Title page

Exploring the geomorphological processes of Qinghai Lake and surrounding lakes in the northeastern Tibetan Plateau, using Multitemporal Landsat Imagery (1973–2015)

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Abstract: Studies of lake's coastline and shape changes and the influencing factors will contribute to knowledge about the geomorphological and hydrological evolutions of those lakes. This study extracted coastlines of Qinghai Lake and surrounding lakes in the northeastern Tibetan Plateau from multitemporal remote sensing data from 1973 to 2015. The geomorphological processes and the reasons for area and coastline variations were then analyzed. The results showed that: the changes of the total lake area were divided into three stages: the stable decrease stage (1973-1988), the fluctuant decrease stage (1988-2005), and the rapidly increase stage (2005-2015). The changes of Qinghai Lake area and Gahai Lake area showed a similar trend as the total lake area. The Erhai Lake area fluctuated from 1973 to 2004 and then increased from 2004 to 2015. Haiyanwan Lake was isolated from Qinghai Lake in 2003 and was linked into Qinghai Lake in 2006, again. The lakes area variations, excluding Erhai Lake and Shadao Lake, were positively correlated with the variation of the Qinghai Lake level, and estuary area variations were significantly negatively correlated to the lake level, indicating that the higher lake level led to more land being submerged. The evolutionary processes of lakes in the Shadao Region were influenced by aeolian sand and lake water balance experiencing relatively low precipitation and strong evaporation. Erhai Lake was also influenced by river runoff from Daotang River. Sediment loads from rivers flowing into Qinghai Lake, except for Buha River, were relative low and only slightly influenced the estuary. Aeolian sand transported by the lake waves and currents from west coast to east coast will form subaqueous barriers, the Shadao Region land area will increase slowly, and the coastline of the Shadao Region will extend towards the lake. Therefore, the diameter of Qinghai Lake from the west to east coast will become shorter, while the diameter from the south to north coast will become longer in future.

Key words: lake surface area; lake level; geomorphological process; remote sensing; Qinghai Lake

1. Introduction

Lakes make up a relatively small percentage of Earth's water body, but are essential components of the global hydrological system, and influence many aspects of ecosystems and human activities (Winter, 2004; Yildirim et al., 2011). Inland lakes in arid areas provide scarce but valuable water resources for fragile environments and human beings (Bai et al., 2011). Changes in the lake's area and water levels, especially endorheic lakes in arid areas, respond significantly to climate change and anthropogenic activities (Mason et al., 1994; Yi & Zhang, 2015). Since the 1960s, many inland lakes have been shrinking or drying up (e.g., Aral Sea, Issyk-Kul, Ebinur, and Bosten), and some of them have disappeared (e.g., Lop Nur, Manas, and Taitema). However, declines in lake's area and water level have contributed to a series of environmental problems in the regions (Tatyana & Igor, 2000; Hao, 2008; Lioubimtseva & Henebry, 2009). Inland lakes are also considered to be sentinels, integrators, and regulators of climate changes (Adrian et al., 2009; Williamson et al., 2009a; Williamson et al., 2009b). Therefore, studying the changes of lake's coastline and area and influencing factors are important tasks that contribute to knowledge about the geomorphological and hydrological evolutions of lakes. These studies also inform coastal zone management, coastline erosion monitoring, water resource evaluation, flood prediction, and wetland protection (Lehner & Doll, 2004; Liu & Jezek, 2004; Ouma & Tateishi, 2007; Yi & Zhang, 2015).

Qinghai Lake, China's largest lake with a closed basin, lies in the Northeast Qinghai-Tibet Plateau (Fig. 1). It lies in a critical transitional zone where the Southeast Asian Monsoon (SEAM), the Westerly Circulation (WC) and the Qinghai-Tibet Plateau Monsoon meet (LZBCAS, 1994; Cui & Li, 2015a). This makes Qinghai Lake very sensitive to climatic changes, and the unique geographical location has made it as an ideal place for global change research, attracting great attention in the international community (An et al., 2012; Li & Liu, 2014). Meanwhile, the lake is one of China's national nature reserves and

influences the ecological security of the Northeast Qinghai-Tibet Plateau (Tang et al. 1992). In the past few decades, 50% of the rivers flowing into the lake have dried up as a result of climate change and human activity (LZBCAS, 1994; Li et al., 2007). The lake level elevation has declined from 3,196.55 m in 1959 to 3,194.26 m in 2012, with a decline rate of $4.75 \text{ cm}\cdot\text{yr}^{-1}$ over the 53-year period (Li et al., 2012). This has resulted in decrease in the lake's surface area, and the isolation of separate lakes from Qinghai Lake (e.g., Gahai Lake, Haiyanwan Lake, Erhai Lake) (Fig.1). The changes in the lake area and hydrology have contributed to a series of environmental problems in the basin; these problems include desertification, erosion, loss of grazing grassland, and deterioration of water quality and quantity (Qin & Huang, 1998; Hao, 2008; Zhang et al., 2011). These changes have made Qinghai Lake an important research site, and many studies have investigated the hydrological processes of Qinghai Lake, including lake level variation, water balance, evaporation, and the lake water's hydrochemistry (Li et al., 2007; Li et al., 2009; Xu et al., 2010; Cui & Li, 2014; Li & Liu, 2014; Cui & Li, 2015a; Liu et al., 2015; Cui & Li, 2016). Several studies have investigated the changes in the size of the Qinghai Lake area using remote sensing technology (Shen & Kuang, 2003; Yin & Yang, 2005; Feng & Li, 2006; Liu & Liu, 2008; Li et al., 2012; Liu et al., 2013; Shen et al., 2013). However, few studies have focused on the changes of lake's area and coastline of Qinghai Lake and surrounding lakes at high temporal resolution (annual scale) over a long timeframe. In general, these data are of low temporal resolution and cover limited time periods, making research more difficult and creating more uncertainty with respect to the study of geomorphological processes of Qinghai Lake.

This background highlights the importance of researching the changes in the coastline and area covered by Qinghai Lake and its surrounding lakes. This is important for exploring the geomorphological evolution of the lakes, and may reveal possible solutions to the basin's environmental problems. Therefore, the objectives of this study were (1) to quantify area and coastline changes as well

as increase and decrease of Qinghai Lake and surrounding lakes during the period from 1973 to 2015, based on a systematic analysis of multitemporal remote sensing data; (2) to further identify the geomorphological processes and the reasons for the area and coastline variations of Qinghai Lake and surrounding lakes; and (3) to discuss the future possible geomorphological evolutions of Qinghai Lake and surrounding lakes under the impacts of climate and human activity. The results will contribute to knowledge about the evolutions of lakes as a result of global climate change in cold and arid alpine environments, and inform water resource management in the Qinghai Lake Basin and the northeastern Tibetan Plateau.

2. Material and methods

2.1. Study area

Qinghai Lake (36°32'-37°15'N, 99°36'-100°47'E) is a brackish lake with water surface area of 4,400 km² and a water volume of 7.16×10¹⁰ m³. It is the largest lake in China (Fig. 1), and lies in the cold and semiarid region of the northeastern Tibetan Plateau at an altitude of ~3,193 m above sea level (a.s.l.) (Fig. 1). The lake is a closed basin with a watershed area of approximately 29,661 km², with no surface water outflows. The maximum and average depths of the lake are 26 m and 16 m, respectively. Due to drops in the lake's water level, new lakes have formed as they have become isolated from Qinghai Lake. For example, Gahai Lake emerged in its current shape during the early Holocene; Erhai Lake was formed more than 100 years ago; and Haiyanwan Lake was formed into its current shape at 1987 (Shi et al., 1958; Chen et al., 1990; LZBCAS, 1994).

The lake lies in a critical transitional zone where the Southeast Asian Monsoon (SEAM), the Westerly Circulation (WC) and the Qinghai-Tibet Plateau Monsoon meet (LZBCAS, 1994; Cui & Li, 2015a). The area has a continental climate, with cold and dry days in the winter and hot and rainy weather in the summer (Fig. 2). The average annual air temperature in the lake area is ~-0.1 °C. The average annual

precipitation is ~357 mm, with more than 65% of that falling as rain in summer. The evaporation rate is 3-4 times higher than the precipitation rate (Li et al., 2007), relatively high at the end of spring into the summer (April to August) and relatively low in the winter (December to February) (Fig. 2). The annual average wind speed is ~3.5 m/s, relatively high in the spring (March to May) and relatively low at the end of summer into autumn (August to October) (Fig. 2).

More than 50 rivers or streams flow into Qinghai Lake (LZBCAS, 1994). The rivers are asymmetrically distributed, with most of them located north and northwest of the lake (Fig. 1; Yan & Jia, 2003). Most rivers are seasonal, with 85% of the annual discharge occurring between June and September (Fig. 2). The main rivers are Buha River, Shaliu River, Haergai River, QuANJI River, and Heima River (LZBCAS, 1994; Li et al., 2007). Together, these 5 rivers have a total discharge of $\sim 1.43 \times 10^9 \text{ m}^3 \cdot \text{yr}^{-1}$; this discharge makes up 80.3% of the total surface water volume flowing into Qinghai Lake.

The estimated human population in the Qinghai Lake Basin in 2004 was 8.56×10^4 people, with a density of 2.9 inhabitants/km² (Chen et al., 2008). This indicates that human activity has a low impact in the basin; these activities mainly include livestock production, some agriculture, and mining.

2.2. Data source

This study used multitemporal remote sensing data from Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM), Landsat Enhanced Thematic Mapper (ETM+) and Landsat Operational Land Imager (OLI) satellite images from 1973 to 2015, with a total of 56 scenes (Table 1). The images were archived on the Earth Resources Observation and Science (EROS) Center (<http://glovis.usgs.gov/>) or the Geospatial Data Cloud of Chinese Academy of Sciences (<http://www.gscloud.cn/>). The path/row of the Landsat MSS images are 143/34 and 143/35; the path/row of the other images are 133/34 and 13/35 (Table 1). Clouds had minimal influence on water body extraction in this study. A Digital

Elevation Model (DEM) was generated from a 10-m interval contour map of the Qinghai Lake Basin.

Figure 1 shows the locations of meteorological and hydrological stations in the Qinghai Lake Basin. Monthly records of lake level and river runoff during the period from 1973 to 2015 were collected from Xiashe hydrological station and Buha River hydrological station, respectively (Fig. 1). For this study, the runoff of Buha River was chosen to represent the hydrological characteristics of rivers flowing into Qinghai Lake. The Buha River is the largest river in the Qinghai Lake Basin (LZBCAS, 1994; Li et al., 2007), with a catchment area of approximately 14,932 km², which is about 50% of the Qinghai Lake Basin. Its discharge is $8.09 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$, which accounts for approximately 50% of the total volume of surface water flowing into Qinghai Lake. Furthermore, from a study methods perspective, only two rivers (Buha River and Shaliu River) have hydrological observation stations at their estuaries, needed to quantitatively estimate runoff. Based on these factors, the Buha River was used as a representative river to represent the hydrological characteristics of all rivers flowing into Qinghai Lake. There are only two weather stations (Tianjun and Gangcha weather stations) in the Qinghai Lake Basin (Fig. 1); the climatic factors (e.g., precipitation and temperature) observed at the Tianjun weather station were consistent with those observed at the Gangcha weather station (Cui et al., 2011; Cui & Li, 2015b). Thus, the Gangcha Weather station is approximately 13 km north of the lake and is the nearest weather station to the lake (Fig. 1). Therefore, monthly climatic factors (precipitation, temperature, evaporation, and wind speed) collected from the Gangcha weather station were used to analyze climate change impacts on lake level and lakeshores of Qinghai Lake and surrounding lakes. Annual data were derived from monthly data.

2.3. Methods

Several methods were used to delineate and extract lake coastlines from optical and radar imagery (Kelley et al., 1998; Alesheikh et al., 2007; Maiti & Bhattacharya, 2009; Yıldırım et al., 2011). The coastline can even be extracted from a single band image, since the reflectance of water is nearly equal

to zero in the reflective infrared bands, and the reflectance of the majority of land covers is greater than water (Kelley et al., 1998; Maiti & Bhattacharya, 2009). Water and land can be also separated directly by using the band ratio between band 4 and 2 (MSS image) and between band 5 and 2 (TM or ETM+ image). The ratio b_2/b_5 is greater than one for water and less than one for land over large coastal zone areas. Actually, this law mistakenly assigns some of the vegetative value land to water (Alesheikh et al., 2007).

This study detected the coastline based on a combination of histogram thresholding and band ratio techniques developed by Alesheikh et al. (2007). The mean high tide line as the coastline was delineated manually by the same person at the same scale to ensure accuracy from each combined TM 543 and MSS 432 pseudo-color image in this study. The mean high tide line as the coastline is expected to be better than the water/land line, which is easily affected by lake ice and the tide (Chu et al., 2005).

Each image was geometrically corrected and rectified to the Universal Transverse Mercator (UTM Zone 47N). The atmospheric correction was done using a haze reduction method. Composite changes (accretion and erosion) for the study area were determined by overlaying, registering and comparing each image's coastline and area relative to the initial 1973 image. The measurements enable precise calculation of the accretion area and erosion area due to coastline movement in the period between different image acquisitions. In recording measurements for each section or each region, a negative value was interpreted as erosion, a positive value was interpreted as accretion, and a very low or zero value represented a stable area. These operations, including coastline detection, were generated using Erdas Imagine 9.2 image processing software, ArcGIS 9.3 software, and ArcView 3.2 software.

3. Results and discussion

3.1. Dynamic changes of Qinghai Lake and surrounding lakes

The coastline vector maps, extracted from satellite images, showed that the coastlines of the Qinghai

Lake and surrounding lakes changed considerably from 1973 to 2015 (Fig. 3). The total lake surface area decreased by 38.10 km² during the period, with a decreasing rate of 0.91 km²·yr⁻¹ (Table 2; Fig. 4f). The general pattern of increase-decrease of the total lake surface area was divided into three periods (Fig. 4f): a stable decrease period (1973-1988), a fluctuant decrease period (1988-2005), and a rapidly increase period (2005-2015). The total surface area of lakes decreased steadily from 4474.32 km² to 4328.14 km² from 1973 to 1988, with a decreased area of 146.18 km² and a rate of decrease of 9.75 km²·yr⁻¹. The total surface area of lakes fluctuated and decreased from 4328.14 km² to 4249.58 km² from 1988 to 2005, with a decreased area of 78.56 km² and a rate of decrease of 4.62 km²·yr⁻¹. The lake surface area increased by 186.63 km² from 2005 to 2015, with a rate of increase of 18.66 km²·yr⁻¹ (Table 2).

For Qinghai Lake, the general pattern of surface area change was divided into four stages (Fig. 4e): the stable decrease stage (1973-1988), fluctuant decrease stage (1988-2002), lowest area stage (2003-2005), and fluctuant increase stage (2006-2015). The Qinghai Lake area decreased from 4420.29 km² in 1973 to 4261.52 km² in 1988, with a decreased area of 158.77 km² and a rate of decrease of 10.58 km²·yr⁻¹. From 1988 to 2002, Qinghai Lake area decreased by 54.82 km², with a rate of decrease of 3.92 km²·yr⁻¹. Due to lake level changes, Haiyanwan Lake (~90 km²) was isolated from Qinghai Lake in 2003 and was then linked into Qinghai Lake in 2006 (Fig. 3), as a result that Qinghai Lake area was relative lower during the period from 2003 to 2005 (Fig. 4e). The Qinghai Lake area increased from 4225.70 km² in 2006 to 4382.60 km² in 2015, with an increased area of 153.89 km² and a rate of decrease of 17.10 km²·yr⁻¹.

The surface area change of Gahai Lake was divided into three stages (Fig. 4d): the quick decrease stage (1973-1987), fluctuant decrease stage (1987-2004) and fluctuant increase stage (2004-2015). The Gahai Lake area decreased by 2.74 km² from 1973 to 1987 and by 0.96 km² from 1987 to 2004, with rates of decrease of 0.20 km²·yr⁻¹ and 0.06 km²·yr⁻¹, respectively. The Gahai Lake area increased by 2.07

km² from 2004 to 2015, with a rate of increase of 0.19 km²·yr⁻¹.

Shadao Lake was isolated from Qinghai Lake in the end of the 1970s; its area decreased from that time through 1989, because it became a closed basin with high evaporation and no surface water inflows. In 1992, the Shadao Lake area increased quickly to 23.98 km² (Fig. 4c), 1.67 times its area in 1989, resulting from surface water inflows from Qinghai Lake, because the Qinghai Lake level showed the largest annual increase of 64 cm in 1989 (Cui & Li, 2016). From 1992 to 2009, there was a high evaporation rate and no surface water inflows, leading to a decrease in the Shadao Lake area from 23.98 km² to 9.36 km², with a loss of 60.9% over the period. Shadao Lake was linked into Qinghai Lake in 2011.

The Haiyanwan Lake area decreased from 2003 to 2005, because it was a closed basin with a high evaporation rate and no surface water inflows (Fig. 4b). Erhai Lake formed more than 100 years ago (Shi et al., 1958; Chen et al., 1990; LZBCAS, 1994). The pattern of area change was divided into two stages (Fig. 4a): the fluctuant stage (1973-2004) and fluctuant increase stage (2004-2015). The area increased from 5.75 km² in 2004 to 7.21 km² in 2015, with an increased area of 1.46 km². In all, the patterns of surface area change among the lakes were different during the period from 1973 to 2015 (Fig. 4), indicating that the influence factors on lake surface area changes were different and complex among the lakes.

3.2. Accretion-erosion area in typical regions

Fig. 3 showed that the coastline and land area changed rapidly in river estuaries (e.g. Buha River estuary, Shaliu River estuary, Daotang River estuary, and Heima River estuary) and around the Shadao Region located to the northeast of Qinghai Lake, similar as results of other previous studies (Shen & Kuang, 2003; Li et al., 2004; Liu & Liu, 2008; Li et al., 2012). However, few studies have focused on the changes of lake's area and coastline of Qinghai Lake and surrounding lakes at high temporal

resolution (annual scale) over a long timeframe. The changing trends of estuary area were similar for the Buha River, Shaliu River, and Heima River (Fig. 5). The general pattern of the land area changes of the three river estuaries were divided into four stages (Fig. 5b, c, d): the rapid accretion stage (1973–1988), slow accretion stage (1988–2003), slow erosion stage (2003–2011), and rapid erosion stage (2011–2015).

For the Buha River estuary (Fig. 5d), the area increased from 331.54 km² to 380.10 km² from 1973 to 1988 and from 380.10 km² to 394.49 km² from 1988 to 2003, with mean net accretion rates of 3.24 km²·yr⁻¹ and 0.96 km²·yr⁻¹, respectively. For the slow erosion stage and rapid erosion stage, the estuary area of Buha River decreased by 20.22 km² and 24.68 km², respectively, with mean net erosion rates of -2.53 km²·yr⁻¹ (slow erosion stage) and -6.17 km²·yr⁻¹ (rapid erosion stage).

According to the Fig. 5c, the estuary area of Shaliu River increased by 12.28 km² in the rapid accretion stage (1973–1988) and 2.98 km² in the slow accretion stage (1988–2003), with mean net accretion rates of 0.82 km²·yr⁻¹ and 0.19 km²·yr⁻¹, respectively. In contrast, the estuary area decreased by 3.81 km² and 8.65 km² during the last two erosion stages, with mean net erosion rates of -0.48 km²·yr⁻¹ and -2.6 km²·yr⁻¹, respectively.

The accretion/erosion areas of Heima River estuary during the four stages (rapid accretion stage (1973–1988), slow accretion stage (1988–2003), slow erosion stage (2003–2011), and rapid erosion stage (2011–2015)) were 2.70 km², 1.06 km², -1.69 km², and -1.97 km², respectively, with mean net accretion/erosion rates of 0.18 km²·yr⁻¹, 0.07 km²·yr⁻¹, -0.21 km²·yr⁻¹, and -0.49 km²·yr⁻¹, respectively (Fig. 5b).

For the Shadao Region, the changes of land area were divided into three stages (Fig. 5a): the rapid accretion stage (1973–1988), fluctuant accretion stage (1988–2005), and rapid erosion stage (2005–2015). The accretion/erosion areas during the three stages were 53.26 km², 34.19 km², and -74.35 km²,

respectively, with mean net accretion/erosion rates of $3.55 \text{ km}^2 \cdot \text{yr}^{-1}$, $2.01 \text{ km}^2 \cdot \text{yr}^{-1}$, and $-7.43 \text{ km}^2 \cdot \text{yr}^{-1}$, respectively (Fig. 5a).

3.3. Reasons for changes of area and coastline of lakes and estuaries

According to the Fig.4, surface area variations of lakes, excluding Erhai Lake and Shadao Lake, showed a similar trend with the variation of the Qinghai Lake level. Lake surface area peaks corresponded to relatively high lake level (e.g., 1973, 1976, 1992, 1994, 2009 and 2012; dotted blue line in Fig. 4). Lake surface area drops corresponded to relatively low lake level (e.g., 1988, 1996, 1998, 2004, and 2014; dotted red line in Fig. 4). Pearson correlation coefficients showed that lake surface area variations, excluding Erhai Lake and Shadao Lake, were highly positively correlated to lake level (Table 3). The absolute values of correlation coefficients were all above 0.554, and all were statistically significant at a p-value of < 0.001 . In contrast, the correlation coefficients between the lake level and lake surface areas of Shadao Lake and Erhai Lake were below 0.409, and the relationships were not statistically significant. These results suggested that large lake surface areas of Qinghai Lake and Gahai Lake were closely related to high lake level.

The variations of the river estuary area were inversely related to the lake level variation of Qinghai Lake (Fig. 5). Peaks in estuary area corresponded to relatively low lake levels (e.g., 1975, 1988, 2003, 2011, and 2014; dotted blue line in Fig. 5). Drops in the estuary area corresponded to relatively high lake levels (e.g., 1976, 1992, 1999, and 2013; dotted red line in Fig. 5). Pearson correlation coefficients showed that estuary area variations were highly negatively correlated to lake level (Table 4). The absolute values of correlation coefficients were all above 0.55, and all were statistically significant at a p-value of < 0.001 . These all indicated that higher lake level led to the submergence of more land area.

The coastline and land area changed significantly and rapidly in the river estuaries of Buha River, Shaliu River, and Heima River (Fig. 3). This is because the river estuary is influenced not only by the

lake level but also by structural geology, meteorological conditions, coastal processes, human activity, runoff, and sediment load entering its river mouth (Zang, 1996; Tian et al., 1997; Chu et al., 2005; Cui & Li, 2011). The average annual sediment load entering Qinghai Lake was 4.98×10^5 t. The sediment load of Buha River was 3.55×10^5 t, which accounted for more than 71.3% of the total sediment load flowing into Qinghai Lake (LZBCAS, 1994; Chen et al., 2008). However, the sediment load and concentration (approximately $0.33 \text{ kg} \cdot \text{m}^{-3}$) were relatively low in the river water of the Qinghai Lake Basin, due to high vegetative cover, smaller river channel gradient, slow runoff, and small rainfall intensity in the basin (Chen et al., 2008). The declining lake level leads to an increase in estuary area, if human activities and lake current do not destroy the coastal zone. The lake level decreased from 3194.90 m on 16 May 1975 to 3194.33 m on 24 July 2014, with a decrease of 0.57 m (Fig. 5). The Buha River estuary area increased by 12.83 km^2 . In contrast, the estuary areas of Shaliu River and Heima River decreased by 0.83 km^2 and 0.16 km^2 , respectively. These results indicated that lake current and wave erosions also influenced the coastline and estuary area because of the strong water circulation around the Haixin Mountain in Qinghai Lake (LZIGCAS, 1979). The sediment loads of other rivers, excluding Buha River, were relative low as they flowed into Qinghai Lake and only slightly influenced the estuary.

The Shadao Region is mainly covered by drifting sand dunes, semi-fixed sand dunes, fixed sand dunes, and several small lakes (Fig. 1). Due to the unique geomorphological mechanism and processes of Shadao Region compared with other areas in the Qinghai Lake Basin, the changes of lake surface areas of Gahai Lake, Shadao Lake and Haiyanwan Lake differed from the change of Qinghai Lake (Fig. 4); the land area changes of Shadao Region differed from those of estuaries (Fig. 5). The sandy materials entering Qinghai Lake were transported from the west to east by the lake waves and currents, forming the subaqueous barriers (Zhang et al., 2003). The sandy barriers gradually became higher and wider, and emerged from the water. This led to lagoons being isolated from the lake when the Qinghai Lake level

and surface area decreased (Fig.1), and then the isolated lakes had no surface water inputs (Zhao et al., 1993; Zhang et al., 2003; Cui et al., 2016). When the Qinghai Lake's surface froze from November through March (Che et al., 2009), a mass of aeolian sand, approximately $1.39 \times 10^6 \text{ t} \cdot \text{yr}^{-1}$, were drifted from the west coast of Qinghai Lake to the east coast (Shadao Region) (Zhang et al., 2003; Chen et al., 2008). This extended the Shadao Region area. Lake level changes also accelerated or decelerated the aeolian landform process. For example, Haiyanwan Lake was isolated from Qinghai Lake in 2003, when the lake level decreased below 3193.03 m, and it was subsequently linked into Qinghai Lake in 2006 when the lake level increased above 3193.02 m (Table 1; Fig. 4).

The geomorphological mechanism and processes of Erhai Lake were like Shadao Region lakes(e.g., Gahai Lake, Haiyanwan Lake), however, the changes of Erhai Lake area differed from the changes of Gahai Lake and Shadao Lake (Fig. 4). The reason would be that surface water from Daotang River flows into Gahai Lake, whereas, no surface water flows into Shadao Region lakes (Cui & Li, 2015b). Therefore, the evolutionary processes of lakes (e.g., Gahai Lake, Haiyanwan Lake) in the Shadao Region were influenced by aeolian sand and the lake water balance under the conditions of relatively low precipitation and strong evaporation. Erhai Lake was also influenced by river runoff from Daotang River.

3.4. Future changes of the Qinghai Lake area and coastline

The results of the relationships and impacts analysis showed that lake surface area was significantly positively correlated with lake level. In contrast, the estuary area was significantly inversely correlated with lake level (Table 3, Table 4). Research on Qinghai Lake level trends could indicate potential changes of the lake surface area and coastline; future studies would provide more information. Different factors influence the lake level change, including natural factors (climate and runoff), human activities, or the comprehensive influences of natural factors and human activities (Kezer & Matsuyama, 2006;

Kiage et al., 2007; Medina et al., 2008; Bai et al., 2011; Yıldırım et al., 2011).

Most of the alpine lakes (e.g. Qinghai Lake, Namco Lake, Silingco Lake) on the Tibetan Plateau remain in their natural conditions and free from human activities. As such, they are most impacted by climate conditions (Lu et al., 2005; Song et al., 2014). The lake level in the closed basin of Qinghai Lake was influenced by precipitation, runoff, and evaporation (Ma, 1996; Li et al., 2007; Zhang et al., 2011; Jin et al., 2013); the primary influences were precipitation and evaporation of SEAM period (Cui & Li, 2016). A tree ring-width chronology of the northeastern Tibetan Plateau, spanning 4,500 years, suggested that large-scale climate warming might be associated with an even greater moisture supply in this region (Yang et al. 2014). If so, the lake's level would rise, due to increasing precipitation and runoff (Christensen et al. 2014; Song et al. 2014). Therefore, the estuary area will decrease in future decades, especially for the estuaries of small rivers. Ultimately, even the isolated lakes in the Shadao Region will be linked into Qinghai Lake.

The sand dunes in Qinghai Lake Basin are mainly distributed surrounding lake, particularly at the northeastern shore. This allows aeolian sand to enter the lake from the east, west, and north directions (Zhao et al., 1993). The discharge of aeolian sand entering the lake is approximately $8.87 \times 10^6 \text{ t} \cdot \text{yr}^{-1}$, and the dust falling from the air enters the lake at a rate of approximately $3.04 \times 10^5 \text{ t} \cdot \text{yr}^{-1}$ (Zhao et al., 1993; Chen et al., 2008). Meanwhile, the sediment load from rivers entering the lake is approximately $4.98 \times 10^5 \text{ t} \cdot \text{yr}^{-1}$ (LZBCAS, 1994). These inputs result in an annual sedimentary thickness in Qinghai Lake of approximately 1.6 mm, leading approximately $2.99 \times 10^6 \text{ m}^3$ of lake water overflows and lake surface area increases. The sandy materials entering the lake are transported by lake waves and currents from west to east, forming subaqueous barriers. The sandy barriers gradually become higher and wider, eventually emerging from the water. This isolates lagoons from Qinghai Lake, while Qinghai Lake surface area decreases (Zhao et al., 1993; Zhang et al., 2003). Aeolian sand, approximately 1.39×10^6

t.yr⁻¹, is drifted from the west coast of Qinghai Lake to the east coast (Shadao Region) during the freezing period of Qinghai Lake (Zhang et al., 2003; Chen et al., 2008). This indicates that land area of the Shadao Region should increase slowly, and the coastline of the Shadao Region should extend towards the lake. Therefore, the diameter of Qinghai Lake from the west to east coast will become shorter, while the diameter from the south to north coast will become longer.

4. Conclusions

Mean high tide lines extracted from multitemporal landsat imagery from 1973 to 2015, with a total of 56 scenes, were used to examine the changing patterns of lake surface area of Qinghai Lake and surrounding lakes. There were four stages of surface area change of Qinghai Lake: a stable decrease stage (1973-1988), a fluctuant decrease stage (1988-2002), a lowest area stage (2003-2005), and a fluctuant increase stage (2006-2015). Haiyanwan Lake (~90 km²) was isolated from Qinghai Lake in 2003 and was linked into Qinghai Lake in 2006. The surface area change of Erhai Lake could be divided into two stages: the fluctuant stage (1973-2004) and fluctuant increase stage (2004-2015).

Variations in lake surface area, excluding Erhai Lake and Shadao Lake, were significantly positively correlated to lake level. Estuary area variations were significantly negatively correlated to lake level. The sediment loads from rivers flowing into Qinghai Lake were relatively low and only slightly influenced the estuary. The lake's evolutionary processes (e.g., Gahai Lake, Haiyanwan Lake) in the Shadao Region were influenced by aeolian sand and the lake water balance under relatively low precipitation and strong evaporation. Erhai Lake was also influenced by runoff from Daotang River.

In future decades, the Shadao Region's land area will increase slowly and the Shadao Region's coastline will extend towards the lake. The diameter of Qinghai Lake will become shorter from west to east coast, while the diameter from the south to north coast will become longer.

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References

- Adrian, R., O'Reilly, C.M., Zagarese, H.S., et al., 2009. Lakes as sentinels of climate change. *Limnology and Oceanography*, 54, 2283-2297.
- Alesheikh, A.A., Ghorbanali, A., Nouri, N., 2007. Coastline change detection using remote sensing. *International Journal of Environmental Science and Technology*, 4 (1): 61-66.
- An, Z.S., Colman, S.M., Zhou, W.J., Li, X.Q., Brown, E.T., Jull, A.J.T., Cai, Y.J., Huang, Y.S., Lu, X.F., Chang, H., Song, Y.G., Sun, Y.B., Xu, H., Liu, W.G., Jin, Z.D., Liu, X.D., Cheng, P., Liu, Y., Ai, L., Li, X.Z., Liu, X.J., Yan, L.B., Shi, Z.G., Wang, X.L., Wu, F., Qiang, X.K., Dong, J.B., Lu, F.Y., Xu, X.W., 2012. Interplay between the Westerlies and Asian monsoon recorded in Lake Qinghai sediments since 32 ka. *Scientific Reports*, 2, 619; DOI:10.1038/srep00619.
- Bai, J., Chen, X., Li, J.L., et al., 2011. Changes in the area of inland lakes in arid regions of central Asia during the past 30 years. *Environmental Monitoring and Assessment*, 178: 247-256.
- Che, T., Li, X., Jin, R., 2009. Monitoring the frozen duration of Qinghai Lake using satellite passive microwave remote sensing low frequency data. *Chinese Science Bulletin*, 54, doi: 10.1007/s11434-009-0044-3.
- Chen, G.C., Chen, X.Q., Gou, X.J., 2008. Ecological environment protection and restoration of the Qinghai Lake Basin. Qinghai People's Press, Xining (in Chinese).
- Chen, K.Z., Bowler, J.M., Kelts, K., 1990. Palaeoclimatic evolutions within the Qinghai-Xizang (Tibet) Plateau in the last 40000 years. *Quaternary Sciences*, (1): 21-31 (in Chinese).
- Christensen, J.H., Kumar, K.K., Aldrian, E., 2014. Climate phenomena and their relevance for future regional climate change. *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Stocker TF, et al. (Cambridge University Press, Cambridge, UK).
- Chu, Z.X., Ma, X.H., Zhang, J.Q., Dong, M.M., Gao, Y.H., 2005. Comparison of mean high tide line and 2 m isobath reflecting erosion and accretion of the Yellow River Delta. *Marine Geology & Quaternary Geology*, 25(4), 23-27 (in Chinese).
- Cui, B.L., Li, X.Y., 2011. The change of the Yellow River Estuary and it's response to the sediment and runoff of the low reaches (1976-2005). *Geomorphology*, 127: 32-40.

399 Cui, B.L., Li, X.Y., 2014. Characteristics of stable isotope and hydrochemistry of the groundwater
400 around Qinghai Lake, NE Qinghai-Tibet Plateau, China. *Environmental Earth Sciences*,
401 71:1159-1167.

402 Cui, B.L., Li, X.Y., 2015a. Stable isotope reveal sources of precipitation in the Qinghai Lake Basin of
403 the northeastern Tibetan Plateau. *Science of the Total Environment*, 527-528: 26-37.

404 Cui, B.L., Li, X.Y., 2015b. Runoff processes in the Qinghai Lake Basin, Northeast Qinghai-Tibet Plateau,
405 China: Insights from stable isotope and hydrochemistry. *Quaternary International*, 380-31: 122-132.

406 Cui, B.L., Li, X.Y., 2016. The impact of climate changes on water level of Qinghai Lake in China over
407 the past 50 years. *Hydrology Research*, 47(2): 532-542.

408 Cui, B.L., Li, X.Y., Li, Y.T., Ma, Y.J. & Yi, W.J. 2011. Runoff characteristics and hysteresis to
409 precipitation in the Qinghai Lake Basin: A case study in Buha River Basin. *Journal of Desert*
410 *Research* 31(1): 247-253 (in Chinese).

411 Feng, Z.K., Li, X.H., 2006. Remote sensing monitoring study for water area change and lakeshore
412 evolution of Qinghai Lake in last 20 years. *Journal of Palaeogeography*, 8(1): 131-141. (In Chinese)

413 Hao, X., 2008. A green fervor sweeps the Qinghai-Tibetan Plateau. *Science*, 321: 633-635.

414 Jin, Z.D., Zhang, F., Wang, H.L., Bai, A.J. & Qiu, X.N. 2013. The reasons of rising water level in Lake
415 Qinghai since 2005. *Journal of Earth Environment* 4(3): 1355-1362 (in Chinese).

416 Kelley, G.W., Hobgood, J.S., Bedford, K.W., Schwab, D.J., 1998. Generation of three-dimensional lake
417 model forecasts for Lake Erie. *Weather Forecast*, 13, 305-315.

418 Kezer, K., Matsuyama, H., 2006. Decrease of river runoff in the Lake Balkhash basin in Central Asia.
419 *Hydrological Processes*, 20, 1407-1423.

420 Kiage, L.M., Liu, K.B., Walker, N.D., et al., 2007. Recent land-cover/use change associated with land
421 degradation in the Lake Baringo catchment, Kenya, East Africa: evidence from Landsat TM and
422 ETM+. *International Journal of Remote Sensing*, 28(19): 4285-4309.

423 Lehner, B., Döll, P., 2004. Development and validation of a global database of lakes, reservoirs and
424 wetlands. *Journal of Hydrology*, 296, 1-22.

425 Li, F.X., Li, L., Shen, F., et al., 2004. Evolution of lakeshore shape of Qinghai Lake and its causes.
426 *Resources Science*, 26(1): 38-44.

427 Li, X.D., Xiao, J.S., Li, F.X., et al., 2012. Remote sensing monitoring of the Qinghai Lake based on EOS
428 /MODIS data in recent 10 years. *Journal of Natural Resources*, 27(11): 1962-1970. (In Chinese)

429 Li, X.Y., Ma, Y.J., Xu, H.Y., Wang, J.H., Zhang, D.S., 2009. Impact of land use and land cover change
430 on environmental degradation in Lake Qinghai watershed, northeast Qinghai-Tibet Plateau. *Land*
431 *Degradation & Development*, 20: 69-83.

432 Li, X.Y., Xu, H.Y., Sun, Y.L., Zhang D.S., et al., 2007. Lake-level change and water balance analysis at
433 Lake Qinghai, west China during recent decades. *Water Resources Management*, 21: 1505-1516.

434 Li, X.Z., Liu, W.G., 2014. Water salinity and productivity recorded by ostracod assemblages and their
435 carbon isotopes since the early Holocene at Lake Qinghai on the northeastern Qinghai-Tibet Plateau,
436 China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 407: 25-33.

437 Lioubimtseva, E., Henebry, G.M., 2009. Climate and environmental change in arid Central Asia: Impacts,
438 vulnerability, and adaptations. *Journal of Arid Environments*, 73, 963-977.

439 Liu, B.K., Wei, X.L., Du, Y.E., et al., 2013. Dynamics of Qinghai Lake area based on environmental
440 mitigation satellite data. *Pratacultural Science*, 30(2): 178-184. (In Chinese).

441 Liu, H., Jezek, K.C., 2004. Automated extraction of coastline imagery by integrating canny edgy
442 detection and locally adaptive thresholding methods. *International Journal of Remote Sensing*, 25(5):
443 937-958.

444 Liu, R.X., Liu, Y.J., 2008. Area changes of Lake Qinghai in the latest 20 years based on remote sensing
445 study. *Journal of Lake Sciences*, 20(1): 135-138. (In Chinese).

446 Liu, X.J., Lai, Z.P., Madsen, D., et al., 2015. Last deglacial and Holocene lake level variations of
447 Qinghai Lake, north-eastern Qinghai-Tibetan Plateau. *Journal of Quaternary Science*, 30(3):
448 245-257.

449 LZBCAS (Lanzhou Branch of Chinese Academy of Sciences), 1994. Evolution of recent environment in
450 Qinghai Lake and its prediction. Science Press, Beijing (in Chinese).

451 LZIGCAS (Lanzhou Institute of Geology, Chinese Academy of Sciences), 1979. comprehensive
452 investigation report of Qinghai lake. Science Press, Beijing (in Chinese).

453 Ma, Y., 1996. Correlations between modern climatic factors and lake level change in Qinghai Lake.
454 *Journal of Lake Sciences*, 8(2): 103-106 (in Chinese).

455 Maiti, S., Bhattacharya, A.K., 2009. Shoreline change analysis and its application to prediction: A remote
456 sensing and statistics based approach. *Marine Geology*, 257, 11–23.

457 Mason, I.M., Guzkowska, M.A.J., Rapley, C.G., 1994. The response of lake levels and areas to climatic
458 change. *Climate Change*, 27, 161-197.

459 Medina, C.E., Enri, J.G., Villares, A.P., 2008. Water level fluctuations derived from ENVISAT Radar
460 Altimeter (RA-2) and in-situ measurements in subtropical waterbody: Lake Izabel (Guatemala).
461 *Remote Sensing of Environment*, 112: 3604-3617.

462 Ouma, Y.O., Tateishi, R., 2007. Lake water body mapping with multi-resolution based image analysis
463 from medium-resolution satellite imagery. *International Journal of Environmental Studies*, 64(3):
464 357–379.

465 Qin, B.Q., Huang, Q., 1998. Evaluation of the climatic change impacts on the inland lake-a case study of
466 lake Qinhai, China. *Climatic Change*, 39: 695-714.

467 Shen, F., Kuang, D.B., 2003. Remote sensing investigation and survey of Qinghai Lake in the past 25
468 years. *Journal of Lake Sciences*, 15(4): 289-296. (In Chinese)

469 Shen, Y.W., Chen, H., Xu, C.Y., 2013. Remote sensing monitoring study for the tendency of Qinghai
470 Lake's water area in last 41 years. *Journal of Water Resources Research*, 2, 309-315. (In Chinese)

471 Shi, Y.F., Chen, L.X., Li, W.Z., Yi, S.M., 1958. The preliminary investigation of natural geography
472 (Geomorphology) around Qinghai Lake. *Acta Geographica Sinica*, 24(1): 33-48 (in Chinese).

473 Song, C., Huang, B., Richards, K., Ke, L., Phan, V.H., 2014. Accelerated lake expansion on the Tibetan
474 Plateau in the 2000s: Induced by glacial melting or other processes?. *Water Resources Research*, 50,
475 doi:10.1002/2013WR014724.

476 Tang, R.C., Gao, X.Q., Zhang, J., 1992. The annual changes of the water level of the Lake Qinghai in the
477 recent thirty years. *Chinese Science Bulletin*, 37(6): 524-524.

478 Tatyana, A.S., Igor, S.Z., 2000. Irrigation expansion and dynamics of desertification in the Circum-Aral

- region of Central Asia. *Applied Geography*, 20, 349–367.
- Tian, S.Z., Du, B.L., Yu, J., 1997. The impact of sea level rise on the coast of Bolai Bay and countermeasures. *Marine Science Bulletin*, 16 (1): 1-9 (in Chinese).
- Williamson, C.E., Saros, J.E., Schindler, D.W., 2009a. Sentinels of change. *Science*, 323, 887-888.
- Williamson, C.E., Saros, J.E., Vincent, W.F., et al., 2009b. Lakes and reservoirs as sentinels, integrators, and regulators of climate change. *Limnology and Oceanography*, 54, 2273-2282.
- Winter, T.C., 2004. The hydrology of lakes. In: O'Sullivan, P.E., Reynolds, C.S., (eds), *The Lakes Handbook*, vol 1: Limnology and Limnetic Ecology. Blackwell Publishing, pp 71-76.
- Xu, H., Hou, Z., An, Z., Liu, X., Dong, J., 2010. Major ion chemistry of waters in Lake Qinghai catchments, NE Qinghai-Tibet plateau, China. *Quaternary International*, 212: 35-43.
- Yan, H.Y., Jia, S.F., 2003. Water balance and water resources allocation of Qinghai Lake. *Journal of Lake Science*, 15(1): 35-40 (in Chinese).
- Yang, B., Qin, C., Wang, J.L., He, M.H., Melvin, T.M., Osborn, T.J., Briffa, K.R., 2014. A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. *PNAS*, 111(8): 2903-2908.
- Yi, G.H., Zhang, T.B., 2015. Delayed response of lake area change to climate change in Siling Co Lake, Tibetan Plateau, from 2003 to 2013. *International Journal of Environmental Research and Public Health*, 12, 13886-13900.
- Yıldırım, Ü., Erdoğan, S., Uysal, M., 2011. Changes in the coastline and water level of the Akşehir and Eber Lakes between 1975 and 2009. *Water Resource Management*, 25: 941-962.
- Yin, Q.J., Yang, Y.L., 2005. Remote sensing monitoring of Lake Qinghai based on EOS/MODIS Data. *Journal of Lake Sciences*, 17(4): 356-360. (In Chinese)
- Zang, Q.Y., 1996. Nearshore sediment along the Yellow River Delta. Ocean Press, Beijing (in Chinese).
- Zhang, D.S., Wu, J.W., Lu, R.J., Zhao, Y.Z., Chen, Y., 2003. Study on the planning of the synthetic control of land desertification in the peripheral area of the Qinghai Lake. *Arid Zone Research*, 20(4):307-331 (in Chinese).
- Zhang, G.Q., Xie, H.J., Duan, S.Q., et al., 2011. Water level variation of Lake Qinghai from satellite and in situ measurements under climate change, *Journal of Applied Remote Sensing*, 5, 053532(1)-053532(15), doi:10.1117/1.3601363.
- Zhao, H.B., He, D.N., Zhang, D.S., Nian, K., Wang, B., 1993. The calculation of sand discharge entering Qinghai Lake and formation of submerged barriers. *Journal of Lake Sciences*, 5(1): 40-46 (in Chinese).

512 **Captions of Figures and Tables**

513 **Fig. 1. Locations of the Qinghai Lake Basin and hydrological stations**

514 **Fig. 2. Monthly variations of climatic factors and Qinghai Lake level**

515 **Fig. 3. Coastline changes of Qinghai Lake and other five regions**

516 **Fig. 4. Variations of surface area of lakes and Qinghai Lake level from 1961 to 2015**

517 **Fig. 5. Variations of river estuary's area and Qinghai Lake level from 1961 to 2015**

518 **Table 1. List of images in this research**

519 **Table 2. Lake surface area of Qinghai Lake and surrounding lakes**

520 **Table 3. Pearson correlation coefficients between Qinghai Lake level and surface area of lakes**

521 **Table 4. Pearson correlation coefficients between Qinghai Lake level and land area of several river**

522 **estuaries and Shadao Region**

523

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541 **Table 1. List of images in this research**

Dates	Satellite/sensor	Path/row (Image 1)	Path/row (Image 2)	Resolution		
				Spatial (m)	Spectral (Band)	Revisit (days)
20/09/1973	Landsat1/MSS	143/34	--	78	4	18
16/05/1975	Landsat2/MSS	143/34	--	78	4	18
21/07/1976	Landsat2/MSS	143/34	--	78	4	18
16/07/1977	Landsat2/MSS	143/34	143/35	78	4	18
15/08/1987	Landsat5/TM	133/34	133/35	30	7	16
31/12/1988	Landsat4/TM	133/34	133/35	30	7	16
16/01/1989	Landsat4/TM	133/34	133/35	30	7	16
28/08/1992	Landsat5/TM	133/34	133/35	30	7	16
27/05/1993	Landsat5/TM	133/34	133/35	30	7	16
21/10/1994	Landsat5/TM	133/34	133/35	30	7	16
21/08/1995	Landsat5/TM	133/34	133/35	30	7	16
17/04/1996	Landsat5/TM	133/34	133/35	30	7	16
26/08/1997	Landsat5/TM	133/34	133/35	30	7	16
12/07/1998	Landsat5/TM	133/34	133/35	30	7	16
08/08/1999	Landsat7/ETM+	133/34	133/35	30	8	16
18/08/2000	Landsat5/TM	133/34	133/35	30	7	16
12/07/2001	Landsat7/ETM+	133/34	133/35	30	8	16
31/07/2002	Landsat7/ETM+	133/34	133/35	30	8	16
31/05/2003	Landsat7/ETM+	133/34	133/35	30	8	16
14/09/2004	Landsat5/TM	133/34	133/35	30	7	16
15/07/2005	Landsat5/TM	133/34	133/35	30	7	16
03/08/2006	Landsat5/TM	133/34	133/35	30	7	16
22/08/2007	Landsat5/TM	133/34	133/35	30	7	16
05/06/2008	Landsat5/TM	133/34	133/35	30	7	16
11/08/2009	Landsat5/TM	133/34	133/35	30	7	16
29/07/2010	Landsat5/TM	133/34	133/35	30	7	16
01/08/2011	Landsat5/TM	133/34	133/35	30	7	16
12/09/2012	Landsat7/ETM+	133/34	133/35	30	8	16
23/09/2013	Landsat8/OLI	133/34	--	30	11	16
24/07/2014	Landsat8/OLI	133/34	--	30	11	16
27/07/2015	Landsat8/OLI	133/34	--	30	11	16

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543

544 **Table 2. Lake surface area of Qinghai Lake and surrounding lakes**

Dates	Qinghai Lake (km ²)	Gahai Lake (km ²)	Shadao Lake (km ²)	Haiyanwan Lake (km ²)	Erhai Lake (km ²)	All lakes (km ²)	Qinghai Lake level (m)
20/09/1973	4420.29	48.03			6.00	4474.32	3195.27
16/05/1975	4394.73	47.70			6.31	4448.74	3194.90
21/07/1976	4404.62	47.37			5.64	4457.62	3195.09
16/07/1977	4390.36	46.84			5.67	4442.88	3194.91
15/08/1987	4285.09	45.29	15.94		6.56	4352.88	3193.87
31/12/1988	4261.52	46.20	14.43		5.99	4328.14	3193.58
16/01/1989	4268.56	46.75	14.36		6.23	4335.89	3193.57
28/08/1992	4274.19	45.55	23.98		6.15	4349.87	3193.83
27/05/1993	4256.29	46.01	23.50		5.90	4331.71	3193.69
21/10/1994	4259.82	45.79	23.33		6.18	4335.13	3193.78
21/08/1995	4251.27	46.02	22.54		5.50	4325.33	3193.58
17/04/1996	4222.95	45.37	21.57		6.12	4296.01	3193.39
26/08/1997	4235.07	45.79	20.09		6.06	4307.00	3193.45
12/07/1998	4215.75	45.76	19.34		5.85	4286.71	3193.23
08/08/1999	4239.99	46.30	19.06		6.08	4311.42	3193.41
18/08/2000	4226.96	45.41	16.53		5.46	4294.35	3193.36
12/07/2001	4205.84	45.57	15.90		5.67	4272.98	3193.06
31/07/2002	4206.70	45.56	14.48		6.22	4272.96	3193.03
31/05/2003	4094.48	45.13	13.56	93.42	5.96	4252.56	3192.88
14/09/2004	4099.50	44.33	11.92	90.82	5.75	4252.33	3192.99
15/07/2005	4099.39	44.42	11.39	88.48	5.91	4249.58	3193.02
03/08/2006	4228.70	44.66	10.91		5.95	4290.23	3193.36
22/08/2007	4227.32	44.84	10.43		6.08	4288.66	3193.35
05/06/2008	4232.89	45.38	9.97		6.43	4294.67	3193.37
11/08/2009	4238.13	44.95	9.36		6.33	4298.77	3193.50
29/07/2010	4264.98	45.07	10.06		6.62	4326.73	3193.69
01/08/2011	4276.37	45.17	13.86		7.05	4342.44	3193.94
12/09/2012	4357.39	45.74			7.08	4410.21	3194.51
23/09/2013	4375.71	46.33			7.37	4429.42	3194.49
24/07/2014	4370.18	46.29			7.40	4423.86	3194.33
27/07/2015	4382.60	46.41			7.21	4436.22	3194.65

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546

Table 3. Pearson correlation coefficients between Qinghai Lake level and surface area of lakes

	All lakes area	Qinghai Lake	Shadao Lake	Haiyanwan Lake	Gahai Lake	Erhai Lake
Qinghai Lake level	0.988*	0.948*	0.347	-0.958	0.788*	0.345

* Correlation is significant at the 0.001 level; others were non-significant.

550 **Table 4. Pearson correlation coefficients between Qinghai Lake level and land area of several river**
551 **estuaries and Shadao Region**

	Buha River estuary	Shaliu River estuary	Heima River estuary	Shadao Region
Qinghai Lake level	-0.991*	-0.966*	-0.959*	-0.979*

552 * Correlation is significant at the 0.001 level.