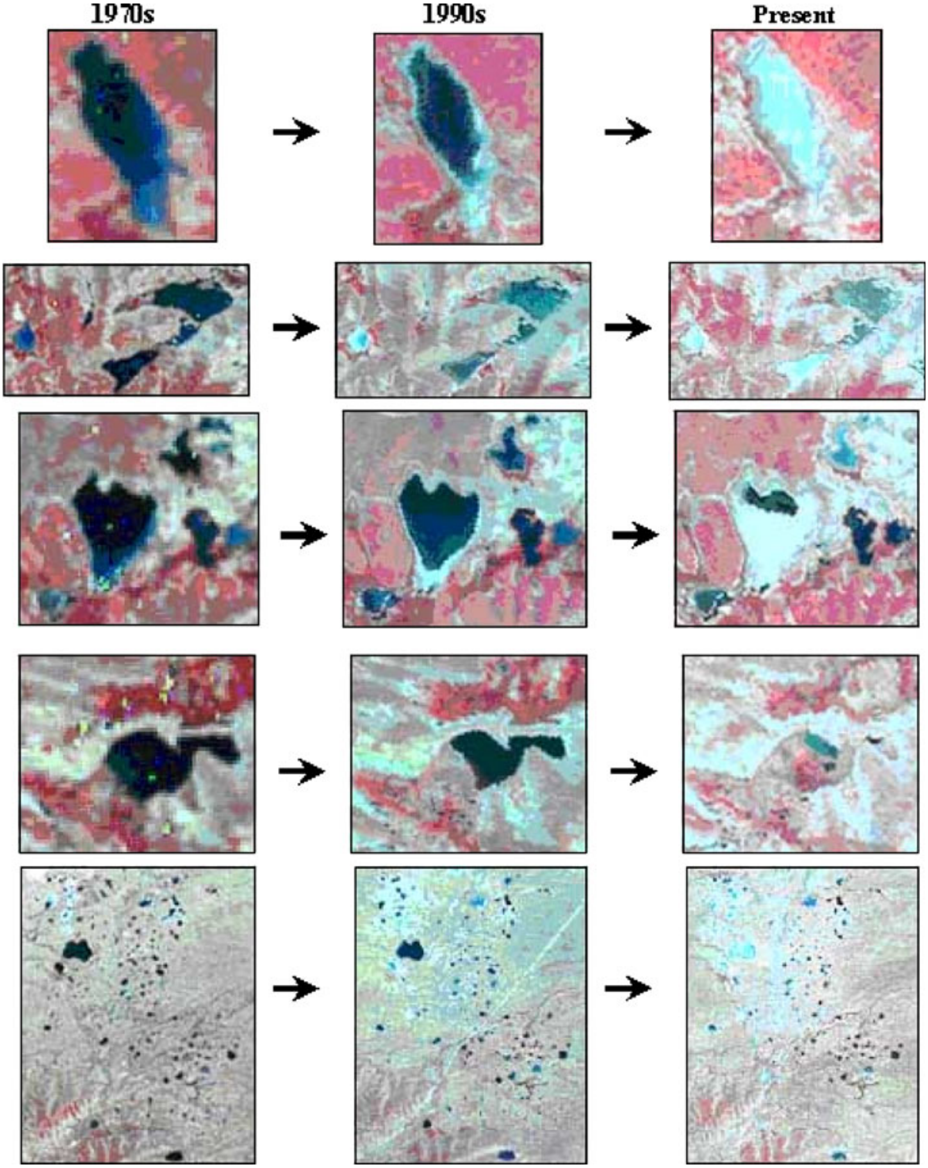


Fig. 5 Shrinkage of inland lakes within the River Source Region. The series are typical examples of the water loss patterns occurred during the 30-year study period

completely before and are now revegetated in the northwestern origin of the Yellow River. There also some former lakebeds never refilled now, which considered to be permanently drained. As surface water decreased, smaller multiple lakes were sometimes created. However, other regions had completely reverse change of lake expansion (Fig. 6), especially the western and northern part in source region of the Yangtze River, and depopulated area in western River Source Region. Some newly

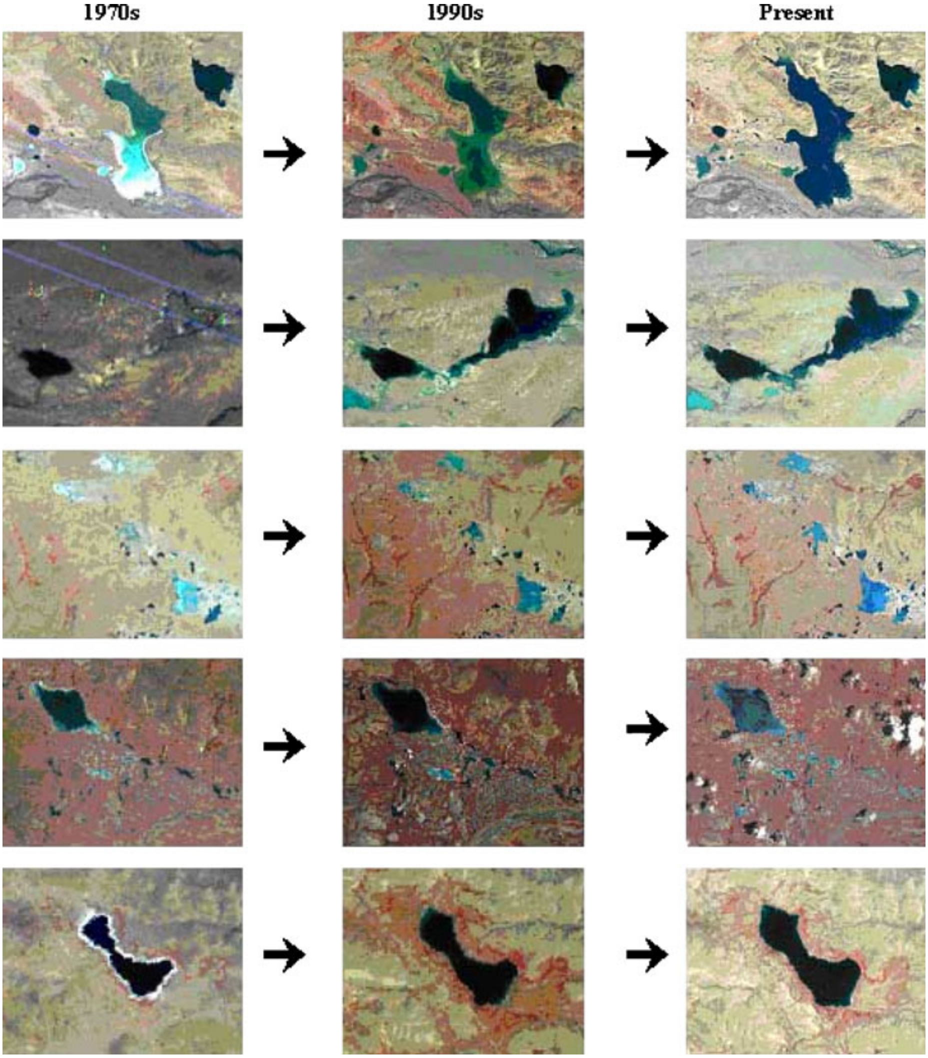
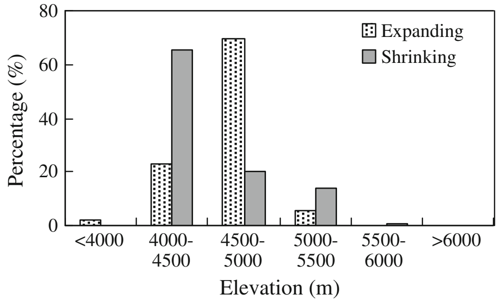


Fig. 6 Expansion of inland lakes within the River Source Region during the 30-year study period

developed lakes were also observed on recent images in the origin of the Yangtze River. Compared the inland lakes in the late 1970s to the early 1990s, main portion of River Source Region were presented as shrinkage trends, except the southwestern part of origin Yangtze River. Severely shrinking area located in western River Source Region. Obviously, former shrinking area became expansion region from 1990s to 2004. Therefore, the greatest change occurred in western River Source Region including the northwestern origin of the Yangtze River, which greatly shrank in the former and expanded after that. And the origin of the Yellow River showed steady shrinkage.

There was a slight increasing trend in closed lake surface area at higher elevation area, with 74.97% of the expanding lakes located at elevation above 4500 m, and

Fig. 7 The relations between the changing lakes and elevations



97.94% at elevation above 4000 m (Fig. 7). While lower elevations mainly had decreasing trends, with 65.3% of the shrinking lakes located at elevation bellow 4500 m and 85.22% below 5000 m. Even within the extent of a single imagery, there was a heterogeneous pattern of changing lake, with some lakes remaining stable since the 1970s while neighboring lakes decreased or increased substantially in surface area. This pattern may be related to the distribution of discontinuous permafrost and subsurface drainage related to warming permafrost (Yoshikawa and Hinzman 2003).

3.3 Trends of annual mean runoff from 1970 to 2004

Figure 8 shows the annual mean cycle of runoff for the two hydrological control stations available in the origin of the Yellow River and the Yangtze River. Mean annual runoff amounts were varied between 60.81 (in 2002) ∼ 261.89 m^3/s (in 1975) at Jimai station (Fig. 8a). It was decreased at a rate of 1.623 m^3/s/year and the annual variation of the runoff is strongly correlated with the cycle of precipitation and wetlands in the origin of Yellow River. Mean annual runoff amounts were varied between 8.89 (in 1979) ∼121.93 m^3/s (in 2002) at Tuotuo River station (Fig. 8b). It was increased obviously at a rate of 1.949 m^3/s/year. The annual variation of the runoff is strongly correlated with the snow and ice melts that indicating primarily the change of the glacier mass turnover from year to year in the origin of the Yangtze River.

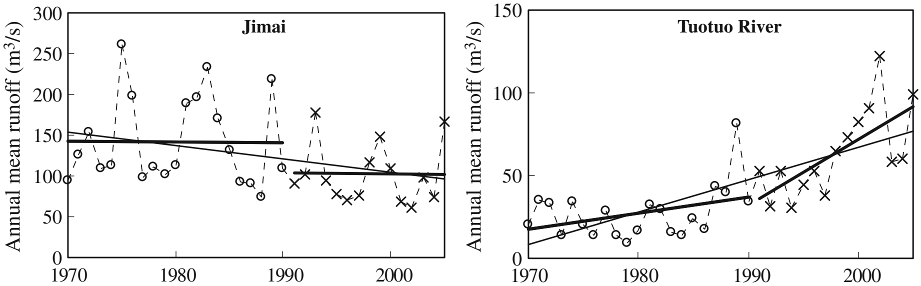


Fig. 8 Annual mean runoff of the two hydrological control stations during 1970–2004

4 Discussion

Lake expansion and shrinkage phenomenon are close related to geological structure, climatic conditions and supplement patterns etc. Climate change especially temperature and precipitation impacts the lake observably. The thawing of permafrost under lake basins due to warming could affect the storage capability of lakes. Therefore, in the background of warming, hydrological regime changes such as augment of runoff, ice and snow melt water, accelerated permafrost thawing and enhanced evaporation would bring complicated effects to water bodies variation synthetically in arid region.

4.1 Climatic warming trends shows the primary driving factor

Generally, precipitation and PET are the two primary climatic factors affected lake changes, and the well consistency between the regional precipitation and the change trends of lakes are presented as controls on the lake balance in the scale of inter-decadal variation. We can see the obviously decreasing precipitation (−1.948 mm/a) and increasing PET (0.305 mm/a) in source region of the Yellow River, and the moisture index showed warm and dry. These trends of precipitation and PET were directly related to the shrinking lakes in this region. However, although the precipitation (−0.036 mm/a) and PET (−0.546 mm/a) in the source region of the Yangtze River were decreased, the lakes mainly showed expanding trends. Therefore, lake changes in this region were primarily controlled by other factors, and the decreasing precipitation and PET were not obviously related to the increase or decrease of lake area.

For extensive and cold River Source Region with average annual temperature below zero, the elevated temperature at a rate of 0.0469°C/a, affected lakes is more obvious than precipitation, especially in origin of the Yangtze River. Although there were obviously expansions or weakening shrinkages of some lakes along the increasing precipitation in the near future, the regional lake area is tending to shrink. The temperature affects lakes more in regional scale, which indicated the responding characteristics of arid and cold environment to climate change. However, the mechanism of lakes affected by climate were more complicated in basins with feedings of glacier melt, which were related to runoff, precipitation and air temperature. Therefore, it indicated the complicated responses of lakes to climate change at the regional scale in River Source Region. The expansion lakes in the origin of the Yangtze River and the shrinkage lakes in the origin of the Yellow River during the last 30 years indicated that the climate affected the lakes not only depending on the single factor such as precipitation or temperature, but also the hydrothermal condition driving by the climate change.

4.2 Permafrost degradation further intensified the shrinkage

Permafrost in River Source Region and even the whole Tibetan Plateau has the trend of degradation at regional scale due to the combined influence of climatic warming and increasing anthropogenic activities. The ground temperatures in large range permafrost regions showed relatively small increasing by 0.1∼0.4°C, and 0.3∼0.7°C in island permafrost zone and seasonally frozen ground region. The distribution boundary of fragmentary permafrost increased by 50–70 m, at the edge of permafrost region in River Source Region according to comparison measured in 1970s and 1990s, such as Xidatan on the Kunlun, Madoi on the Buqing Mountains, Ximenco on the Nianbaoyuze Mountains and southwest slope of Anyemaqen Mountains. The source region of the Yangtze River was characterized of high relief and harsh climate, and it showed comparatively small change degree than other marginal permafrost area, though experienced permafrost degradation responding to climate warming. During the past 30 years, ground temperature in predominantly continuous permafrost area in source region of the Yangtze River were increased obviously, especially the Kunlun Pass, Cumar River basin and Fenghuo Mountain pass etc. The ground temperature in the upper layer (0∼40 cm) of the island permafrost zone on southeastern source region of the Yangtze River decreased by about 0.3∼0.7°C during 1980s and 1990s. However, being the merging areas of vast continuous permafrost zone and seasonally frozen ground region, uncoincidently frozen ground and residual thawed layers in the vertical profile were increased in the source region of the Yellow River responding to warming (Wang 1998). The ground temperature in seasonally frozen ground region on northern source region of the Yellow River has risen by 0.4∼0.6°C during the near 20 years, such as the island permafrost zone of Qumarleeb. The permafrost retreated by 15 km along G214 that is a national highway nearby Madoi. However, although ground temperature evidently increased widespread, negative trends occurred on southern parts and decreased by 0.1∼0.2°C in the upper layer of 0∼10 cm during the same periods, which would related to the cooling effects of dense shrub vegetation.

In continuous permafrost, total lake area increased and lake number risen. This trend of net growth in total lake number and area were contrasted sharply with most northwestern and southern regions of discontinuous and island permafrost, all of which experienced net declines. The declines have outpaced lake gains and led to an overall loss to the region. The spatial pattern of lake disappearance strongly suggested that the observed losses were drove by permafrost thawing. Geophysical surveys in River Source Region also suggested that warming temperatures lead to thinning and eventual breaching of permafrost, which may be the reason for shrinkage of most large and mature closed-lakes. As mentioned by Smith et al. (2005) and Riordan et al. (2006), initial warming leads to the lake expansion and followed by drainage as the permafrost degrades still further. Then it resulted to a declining water surface. It were supported by broad geographic patterns observed in River Source Region that lake increased in continuous permafrost and lost in thinner and less contiguous. It also supported by the fact that permanently drained lakes were commonly found alongside undisturbed neighbors, and the vanished lake occurred within the continuous permafrost boundary. These phenomenons suggested a spatially patchy process rather than a direct climatic mechanism. The implications of this analysis were that lake area in regions over thin and warm permafrost may shrank, and newly developed small lakes may form.

4.3 Impact of water supply pattern on lake change

The water supplies of water system in River Source Region are variable, including rainfall recharge, melting ice and snow feeding, groundwater recharges and mixed supply. Water systems in the origin of the Yangtze River such as Tuotuo River, Dangqu, Gaerqu and Buqu etc. are primarily supplied by melt water originated from large glaciers of Tanggula mountain system, and the Qiemuqu and Qushian River are originated from glacial area of Anyemaqen Mountains. However, most branch rivers in the origin of Yellow River, and the Chumar River and Beilu River of the Yangtze River are mainly supplied by rainfall (Xie et al. 2003). Furthermore, snow and ice melt, summer rainfall, groundwater and released soil moisture of permafrost provides the origin for most of the inland lakes in River Source Region.

Since 1970s, lakes mainly recharged of glacier melt water showed expanding trends in River Source Region. The crucial driving forces were increasing snow and ice melt water, along with the variation of dry and wet status driving by glacier retreating. It could be evaluated by the obviously increasing runoff at Tuotuo River hydrological station. For example, although Hohsai Lake located at Kokoxili had been shrunk during historical period, it would be desalted and expanded in the near future for recharging of Kunlun glacier. Yaxi Co situated in the north bank of Tuotuo River and Dorgai Co jointed the Chumar River expanded evidently due to increasing river supplement.

Lakes mainly recharged of precipitation were shown shrinking trend, especially in the origin of the Yellow River. The gradually reduced recharge source led to lake shrinkage due to directly increasing temperature and evaporation, ecological degradation and anthropogenic activities despite the slightly enhancing precipitation (Zhang et al. 2004a; Lu et al. 2005). Furthermore, several lakes located in the intermountain basin and recharged by rainfall, runoff or rainfall and glacier melt water showed downtrend in water-level. It also could be evaluated by the decreasing runoff at Jimai Station. Water surface evaporation and land surface evapotranspiration in lake area increased sharply along with climate warming. The lake surface would continue to shrink if annual precipitation increased less than 10%, however, it would began to expand and desalt if increased more than 20% (Shi and Zhang 1995). A great deal of large and middle lakes were split to clusters of saline lakes, and many small lakes gradually vanished. For example, the Mitijiangmuco has shrunk, salinized and split into four strings of lakes. Ulan Ul Lake has split into five small lakes and developed multiple-steps lake-shore terrace. Quemoco located in Tuotuo River and Hulu Lake in Kokoxili has decreased by almost half. Gourenco had been a salt lake in 1960s, a saline lake in 1980s and now a dried saline lake.

5 Conclusions

There were several climatic and non-climatic potential reasons for the long-term trend in inland lake shrinkage and expansion. Aside from permafrost degradation, water supplement pattern, the ultimate effect of continued climate warming on high-latitude, permafrost-controlled lakes may well be their widespread disappearance forces. Clearly, other factors also influenced lake change such as retreating glaciers and uplifting process, shallow water tables and extensive, low-permeability wetlands, which ensure continued survival of many lake, even permafrost is absent (Smith et al. 2005). However, the glaciers and uplift process are difficult to show in this paper. Overlay of our lake maps with detailed wetland distribution showed that lake only existed as perch systems on wetlands. Of course, one source of potential error in our estimates was the larger pixel size of 30 m in our latest period using satellite imagery. Since water strongly absorbs mid-infrared radiation and sub-pixel water absorption typically led to an overestimate of water pixels, there would be a tendency to overestimate lake using satellite imagery. Water budget of lakes remained deficit for a fairly long period is the primary reason for declining lake.

There were three types of changing patterns for inland lakes: (1) lakes with expanded area and increased water level (Fig. 4). Influenced by warm and dry climate, lakes with main recharged source of glacier or directly linked to rivers expanded and desalted due to thawing and retreating glaciers, increasing precipitation, thawing permafrost and ground ice. (2) Lakes with small change or even unchanged, due to the stable supplement of runoff especially the groundwater runoff. (3) Lake shrinkage with declined water level (Fig. 5). Numerous lakes with recharged source of precipitation or runoff were shrank, salted, dried and disappeared generally, due to the direct result by regional warm and dry climate. The primary reason for the declined water level is the precipitation and runoff cannot offset the evaporation.

The climatic fluctuation and hydrological environment change significantly influenced the ecological environment. Lake shrinkage would led to reducing recharge of water-vapor flux, weakening regional runoff generation and regulation ability, intensifying desertification and accelerating arid climate. On the contrary, lake expansion would induce to the expanded water surface, increasing evaporation, and thus lost partial recharge of water source. Therefore, we need to further analyze the historical trends, variability, geographic scope, and mechanisms of changing lakes. Because the signal of lake that we have detected in this study may have implications for more widespread changes in ecosystem services due to changing water table within River Source Region and throughout Tibetan Plateau. A lowering of the water table would affect the structure and function of wetlands adjacent to lake, and vegetation dynamics transferred from the conversion of wetlands towards upland vegetation. These changes have the potential to affect two classes of ecosystem services for wetlands: (1) climate regulation services are likely to be affected in a complex manner as a lowering of the water table can enhance the release of carbon dioxide by exposing soil carbon to aerobic decomposition, but it would likely decrease the emissions of methane to the atmosphere (McGuire et al. 2006), and (2) lowered water table could have profound consequences for provisioning services of natural reserve, which provide breeding habitat for millions of wild life forms.

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