Large drainages from short-lived glacial lakes in the Teskey Range, Tien Shan Mountains, Central Asia

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Abstract

Four large drainages from glacial lakes occurred during 2006–2014 in the western Teskey Range, Kyrgyzstan. These floods caused extensive damages, killing people and livestock as well as destroying property and crops. Using satellite data analysis and field surveys of this area, we find that the water volume that drained at Kashkasuu glacial lake in 2006 was 198,000 m^3, that at western Zyndan lake in 2008 was 437,000 m^3, that at Jeruy lake in 2013 was 163,000 m^3, and that at Karateke lake in 2014 was 169,000 m^3. Due to their subsurface outlet, we refer to these short-lived glacial lakes as "tunnel-type" that drastically grows and drains over a few months. From spring to early summer, such a lake either appears, or in some cases, significantly expands from an existing lake (but non-stationary), and then drains during summer. Our field surveys show that the short-lived lakes forms when an ice tunnel through a debris-landform gets blocked. The blocking is caused either by the freezing of stored water inside the tunnel during winter or by the collapse of ice and debris around the ice tunnel. The draining occurs then through an opened-up ice tunnel during summer. The growth–drain cycle can repeat when the ice-tunnel closure behaves like that of typical supraglacial lakes on debris-covered glaciers. We argue here that the geomorphological characteristics under which such short-lived glacial lakes appear are (i) a debris-landform containing ice

(ice-cored moraine complex), (ii) a depression with water supply on a debris-landform as a potential lake-basin, and (iii) no visible surface outflow channel from the depression, indicating existence of an ice tunnel. Applying these characteristics, we examine 60 depressions (> 0.01 km^2) in the study region and identify here 53 of them that may become short-lived glacial lakes, with 33 of these having a potential drainage exceeding 10 m^3/s in peak discharge.

1. Introduction

The northern Tien Shan in Kyrgyzstan, Central Asia, contains many small glacial lakes at glacier fronts. Compared to many large proglacial lakes in the eastern Himalayas that exceed 0.1 km^2 (Komori et al., 2004; Nagai et al., 2017), 74% of the lakes in the study region had area extents of less than 0.01 km^2 in 2014 (Narama et al., 2015). Nevertheless, in recent decades, rapid drainage from such lakes in the Central Asian Mountains has caused severe damage for residents in nearby mountain villages (Kubrushko and Staviskiy, 1978; Kubrushko and Shatravin, 1982; Narama et al., 2009; Mergili and Schneider, 2013). More recently, catastrophic damage occurred in 1998 from an outburst of the Archa–Bashy glacial lake in the Alay Range of the Gissar–Alay region. This small lake, which had formed on a debris landform at the glacier front, suddenly released over 50,000 m^3 of water. Although the volume of released water was relatively small, the flood killed more than 100 residents along the river in Shahimardan village in Uzbekistan (UNEP, 2007), demonstrating that flood volume alone is an insufficient indicator of damage potential.

In a similar event on 7 August 2002 in the Shahdara Valley, Pamir, Tajikistan, a 320,000 m^3 drainage from a small lake caused a mud-flow that buried the Dasht village on the alluvial fan and killed 25 people (Mergili et al., 2012). In the northern Tien Shan, a drainage occurred from the western Zyndan glacial lake in the Teskey Range on 24 July 2008 (Narama et al., 2010a). The latter event discharged 437,000 m^3 of water, causing extensive damage, killing three people and many livestock as well as destroying a bridge, a road, two houses, crops and an important fish-hatchery. These lakes are a type of short-lived glacier lakes (non-stationary, but existing only over a short period) that appear and discharge within a few months or one year (Narama et al., 2010a;

Mergili et al., 2013).

Unlike the supraglacial cases (e.g., in the Italian Alps; Haeberli, et al., 2002; Harrsion et al. 2015), the Central-Asian cases are a different type of short-lived glacial lake that appear at the glacier front on debris-landforms with buried ice. Monitoring of such lakes is complicated due to the sudden and short appearance of the lakes (Narama et al., 2010a). Also, their drainage through ice tunnels differs from that from many other glacial-lake-outburst floods (GLOFs) in the eastern Himalayas (Bhutan and eastern Nepal), which discharge through the failure of a moraine dam (Yamada and Sharma, 1993; Watanabe and Rothacher, 1996; Komori et al., 2012). In addition, the growth period of a short-lived lake also differs from the large proglacial lakes that have continued to expand since the 1950s–1960s in the eastern Himalayas (Ageta et al., 2000).

In the western Teskey Range of the Tien Shan mountains, several large floods occurred from a glacial lake at the Angisay Glacier in 1974, 1975, and 1980 (Kubrushko and Staviskiy, 1978; Kubrushko and Shatravin, 1982). Since then, large drainages have occurred at Kashkasuu glacial lake in 2006, at western Zyndan lake in 2008, at Jeruy lake in 2013, and at Karateke lake in 2014. Among them, the drainage from the western Zyndan lake was examined in Narama et al. (2010a). To understand the geomorphological characteristics of this type of short-lived glacial lake, we examine all four of these above recent floods as well as depressions with short-lived lakes using field-surveys and satellite data. To help decrease the damage from such glacier-related disasters, we assess the locations and volumes of these depressions and current glacial lakes. In addition, we discuss the geomorphological characteristics that lead to short-lived glacial lakes.

2. Study area

Along the southern shoreline of Lake Issyk-Kul in Kyrgyzstan, Central Asia, lie the Teskey Range, Tien Shan mountains (Fig. 1). The Tien Shan is a reactivated area of Paleozoic deformation. Although this region had a low-relief surface following the Paleozoic orogenies, Late Cenozoic deformation has resulted in this surface being warped across a series of mountain ranges cored by crystalline basement and previously deformed Paleozoic sedimentary and metamorphic rocks (Abdrakhmatov et al., 2001; Burgette et al., 2017). Here, surrounding Lake Issyk-Kul, lies the Issyk-Kul basin, bound to the south by the actively growing Teskey Range. The Teskey Range has a ridgeline at 4800–3700 m asl above small alpine glaciers.

Most precipitation here occurs in May–July, when the weakened Siberian High allows moisture to arrive from the west (Aizen et al., 1995). In general, the northern Tien Shan (outer ranges of the Tien Shan) blocks moisture carried by the Westerlies, causing larger annual precipitation amounts in the Pskem, Talas, Kyrgyz, Ili, and Kungöy Ranges, compared to the Teskey Range (Narama et al., 2010b) . In this range, the average annual precipitation ranges from 363 mm (1981-1999) in the western part (Karakujur station; 3000 m asl), to 247 mm (1981-1999) in the central part (Tien Shan station; 3600 m asl), to 597 mm (1981-1987) in the eastern part (Chong-Kyzylsuu; 2550 m asl).

Glacier shrinkage in the outer and inner ranges also varies significantly throughout the Tien Shan (Narama et al., 2010b). The glacier area has decreased less in the west than in the east (Narama et al., 2006; Katuzov and Shahgedanova, 2009).

The population and villages are distributed over the northern part of the Teskey Range. There, villagers use the large alluvial fans at the mountain piedmont as pasturage or agricultural fields.

3. Methods

3.1 Field surveys

In the study area of the western Teskey Range, we investigated glacial lakes and three recent (2006–2014) large drainages based on field surveys (2007–2016) and satellite data analysis. The drainages include those from the Kashkasuu, Jeruy, and Karateke glacial lakes shown in Fig. 1. From the western Zyndan lake within the study area, a large drainage on 24 July 2008 was reported in Narama et al. (2010a). We visited 25 glacial lakes including lakes that caused a large drainage, and investigated landforms (distance and location of ice tunnel, depression of lake basin) and lake levels after drainage using a Trimble GeoExplorer 6000 (cm-precision edition) and a Leica GPS 900. We obtained a positional accuracy of within 10 cm through differential post-processing of Trimble GPS data using the Kyrgyz GPS reference station. To estimate the water volume of current lakes, we measured water depths in 10 current lakes in the area using an inflatable boat (PVL-260) and a fish finder with GPS （LOWRANCE HDS-5; Fig. 1). In the downstream zones of Jeruy and Karateke lakes, we investigated clast diameter, sedimentary facies, extent of flood deposit, and the eroded channel. In addition, we interviewed residents of Jeruy village about local floods.

3.2 Satellite data analysis

We investigated the evolution of the Kashkasuu, Jeruy, and Karateke lakes using the Advanced Land Observing Satellite (ALOS) with the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM; 2.5-m resolution), as well as the ALOS AVNIR-2 (10-m resolution), Landsat7 ETM+, and Landsat8 OLI data. The ALOS and Landsat images were fused, and pan-sharpened images using the PCI Geomatica software were used to estimate glacial lake areas by manual mapping of the glacial lake boundaries. We also estimated the water volumes after drainage using ALOS PRISM digital surface models (DSMs). The PRISM DSMs were processed by JAXA EORC as a high-level product. The standard deviations of the PRISM DSM height errors (PRISM DSM without Ground Control Points, GCPs, minus reference DSM) are between 4.9 and 8.7 m (Takaku and Tadono, 2009; Tadono et al., 2012).

A short-lived glacial lake appears at a depression (shallow hollow) on the debris landforms at glacier fronts. To estimate the location and maximum volume of a potential lake-basin, we used a water-filling model to extract depressions on the debris-landforms at glacier fronts. The model used PRISM DSM data taken on 17 Sep. 2007, 19 Nov. 2007, 28 Apr. 2010, 10 Aug. 2010, 10 Nov. 2010, and 27 Nov. 2010. We set 0.01 km^2 as the minimum depression size, because recent drainages with damages are caused from short-lived lakes exceeding 0.01 km^2. To test the accuracy of the water-filling model, we compare its result to an estimate based on GPS data from the western Zyndan lake before its drainage (24 July 2008). As shown in Fig. 2, the GPS data along the shoreline (ice line) of the western Zyndan lake before drainage coincides well with the extracted outline of the depression from the model.

For assessment of floods, it is of significant advantage to anticipate the flow type and map the landform of a valley mouth reached by the flood because the latter determines the range and form of the debris spread. To distinguish debris-flow types (i.e., debris flow vs. water flood), we estimated the erodible channel distance as the distance over which the channel has an angle exceeding 10° using the SRTM DEM (30-m resolution). In addition, we used satellite data to classify the lowland landforms in 23 valleys in the northern part of the western Teskey Range into valley landform and alluvial fan.

4. Results

4.1. Evolution of three short-lived glacial lakes

In the following, we consider the area changes of the Kashkasuu lake in 2006, Jeruy lake in 2013, and Karateke lake in 2014. (The western Zyndan lake is described in detail in Narama et al., 2010a). Figure 3 shows their changes observed from satellite images, Fig. 1 shows their locations. Kashkasuu lake in the southern part of the Teskey Range is has direct contact to a glacier, a lake type termed here glacier-contact type. In Fig. 3A, we show its lake area has increased on 21 June 2005 (compared to 6 Sept. 2004, not shown), and remains nearly the same on 23 May 2006. It grows until 26 July 2006, expanding to 0.025 km^2, but the lake shrinks again to 0.004 km^2 on 11 August 2006. Thus, lake water has discharged between 26 July and 11 August 2006. Based on the lake area on 26 July 2006 and the PRISM DSM, we estimate that 198,000 m^3 of water volume discharged.

To the northwest of Kashkasuu lies Jeruy glacial lake. Images in Fig. 3B show this lake to be not recognizable on 18 May 2013, but clearly visible by 19 June 2013. By 6 August 2013, it has grown to 0.033 km^2 with an estimated volume of 163,000 m^3. The lake, which has glacier contact, drains on 15 August 2013, but some water remains on 23 September.

Nearby and to the east lies Karateke lake. This lake is without glacier contact and located on a debris-landform at the glacier front. Figure 3C shows the lake area to be only 0.001 km^2 on 5 May 2014, but expanding to 0.02 km^2 on 30 June 2014, and then decreasing to 0.015 km^2 on 16 July immediately before drainage on 17 July 2014.

After drainage, its area becomes 0.0016 km^2. During this drainage, 169,000 m^3 of water was discharged.

These three lakes, as well as the western Zyndan lake that discharged 437,000 m^3 on 24 July 2008 causing a large flood (Narama et al., 2010a), all appeared in May, grow rapidly in June and July (Fig. 4), then discharged between mid-July and mid-August. Thus, all four lakes are examples of a "short-lived glacial lake" that suddenly appears and grows during two or three months, with drainage occurring in the summer. Considering the growth of the lakes, the Kashkasuu glacial lake appeared and remained from the previous year, but then grew suddenly. But the Karateke, Jeruy, and western Zyndan lakes evolved and grew from an initially empty basin during the same year.

4.2 Geomorphological evidence of drainage from the short-lived lakes

To better understand the behavior of the lakes, particularly their drainage, we investigated adjacent landforms in a field survey. At the Kashkasuu lake, in 2007, a debris landform containing ice was found at the glacier front. The ice-rich debris landforms are also called moraine complex (Shatravin, 2007; Janský et al., 2010; Bolch et al., 2014). The debris-landform, composed of debris and ice, remained from glacier shrinkage. The Kashukasuu lake expanded on the large depression (hollow) with glacier contact. No surface channels were visible, but we observed a subsurface channel that developed inside of the debris landform. It was a 300-m-long ice tunnel with a water-stream from the lake to the tunnel outlet. The lake water discharged through this ice tunnel between 26 July and 11 August 2006 (Fig. 3A). From August 2006 (before drainage) to September 2007, GPS data shows the lake level dropping by 10 m. This large drainage damaged the mountain road and a bridge along the Uchemchek River.

We observed exposed ice and ice tunnels on similar debris-landforms in front of the Jeruy and Karateke Glaciers (Fig. 5A, B). Both debris-landforms contain buried ice. Jeruy lake appeared on the depression of a basin with glacier contact. Karateke lake also formed at an empty depression, but without glacier contact. For the Karateke lake, meltwater from the glacier terminus flows into the depression. But for the outlets of both lakes, we observed no visible surface outflow channel from either depression.

However, we found the Jeruy depression to have a 250-m-long ice tunnel and the Karateke to have a 500-m-long one. For the Karateke lake, the ice tunnel is 4 m wide at the entry point of the debris landform (Fig. 5C). The middle point of the ice tunnel is 5 m deep and shown in Fig. 5D.

Our field survey thus indicates that lake water from the Kashkasuu, Jeruy, and Karateke lakes discharged through ice tunnels inside of debris-landforms, as was found previously also for the western Zyndan lake (Narama et al., 2010a). In these debris-landforms, there are no visible surface outflow channels, and most meltwater from the glacier flows through an ice tunnel. Hence, we consider these short-lived glacial lakes as "tunnel-type" to distinguish them from those that discharge through different mechanisms (e.g., dam failure, surface channel blockage).

4.3 Flood deposits and landforms

Regarding the flood deposits from the lakes studied, the Jeruy and Karateke Valleys are located side by side (Fig. 1), but they produce different flood types and damage. The flood deposits from the Jeruy drainage consist of matrix-support deposits of clasts of mostly 0.20–0.30 m diameter but also including boulders of 1–3 m diameter (Fig. 6A). From an interview of a local resident of Jeruy village we confirmed that the flood velocity of the Jeruy drainage was slow on the alluvial fan. The flood stream from the Jeruy glacial lake separated into two routes on the large alluvial fan and did not flow along the present water stream. On the alluvial fan, the flood caused a bridge collapse and damaged an irrigation channel, a road, many tombs, an agriculture field, and a line of house. On the other hand, flood deposits from Karateke lake consist of clast-supported deposits with large boulders of 1–2 m diameter (Fig. 6B). Flood deposits are limited to the riverbed. Damages from the Karateke flood were limited to two bridges along the river. The flood deposits of the western Zyndan were similar to the Karateke deposits.

For the Jeruy Valley (Fig. 6C), the uneroded flat riverbed section in the upper part is short and the erosion section is long. In contrast, for the Karateke Valley the upper part consists of a flat valley with only a short highly eroded section (Fig. 6D). The different erosion distances are related to the valley landforms in the upper valley part from past glaciation. When a steep slope starts at the end of a flat valley, the flood-wave is able to gain debris, transforming to a debris-flow. As an indication of the flood wave with predominant water content in the upper part of the Zyndan Valley, grass flattened by water was observed in the riverbed after drainage from the western Zyndan lake (Narama et al., 2010a). The degree of entrainment and the resulting changes in water and debris content influence the velocity of the flow (Breien et al., 2008). In the flat valley section below the Karateke lake, we also observed flattened grass along the river. Above the highly eroded section of the Jeruy drainage, drainage water that does not include much debris led to slow velocities of the mass flow on the alluvial fan. In contrast, dense debris flows could be quite mobile. During experiments in Kazakhstan in 1973, the mean density of highly mobile debris flow reached 2200 kg/m^3 with water content below 10% (Evans and Delaney, 2015; Baimoldaev and Vinohodov, 2007). When the eroded material is dry, entrainment produces a high concentration of solids in the slurry with associated increases in the viscosity, cohesion, and friction, all of which could reduce the mobility (Breien et al., 2008).

4.4. Volume size of existing lakes and depressions

To estimate the water volume and basin form of current glacial lakes, we measured the depths and geolocations of 10 lakes using an inflatable boat and fish finder with GPS. All 10 lakes were less than 30 m deep. Profiles of three of them are shown in Fig. 7. Lakes in the study area are small. Of the 160 glacial lakes over 0.001 km^2 in the Teskey Range, 68% of them are less than 0.01 km^2 (Narama et al., 2015). The resulting profiles of the lake-basins at glacier fronts are asymmetric as shown in Fig. 7B and C, with greater depth and steeper slope at the glacier terminus side. We found a submerged moraine at the lake bottom of the eastern Zyndan lake. Such a moraine prevents a complete discharge of all lake water, but most observed lakes had no such internal barriers.

The short-lived glacial lake type studied here appears at a depression on a debris landform containing buried ice. To find the locations of such depressions in the northern part of the western Teskey Range, we used the PRISM DSMs (2.5-m resolution) to measure the distribution and volume of depressions of potential lake-basins. In total, we found 60 depressions exceeding 0.01 km^2. A short-lived glacial lake can appear at such a depression only if it receives sufficient meltwater. Thus, we distinguished the depressions as those with glacier contact and those without glacier contact (Fig. 8). Of the 60 depressions, 38 (i.e., 63%) of the depressions had glacier contact in which melt water can inflow from glacier termini.

The depressions without glacier contact are of water accumulation and non-accumulation types. The depressions of water accumulation type can get melt water from the glacier because the depression is connected to it via one or more subsurface channels. In contrast, the non-accumulation type is not connected to a water channel and cannot get substantial amounts of water within short time. We found 22 depressions of the water accumulation type, and each may become a short-lived lake such as the Karateke lake (Fig. 3C). In addition, we determined whether or not the depression had a surface outflow channel. Among the 60 depressions, 7 depressions had a surface outflow channel and thus cannot hold a short-lived lake of the tunnel-type studied here.

The relationship between area and volume of the 10 measured lakes agrees with those found previously. In the plot of Fig. 9, we also show the four large drainages of Kashkasuu, w-Zyndan, Jeruy, and Karateke glacial lakes, as well as depressions in this study area, and six lakes from previous studies in the Kyrgyz and Ili Ranges (personal communication of I. Severskiy; Janský et al., 2010). The regression line formula between area and volume was calculated using only measurement data (this study and previous studies), and was then used to estimate the water volume of current lakes. For example, the formula shows that lakes exceeding 0.02 km^2 have a minimum lake volume of over 150,000 m^3. In comparison, the Karateke lake, which had an area of 0.015 km^2, had a drainage volume of 169,000 m^3, the minimum drainage among our four large drainages.

5. Discussion

5.1 Geomorphological characteristics of tunnel-type, short-lived glacial lakes

The field surveys of the four short-lived lakes revealed that, in each case, water discharged through an ice tunnel inside an ice-rich debris landform. Our satellite observations of these short-lived glacial lakes show them to appear as a small pond in

May and to expand suddenly in June–July. The field surveys showed this behavior to be due to i) the blockage and closure of ice tunnels, and ii) rapid melting of snow and ice in the upstream area. The ice tunnels become blocked due to freezing of stored water during winter or deposition of ice and debris by tunnel collapse. Later, their drainage between the end of July and mid-August occurred when their ice tunnel opened, due to subsurface ice melting or evacuation of debris at the closure point.

This drainage process seems similar to the opening of an englacial channel for a supraglacial lake on a debris-covered glacier (Benn et al., 2001; Gulley et al., 2009). Supraglacial lakes have a seasonal variability and can be transient or recurring, depending on the connectivity to englacial network (Miles et al., 2016, 2017; Benn et al., 2017; Narama et al., 2017). The formation and sudden drainage of supraglacial ponds also have occurred in the Cordillera Blanca, Peru (Emmer et al. 2015). Several large drainages from supraglacial lakes through englacial conduits have occurred on debris-covered glaciers without a large proglacial lake in front of them (Richardson et al., 2009; Komori et al., 2012; Rounce et al., 2017). In north-western Nepal, a supraglacial lake that developed temporally at a depression on a small alpine glacier caused a large drainage through an englacial conduit (Kropáček et al., 2015).

This drainage process differs from that typical for glacial lake outburst floods (GLOFs) in the eastern Himalayas. The Himalayan GLOF type occurs from a large proglacial lake that has expanded for several decades but then its moraine dam fails (Yamada and Sharma, 1993; Ageta et al., 2000). Such a lake typically does not refill to the same level it had before failure. However, the lake area might expand again backwards due to glacier recession, or the water level might increase due to blockage of an outlet channel when a large-scale failure occurs at the moraine's inner slope (Ageta et al., 2000) or the dam opening is blocked by snow and ice (Huggel et al. 2003). After drainage, the failure is visible as a V-shaped channel excavated across the moraine dam (Breien et al., 2008; Komori et al., 2012).

In contrast, the short-lived glacial lake type studied here appears and expands for a few months, and then discharges through ice tunnels. The lake appears in a depression that develops after recent glacier recession (Narama et al., 2010a). After drainage, vertical subsidence occurs along the subsurface channel in the debris landform.

Such a short-lived glacial lake type recurs when its ice tunnel closes, similar to that on a supraglacial lake on a glacier or on a debris-covered glacier (Kropáček, et al., 2015; Benn et al., 2017; Narama et al., 2017). For example, at Angisay Glacier in the Teskey Range (Fig. 1), several floods occurred from the same glacial lake in 1974, 1975, and 1980 (Kubrushko and Staviskiy, 1978; Kubrushko and Shatravin, 1982). The repeated floods indicate that the lake water refills at the same lake basin due to a repeated closure of the ice-tunnel. Although existence of the lake could not be confirmed, the Ak-Say Glacier of the Kyrgyz Range also had repeated drainages in the 1980s (Janský et al., 2010; Zaginaev et al., 2016).

5.2 Identifying potential lake-basins of short-lived glacial lakes

In addition to monitoring existing lakes, our findings suggest that one should also monitor empty depressions in which a short-lived glacial lake may form. But which depressions should be monitored? We narrow down the possibilities in the following way:

One characteristics to rule out some cases is a clear source of meltwater. That is, a short-lived glacial lake cannot appear at a depression in which meltwater cannot inflow at substantial amounts. Among the 60 depressions (> 0.01 km^2) we examined, 38 of them had glacier contact and thus can get melt water directly from glacier termini. The remaining 22 depressions had no glacier contact, but could also accumulate water type such as the Karateke lake (Fig. 3C). As another geomorphological feature to rule out potential hazardous cases, we exclude basins with surface outflow channels from the depressions. As a result of these two restrictions, 53 depressions among 60 depressions are found to be potential basins for a tunnel-type, short-lived glacial lake.

Considering now the factors that influence drainage volume from a short-lived lake, one factor is the volume of the depression. For example, a supraglacial lake formed in a large depression caused a large drainage from the Tshojo Glacier in the Lunana region, Bhutan (Yamanokuchi et al., 2009). The Karateke lake drainage had a volume of 169,000 m^3, the smallest of the four large drainages we studied, and the lake had an area of 0.015 km^2. Thus, we recommend to monitor depressions with area exceeding 0.01 km^2, thus taking also into account moderate future expansion.

Other factors are the timing of the ice-tunnel opening and the melting rate of ice and snow, both of which affect the water filling of the depressions. In the study area, the lake water of the western Zyndan glacial lake overflowed before a large drainage on 24 July 2008. The overflow was due to a high snow/ice melting rate and a late timing of ice-tunnel opening (Narama et al., 2010a). In contrast, an early timing of ice-tunnel opening or a small upstream melt rate might cause only a partial discharge.

In addition, the width of the ice tunnels and distance to the closure point determine the total stored water volume (lake plus conduits) because the closure point may be far downstream from the lake in the ice tunnel. Thus, the drainage volume depends on (i) volume of the depression, (ii) timing of the ice-tunnel opening, (iii) melt rate of ice and snow, (iv) size of the ice tunnel, and (v) closure point of the ice tunnel.

5.3 Transition to debris flow

For lakes of tunnel type, the flood wave without moraine deposits can transform into a debris flow where the channel gets steeper and the wall-material erodible. The change occurs because banks of the channels in the study area are often composed of loose material (Haeberli, 1983; Clague and Evans, 1994, Breien et al., 2008; Evans and Delaney, 2015). The mobility of the debris flow also depends on the type of loose erodible material. In the Ili Range of the northern Tien Shan, some cases of drainage started with a small initial failure volume that then increased by entrainment of material from the path, acquiring much debris from the middle of a steep mountain slope, resulting in very large deposits that exceeded 10^6 m^3 (Evans and Delaney, 2015).

Two main types of debris flows occur, viscous and stony (Takahashi, 2004; 2009). For example, the Jeruy and Karateke lakes have about the same elevation (3815 and 3757 m asl), and similar maximum discharge (Qmax) values of 13.9 and 14.2 m^3/s, but Jeruy's debris-flow type was a viscous flow with matrix-supported deposits (Fig. 6A), whereas Karateke's was a stony debris-flow with clast-supported deposits (Fig. 6B). To help us understand these differences, we also investigated the debris flows that occurred on 3 June 2009 from the Takyltor Glacier in the Kyrgyz Range.

Where does the channel erosion occur? According to Hungr et al. (1984), net deposition in a channel starts where the channel angle is about 10° or less. Thus, the other regions are sections that can erode. Here, we use the distance over which the channel exceeds 10 degrees as defining the 'erodible channel distance'. This erodible channel distance agrees well with the actually eroded distance in the western Zyndan lake case (Narama et al., 2010a). Although the slope angles (H/L ratio) of the erosion section are about the same here, the erodible channel distance vary, though, significantly by valley (i.e., Karateke Valley vs Jeruy Valley; Fig. 6C, D).

Observations show that entrainment make debris flows more and more erosive, resulting in a feedback effect (Breien et al., 2008). This effect partly explains the high rate of volume increase observed in many debris flows and is probably often necessary to achieve long runouts in subaerial flows.

We characterize potential flows by the erodible channel distance and the estimated maximum discharge. We estimate here the maximum discharge of 60 depressions and existing lakes using the duration of discharge and $Q_{max} = 46(V/10^6)^{0.66}$ (tunnel event; Walder and Costa, 1996), with a water volume V. This formula neglects the possible role of tunnel size in total drainage volume. For an existing lake, V is estimated using the regression formula in Fig. 9. In the study area, the erodible channel distances range between 166 and 6016 m, and the maximum slope gradients of the mean erodible channel distance are 11.5–20.9°. We also characterize actual drainage events (the above four recent floods) using these two parameters.

The results, plotted in Fig. 10, suggest a classification in which each drainage is either a debris flow or water flood. Many short-lived lakes change from water flood to debris flows, involving debris entrainment (stony flow or viscous flow), due to the channel wall having looser material (including composition of material; fragmented rock or surficial materials; Evans and Delaney, 2015). With a transition boundary at an erodible channel distance of about 1500 m, the western Zyndan, Karateke, Jeruy, Kashkasuu, and Takyltor floods are classified as debris flows in Fig. 10, and they have Qmax values of 14–27 m^3/s. Among the 53 depressions, 33 depressions exceed 10 m^3/s in possible maximum discharge (Fig. 10). But for the existing lakes, most have a Qmax below 10 m^3/s.

Thus, the drainage of short-lived lakes in the study region shows a transition between water flood and debris flow. Depending on the situation, the debris flow may be stony or viscous flow. The debris entrainment in this flow may deposit a large amount of debris. Although the influence of most debris flows from the short-lived lakes is limited to the valley mouth or river sides on the mountain piedmont, the deposition region may in some cases have a long runout if the fluidity increases with distance along the flow.

5.4 Differences in flood damage

On the alluvial fan downstream of the Jeruy Valley, two debris-flow streams separated from the present river channel and caused large damages to agriculture fields, irrigation infrastructure, roads, and many tombs. In comparison, in the Karateke Valley only two bridges were broken because the outburst stream was limited along the river. In Shahimardan village, where a flood killed more than 100 residents (UNEP, 2007), many residents live along the river. In the Dasht village, where a flood killed 25 people (Mergili et al., 2012), the debris-flow covered the village on the alluvial fan.

The degree of flood damage is related to the local land-use and the landform type at the valley mouth such as alluvial fan. During the western Zyndan lake drainage in 2008, the flood damaged a kashaal (animal cottage) on the alluvial fan (Narama et al., 2010a). Among 23 valleys in the study area in the northern-western part of the Teskey Range (Fig. 1), 14 valleys are of valley landform (Karateke case) and 9 valleys are of alluvial fan type (Jeruy case). The drainages from the four short-lived lakes studied here are less than 500,000 m^3 and their flood damages are limited along the river or alluvial fan. As most depressions are up to 500,000 m^3 in this region, most flood damages are considered to be likely limited along the river or alluvial fan at the valley mouth. Although some large depressions have existed here, we know of no case in which a large lake had a large drainage. However, for risk mitigation, drainages from short-lived lakes should become an integral part of river basin management in the region, considering in particular depression volume, flood type, land-use and landforms potentially affected.

6. Conclusions

In the western Teskey Range, recent large lake drainages have come from the tunnel-type of short-lived glacial lakes, which appears and then drains within a few months. These lakes were found to typically appear as small ponds in May, then expand suddenly in June–July due to rapid melting of ice and snow in the upstream area. The lake damming appears due to blockage and closure of ice tunnels, as a result of winter freezing of stored water, or deposition of ice and debris by tunnel collapses. The drainage then occurs between the end of July and mid-August when the ice tunnel re-opens, due to ice melting or the blocked section flushed away. Using the estimated drainage volumes from the current lakes or depressions, we argue that their flood damages will occur only at their alluvial fans or along the river at their mountain piedmont. Most drainage events led to debris-flows.

The geomorphological characteristics under which these lakes appear were found to be (i) a debris-landform including dead ice (ice-cored moraines) with the potential to form an ice tunnel, (ii) a depression (> 0.01 km^2) on the debris-landform with sufficient water supply, and (iii) no visible outflow channel from the depression, thus requiring the water to exit through an ice tunnel.

The comparably short period of a few months between appearance and drainage of the short-lived lake type studied here poses a special challenge to the application of satellite remote sensing for monitoring them. However, new satellite constellations such as Sentinel-2 (5 days repeat; Kääb et al. 2016) or the Planet cubesat constellation (daily repeat, Kääb et al. 2017) will help to detect even short-term changes. The applicability of Sentinel-1 radar data (6 days repeat) for monitoring these lakes remains to be tested (Strozzi et al., 2012). For such systematic surveillance, the type of prioritization of potentially dangerous sites as proposed here is essential. We propose an early information network based on monitoring with satellite data that informs responsible authorities and possibly local people when a lake appears. As glacier-lake workshops in the Ladakh region of India (Ikeda et al., 2016) and in Jeruy village (study area) showed, improvement of knowledge and land-use can help reduce the impacts of large drainage floods form glacial lakes.

In the Tien Shan, depressions (> 0.01 km^2) in which water can inflow should be monitored, just as we now monitor glacial lakes, and their potential associated hazards considered. Lake monitoring using satellite data should proceed based on the criteria of potential dangerous lakes outlined here such as the location and volume of the lakes and depressions, the flood type, and landform on the mountain pediment.

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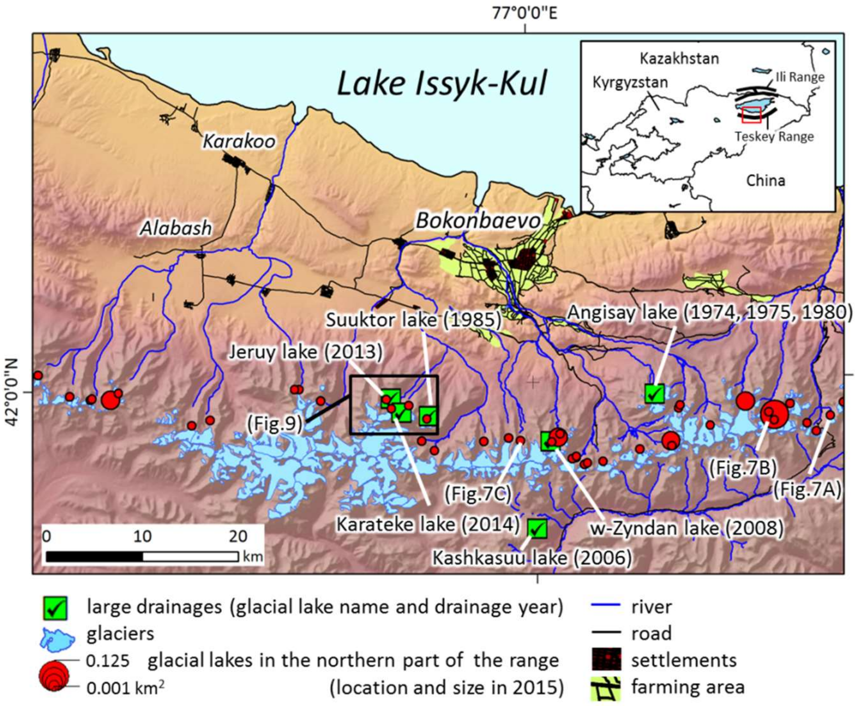

Fig. 1. The study area in the western part of the Teskey Range, Kyrgyzstan. Green boxes show the location of large drainage events with the name and year labeled. Location and size of red circles show locations and size of lakes in 2015.

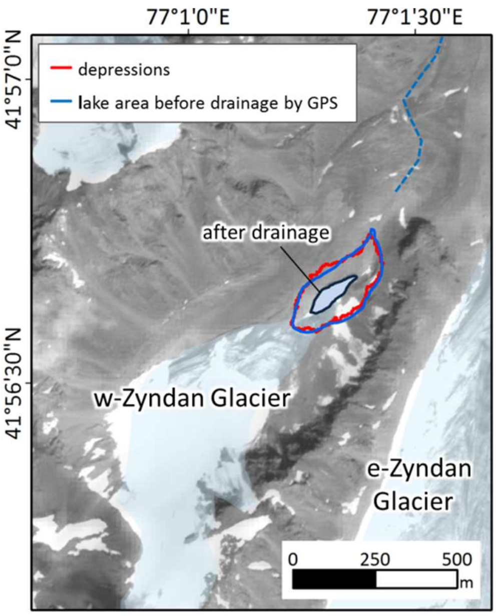

Fig. 2. Western Zyndan glacial lake at which a large drainage occurred in 2008 (location in Fig. 1). The blue line shows the lake perimeter before drainage according to GPS measurements in 2008. The red line shows the depression according to ALOS PRISM DSM data.

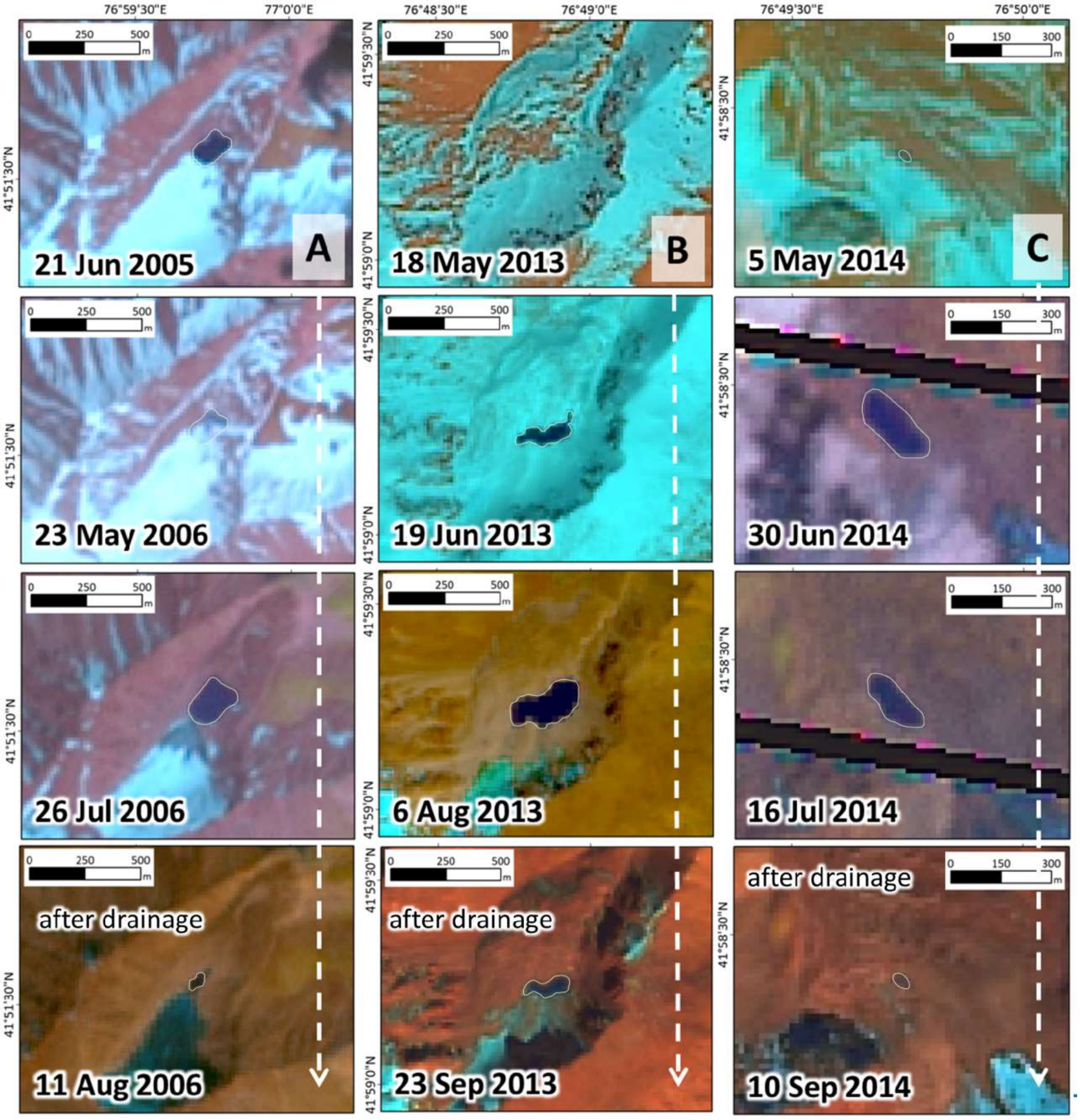

Fig. 3. Changes of three lakes. Left column (A) is Kashkasuu, middle (B) is Jeruy, and right (C) is Karateke lake. Images are from Landsat7 ETM+ and ALOS AVNIR-2 and PRISM data. The locations are in Fig. 1.

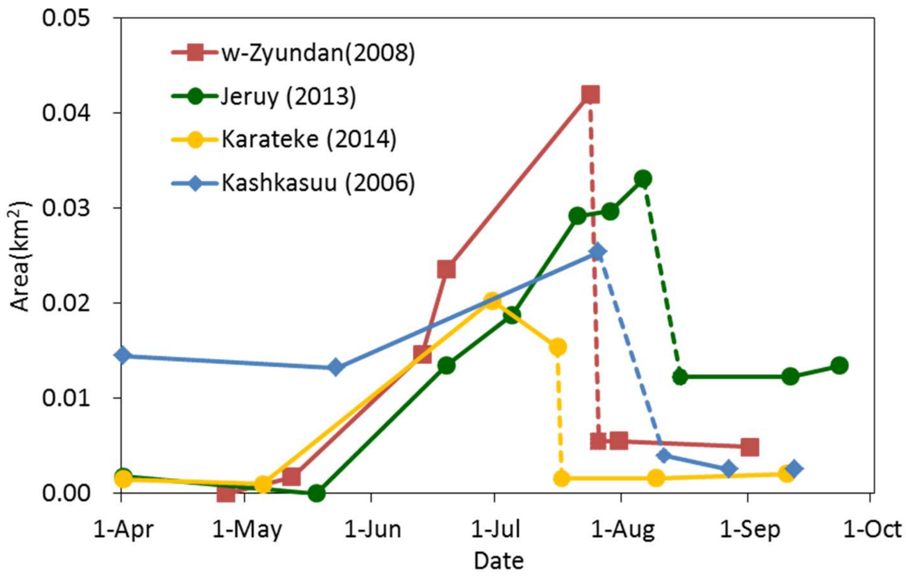

Fig. 4. Seasonal area changes of four short-lived glacier lakes. Dashed line segments indicate drainages.

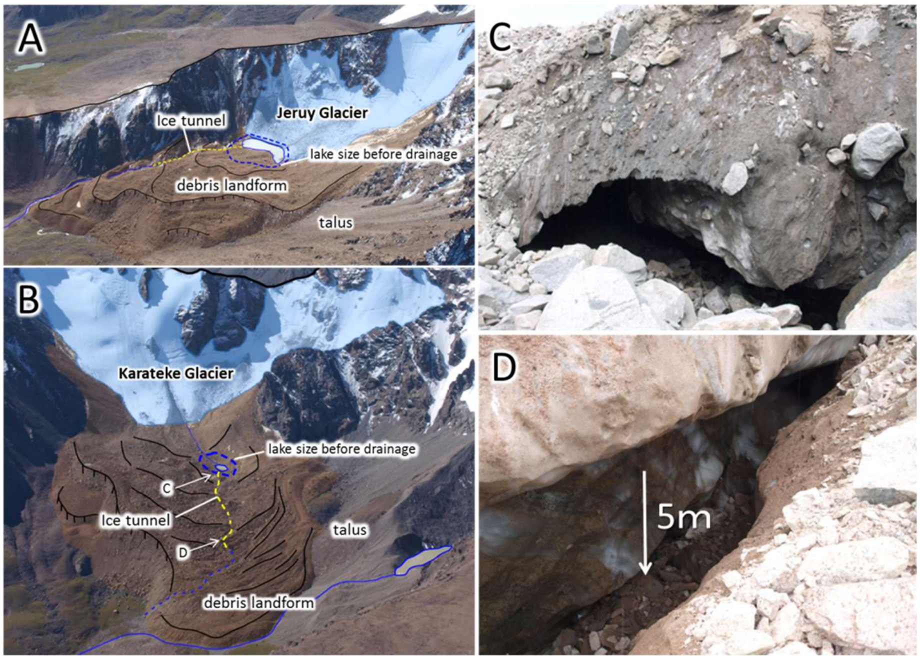

Fig. 5. Surface details of Jeruy and Karateke Glaciers (locations in Fig. 1). In A) and B), the blue dashed lines show the lake size before drainage. Yellow dashed lines locate ice-tunnels. C) The ice tunnel in the middle of the debris landform. D) The entry point of the ice tunnel at the front of Karateke Glacier. The glacial lake with glacier contact expanded into Jeruy Glacier, and the glacial lake without glacier contact developed in front of Karateke Glacier.

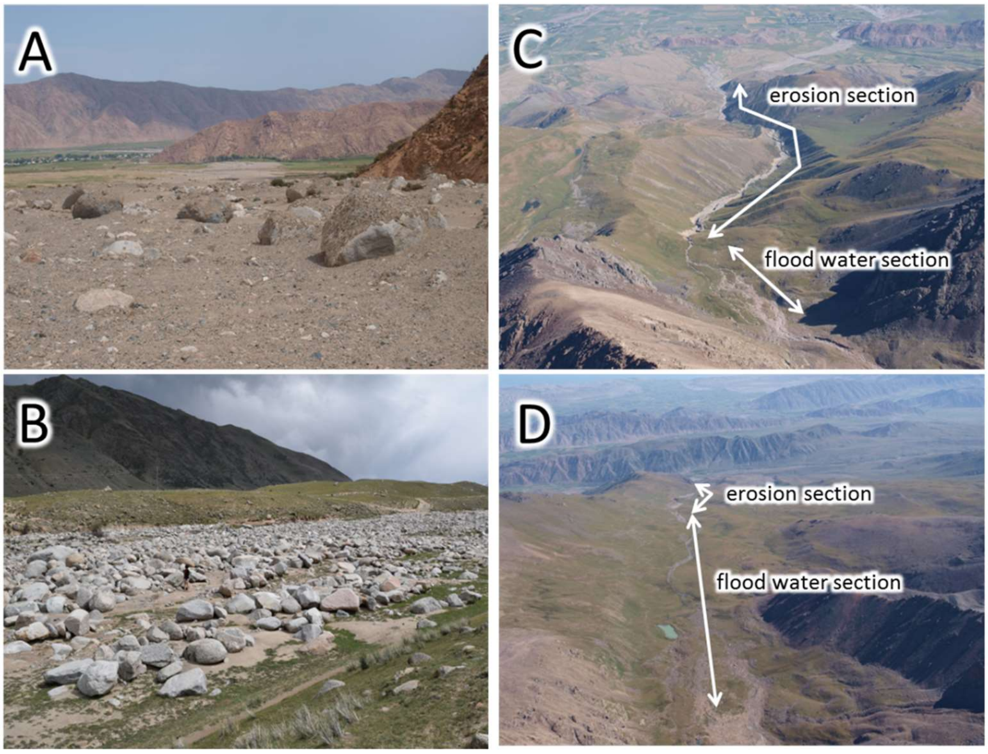

Fig. 6. Flood deposits and valley landforms in the Jeruy (left column) and Karateke (right column) Valleys.

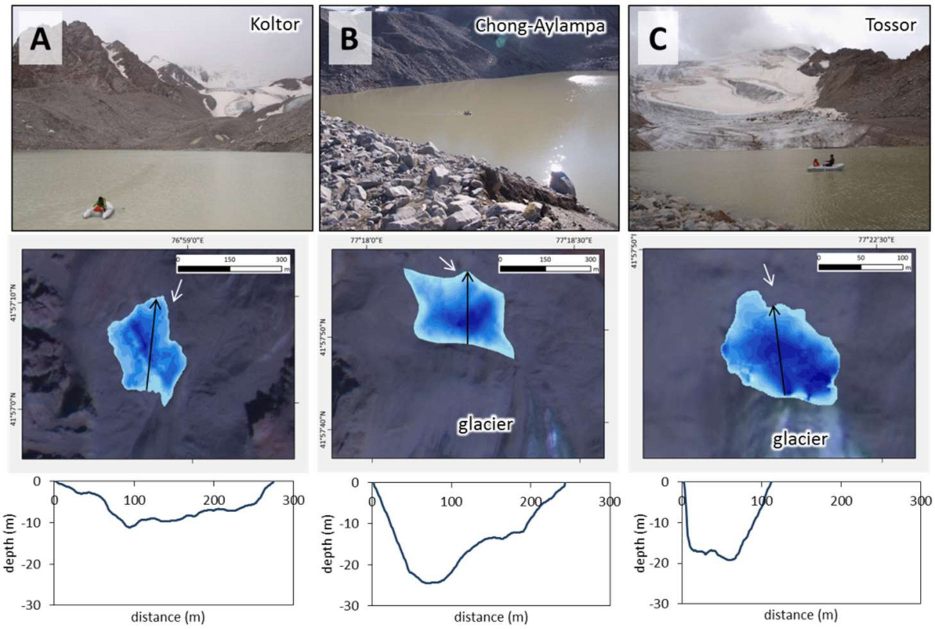

Fig. 7. Photos, lake-basin maps, and depth profiles of three glacial lakes. (A) Koltor, (B) Chong-Aylampa, (C) Tossor lakes (locations in Fig. 1). Black and white arrows on the lake-basin maps show each basin profile line and photo direction, respectively.

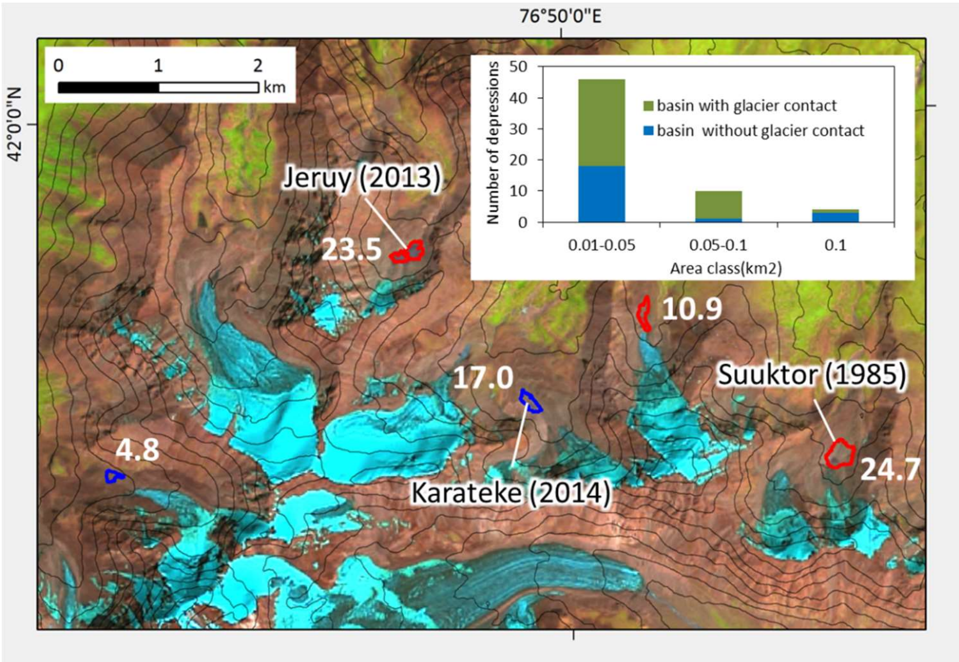

Fig. 8. Depressions at glacier fronts in the study area (locations in Fig. 1). Units are 10^4 m^3. Blue lines are depressions, and red lines depressions with the lake in 2015. The inset shows size, number, and type (with glacier contact or without glacier contact) of depressions in the study area.

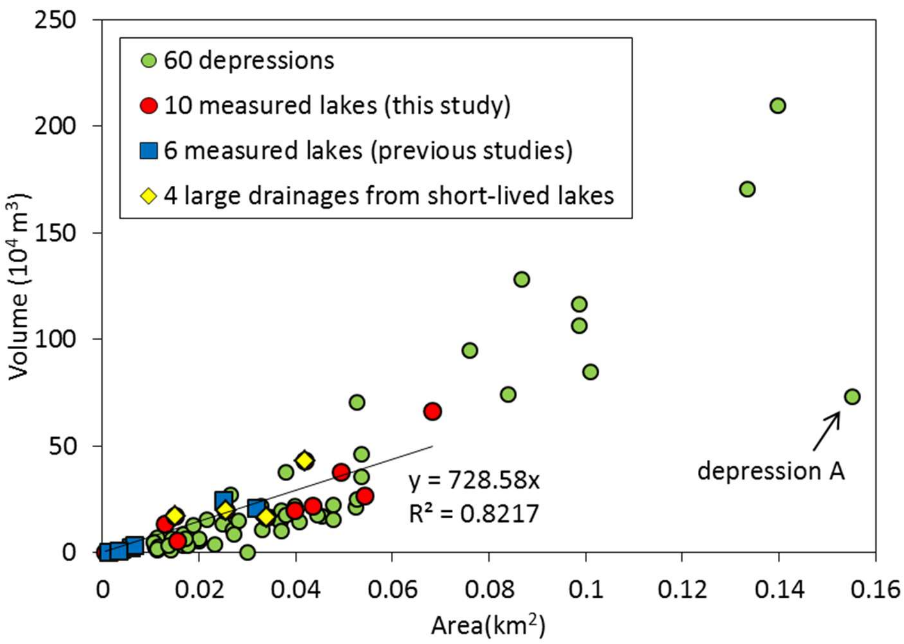

Fig. 9. Volume and area of directly measured lakes and depressions. Depression A has a lake area of more than 30% of the maximum filling area possible. (Data from 6 previously studied lakes, this study, and personal communication of I. Severskiy; Janský et al., 2010)

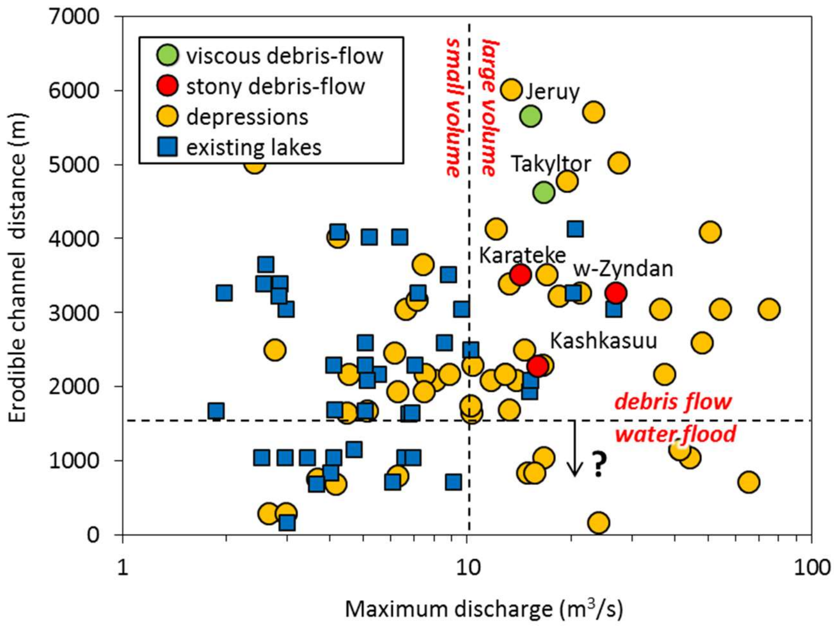

Fig. 10. Debris-flow types in the study area. The horizontal dashed line separates the debris flows from those with little debris, which we call simply 'water flood'. The vertical dashed line separates the high-volume flows (four drainage class) from the relatively low-volume flows.