Estimation and trend detection of water storage at Nam Co Lake, central Tibetan Plateau

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1. Introduction

Climate changes are expected to seriously affect the water resources of the Tibetan Plateau (Immerzeel et al., 2010). Inland lakes that are widely distributed on the Tibetan Plateau have minimum impact of human activities and are an important component of the water supply in China. The enlargement and shrinkage of inland lakes reflect the changes in water and heat balance, which is a sensitive indicator of the climate change (Shi, 1990). Lake water storage variation provides information about temperature, rainfall, humidity and solar radiation, while regional water storage variations reflect the climate change in a larger scale (Redway, 1924; Hartmann, 1990; Jones et al., 2001; Novaky, 2008). Lake water level variation directly records the process of water storage balance in the basin, which is a quite sensitive response to the climate change (Li et al., 1998). Therefore, fluctuation of inland lakes in the Tibetan Plateau (variation of area, water level, water storage, etc.) is an important indicator of climate change. Understanding these variations and the role of climate is important for water resource management as well as for predicting future changes in lake hydrology as a result of climate change.

Existing research on lake variations mainly focus on the monitoring of area changes in lake. Due to the wide monitoring scope, fast speed and low cost, remote sensing technology has unique advantages in the dynamic monitoring of lakes in inaccessible areas of the Tibetan Plateau (Quincey et al., 2007; Chu et al., 2008; Yang et al., 2008). Previous work utilized middle and high resolution optical image data to analyze the fluctuation in the area of main lakes on Tibetan Plateau and the results indicated that lakes which depend on the supply of glacial meltwater in the middle and northern Tibetan Plateau are stable and tending to enlarge, including Nam Co Lake, Serlingcuo Lake, Palgon Lake and Hala Lake (Yang et al., 2003; Zhao et al., 2006; Wu and Zhu, 2008). Lakes located in the northeastern and western Tibetan Plateau, which depend on the supply of inland rivers and rainfall are shrinking, including Qinghai Lake, Yamdrok Lake, Zhari Namco Lake, Dangre Yong Lake, Ayakkum Lake and Ulan Ul Lake (Morrill, 2004; Lu et al., 2008; Yang et al., 2008). Previous work utilized middle and high resolution optical image data to analyze the fluctuation in the area of main lakes on Tibetan Plateau and the results indicated that lakes which depend on the supply of glacial meltwater in the middle and northern Tibetan Plateau are stable and tending to enlarge, including Nam Co Lake, Serlingcuo Lake, Palgon Lake and Hala Lake (Yang et al., 2003; Zhao et al., 2006; Wu and Zhu, 2008). Lakes located in the northeastern and western Tibetan Plateau, which depend on the supply of inland rivers and rainfall are shrinking, including Qinghai Lake, Yamdrok Lake, Zhari Namco Lake, Dangre Yong Lake, Ayakkum Lake and Ulan Ul Lake (Morrill, 2004; Lu et al., 2008; Yang et al., 2008).
Still, research related to water storage only exists in three areas with hydrological observation stations, namely, Qinghai Lake, Yamdrok Lake and Zabuye Salt Lake (Ding and Liu, 1995; Li et al., 2005; Qi and Zheng, 2006; Bian et al., 2009), and the water storage research of lakes in other areas of the vast Tibetan Plateau is limited.

This study focuses on the Nam Co lake, the largest lake on Tibetan plateau as well as the highest large lake in the world. Altogether 42 images of three kinds of remote sensing image data were used in combination with hydrological data actually measured in the field, and meteorological station data, to quantitatively acquire the information of surface fluctuation, water storage variation, and to study the lake response to climate change from 1976 to 2009 for the first time. The results provide theoretical support and data for further understanding the processes and extent of water resource response to global climate change, and provide a scientific basis for rational development and utilization of water resource in Tibetan plateau.

2. Study area and data

Nam Co Lake is the largest lake in the Tibet Plateau as well as the highest large lake in the world. It is located at 90°16′–91°03′E, 30°30′–30°55′N (Fig. 1). It belongs to Damxung County of Lhasa City and Baingoin County of Nagqu Prefecture of Tibetan Autonomous Region. Its elevation is 4718 m and the water area is 1920 km² measured in 1979 (Guan et al., 1984), and the maximum depth is over 90 m (according to the data measured from 2005 to 2007).

Nam Co Lake Basin is located at 89°21′–91°23′E, 29°56′–31°7′N, with an area of 10,610 km². It is a closed basin in the north of Gangdise-Nyainqentanglha Mountain in the plateau lake basin region of southern Qiangtang in Northern Tibet. The average altitude of Nyainqentanglha Mountain in the southeast of the basin is about 5500 m. There are many modern glaciers on the mountain, mostly short and small ones, and the glacial meltwater directly flows into the lake in a comb-like form passing a short distance of piedmont area. Northern and northwestern parts of the basin belong to a gently undulating, low mountainous area whose average altitude is about 5000 m. The whole basin receives strong solar radiation and gets a long duration of sunshine, which can reach 2900–3200 h a year. The basin belongs to the plateau subfrigid monsoon semiarid climate zone, which is cold and has no distinct seasons. The annual temperature range is larger than daily variability.

Because of its special geographical position, Nam Co Lake is barely influenced by human activities, and its water fluctuation only reflects long-term climate change information.

There was no meteorological observation station or hydrological station in the basin before 2005. After 2005, the Institute of Tibetan Plateau Research established the Nam Co Lake Multi-Layer Comprehensive Observation and Research Station (Nam Co Lake Station) of China Academy of Sciences and gradually began the monitoring of some regular parameters. Researchers conducted
three comprehensive investigations from 2005 to 2007 and obtained the water depth data of Nam Co Lake (Wang et al., 2009).

In this paper 42 visible and near infrared remote sensing images from landsat MSS/ETM, CBERS and HJ-1A/1B satellites covering the study area from 1976 to 2009 were used to estimate water surface areas in different time periods. The details of their acquisition time and spatial resolution can be found in Table 1. The ground pixel resolution of CBERS image is 19.5 m, and its 5 bands according to spectral response ranges from visible light to near infrared spectrum are 0.45–0.52 μm, 0.52–0.59 μm, 0.63–0.69 μm, 0.77–0.89 μm and 0.51–0.73 μm respectively. The ground pixel resolution of the HJ-1A/1B image is 30 m, and its 4 bands are 0.43–0.52 μm, 0.52–0.60 μm, 0.63–0.69 μm and 0.76–0.90 μm respectively.

The regular monitoring data of the 11 meteorological stations around Nam Co Lake from 1976 to 2009 were used, including daily average temperature, lowest temperature, highest temperature, rainfall, sunshine duration, wind speed and water vapor pressure. The locations of all the meteorological stations are listed in Table 2, and some of them are shown in Fig. 1.

### 3. Methodology

#### 3.1. Water storage calculation

The water storage $W$ for a lake can be written as 

$$W = \int (S, H)$$

where $S$ is the lake surface area, $H$ is the water depth of the lake underwater landform.

A series of multi-temporal remote sensing images were used to acquire the lake surface area ($S$) in different periods. First, all the images were conducted geometric correction, registering and inlaying, and the inaccuracy is controlled within a pixel. Then according to the characteristics of the sensors CBERS and HJ-1A/1B, band 4, 3 and 2 (red, green, blue) were adopted to determine the lake surface area; as to the landsat satellite data, a total of six bands of ETM + band 1–5 and band 7 were utilized to confirm the lake surface area according to the band threshold value and spectral relationships of each ground object, supplemented by visual interpretation method to rectify the result (Niu et al., 2008).

The lake underwater landform data ($H$) were obtained through measurements taken in the field. Based on the lake bathymetric survey data measured from 2005 to 2007 with the accuracy of 0.01 m and 305721 measuring points, we drew the isotopic map (Fig. 2), and then established the underwater landform digital elevation model (DEM) with grid units of 30 m × 30 m by the extended module (3D Analyst) in ArcMap.

And formula (1) can be further written as

$$W = \sum_{i=1}^{n} S_i \times \Delta h$$

where $n$ is the equally parted cells number of the elevation difference, $\Delta h = (h_i - h_{i-1})/n$ is the distance with each cell, and $S_i$ is the water surface area with the elevation of $h_i + (i - 1)\Delta h$, which can be automatically derived from the DEM data mentioned above.

Then, the series of water storage data ($W$) were obtained by the “Area and Volume” module of 3D analysis in ArcGIS, utilizing the calculation of excavation and filling based on the underwater landform DEM and the lake surface area data.

#### 3.2. Lake surface evaporation and precipitation estimation

Since there was no meteorological station in the Nam Co basin before 2005, it is very difficult to accurately estimate the average rainfall and evaporation of the whole basin. Because there is so few records on the direct evaporation of the lake surface, in this paper the Penman–Monteith model recommended by the Food and Agriculture Organization (FAO) of the United Nation was adopted to estimate the lake evaporation (Allen et al., 1998), and the formula is:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{1000}{T} U_2(e_s - e_d)}{\Delta + \gamma(1 + 0.34U_2)}$$

where $\Delta$ represents the curve slope of saturated water vapor pressure ($\text{kPa} \cdot \text{C}^{-1}$) at temperature $T$; $R_n$ represents the solar net radiation at the top layer (MJ m$^{-2}$ d$^{-1}$); $G$ represents soil-pass heat (MJ m$^{-2}$ d$^{-1}$); $\gamma$ is the dry–wet constant ($\text{kPa} \cdot \text{C}^{-1}$); $T$ is the average monthly temperature ($\text{C}$); $U_2$ is the wind speed at the height of 2 m (m/s); $e_s$ and $e_d$ are the saturated water vapor pressure and actual water vapor pressure (kPa) respectively at temperature $T$.

The thin-plate spline method (TPS) (Hutchinson, 1998) was adopted to interpolate the evaporation and precipitation data of the whole basin considering the terrain factor, and the lake surface evaporation and precipitation time series data were further extracted, based on the 11 stations near the study area.

### Table 1

Remote sensing data and digital elevation model (DEM) data used in this paper. DEM is downloaded from: http://asterweb.jpl.nasa.gov/gdem-wist.asp.

<table>
<thead>
<tr>
<th>SN</th>
<th>Data type</th>
<th>Acquisition time (year/month/day)</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Landsat2 MSS</td>
<td>1976/11/11; 1976/12/17; 1977/01/22; 1977/02/09</td>
<td>57</td>
</tr>
<tr>
<td>2</td>
<td>Landsat4 TM</td>
<td>1989/01/19; 1992/12/13; 1993/01/14; 1993/03/03</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>Landsat5 TM</td>
<td>1991/09/14; 2007/05/15; 2009/10/17; 2009/12/04</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>Landsat7 ETM</td>
<td>1999/12/17; 2000/03/06; 2000/04/07; 2000/10/16; 2008/11/01; 2000/12/19; 2001/02/25; 2001/06/13; 2001/11/04; 2001/12/06; 2002/02/24; 2002/03/28; 2002/05/15; 2002/12/09; 2003/01/10; 2003/04/16</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>CBERS-CCD</td>
<td>2003/11/07; 2004/09/14; 2004/10/10; 2005/11/30; 2006/01/21</td>
<td>19.5</td>
</tr>
<tr>
<td>6</td>
<td>HJ-CCD</td>
<td>2008/12/13; 2009/01/07; 2009/02/06; 2009/03/14; 2009/04/16; 2009/05/19; 2009/06/25; 2009/08/30; 2009/11/08</td>
<td>30</td>
</tr>
</tbody>
</table>

### Table 2

Meteorological stations used in this paper.

<table>
<thead>
<tr>
<th>SN</th>
<th>Station</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Altitude (m)</th>
<th>Record period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baingoin</td>
<td>31°23’</td>
<td>90°01’</td>
<td>4700</td>
<td>1956.10–2009.12</td>
</tr>
<tr>
<td>2</td>
<td>Damxung</td>
<td>30°29’</td>
<td>91°06’</td>
<td>4200</td>
<td>1962.08–2009.12</td>
</tr>
<tr>
<td>4</td>
<td>Xainza</td>
<td>30°57’</td>
<td>88°38’</td>
<td>4072</td>
<td>1990.04–2009.12</td>
</tr>
<tr>
<td>5</td>
<td>Amdo</td>
<td>32°21’</td>
<td>91°06’</td>
<td>4800</td>
<td>1965.11–2009.12</td>
</tr>
<tr>
<td>7</td>
<td>Lhasa</td>
<td>29°40’</td>
<td>91°08’</td>
<td>3648.7</td>
<td>1955.01–2009.12</td>
</tr>
<tr>
<td>8</td>
<td>Tsetang</td>
<td>29°15’</td>
<td>91°46’</td>
<td>3551.7</td>
<td>1956.09–2009.12</td>
</tr>
<tr>
<td>10</td>
<td>Sokshar</td>
<td>31°53’</td>
<td>93°47’</td>
<td>4022.8</td>
<td>1956.11–2009.12</td>
</tr>
<tr>
<td>11</td>
<td>Lhari</td>
<td>30°40’</td>
<td>93°17’</td>
<td>4488.8</td>
<td>1954.11–2009.12</td>
</tr>
</tbody>
</table>
3.3. Analysis of long-term trends in meteorological variables and water storage

To assess the significance of climatic factors and lake water storage trends, we employed the non-parametric Mann–Kendall test (Mann, 1945; Kendall, 1975) to conduct trends analysis. This test has been identified as one of the most robust techniques available to uncover and estimate linear trends in environmental data (Hess et al., 2001). As to the series $X_t = (x_1, x_2, \ldots, x_n)$, this method defines the standard normal variate $U_{MK}$ as:

$$U_{MK} = \frac{S}{\sqrt{\text{Var}(S)}}$$

(4)

where $S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)$

(5)

$$\text{sgn}(x) = \begin{cases} 1, & x > 0 \\ 0, & x = 0 \\ -1, & x < 0 \end{cases}$$

(6)

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n}ti(i-1)(2i+5)}{18}$$

(7)

where $S$ denotes the relationship between the number of observation pairs $(x_i, x_j, j > i)$, and $n$ is the total number of samples. A time series has a clear trend, defined as a level of significance of 5%, if $|U_{MK}| > U_{a/2} = 1.96$. A positive $U_{MK}$ indicates an increasing trend in the time series, while a negative $U_{MK}$ indicates a decreasing trend.

4. Results

4.1. Water storage of Nam Co Lake

According to the lake underwater landform data acquired in the field, the maximum lake depth is about 98 m, and the average lake depth is about 45.63 m. Fig. 3 shows the water level-storage curve based on the calculation from Section 3.1.

The multi-year mean water storage of Nam Co Lake is $842.36 \times 10^8$ m$^3$, with the maximum $870.30 \times 10^8$ m$^3$, the minimum $786.06 \times 10^8$ m$^3$, and the coefficient of variation of 0.033.

4.2. Water storage intra-annual variation

Selecting 2009 as a sample study period, based on the water surface areas obtained from the 10 images and bathymetric survey data, the intra-annual variation trend of water storage and surface area of Nam Co Lake can be acquired (Fig. 4). The intra-annual variation show that the water storage increases from March ($861.68 \times 10^8$ m$^3$) to late September and early October ($876.69 \times 10^8$ m$^3$), then begins to decrease until December ($870.30 \times 10^8$ m$^3$). The lake surface fluctuation appears to be similar (Table 3).

The intra-annual character of lake water storage fluctuation is in line with that of the precipitation, which appears to increase from late April and reaches the maximum at the end of the warm season (from April to October) (Fig. 5).
4.3. Water storage inter-annual variation

Fig. 6 shows the inter-annual variation in water storage and lake surface area of Nam Co Lake in the past 34 years based on the water surface areas obtained from the 42 images and bathymetric survey data. From 1976 to 2009, the lake water storage is obviously increased from $786.06 \times 10^8$ m$^3$ to $870.30 \times 10^8$ m$^3$. The period can be divided into three phases with the respective tendency values listed in Table 4, which shows that the greatest increases and largest number of significant upward trends for lake water storage occurred during 1999–2006, with a tendency value of $6.41 \times 10^8$ m$^3$/a, and then maybe have gone into the placidly increasing phase. The lake surface area also showed the same character.

A comparative analysis of lake storage series and climate factor series shows a similar trend. Liu et al. (2009) concluded that the climate is the main factor affecting the lake water variation.

The seasonal variation of lake water storage during 1976–2009, showed that all years increased from each April and to late September and early October, then decrease until March of the next year. This result is basically in line with the in field measured water level variation trend of Nam Co Lake (Chen et al., 2009).

We also selected the data from the same month in different years to make further comparisons. Compared with the lake water storage in November 1976, the storage in November of 2000, 2001, 2003, 2005 and 2009 increased by 5.05%, 5.91%, 7.31%, 9.05% and 10% respectively; compared with the lake water storage in January of 1977, the storage in January of 1989, 1993, 2003, 2006 and 2006 increased by 0.87%, 1.48%, 6.03%, 8.53% and 8.61% respectively.

The spatial perspective, the east and west flat bank areas of the lake obviously enlarge, while the south and north abrupt slope areas of the lake enlarge slightly (Fig. 7). Compared with the lake surface area in November of 1976, areas in November of 2000, 2002, 2004, 2006 and 2008 increased by 2.87%, 4.48%, 6.03%, 8.53% and 8.61% respectively.

Table 3

<table>
<thead>
<tr>
<th>Month</th>
<th>Water storage ($10^8$ m$^3$)</th>
<th>Surface area (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>865.16</td>
<td>2009.65</td>
</tr>
<tr>
<td>2</td>
<td>868.35</td>
<td>2012.70</td>
</tr>
<tr>
<td>3</td>
<td>861.68</td>
<td>2005.73</td>
</tr>
<tr>
<td>4</td>
<td>870.80</td>
<td>2014.66</td>
</tr>
<tr>
<td>5</td>
<td>873.07</td>
<td>2017.41</td>
</tr>
<tr>
<td>6</td>
<td>875.54</td>
<td>2019.89</td>
</tr>
<tr>
<td>8</td>
<td>876.37</td>
<td>2020.73</td>
</tr>
<tr>
<td>10</td>
<td>876.69</td>
<td>2021.92</td>
</tr>
<tr>
<td>11</td>
<td>875.86</td>
<td>2020.06</td>
</tr>
<tr>
<td>12</td>
<td>870.30</td>
<td>2015.35</td>
</tr>
<tr>
<td>Mean value</td>
<td></td>
<td>871.38</td>
</tr>
</tbody>
</table>

Fig. 3. Water level-storage capacity curve of Nam Co Lake.

Fig. 4. Nam Co lake water storage and surface area variation trend in 2009. (The data of 2009 are lack of July and September because the images of the corresponding period were not acquired.)

Fig. 5. Monthly water storage of the Nam Co Lake in 2009 and the monthly total precipitation and evaporation of 2008 measured by the Nam Co station. The precipitation and evaporation data come from the daily observation data acquired by Nam Co Lake Multi-Layer Comprehensive Observation and Research Station of China Academy of Sciences. The lake water storage data of 2009 is lack of July and September because the images of the corresponding period were not acquired.

Fig. 6. Interannual variation trend of water storage and surface area of Nam Co lake of 1976–2009.
2001, 2003, 2005 and 2009 are enlarged by 41.06 km², 48.00 km², 59.32 km², 73.26 km² and 80.70 km² respectively. Additionally, the reasons for the seasonal variation of Nam Co Lake are summarily analyzed. In the Nam Co Lake Basin, the temperature rises to about 0 °C in April and enters the warm period which is from April to October. The centralized rainfall from June to September reach over 90% of a year’s total according to the meteorological station data analysis. Therefore, the rainfall supply for the lake reaches the maximum in the end of summer, along with the timing of glacial meltwater, and the lake surface area reaches the maximum value. After October, the temperature falls below 0 °C, the rainfall becomes rare and the glacial meltwater also decreases, and the lake surface area decreases.

### 4.4. Climate change

Climate change directly or indirectly influences the fluctuation of lake water storage, and it is an important driving factor for lake variability (Holzhauser et al., 2005). By correlation analysis of the mean monthly temperature acquired by the Nam Co station and the neighboring meteorological stations, from December 2005 to December 2007, Chen et al. (2009) found a positive relationship between them. Therefore, this paper selects the annual mean air temperature measured by Baingoin Station to conduct trend analysis of Nam Co Lake basin, and the data of rainfall and evaporation are acquired according to the methods mentioned above.

We used the non-parametric Mann–Kendall test to evaluate annual trends in air temperature, precipitation and evaporation on the Nam Co Lake during 1971–2009 based on the data acquired (Table 5). A general pattern of warming temperature and decreasing evaporation on the lake is evident, whereas the precipitation showed an increasing trend, but with \( p \geq 0.05 \) (Fig. 8). Regional annual mean air temperature increased significantly \( (p = 0.008) \) by 0.404 °C/10 a, and the annual mean evaporation decreased significantly \( (p = 0.0000976) \) by 40.89 mm/10 a during the period (Fig. 8).

We chose air temperature, precipitation and evaporation data of the same year as water storage data, and normalized the four series

<table>
<thead>
<tr>
<th>Period</th>
<th>Water storage ( (10^8 \text{ m}^3) )</th>
<th>Lake surface area ( (\text{km}^2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At the beginning of each period</td>
<td>At the end of each period</td>
</tr>
<tr>
<td>1976–1999</td>
<td>786.06</td>
<td>824.35</td>
</tr>
<tr>
<td>2006–2009</td>
<td>866.97</td>
<td>870.30</td>
</tr>
</tbody>
</table>
for further analysis of the trends (Fig. 9). Results indicate that the variation and trend of the water storage correlated well with air temperature and is in general agreement with precipitation, except two anomalous years. Evaporation is always more than precipitation during the study period, which indicates that the enlarging status of lake water storage is closely related to the supply of runoff.

Nam Co Lake is a closed inland lake, whose water storage supply depends on three sources: precipitation, stream runoff and underground runoff. The increasing precipitation on the lake directly contributed to the increment of the lake water storage. Also the lake’s south bank is the steep Nyainqentanglha Mountain, whose glacial meltwater flows into the lake in a comb-like form and comprises the important part of stream runoff (Guan et al., 1984). So it is also an inland lake with the dependence on the supply of glacial meltwater (Keil et al., 2010; Wang et al., 2010). The detailed runoff data of the Qugaqie River, which lies in the south of the Nam Co basin, shows strong daily amplitudes of 2–5 m³ s⁻¹, caused by glacial melting and freezing processes in the headwater area (Zhou et al., 2006). The increase in glacial meltwater against the background of increasing temperature makes important contributions to maintaining the increment status of the lake’s water storage. Considering the underground runoff, since

### Table 5

Annual Mann–Kendall test results for air temperature, precipitation and evaporation series. Numbers in bold are statistically significant. Positive values indicate increasing trend, negative ones indicate decreasing trend.

<table>
<thead>
<tr>
<th>Series</th>
<th>Average annual mean value</th>
<th>MK coefficients</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual mean air temperature of Nam Co Lake</td>
<td>~0.28 °C</td>
<td>2.640395</td>
<td>0.008281</td>
</tr>
<tr>
<td>Precipitation on the lake</td>
<td>410.94 mm</td>
<td>1.704811</td>
<td>0.08823</td>
</tr>
<tr>
<td>Evaporation on the lake</td>
<td>1183.96 mm</td>
<td>~3.89883</td>
<td>0.0000976</td>
</tr>
</tbody>
</table>

*p < 0.05.
**p < 0.01.
***p < 0.001.

Fig. 8. Interannual variation trend analysis of air temperature in the Nam Co lake basin, precipitation and evaporation on the lake from 1971 to 2009.

Fig. 9. Interannual variation trend analysis of normalized series of air temperature, precipitation, evaporation and water storage from 1976 to 2009.
piezometric data is scarce around the lake, quantifying groundwa-
ter flow around the lake using physical approaches was not possi-
ble. The Nam Co Lake is in the untraversed central Tibetan Plateau, and
the groundwater has never been exploited for any purpose. As
for the average annual variation, the groundwater can be supposed to
be invariable. So the increased precipitation and stream runoff
may be the main factors contributed to the enlarging of the lake.
Zhu et al. (2010) concluded that the increased amount of water
storage from precipitations accounted for 46.67% of total increased
water supplies, while the increased stream runoff coming from gla-
cier melt water reached 52.86% of total increased water supplies
based on very rough estimation. It is obvious that the water storage
of Nam Co Lake has significant responds significantly to the climate
warming. Further studies need to be carried out based on more
investigation and data in the future.

5. Discussion

Climate warming speeds up water transport and percolation
into the subsurface (ground), which directly influences the high-
land lake volume. Closed lakes (those without surface outlets) dis-
play considerable volume changes, which are relatively easy to
model in the absence of significant ground water exchange. Mea-
surements of closed lake water storage changes are, therefore,
not only important for hydrological and economic purposes, but
can also provide a climate record, particularly in highland regions,
where such monitoring is often extremely sparse.

Previous research on lake water level and water balance on the
Tibetan Plateau are mainly conducted on a scale of 1000 years or
even 10000 years. Most of these research utilize various proxy in-
dexes such as spore and pollen, varve, midge and ostracods to rees-
tablish the lake fluctuation sequence since Late Pleistocene (Cong
et al., 2007; Yao et al., 2007; Li et al., 2008; Zhang et al., 2008).
These research belong to the category of paleoeclimatology.

Research on lake water level and water balance in recent dec-
ades were focused mainly on Qinghai Lake (Zhou and Wang,
1996; Li et al., 2007), Yamdrok Lake (Liu, 1995; Bian et al., 2009).

and Zabuye Salt Lake (Qi and Zheng, 2006) where hydrological sta-
tions exist. Qinghai lake is located in the northeastern Tibetan Pla-
tea, in a high cold semiarid climate zone, Yamdrok lake is located
in southern Tibet which belongs to a bush and grassland semiarid
climate, and Zabuye Salt Lake is located in the central region of Ti-
betan Plateau, on the north side of western Gangdise Mountain,
which belongs to plateau subfrigid climate zone. Generally, these
three lakes all depend on the river supply of each basin and the
water levels appear to descend in most years or the whole
period. While Nam Co Lake depends on the glacial meltwater sup-
ply and the water level appears to fluctuate and increase in recent
decades. Therefore, the increasing glacial meltwater brought by cli-
mate warming is maybe one of the main reasons that big lakes
maintain the stable surfaces or even enlargement on Tibetan Pla-
tea in recent decades. These studies all indicate the sensitive re-
sponse of lake variation to the climate change on the Tibetan
Plateau. Climate change is the main reason driving the lake vari-
ability of Tibetan Plateau.

Otherwise, our estimate of water storage in the Nam Co Lake is
innovative in areas without historical hydrological data on the Ti-
betan Plateau. As mentioned above, the earlier work about high-
land inland lakes mainly lies in the lake-level data measured by
hydrological gauges. In this study, coupled with bathymetry DEM
generated from field measuring on the Nam Co Lake, satellite
images scattered into the study period were used to delineate
the temporal-series changes in the lake surface areas and water
storage. Similar studies were conducted in other regions of the
world. Harris (1994) chose Lake Abiyata in the highlands of Ethio-
pia and detected its volume variations by 1 km-resolution AVHRR
data and bathymetry measurements. The results showed that
accurate data on closed lakes with areas \~{} 100 km² can be obtained
from 1-km resolution data using the LIC technique, and a time ser-
ies of areas produced from AVHRR demonstrate significant mea-
surable variability, which is comparable to that observed in earlier
ground-based measurements. A remote sensing program at the
Mullard Space Science Laboratory (MSSL) that aimed to moni-
tor short- and medium-term lake volume changes derived
lake levels and lake areas using satellite radar altimeters and satel-
ite imaging radiometers respectively, and interpreted them in
terms of aridity variations as a measure of regional climate change
(Birkett and Mason, 1995). Bastawesy et al. (2008) estimated water
loss from Tushka lakes in Egypt using ASTER images and SPOT-4
images and bathymetry DEM data, and achieved better calcu-
lations. Swenson and Wahr (2009) examined trends in the water
storage and lake levels of multiple lakes in the Great Rift Valley re-
gion of East Africa for the years 2003–2008, using satellite gravi-
metric and altimetric data. Remote sensing data and techniques
are more and more widely used to monitor variations in inland
lakes, especially in areas without historical hydrological data, and
proved their reliability.

Beginning in 2001, IGBP conducted research on global climate
change for the second decade and deemed the Tibetan Plateau as
a key region due to its high sensitivity to climate change. Tibetan
Plateau is called the “Asian Water Tower”, and its water source
variations and hydrological processes are a key component of glo-
bal change research. The variation of the cryosphere and water
sources of the Tibetan Plateau and adaptation strategies, along
with the surface process changes of Tibetan Plateau and its influ-
ence on surrounding areas, are key scientific problems that need
to be solved urgently. Compared with earlier research, this paper
acquired a long-term lake fluctuation sequence about the area
and its water storage, and discussed about the intra-annual and in-
ter-annual variation characteristics of Nam Co Lake from 1976 to
2009. The methods presented herein provide an important source
of data on past water variation on the Tibetan Plateau, and provide
a necessary foundation for further research about water balance,
hydrologic processes and the hydrological response to climate
change.

6. Conclusion

There was previously very little research on the estimation of
water storage for highland lakes due to the lack of sufficient hydro-
logical records. This study has provided an estimation method and
a comprehensive 34-year analysis of intra-annual and inter-annual
variations in Nam Co Lake's water storage, using remote sensing
data, in situ bathymetric survey, historical meteorological records,
and GIS techniques. Results include the following:

- Nam Co Lake is a closed highland inland lake, with a multi-year
  mean water storage of 842.36 × 10⁶ m³. The water level-storage
  curve and the isobathic map showed that Nam Co is a deep,
  high-altitude lake with a large, flat basin lying in the central
  part of the lake, with more than 90 m water depth.
- Our estimation of water storage in the Nam Co Lake is innova-
tive, and is much different from earlier work. Most of the earlier
work on historical water storage levels was based on field
hydrological records. In this study, satellite images acquired
from 1976 to 2009, along with bathymetry DEM generated from
in situ data, were used to estimate the changes in the lake sur-
face areas and water storage. By combining these extracted
water surfaces with the lake’s 3D profile, accurate water storage
can be estimated. Our results concerning the intra-annual and
inter-annual variations in lake storage demonstrate that historical water surface extracted from remotely sensed data is feasible and reliable. The method used in this study can be applied to other areas where historical hydrological records are not available.

- Growth of the Nam Co Lake was observed over the late 20th and early 21st centuries in response to climate change. This study indicates that the lake water storage obviously increased from 786.06 × 10^6 m^3 to 870.30 × 10^6 m^3, with the area enlargement from 1927.48 km^2 to 2015.35 km^2 from 1976 to 2009, and the lake growth with great changing rate during 1999–2006, which are quite consistent with climate change trend. The monitoring results also show that the water storage increased from March, and reached the largest amount in late September and early October, then began to decrease up to December each year, which corresponds to the lake level change recorded at the Nam Co station.

- Trends in meteorological variables were studied. The annual mean air temperature and annual precipitation trended upward at the 1% and 10% significant levels respectively, while the evaporation on the lake trended downward at the 0.1% significant level in the Nam Co basin. Climate change was the main factor contributing to variations in lake water storage. The analysis of water storage supply also provides further evidence of lake growth as a proxy indicator of climate change in these permafrost highland lakes.

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References

Immerzeel W.W. et al., 2010. Climate change will affect the Asian water towers. Science 328 (5984), 1382–1385.