Changes of glacial lakes and implications in Tian Shan, central Asia, based on remote sensing data from 1990 to 2010

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Abstract
Changes of glacial lakes and implications were assessed for the Tian Shan Mountains from 1990 to 2010, based on Landsat Thematic Mapper/Enhanced Thematic Mapper Plus images. The total area of glacial lakes has expanded greatly over the last 20 years, at an average rate of $0.69 \pm 0.12 \text{ km}^2 \text{ a}^{-1}$ or $0.8 \pm 0.1\% \text{ a}^{-1}$. Eastern Tian Shan contributed nearly half that increase ($\approx 0.34 \pm 0.03 \text{ km}^2 \text{ a}^{-1}$), followed by northern Tian Shan at $0.17 \pm 0.03 \text{ km}^2 \text{ a}^{-1}$. Both widespread climate warming and glacier shrinking led to glacial lake areal expansion, while small to medium ($< 0.6 \text{ km}^2$) lakes responded most sensitively to glacier retreat. The closer the hydrologic connection of lakes to glaciers, the greater the areal expansion rate. An average $\approx 0.007 \pm 0.002 \text{ Gt a}^{-1}$ of glacier meltwater has been temporarily held in lakes over the past two decades. The increasing quantity of melt available for lake formation and growth may simultaneously increase the frequency and damage of glacial lake outburst floods or debris flows in this region. Sixty potentially dangerous glacial lakes are identified, among which 12 have an outburst probability status of ‘high’, 25 ‘medium’ and 23 ‘low’.

Keywords: Tian Shan, remote sensing, glacial lake, impacts

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1. Introduction

Glacial lakes, which form when a glacier retreats or are predominantly supplied by glacier meltwater, are widely distributed in glaciated regions. In the context of global warming, glacier shrinkage prevails at high elevations in Asia, providing significant contributions to sea level rise and promoting glacier-induced hazards (Fujita and Nuimura 2011, Zhang et al 2012, Yao et al 2012, Bolch et al 2012, Jacob et al 2012, Benn et al 2012, Sorg et al 2012, Gardner et al 2013). However, there are some glaciers with slight mass gain in the central Karakoram and western Pamir mountains (Kääb et al 2012, Gardelle et al 2013). The retreat of glaciers has resulted in obvious increase of water storage in lakes on the Tibetan Plateau ($8.76 \text{ Gt a}^{-1}$) (Zhang et al 2013) and northern Tian Shan ($0.22 \pm 0.47 \times 10^6 \text{ m}^3$) (Bolch et al 2011), and areal increase of lakes in the Northern Patagonian Ice Field ($0.98 \text{ km}^2 \text{ a}^{-1}$) (Loriaux and Casassa 2013) and Chinese Himalayas (Wang et al 2012b). However, there have been contrasting spatiotemporal evolutions in glacial lakes...
Figure 1. Distribution of glacial lakes and potentially dangerous glacial lakes (PDGLs) in Tian Shan Mountains. Glacier outlines are from the Randolph Glacier Inventory (RGI), with some outlines in western Tian Shan and part of eastern Tian Shan obtained in the present work.

(Zhang et al. 2013, Loriaux and Casassa 2013, Wang et al. 2012b). For example, along the Hindu Kush Himalaya, glacial lake coverage has grown continuously by 20%–65% in the East Himalaya, and shrunk in the Hindu Kush (−50%) and Karakoram (−30%) from 1990 to 2010 (Gardelle et al. 2011). Glacial lake change and its induced hazards are of increasing concern. Scholars have proposed appropriate indicators to qualitatively evaluate breach probabilities of glacial lake outburst floods (GLOFs) according to lake characteristics. These indicators mainly involve the freeboard of the lake, dam type and geometry, parent glacier and lake basin settings, which can be measured from remote sensing data (Clague and Evans 2000, Richardson and Reynolds 2000, Huggel et al. 2004, Wang et al. 2008). In recent years, much progress has been made on semiquantitative and quantitative estimates of breach probabilities of GLOFs in large-scale and inaccessible glaciated regions, using remotely obtained indicators and geostatistical methods. The breach probabilities of GLOFs have been successfully quantified in the Alps (Huggel et al. 2004, 2002), northern Tian Shan (Bolch et al. 2011), the Himalayas (Fujita et al. 2013, Worni et al. 2012, Wang et al. 2012a, Wang 2011b), British Columbia (McKillop and Clague 2007), Pamir (Mergili and Schneider 2011), New Zealand (Allen et al. 2009), Peru (Emmer and Vilímek 2013) and other glaciated regions.

The earliest interest in Tian Shan glacial lakes traces to a report on Merzbacher Lake (Merzbacher 1905). Since then, there has been a focus on these lakes from the standpoint of water resource change and lake-induced disaster assessment. Achievements have mainly included the following: analysis, simulation and forecasting of outburst floods regarding Merzbacher Lake (Ng et al. 2007, Ng and Liu 2009, Shen et al. 2009, Xie et al. 2013); typical lake evolution and outburst hazard analysis (Janský et al. 2009, 2010, Narama et al. 2010a); identification and assessment of potentially dangerous glacial lakes (Bolch et al. 2011, Mergili and Schneider 2011); impacts of glacier meltwater on high-altitude lake basins (Li et al. 2011a) and the thermal regime of supraglacial lakes atop debris-covered glaciers (Wang et al. 2012c). Increasing air temperature, heterogeneously changing precipitation rates and continued glacier shrinkage have therefore raised concerns about the future role of Tian Shan glaciers as a source of fresh water, and potential hazards related to glacier retreat (Sorg et al. 2012). We still lack comprehensive understanding about glacial lake change and its response to widespread glacier shrinking and climate warming across the entire Tian Shan Mountains. To address this, we conducted three phases of glacial lake inventories, based on Landsat Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+) satellite images from 1990–2010. Changes and responses of glacial lakes to glacier wastage were analysed in detail. Potentially dangerous glacial lakes (PDGLs) were first-order identified, based on selected outburst hazard indicators.

2. Study region

The Tian Shan Mountains cover about 39°–46°N and 69°–95°E in central Asia. The principal mountains stretch ≈2500 km from western Kyzyl-Kum in Uzbekistan, across Kazakhstan and Kyrgyzstan, to the east of Hami in China. Based on mountain ranges, drainage and climate features, Tian Shan was subdivided into the following regions: western, northern, central and eastern (figure 1). Tian Shan is heavily glaciated and covered by ≈14 641 km² of glacial area according to Randolph Glacier Inventory (RGI) data (table S1 available at stacks.iop.org/ERL/8/044052/mmedia). More glaciers aggregate in the central and eastern regions, with ≈9123 km² and ≈4532 km² glacial areas, respectively; only ≈756 km² and ≈231 km² such areas are found in the northern and western regions (table S1 available at stacks.iop.org/ERL/8/044052/mmedia). The western region includes the Fergana, Pskem, Chatkal and Gissar ranges. In winter and spring, this region is under weak influence from the Siberian anticyclonic circulation and moderate southwest cyclonic circulation, which bring in warm moist air and maximize precipitation in winter and spring. The northern region includes the Kungej, Zailijskij, Kirgizskij, Junggar
Alatau and others. This area is under the influence of the Siberian High circulation, which decreases precipitation in winter. Cyclones with cold humid air masses in spring and summer generate maximum precipitation. Central Tian Shan includes many high ridges of inner ranges, and extends to the outer edge of Khan Tengri Mountain. This region has high ridges, which block the entrance of moist air masses in winter. However, the development of convection and intensification of unstable air results in summer maximum precipitation. Eastern Tian Shan is east of the Kokshaal-Too Range. This is the driest region in Tian Shan, since moisture in air masses from the Atlantic Ocean is lost during their long trek from the source (Aizen et al. 1995, Sorg et al. 2012).

3. Methods

3.1. Data source

We used 78 orthorectified Landsat TM/ETM+ images, downloaded from the United States Geological Survey for the years 1990, 2000 and 2010. About 79.5% of these images were from August–October. To fill in minor gaps caused by poor-quality images, we used images from 1–2 years outside the aforementioned years. The Shuttle Radar Topography Mission (SRTM-4) digital elevation model was used to derive slope and elevation information for the Tian Shan Mountains. We acquired daily temperature and precipitation data between the 1970s and 2010s from 16 meteorological stations in the study area (figure 1), from the US National Climatic Data Center and the China Meteorological Administration. We also used high-resolution Google Earth images as auxiliary data to classify lake types. These were mainly images from SPOT-5 with 2.5 m resolution, GeoEye with 1.65 m resolution, and QuickBird with 2.62 m resolution.

3.2. Glacial lake mapping

Data processing mainly involved extracting lake area information from remote sensing images. Automatic methods of water-pixel extraction have typically been developed to acquire glacial lake boundaries, and then lake areas are calculated by GIS software (Huggel et al. 2002, Ye et al 2007, Li et al 2011b, Wang et al 2012b). We used the decision-tree method (Gardelle et al 2011) to automatically extract glacial lake area information. We first computed the normalized difference water index (NDWI) from bands 4 and 1 of the Landsat TM/ETM+ images (Huggel et al 2002):

$$NDWI = \frac{TM4 - TM1}{TM4 + TM1}.$$  \hspace{1cm} (1)

Then, appropriate NDWI thresholds were manually chosen for different images, to obtain binary images from which we could initially distinguish water and non-water information. In the TM/ETM+ images, mountain shadows usually have spectral characteristics similar to those of lake water. Nonetheless, the water surface slope is theoretically much smaller than that of mountain shadows. Thus, for the purpose of eliminating terrain shadows from the binary images of water and non-water, each image was overlaid with a slope map derived from the SRTM. For the slope threshold, we followed the process of extracting lake boundaries in the Himalaya (Wang et al 2012b); namely, water pixels with slope less than 5° were assumed to be lakes, and otherwise to be shadows. Nevertheless, there are limitations to automatic extraction of lake boundaries, especially in differentiating frozen water from ice. Thus, manual examination is needed to check errors in each glacial lake map owing to automatic extraction (figure 2).

Further complementary rules were established to clarify a glacial lake in terms of operationalization when cataloguing lakes in Tian Shan, as follows: (1) glacial lakes with area more than 0.002 km² were recorded (in Landsat images, the 0.002-km² threshold is approximately equivalent to a cluster of uninterrupted water body of about three pixels); (2) glacial lake inventories only catalogued lakes located within 10 km of the current ice margin.

The accuracy of extracted lake information depends on pixel resolution, image quality, radiometric and geometric corrections, classification algorithms, threshold value selection, expert experience and others (Paul et al 2004, Hall et al 2003, Gardelle et al 2011). It is difficult to describe accuracies precisely, because of a lack of ground-based measurements. Here, lake area error was estimated based on ±1 pixel lake outline uncertainty (see supplementary methodological information available at stacks.iop.org/ERL/8/044052/mmedia) for calculating errors of lake area. As the literature emphasizes, sensor resolution and data preprocessing are not important in temporal change of glacial lakes over the entire region, but rather affect changes from pixel to pixel (Gardelle et al 2011, Wang et al 2012b). However, seasonal discrepancies caused by ice and snow meltwater undoubtedly produce seasonal variation of glacial lake area, especially for some seasonally surviving lakes (e.g., for supraglacial lakes, which are maximum in summer but may shrink or disappear below the mapping threshold in winter). Overall, 89.7% of source images for glacial lake mapping were acquired from June to October, when glacial lakes have their highest water levels and largest areas. This is because Tian Shan has the highest temperature and maximum precipitation during this period.

To assess impacts of glacial lake changes, four types of lake were classified visually from Google Earth images, based on hydrologic relationships between the lakes and their mother glaciers. In the glacial lake inventory, supraglacial lakes were recorded as type I, lakes contacting the glacier terminal or margin as type II, lakes not contacting the glacier but directly fed by glacier meltwater as type III, and lakes not directly receiving glacier discharge as type IV.

3.3. Evaluation of PDGLs

Two steps were involved in identifying PDGLs and evaluating the risk of GLOFs associated with PDGLs in the Tian Shan Mountains, namely ‘preparatory detection’ and ‘qualitative evaluation’ (figure 2). In the preparatory detection steps, the source of lake water, lake area changes and distances
between lake and glacier were examined. First, under a background of indistinct trends in precipitation, it is reasonable that continuous meltwater is the predominant source of lake water in Tian Shan. Only glacial lakes that were greatly expanding directly from glacier meltwater input were considered candidate PDGLs, since such continuous input would ultimately interrupt the balance of water in the lake basin and consequently increase the risk of lake failure. Second, the smaller the distance of a glacial lake from its parent glacier terminus, the more associated their dynamics, so this distance is the most direct measure of their linkage (Wang et al. 2012b). Third, only a glacial lake larger than a certain size could possibly cause damage. Therefore, a threshold lake size should be established. This is usually dynamic, and should be adjusted according to the intensity and frequency of human activity in the mountains. Guided by the aforementioned concepts, a PDGL in the Tian Shan Mountains must meet the following conditions simultaneously.

- Lake basin is directly fed by glacier meltwater.
- Lake area increasing over the past two decades.
- Lake basin within 1 km of the nearest glacier terminus.
- Lake size > 0.1 km².

Next, four key indicators—dam geometry, dam component, freeboard and potential for lake impacts—were used to qualitatively evaluate outburst probabilities of PDGLs obtained from preparatory detection (figure 2). The four selected indicators were included because they met three predesigned criteria. First, the indicators have been used worldwide to assess dangerous glacial lakes in glaciated regions (Huggel et al. 2004, McKillop and Clague 2007, Bolch 2007, Worni et al. 2012). Second, the indicators had qualitative or semiquantitative criteria for determining grades of potential hazard. Third, the indicators could be measured through remote sensing data. Usually, there are four different dam-type glacial lakes, namely, moraine, ice or bedrock, and no dams (lakes in flat-topography valleys in glacier forefields) in glaciated regions (Worni et al. 2012). Moraine- and ice-dammed lakes may have high dam-failure potential, whereas bedrock-dammed lakes are generally stable (Huggel et al. 2004). No non-moraine-dammed lake outburst hazard events have been recorded in the Chinese Himalayas (Wang et al. 2012a). Thus, we used different indicators to qualitatively evaluate hazard rates of moraine-dammed and non-moraine-dammed lakes. Summarizing rules for evaluating the qualitative outburst probability of PDGLs from available documents (Huggel et al. 2004, Bolch 2007, McKillop and Clague 2007, Mergili and Schneider 2011,
9.5 ± expanded by 16.7 ± number of lakes increased by 22.5% and total lake area increase from 1990 to 2010. During the past 20 years, the generally characterized by areal expansion and numerical table 1).

4. Results

4.1. Lake variation in different regions

We inventoried 1667 glacial lakes in the Tian Shan Mountains, with total area 96.5 ± 14.2 km² in 2010. The lakes are largely in central and eastern Tian Shan, representing 40.5 ± 5.2% and 29.8 ± 4.6% of total glacial lake area, respectively. Only 9.5 ± 1.5% was detected in western Tian Shan (figure 1, table 1).

Glacial lakes in Tian Shan varied continually, and were generally characterized by areal expansion and numerical increase from 1990 to 2010. During the past 20 years, the number of lakes increased by 22.5% and total lake area expanded by 16.7 ± 2.9%, representing growth rates of about 1.1% a⁻¹ and 0.8 ± 0.1% a⁻¹, respectively. Considering mean lake area variation, there were three change modes in different subregions over each decade. (1) In western and northern Tian Shan, respectively, glacial lake growth rates declined from 1.3 ± 0.2 and 1.9 ± 0.4% a⁻¹ before 2000 to 0.4 ± 0.1 and 0.7 ± 0.1% a⁻¹ after 2000. (2) In central Tian Shan, lake area decreased by −0.1 ± 0.1% a⁻¹ in the first decade, but increased by 0.6 ± 0.1% a⁻¹ in the later decade. (3) In eastern Tian Shan, lake expansion rate in the first decade was on average 0.3 ± 0.0% a⁻¹ smaller than that in the later decade (figure 4). Regarding net change of total lake area (0.69 ± 0.12 km² a⁻¹) over the past two decades across the whole of Tian Shan, nearly half of this expansion (0.34 ± 0.06 km² a⁻¹) was concentrated in the eastern region, followed by the northern region at ≈0.17 ± 0.03 km² a⁻¹.

There were smaller net lake area expansion rates in the western and central regions, at 0.09 ± 0.02 km² a⁻¹ and 0.08 ± 0.02 km² a⁻¹, respectively (figure 3).

4.2. Lake changes of different types and sizes

Different-sized glacial lakes had significantly varying areal changes. There are currently 1667 glacial lakes in Tian Shan, of which 1216 have been tracked over a 20-year period (without regard to the 451 lakes newly formed during 1990–2010). From lake-change percentages of the 1216 lakes over the last 20 years, small lakes varied more drastically than larger ones; e.g., lakes less than 0.01 km² varied from −75.1 ± 20.6% to 419.9 ± 65.9% (figure 4(A)). For different size ranges of lake, three change features were identified. (1) Small lakes (<0.01 km²) decreased in area at an average rate of 1.8 ± 1.5%. (2) Lake sizes between 0.01 and 0.6 km² expanded from ≈4.3 ± 0.5 to 19.5 ± 0.6%.

### Table 1. Number and area of glacial lakes in subregions of Tian Shan Mountains, in 1990, 2000 and 2010.

| Year | Western Tian Shan | Northern Tian Shan | Central Tian Shan | Eastern Tian Shan | Whole Tian Shan |
|------|-------------------|--------------------|------------------|-------------------|----------------|
|      | Num    | Area (km²) | Num    | Area (km²) | Num    | Area (km²) | Num    | Area (km²) | Num    | Area (km²) |
| 1990 | 125    | 7.37 ± 1.11 | 353    | 15.89 ± 2.90 | 512    | 37.38 ± 6.47 | 371    | 22.08 ± 3.19 | 1361   | 82.72 ± 11.87 |
| 2000 | 157    | 8.77 ± 1.38 | 397    | 18.01 ± 3.24 | 536    | 36.10 ± 7.41 | 445    | 25.06 ± 3.71 | 1535   | 88.83 ± 13.04 |
| 2010 | 164    | 9.15 ± 1.42 | 425    | 19.53 ± 3.43 | 557    | 39.05 ± 4.99 | 521    | 28.79 ± 4.39 | 1667   | 96.50 ± 14.23 |

Figure 3. Change of glacial lake area during the past two decades in Tian Shan (in percentages; relative area changes over a decade).

Wang et al 2012a, Worni et al 2012), general decision standards for qualitative evaluation are shown in figure 2.

Figure 4. Changes of different-sized glacial lakes in Tian Shan from 1990 to 2010 (A) changes of individual glacial lakes, as percentages; (B) average changes of different glacial lake sizes, as percentages).

![Figure 3: Change of glacial lake area during the past two decades in Tian Shan](image1)

![Figure 4: Changes of different-sized glacial lakes in Tian Shan](image2)
Figure 5. Mean change rates of different types of glacial lake from 1990 to 2010. Type I, supraglacial lakes; type II, lakes contacting glacier terminal or margin; type III, lakes not contacting the glacier but directly fed by glacier meltwater; type IV, lakes not directly receiving glacier discharge.

(3) Change percentages of larger lakes (>0.6 km$^2$) varied weakly, $-0.4 \pm 0.3$–$4.6 \pm 0.3\%$ on average (figures 4(A) and (B)). Overall, smaller lakes changed greatly and larger lakes slightly.

Among the four lake types (I–IV described in section 3.2) of Tian Shan in 2010, only 2.1 ± 0.5% of total lake area was supraglacial lake (type I). Type III was the most widely developed, with 70.6 ± 10.2% of total lake area, followed by types II and IV with 16.8 ± 2.2% and 10.5 ± 1.8%, respectively. In short, lakes fed by meltwater were the most detected in 2010, amounting to 89.5 ± 12.9% of total lake area in Tian Shan. Furthermore, the glacial lake types showed contrasting evolution over 1990–2010 (figure 5). Type II expanded the most, with average rates 26.4 ± 5.3% or 1.3 a$^{-1}$ ± 0.3% a$^{-1}$. Type III also increased noticeably, with rates 18.3 ± 2.5% or 0.9 ± 0.1% a$^{-1}$. Average increase of supraglacial lake (type I) area was smaller, at rates 5.7 ± 3.3% or 0.3 ± 0.2% a$^{-1}$. Type IV slightly decreased, with average rates $-2.5 \pm 2.9\%$ or $-0.1 \pm 0.2\%$ a$^{-1}$. This shows that, for pro- or lateral-glacial lakes, the closer the hydrologic connection of the lake with the glacier, the more rapid the expansion of lake area. Lakes that did not directly receive glacier meltwater had an indistinct decreasing area trend.

4.3. Potentially dangerous glacial lakes

Among the 1667 lakes in the Tian Shan Mountains in 2010, there were 60 PDGLs, with total area 17.2 ± 0.7 km$^2$ (figure 1). These PDGLs were primarily characterized by rapid areal expansion rates. Among the 60 PDGLs, 12 were newly formed, and the other 48 expanded at average rates 46.8 ± 3.1% or 2.3 ± 0.2% a$^{-1}$, nearly three times the average expansion rate of all lakes in Tian Shan from 1990 to 2010. Guided by the prioritization of outburst probability shown in figure 2, we identified 12 glacial lakes with ‘high’ probability, 25 ‘medium’, and 23 ‘low’. The distribution of PDGLs proved spatially heterogeneous (figure 1; table S2 available at stacks.iop.org/ERL/8/044052/mmedia). No PDGLs were detected in western Tian Shan. In the eastern, central and northern regions, 20, 21, and 19 PDGLs were identified, respectively. About 67% (eight lakes) with high outburst probability were in the central region, and three in the eastern region. In the northern region, 18 PDGLs were found in Junggar Alatau, and only one in Kunje Alatau (figure 1).

5. Discussion

5.1. Lake variation and climate change

The change of glacial lakes formed under certain topographic conditions has a close relationship to climate change. Variation of lake area depends on the balance of incoming and outgoing water in the lake basin. For a given basin, temperature rise (increase of meltwater), precipitation increase and evaporation decrease all expand lake area. Across the whole of Tian Shan, temperature increased consistently and precipitation varied less homogeneously. Meteorological station records indicate that average air temperature increased in Tian Shan at 0.01 °C a$^{-1}$ and average precipitation by 1.2 mm a$^{-1}$, from the middle of the last century to the year 2000 (Giese et al 2007, Aizen et al 1997). In central Tian Shan, weather stations reveal strong climatic warming during the ablation season beginning in the 1950s, at a rate 0.02–0.03 °C a$^{-1}$. However, no station has exhibited a significant long-term trend in precipitation (Aizen et al 1995). In northern Tian Shan, trend and correlation analysis for the period 1879–2000 at 16 climate stations showed a temperature increase. There was a small increase in precipitation on average, but no clear trend (Bolch 2007). Air temperature and precipitation increase rates in the Chinese Tian Shan (eastern and central regions; figure 1) were $\approx0.03°$C a$^{-1}$ and 1.1 mm a$^{-1}$, respectively, and the annual change of potential evaporation declined by $\approx2.5$ mm a$^{-1}$ from 1960 to 2006 (Li 2010, Zhang et al 2009). Our analysis of climate records indicates that air temperature rose at rates between 0.032 and 0.074 °C a$^{-1}$ during 1971–2010, with confidence level 0.02–0.03 °C a$^{-1}$ during 1971–2010, with confidence level $<0.05$ (only the confidence level of air temperature increase at Kuche station was $<0.1$). Precipitation generally increased, but with no significant trend and spatial inconsistency, based on records of the 16 weather stations in the study area from 1971 to 2010 (table 2; figure 1). Overall, both warmer and wetter conditions have provided a climate favourable to lake expansion since the middle of the last century in Tian Shan, although the former conditions were statistically significant and the latter were not so.

The diversity of climate characteristics in Tian Shan subregions is predominantly controlled by atmospheric circulations and precipitation regimes (Aizen et al 1995). Although there was no clear widespread wetter trend over the mountains, 11 of the 16 weather station records reveal rates of increase of 0.6–2.8 mm a$^{-1}$ (table 2). During 1990–2010, lakes in the eastern region had the greatest expansion rates, in both net area ($\approx0.352$ km$^2$ a$^{-1}$) and change percentage (31.9%). This was in accord with uniform increasing trends of precipitation recorded by all six available weather stations in the eastern region from 1971 to 2010. In addition, precipitation increased with elevation, about 10–60 mm per 100 m, with a maximum in a certain elevation interval (Hu
Table 2. Variation of linear trends of mean annual temperature over past 40 years in Tian Shan Mountains.

| Subregion             | Weather station | Elevation (m asl) | Period       | Temperature (°C) | Precipitation (mm) |
|-----------------------|-----------------|-------------------|--------------|------------------|--------------------|
|                       |                 |                   |              | Average          | Rate (°C a⁻¹)      | Significance       |
| Western Tian Shan     | Fergana         | 577               | 1971–2006    | 14.60            | +0.047             | <0.001             |
|                       | Bishkek         | 760               | 1971–2010    | 11.22            | +0.038             | 0.024              |
|                       | Pskem           | 1258              | 1971–2000    | 7.81             | +0.147             | <0.001             |
|                       |                 |                   |              |                  |                    |                    |
|                       |                 |                   |              | Average          | Rate (mm a⁻¹)      | Significance       |
|                       |                 |                   |              | 185.3            | +1.40              | 0.178              |
|                       |                 |                   |              | 408.4            | −3.23              | 0.322              |
|                       |                 |                   |              | 541.0            | −13.32             | 0.046              |
|                       |                 |                   |              |                  |                    |                    |
| Northern Tian Shan    | Zharkent        | 645               | 1971–2010    | 10.64            | +0.052             | <0.001             |
|                       | Almaty          | 851               | 1971–2006    | 10.15            | +0.048             | <0.001             |
|                       | Zhaosu          | 1677              | 1971–2008    | 3.55             | +0.042             | <0.001             |
|                       |                 |                   |              | 244.3            | −2.33              | 0.612              |
|                       |                 |                   |              | 659.8            | +2.84              | 0.23               |
|                       |                 |                   |              | 501.7            | +0.67              | 0.61               |
|                       |                 |                   |              |                  |                    |                    |
| Central Tian Shan     | Akqi            | 1984              | 1971–2008    | 6.70             | +0.034             | <0.001             |
|                       | Naryn           | 2041              | 1971–2010    | 4.57             | +0.032             | 0.005              |
|                       | Torugart        | 3504              | 1971–2008    | −3.10            | +0.032             | <0.001             |
|                       | Tian Shan       | 5639              | 1973–2010    | −6.38            | +0.074             | <0.001             |
|                       |                 |                   |              | 215.5            | +1.79              | 0.108              |
|                       |                 |                   |              | 272.8            | −0.63              | 0.693              |
|                       |                 |                   |              | 242.0            | +1.93              | 0.031              |
|                       |                 |                   |              | 197.5            | −7.14              | <0.001             |
|                       |                 |                   |              |                  |                    |                    |
| Eastern Tian Shan     | Daxigou         | 3545              | 1971–2010    | −4.91            | +0.035             | <0.001             |
|                       | Kuche           | 1100              | 1971–2010    | 11.49            | −0.013             | 0.096              |
|                       | Balltang        | 1677              | 1971–2010    | 2.26             | +0.092             | <0.001             |
|                       | Yiwu            | 1728              | 1971–2002    | 3.99             | +0.033             | 0.002              |
|                       | Baluntai        | 1739              | 1971–2008    | 6.75             | +0.057             | <0.001             |
|                       | Bayin           | 2458              | 1971–2008    | −4.17            | +0.036             | 0.033              |
|                       |                 |                   |              | 468.4            | +2.79              | 0.007              |
|                       |                 |                   |              | 76.0             | +0.57              | 0.149              |
|                       |                 |                   |              | 222.7            | +1.15              | 0.093              |
|                       |                 |                   |              | 101.8            | +0.96              | 0.160              |
|                       |                 |                   |              | 215.4            | +1.69              | 0.078              |
|                       |                 |                   |              | 269.5            | +1.39              | 0.062              |

* Period of precipitation in Bishkek is from 1971 to 1993.
et al. (2004). This interval was usually 2500–3500 m in western and northern Tian Shan, and greater than 3500 m in the central and eastern regions, which coincides with the elevation bands of maximum lake area distribution (Aizen et al. 1995).

5.2. Lake expansion and glacier shrinkage

Glacial lakes are mainly fed by glacial meltwater, and lake area variation is closely tied to dynamics of the mother glacier (Wang et al. 2012b, Yao et al. 2010). Glaciers in different subregions of Tian Shan retreated greatly beginning in the mid-20th century, with areal change rates ranging from −0.26 to −0.83% a⁻¹ (table 3). The present work shows that lake types I, II and III, directly fed by glacier meltwater, expanded at average rates of 0.3 ± 0.2 to 1.3 ± 0.3% a⁻¹. Type IV, with no direct inflow of meltwater, decreased weakly at −0.1 ± 0.2% a⁻¹. Jacob et al. (2012) reported glacier wastage of −5 ± 6 Gt a⁻¹ for the whole of Tian Shan between 2003 and 2010, based on gravimetric measurements (GRACE). A recent study revealed slightly more mass loss (−7.5 ± 3.4 Gt a⁻¹) between 2003 and 2009 (Gardner et al. 2013). This suggests that an increase in meltwater caused glacial lake expansion over the last 20 years. Medium and small lakes (<0.6 km²) hydraulically connected to glaciers are more sensitive to glacier retreat. Remarkably, ≈3% of lake types II and III of size <0.6 km² expanded one to four times over their original areas (figure 4(A)).

Nevertheless, there is no evidence that the expansion rate of glacial lakes was proportional to the glacier shrinkage rate in both the subregions and entire Tian Shan from 1990 to 2010. No discrepancies of glacier retreat rates were discovered across different subregions (table 3), whereas glacial lakes expanded at a much higher rate (≈1.6 ± 0.3% a⁻¹) in eastern than central Tian Shan (≈0.2 ± 0.0% a⁻¹). This suggests that (1) whereas glacier shrinkage rate in the literature is usually represented by glacier area (table 3) and not by volume, glacial lake changes may be more appropriately interpreted by changes of glacier volume; (2) glacial lake changes actually have multiple causes. To precisely describe the causes of lake expansion requires detailed study of coupling between glacier melt runoff and lake basin hydrology and, more generally, of physical links between climate change, glacier response and lake development.

5.3. Impacts on melt resource

Recent studies have shown that the mass balance on the Tibet Plateau derived from GRACE had a positive rate (Jacob et al. 2012), which could be due to the increased water mass in lakes (Zhang et al. 2011, 2013). Given a continuous air temperature rise and glacier degradation, it is reasonably foreseen that the area and volume of glacial lakes will continue to expand. Apart from the majority of meltwater exiting the original glaciated regions and joining river systems, a considerable amount of meltwater is retained by glacial lake expansion. In other words, the formation and development of glacial lakes in glaciated regions somewhat retards meltwater escape to the sea. Although available data cannot precisely determine how much meltwater is retained by glacial lakes in Tian Shan, we can make a rough estimate based on two reasonable assumptions.

- Given the heterogeneous change of precipitation and unremarkable decline of potential evaporation rate in Tian Shan (Sorg et al. 2012, Li 2010), it is reasonably supposed that the expansion of glacial lakes having direct hydrologic connection to glaciers (types I, II and III) resulted from the increase of glacier meltwater.
- The volume of glacial lakes is generally approximated by a regression of lake area and mean depth (Huggel et al. 2002, Wang et al. 2012a).

Data of measured area (A) and mean depth (D) of 39 glacial lakes were collected from the literature (table S3 available at stacks.iop.org/ERL/8/044052/mmedia), and the empirical relationship between the two is

\[ D = 0.096A^{0.426} \]

\[ R^2 = 0.812, \alpha < 0.001 \] (figure 6). The equation for water volume (V) is therefore

\[ V = 0.096A^{1.426} \]

Converting net area changes of glacial lake types I, II and III (lake types directly fed by meltwater) to water volumes, we obtained the approximate glacier meltwater retained by glacial lakes. Calculation shows that a water volume ≈2.07 ± 0.27 Gt was stored in all the lakes (types I, II, III and IV), of which ≈1.67 ± 0.20 Gt was in lakes of types I, II and III in 2010 in Tian Shan. During the last 20 years, ≈0.14 ± 0.03 Gt or ≈0.007 ± 0.002 Gt a⁻¹ of additional meltwater was retained by glacial lakes in the mountains. Between 2000 and 2010, total water increase of glacial lakes was ≈0.016 ± 0.002 Gt a⁻¹. Compared with glacier wastage of −7.5 ± 3.4 Gt a⁻¹ between 2003 and 2009 in Tian Shan (Gardner et al. 2013), ≈0.2 ± 0.0% of the glacier meltwater was held in glacial lakes during the last decade. This proportion, though relatively small, is still extremely significant for the ecological and social development of an inland arid region such as Tian Shan.

5.4. Glacial lake hazards

A large number of GLOF events were reported in Tian Shan from the 1950s to 2000s (UNEP 2007, Narama et al. 2012b, Yao et al. 2010). Given a continuous air temperature rise and glacier degradation, it is reasonably supposed that the expansion of glacial lakes having direct hydrologic connection to glaciers (types I, II and III) resulted from the increase of glacier meltwater. Given the heterogeneous change of precipitation and unremarkable decline of potential evaporation rate in Tian Shan (Sorg et al. 2012, Li 2010), it is reasonably supposed that the expansion of glacial lakes having direct hydrologic connection to glaciers (types I, II and III) resulted from the increase of glacier meltwater.
Table 3. Change rates of glacier area in Tian Shan Mountains.

| Subregion of Tian Shan | Studied area           | Period    | Glaciers area in start year (km$^2$) | Glaciers area in end year (km$^2$) | Rate of shrinkage (% a$^{-1}$) | Source of data          |
|------------------------|------------------------|-----------|--------------------------------------|-----------------------------------|------------------------------|-------------------------|
| Western Tian Shan      | Pskem                  | 1970–2000 | 219.8                                | 177.0                             | 0.65                         | Narama et al (2010b)    |
|                        |                        | 2000–2007 | 177.0                                | 168.7                             | 0.67                         | Aizen et al (2006)      |
|                        | Ala Archa              | 1963–2003 | 42.83                                | 36.31                             | 0.38                         | Niederer et al (2008)   |
|                        | Sokoluk                | 1963–2000 | 31.72                                | 22.80                             | 0.76                         |                        |
| Central Tian Shan      | At-Bashy               | 1970–2000 | 113.6                                | 99.9                              | 0.40                         | Narama et al (2010b)    |
|                        | SE Fergana             | 1970–2000 | 99.9                                 | 95.7                              | 0.60                         | Narama et al (2010b)    |
|                        | 2000–2007              | 190.1     | 172.6                                | 0.31                              | 0.07                         |                        |
|                        | 2000–2007              | 190.1     | 172.6                                | 0.31                              | 0.07                         |                        |
| Eastern Terskey Alatau | 1965–2003              | 120.0     | 104.9                                | 0.33                              | 0.33                         | Kutuzov and Shahgedanova (2009) |
| Aksu watershed         | 1964–2003              | 2267.71   | 2067.41                              | 0.23                              | 0.23                         | Li et al (2010)         |
| Kukusu watershed       | 1963–2004              | 265.81    | 215.35                              | 0.46                              | 0.46                         | Gao et al (2011)        |
| Northern Tian Shan     | Terskey Alatau         | 1971–2002 | 245.0                                | 226.6                             | 0.24                         | Narama et al (2006)     |
|                        | Ili-Kunguj             | 1970–2000 | 672.2                                | 590.3                             | 0.41                         | Narama et al (2010b)    |
|                        | 2000–2007              | 590.3     | 564.2                                | 0.63                              | 0.63                         |                        |
|                        | Zailiyski, Kungej Alatau | 1955–1999 | 243.5                                | 165.4                             | 0.73                         | Bolch (2007)            |
| Eastern Tian Shan      | Kaidu watershed        | 1963–2000 | 55.0                                 | 48.0                              | 0.34                         | Li et al (2006)         |
|                        | Urumqi watershed       | 1964–2005 | 48.67                                | 32.05                             | 0.83                         | Li et al (2010)         |
|                        | Harkeki Range          | 1972–2005 | 3.64                                 | 3.28                              | 0.30                         | Li et al (2011c)        |
|                        | 1962–2006             | 144.1     | 112.9                                | 0.49                              | 0.49                         | Li et al (2011c)        |
| Chinese Tian Shan      | Eastern Tian Shan and east part of Central Tian Shan | 1960–2009 | 0.31$^a$                             |                                  |                              | Wang et al (2011a)      |

$^a$ A calculated annual percentage of area changes from ten drainages in Chinese Tian Shan.

2009, 2010a). The most notable, Merzbacher Lake in central Tian Shan (79° 53.8E, 42° 13.8N), breached in a nearly annual cycle because of periodic inflow of meltwater or ice since the 1930s (Ng et al 2007, Shen et al 2009). Continuous expansion of glacial lake area will produce more potentially dangerous lakes in Tian Shan. For example, in the Zailijskij and Kungej Alatau of northern Tian Shan, 47 of the 132 glacial lakes had a high outburst risk (Bolch et al 2011). The rapid expansion of glacial lakes with potentially dangerous status requires urgent attention, because of at least two aspects. (1) These lakes have high vulnerability to failure, because of increasing pressure of static water on the dams. (2) The lake area expansion will increase the magnitude of outburst floods, since the size of peak flow in such floods is directly related to lake water volume. Thus, to thoroughly evaluate the impacts of glacial lake changes, comprehensive identification of PDGLs and prioritization by breach probability are especially necessary. Based on five indicators widely used in the literature, we inventoried 60 PDGLs in the Tian Shan Mountains in 2010, which are recommended for further and detailed breach-risk assessment. Intensive investigations are urgent for the 12 high- and 25 medium-risk lakes.

Identification of PDGLs and evaluation of their outburst probabilities is a systematic process involving climate conditions, glacier dynamics and physical properties, rock or snow activity, rate of lake formation and growth, dam geometry and components, down-valley characteristics and others. For this, more multi-source and in situ data are required (Richardson and Reynolds 2000, Huggel et al 2004, McKillop and Clague 2007, Bolch 2007, Haeberli 2010, Fujita et al 2013). Herein, we only present a first-order estimate of outburst probability of PDGLs, based on the selected physical indicators from remote sensing data. These indicators are intended to weigh the dam breach probability, as modulated by mechanisms of surging momentum (indicated
by the potential for lake impacts and dam properties), overflow incision and seep enlargement (appraised by dam properties and freeboard). Further, evaluating PDGL hazards involves not only physical aspects but social factors (e.g. population density, economic activity, response, preparedness and prevention) (Carey 2005, Hegglin and Huggel 2008). Our rough evaluation indicates the priority for further integrated assessments of glacial lakes in the Tian Shan Mountains.

6. Conclusion

Tian Shan is currently home to 1667 glacial lakes, with total area 96.5 ± 14.2 km². These lakes are largely in the central and eastern regions, which contribute 40.5 ± 5.2% and 29.8 ± 4.6% of total glacial lake area in Tian Shan, respectively. Only 9.5 ± 1.5% of present-day glacial lakes are in the western region. Under substantial climate warming and glacier shrinkage, the number and area of lakes over the past 20 years in Tian Shan increased by 22.5% and 16.7 ± 2.9%, respectively. The fastest expansion rate of lake area was in the eastern region, with averages ≈1.6 ± 0.3% a⁻¹ or 0.34 ± 0.06 km² a⁻¹, apparently attributable to warmer and wetter climate trends. Overall, small to medium lakes (<0.6 km²) were clearly sensitive to glacier wastage, since they had faster relative growth rates than did large lakes (<0.6 km²).

Extensive glacial lake expansion in the arid Tian Shan owes much to widespread temperature rise and glacier shrinkage. The great extension of glacial lakes only slightly retards loss of the meltwater resource from climate warming. A rough estimate showed that the net increase of glacial lake area (13.8 ± 2.4 km² or 0.69 ± 0.12 km² a⁻¹) caused by direct inflow of meltwater was equivalent to retaining ≈0.14 ± 0.03 Gt or ≈0.007 ± 0.002 Gt a⁻¹ meltwater in the lakes over the past 20 years. In the last decade, the increase rate of total lake water volume was ≈0.016 ± 0.002 Gt a⁻¹, representing ≈0.2 ± 0.0% of annual glacier mass lost in Tian Shan.

Continuous expansion of glacial lake area could potentially increase the frequency and damage of GLOFs or debris flows in the mountains. Sixty PDGLs were first-order identified, among which 12 had a high outburst probability status, 25 medium status and 23 low. The distribution of PDGLs proved spatially heterogeneous, with about 67% (eight lakes) in the high probability category in central Tian Shan and three in the eastern region. It is recommended that lakes in the high and medium categories be considered for further, detailed risk assessment.

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