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

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Abstract

During 2006-2014 in the western Teskey Range, Kyrgyzstan, four large drainages from glacial lakes have occurred. These flooding events caused extensive damage, killing people and livestock as well as destroying bridges, roads, homes, and crops. According to satellite data analysis and field surveys, the volume of water that drained at Kashkasuu glacial lake in 2006 was 198,000 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 tunnel outlet, we refer here to these glacial lakes as a "tunnel-type" of short-lived glacial lakes that drastically grow and drain over several months. From spring to early summer, such a lake either appears, or in some cases, significantly expands from an existing lake, and then drains during summer. Our field surveys show that these short-lived lakes form when the ice tunnels inside a debris landform get blocked. The blocking is caused either by the freezing of stored water during winter or from collapse of the ice tunnel. The draining occurs through an open ice tunnel during summer. The growth–drain cycle can repeat when the ice-tunnel closure behaves like that on supraglacial lakes on debris-covered glacier. We argue here that the geomorphological conditions in which such a short-lived glacial lake appears are (i) existence of an ice-containing debris-landform (moraine complex), (ii) existence of lake-basin depressions having its water supply on a debris-landform, and (iii) no surface water channel from lake-basin depressions. Using these geomorphological conditions, we examined 60 lake-basin

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depressions (> 0.01 km^2) in this region and identify here 56 of them that are potential locations for a short-lived glacial lake.

1. Introduction

The northern Tien Shan in Kyrgyzstan, Central Asia contains many small glacial lakes at glacier fronts (Narama et al., 2015). These lakes are of limited size, with areal extents of 0.001–0.05 km^2 compared to the large proglacial lakes in the eastern Himalayas that exceed 0.1 km^2 (Komori et al., 2004). 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 Shatrabin, 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. The small lake, which had formed on a debris-landform on 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), stressing that glacial lake or flood volume alone is an unsufficient indicator for the 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, Kyrgyzstan, 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.

The western Zyndan and Dasht lakes were a type of short-lived glacier lakes that appeared and discharged within several months or one year (Narama et al., 2010a; Mergili et al., 2013). A short-lived glacial lake reported earlier occurred in the Italian Alps in 2002 when a large supraglacial lake appeared at a hollow on a surging glacier (Haeberli, et al., 2002; Tamburini, 2003; Kääb et al., 2004). Within four months, 3,000,000 m^3 of meltwater was stored and then drained. However, the Central-Asian cases are a different type of short-lived glacial lakes that appear at the glacier front, not supraglacial, on ice-containing debris-landforms. Monitoring of such lakes is complicated due to the sudden and short appearance of the lakes (Narama et al., 2010a). Their drainage through ice tunnels differs from that from many other glacial lake outburst floods (GLOF) in the eastern Himalayas (Bhutan and eastern Nepal), which are

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caused by the collapse of moraines. 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).

To understand the characteristics of this type of short-lived glacial lakes, we use field-survey results and satellite data analysis to investigate recent short-lived lakes along the southern shoreline of Issyk-Kul Lake, Kyrgyzstan in the western Teskey Range. These lakes had caused damage from large drainages. In this region, several large floods occurred from a glacial lake at the Angisay Glacier in 1974, 1975, and 1980 (Kubrushko and Staviskiy, 1978; Kubrushko and Shatrabin, 1982). To help decrease the damage from glacier-related disasters, we assessed the locations and volumes of short-lived glacial lakes. In addition, we discuss the geomorphological conditions that lead to short-lived glacial lakes and the resulting flood type.

2. Study area

We investigated glacial lakes in the western Teskey Range along the southern shoreline of Lake Issyk-Kul, in the Tong district of Kyrgyzstan, Central Asia (Fig. 1). The Teskey Range, which lies in the inner Tien Shan, has a ridgeline at 4800–3700 m a.s.l. above small alpine glaciers. Most precipitation 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, than that in the Teskey Range, lying south of Lake Issyk-Kul and in the interior (Narama et al., 2010b). Throughout the region, 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) of the Teskey Range. 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 that 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 fan at the mountain piedmont as pasturage or agricultural fields.

3. Methods

3.1 Field surveys

In the study area in the Tong region of the western Teskey Range, we investigated glacial lakes and four recent (2006–2014) large drainages based on field surveys (2007–2016) and satellite data analysis. The drainages investigated include the Kashkasuu, western Zyndan, Jeruy, and Karateke glacial lakes shown in Fig. 1. In the western Zyndan lake, a large drainage 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, lake basin) and lake levels after drainage using a Trimble GeoExplorer 6000 and a Leica GPS 900. To estimate the water volume of current lakes, we measured water depths in 10 current lakes in Teskey and Ili Ranges using an inflatable boat (PVL-260) and a fish finder with GPS（LOWRANCE HDS-5; Fig. 1）. In the downstream part of Jeruy and Karateke lakes, we investigated flood sediments and eroded channels. 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. 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 GCP 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 lake-basin depression (shallow hollow). To estimate the location and maximum volume of such a lake, we used a water-filling model to extract lake-basin depressions exceeding 0.01 km^2 on the debris-landforms of glacier fronts. The model used ALOS 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 lake-basin-depression size because recent drainages with damages are caused from lakes exceeding 0.01 km^2.

The accuracy of the lake-basin depression areas are verified by comparison to GPS data from the western Zyndan lake before drainage in 24 July 2008. As shown in Fig. 2, the GPS data along the shoreline (ice line) of the western Zyndan lake before drainage coincides with the extracted outline of the lake-basin depression. For mitigation, it is of significant advantage to know the debris-flow type because it decides the range of flood velocity and debris spread. To distinguish debris-flow types (i.e., viscous vs stony; Takahashi, 2009), we measured the eroded channel distance, defined as the distance over which the channel has an angle exceeding 10° using SRTM DEM (30-m resolution). In addition, we investigated the flood deposits, landforms, and damage to the mountain piedmont.

4. Results

4.1. Evolution of three short-lived glacial lakes

In the following we examine changes of the Kashkasuu (2006), Jeruy (2013), and Karateke (2014) glacial lakes, all of which had a large drainage in the year given in parantheses (Fig. 1). Kashkasuu lake in the southern part of the Teskey Range, which has glacier contact, was small on 6 September 2004, but larger by 21 June 2005 (images not shown). In Fig. 3A (left column), we show that this lake area existed on 21 June 2005, but by 23 May 2006, the lake area remains the same area. It grows until 26 July 2006, expanding to 0.025 km^2, but then shrinks again to 0.004 km^2 on 11 August 2006. By using the observed lake area and ALOS PRISM DSM, we estimate the water volume on 26 July as 198,000 m^3. From August 2006 (before drainage) to September 2007, GPS data shows the lake level dropping by 10 m. This large drainage caused damages to the mountain road and a bridge along the Uchemchek River.

To the northwest lies Jeruy glacial lake (Fig. 1). Images in Fig. 3B show this lake to be undiscernible on 18 May 2013, but clearly visible by 19 June 2013. By 6 August, it has grown to 0.033 km^2 with an estimated volume of is 163,000 m^3. The lake, which has glacier contact, drains on 15 Aug 2013, but some water remains. Nearby and to the east lies Karateke lake (Fig. 1). This lake is of non-glacier-contact type located on a debris-landform at the glacier front of Karateke Glacier. Figure 3C shows the lake area to be only 0.001 km^2 on 5 May 2013, but expanding to 0.02 km^2 on 30 June, and then decreasing by 0.015 km^2 on 16 July immediately before drainage on 17 July 2014. During this drainage, 169,000 m^3 or more of water was discharged.

Regarding area plots of these lakes and a fourth lake (western Zyndan), the lakes appear in May, and grow rapidly in June and July (Fig. 4). Then they discharge between mid-July and mid-August. The western Zyndan glacial lake caused a large flood on 24 July 2008, with 437,000 m^3 of discharge (Narama et al., 2010a). Thus, these lakes are examples of a “short-lived glacial lake” that suddenly appear and grow during two or three months, with drainage occurring in the summer.

4.2 Landforms and flood deposits of the Kashkasuu, Jeruy, and Karateke lakes

To better understand the behavior of the lakes, particularly their drainage, we investigated their landforms in a field survey. At Kashkasuu lake, in 2007, a debris-landform including dead ice were found at the lake front. The debris-landform composed of debris and ice remained from glacier shrinkage. Such a landform is called a moraine complex (Janský et al., 2010; Bolch et al., 2014; Yamamura et al., submitted). No surface channels are visible on this debris-landform but we observed an ice tunnel of 300 m length with a water-stream in its central part. Lake water discharged through this ice tunnel between 26 July and 11 August 2006.

We observed similar debris-landforms in front of the Jeruy and Karateke Glaciers (Fig. 5A, B). Both debris-landforms include much ice. The empty lake-basin depression (hollow) of Jeruy lake is a glacier-contact type. Karateke lake also occurs at an empty lake-basin depression, but it is without glacier contact. For Karateke, meltwater from the glacier terminus flows into the lake-basin depression. But for the outlets of both lakes, we observed no surface channel from either lake-basin depressions. However, we found Jeruy to have a 250-m-long ice tunnel and Karateke to have a 500-m long one. For Karateke lake, the ice tunnel is 5 m deep and 2–4 m wide at the entry point of debris landform (Fig. 5C), and the middle point of the ice tunnel is shown in Fig. 5D.

Our field survey indicates that lake water from the Kashkasuu, Jeruy, and Karateke lakes discharged through ice tunnels inside of debris-landforms, as was found previously for the western Zyndan lake (Narama et al., 2010a). Concerning the lakes' growth, the Kashkasuu glacial lake remained from the previous year, but grew suddenly. The Karateke and Jeruy lakes grew from an initially empty basin. In sum, these short-lived glacial lakes began from an empty basin or a basin that already has a lake. In these debris-landforms, the surface channels are invisible, and most meltwater from glacier flows through an ice tunnel. Hence, we consider these short-lived glacial lakes as the "tunnel-type" to distinguish them from those that discharge via other means.

Regarding the flood deposits from these four lakes, 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 mostly 20-30 cm clasts but also including 1–3-m boulders (Fig. 6A). From an interview of a local resident of Jeruy village, we confirmed that the flood velocity of Jeruy drainage was slow on the alluvial fan. The flood stream from 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 as well as damaged

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an irrigation channel, a road, monuments, an agriculture field, and a line of houses. On the other hand, flood deposits from Karateke lake are composed of large boulders 1–2 m without matrix (Fig. 6B). Damages from the Karateke flood were limited to bridges along the river. The western Zyndan deposits 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. The amount of debris that drainage water can acquire on its way differs due to different erosion distances, which are related to the conditions of past glacier erosion and according valley types in the upper part. In the Karateke Valley, the upper part is a flat U-shaped valley with only a short highly eroded section (Fig. 6D). A steep slope starts at the upper point of this section and thus the flood-wave gains debris, transforming to a debris-flow. Above the highly eroded-section, drainage water that does not include much debris has high mobility (lower density).

4.3. Volume size of current lakes and lake-basin depressions

To estimate the water volume and basin-form of the present glacial lakes, we measured the depths and geolocations of 10 lakes in the Teskey and Ili Ranges using an inflatable boat and fish finder with GPS. All 10 lakes were less than 30 m deep. Profiles of three of them are found in Fig. 7. Lakes in this region are smaller than the large proglacial lakes in the eastern Himalayas, as well as Petrov Lake (3.94 km^2; Engel et al., 2012) in the Ak-Shiyrak Range and Lake Merzbacher (2.88 km^2; Xie et al., 2013) at the Southern Inyrchek Glacier in the central Tien Shan. The profiles of the lake-basins in glacier fronts are asymmetric as shown in Fig. 7B, C, with greater depth and steeper slope at the glacier terminus side. A submerged moraine at the lake bottom was confirmed for the eastern Zyndan lake. Such a submerged moraine prevents a complete discharge of all lake water, but most observed lakes had no such submerged moraine.

Figure 8 shows the relationship between area and volume of the 10 measured lakes in Teskey and Ili Ranges using our inflatable boat and fish finder with GPS. For this plot, we added six lakes from previous studies in the Kyrgyz and Ili Ranges (personal communication of I. Severskiy; Janský et al., 2010), four large drainages of short-lived glacial lakes, and lake-basin depressions in Tong region. The relationship between area and volume is roughly the same in this region. The relational line formula between area and volume was calculated by only observation data (this study and previous studies), to estimate a water volume of current lakes. The figure shows that lakes exceeding 0.015 km^2 have a minimum lake volume over 150,000 m^3, an amount that in past drainages have caused damages downstream.

To find the locations of short-lived glacial lake in the northern part of the western Teskey Range, we investigated the distribution and volume size of lake-basin depressions on debris-landforms at glacier fronts using ALOS/PRISM DSMs (2.5-m resolution; Fig. 9). The water volume of lake-basin depressions was calculated based on ALOS/PRISM DSMs (2.5-m resolution). In the Tong region of the western Teskey Range, we found 60 lake basins exceeding 0.01 km^2. We distinguished the lake-basin depressions according to those with glacier contact and those without glacier contact (Fig. 9). Of the 60 basins, 38 basins are of glacier-contact type. Among these, 24 basins already host a lake, but also have space to accumulate more water. The 38 lake-basins with glacier contact can accumulate water. 22 lake-basin depressions are without glacier contact. These lake-basins cannot get water accumulated in case that water stream channel dose not contact with lake basin.

5. Discussion

5.1 Characteristics of tunnel-type, short-lived glacial lakes in the Teskey Range

Consecutive satellite images show that glacial lakes in the study region with recent large drainages were short-lived glacial lakes. The field survey of these lakes revealed that their lake water discharged through an ice tunnel inside of debris-landform in the glacier front as well as inside dead ice. Our observations of these short-lived glacial lakes show them to appear as a small pond in May and expand suddenly in June–July due to 1) the blockage and closure of ice tunnels, and 2) rapid melting of ice and snow. The ice tunnels are blocked due to freezing of stored water during winter or blocking by deposition of ice and debris due to tunnel collapse. The drainage of four short-lived glacial lakes occurred between end of July and mid-August when their ice tunnel opened, due to ice melting at the closure point.

The drainage process for the tunnel-type, short-lived glacial lakes is the same as that for supraglacial lakes on debris-covered glaciers (Gulley et al., 2009; Benn et al., 2012). The supraglacial lakes have a seasonal variability and can be recurring or transient (Benn et al., 2001; Miles et al., 2016; Narama et al., 2017). In addition, the process can cause a large drainage from a debris-covered glacier without a large proglacial lake (e.g., Komori et al., 2012; Rounce et al., 2017). But the supraglacial lakes connect to the englacial drainage network in June–July, thus draining earlier than the short-lived glacial lakes.

In contrast, the drainage of the type of short-lived glacial lakes investigated here differs from that for a glacial lake outburst flood (GLOF) in the eastern Himalayas. The Himalayan GLOF occurs by moraine collapse from large proglacial lakes that have expanded for several decades (Ageta et al., 2000). Glacial lakes that experience moraine

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collapse do typically not re-form. In contrast, the short-lived glacial lakes appear and expand for several months, and then their lake water discharges through ice tunnels. Such a short-lived glacial lake type recurs when its ice tunnel closes like that on a supraglacial lake on a debris-covered glacier. On the Angisay Glacier of the Teskey Range (Fig. 1), substantial floods from a glacial lake occurred in 1974, 1975, and 1980 (Kubrushko and Staviskiy, 1978; Kubrushko and Shatrabin, 1982), indicating the repeatable closure of its ice-tunnel and refill at the same lake-basin depression. Although existence of lake could not be confirmed, the Ak-Say Glacier of the Kyrgyz Range also had repeated drainage in the 1980s (Janský et al., 2010; Zaginaev et al., 2016).

5.2 Geomorphological conditions of tunnel-type, short-lived glacial lake

A short-lived glacial lake appears in a lake-basin depression in a debris landform that contains much ice. The Kashkasuu, Jeruy, and w-Zyndan lakes formed in lake-basin depressions in glacier frontal areas that appeared due to recent glacier shrinkage. Although Bolch et al. (2011) could estimate the flood area from current lakes in the Ili Range, our finding suggests that we also should monitor empty lake-basin depressions in which a short-lived glacial lake may appear. But which lake-basin depressions should be monitored? We narrow down the possibilities in the following.

A short-lived glacial lake cannot appear at a lake-basin depression in which meltwater cannot inflow. Among 60 lake-basin depressions (> 0.01 km^2) found using ALOS PRISM DSMs (2.5-m resolution), 38 (i.e., 63%) lake-basin depressions with glacier contact had water inflows. The remaining 24 lake-basin depressions without glacier contact nevertheless connected to a water stream from a glacier terminus. In addition, we investigated the existence of surface channels in the downstream part of the lake-basin depressions that did not show the development of an ice tunnel. 56 lake-basin depressions have geomorphological conditions (described below) in which water could inflow but does not have a surface channel in the downstream part of lake-basin. These lake-basin depressions are potential locations for a tunnel-type, short-lived glacial lake. Lake-basin depressions of the glacier-contact type form at the glacier front due to recent glacier shrinkage. Thus, the recent increase in the glacier-contact type of short-lived glacial lakes might be related to an increase in number and size of lake-basin depressions due to recent glacier shrinkage.

The size of the lake-basin depression is an important factor. For example, a supraglacial lake formed in a large lake-basin depression (Yamanokuchi et al., 2009) caused a large drainage from the Tshojo Glacier in the Lunana region, Bhutan (Komori

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et al., 2012). In the study area, the lake water of the western Zyndan glacial lake overflowed before becoming a large drainage due to the high snow/ice melting rate and late opening of the ice tunnel (Narama et al., 2010a). For these cases of sudden appearance and drainage, we consider environmental conditions for large drainage, first the maximum volume of lake-basin depressions as shown in Fig. 9. The larger lake-basin depressions having a water supply are potentially dangerous lake-basin depressions. In addition, the distance and width of the ice tunnels from closure point determine the total stored water volume (lake plus conduits) because the closure point may be downstream in the ice tunnel. When little melting of snow and ice occurs or the ice tunnel opens early, only a partial discharge may occur. In general, the drainage volume depends on (i) volume of the lake-basin depression, (ii) size of the ice tunnel, (iii) closure point of the ice tunnel, (iv) timing of ice-tunnel opening, and (v) the melting rate of the ice and snow.

5.3 Flood type of drainage

Despite having some similar lake-bed characteristics, Jeruy and Karateke lakes had different debris flows (i.e., viscous vs stony; Takahashi, 2004; 2009). These two lakes have about the same elevation (3815 and 3757 m asl respectively), and similar Qmax values (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 stony debris-flow with clast-supported deposits (Fig. 6B). For better insight, we also investigated the debris flow that occurred on 3 June 2009 from the Takyltor glacier in the Kyrgyz Range. There, the deposits also consist of middle range between matrix support and clast support, we treat the flow as a viscous flow.

As the travel angle for debris-flows with coarser-grained (clast supported) material is lower than that with a high proportion of fine material (matrix supported; Rickenmann, 2005), the characteristics of the debris-flow type differ in each situation. The magnitude of debris-flow is characterized as the total volume of debris material transported to the terminal deposition area and expressed as “a channel debris yield rate” together with the length of the channel (m^3/m; Hungr et al., 1984; Fannin et al., 1992; Fannin et al., 2015). Huggel et al. (2002) classified debris flows and flood waves using relationship between the travel angle and Qmax value. We could not use the characterization because the slope angles (H/L) of the erosion section are about the same here. However, the erosion slope distance varies significantly by valley (i.e., Karateke Valley vs Jeruy Valley; Fig. 6C, D).

In each valley, the drainage water stream changes to the proportion of water

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and material through the erosion section. In the upper part of the Zyndan Valley, the eroded part was only a small moraine. Another indication of debris-free drainage water was the observed grass flattened by water in the riverbed after drainage from the western Zyndan lake (Narama et al., 2010a). However, the water flood here can change to a debris flow by acquiring debris in the intermediate steep slope because the landform consists of loose materials and banks along the channel in the study area. In some cases of drainage from a glacial lake in the Tien Shan, a small initial failure volume has increased by entrainment of materials from the path of the flow, for example, acquiring much debris from the middle of a steep mountain slope (Evans and Delaney, 2015), resulting in very large deposits that can exceed 10^6 m^3.

According to Hungr et al. (1984), net deposition in a channel starts when the channel angle becomes about 10° or less. Thus, we use the distance over which the channel exceeds 10 degrees as defining the 'erosion-slope distance'. That is, the channel section that is expected to erode. The erosion-slope distance (> 10°) coincides with the eroded part of the valley in the western Zyndan lake case (Narama et al., 2010a). We characterize the proportion of debris material by the erosion-slope distance and maximum discharge (Fig. 10). Maximum discharge of lake-basin depressions and current lakes was estimated using $Q_{max} = 46(V/10^6)^{0.66}$ (tunnel event; Walder and Costa, 1996) with a water volume V and the duration of discharge. A water volume V of current lake was estimated using the formula in Fig. 8 In the study area, the erosion-slope distances with angles exceeding 10 degrees range between 166 and 6016 m, and maximum slope gradients of the mean erosion-slope distance are 11.5–20.9°.

As a classification of past floods (western Zyndan, Karateke, Jeruy, Kashkasuu, and Takyltor floods), we separate debris-flow types into stony flow and viscous flow (Fig. 10). A viscous flow of the Jeruy and Takyltor lakes has a long erosion part. Many lake-basin depressions are of stony type. Recent Qmax from the short-lived glacial lakes are 14–27 m^3/s. Among the 60 lake basins, we find 39 that exceed 10 m^3/s possible maximum discharge (Fig. 10). We are aware, that variations in sediments available at the erosion reaches, and potential loss of sediments at some reaches instead of uptake, will modulate our simple classification, but we still believe our scheme is suitable for the first-order prioritization suggested here.

The degree of flood damage from the Jeruy-lake discharge differed from that from Karateke. On the alluvial fan downstream of Jeruy Valley, two debris-flow streams separated from the present water stream and caused large damages to agriculture fields, irrigation, roads, and monuments. In comparison, in the Karateke Valley, only two bridges were broken because the stream was limited along the river. In Shahimardan

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village, where the flood killed more than 100 residents (UNEP, 2007), many residents live along the river. In the Dasht village, where the flood killed 25 people (Mergili et al., 2012), the debris-flow covered the village on the alluvial fan.

Land-use and landform affect the degree of damage. In the western Zyndan lake in 2008, the flood damaged a kashaal (animal cottage) on the alluvial fan (Narama et al., 2010a). Piedmont landforms of 23 valleys in Tong region, 14 valleys are valley-bottom landform (Katateke case) and 9 valleys have alluvial fan (Jeruy case). The drainages from the four short-lived lakes studied here are less than 500,000 m^3 in this region and their flood damages are limited along the river or alluvial fan. As most lake-basins are within 500,000 m^3 in this region, most flood damages are also limited along the river or alluvial fan at the mountain piedmont. Although some large lake-basin depressions existed, there is no case documented in which a large lake had a large drainage. However, for risk mitigation, we should consider a short-lived lake disaster including lake-basin volume, flood type, land-use and landforms as one package of river basin.

6. Conclusions

In the Tong region of the western Teskey Range, recent large drainages have come from the tunnel-type of short-lived glacial lakes that appear and then drain again over the course of two–three months. These lakes were found to appear as small ponds in May, then expand suddenly in June–July due to more rapid melting of ice and snow. The lake dammings appear due to blockage and closure of ice tunnels, which occurs during winter due to freezing of stored water, blocking by debris, or blocking by tunnel collapses. We found that the drainage occurs between the end of July and mid-August when the ice tunnel opens, due to ice melting of the closure point.

The geomorphological conditions in which these lakes appear were found to be (i) existence of debris-landform including dead ice, able to form an ice tunnel, (ii) existence of a large lake-basin depression (> 0.01 km^2) on debris-landforms with water supply, in order to cause large drainages, and (iii) no outgoing visible surface channel from the depressions, requiring the water to exit through an ice tunnel. We argue that lake-basin depressions (> 0.01 km^2), in which water can inflow, should be monitored equally to existing glacial lakes in the Tien Shan, and their hazard not be overlooked.

Using the estimated drainage volumes from the current lakes or lake-basin depressions, we argue that their flood damages will occur only in their alluvial fans or along the river at their mountain piedmont. Most drainage events in the Tong region of the western Teskey Range are stony debris-flow with clast-support deposits. Lake monitoring using satellite data should proceed based on new criteria of potential dangerous lakes such as the location and volume of the lakes and lake-basin depressions, the flood type, and landform in the mountain pediment. The comparably short period between appearance and drainage of the short-lived lake type studied here of a few months 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 facilitate detection even of short-term changes. 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 by satellite data that goes to the government and local people when a lake appears. As glacier-lake workshops in the Ladakh region of India (Ikeda et al., 2016) showed, improvement of knowledge and land-use can help reduce the impacts of large drainage floods form glacial lakes.

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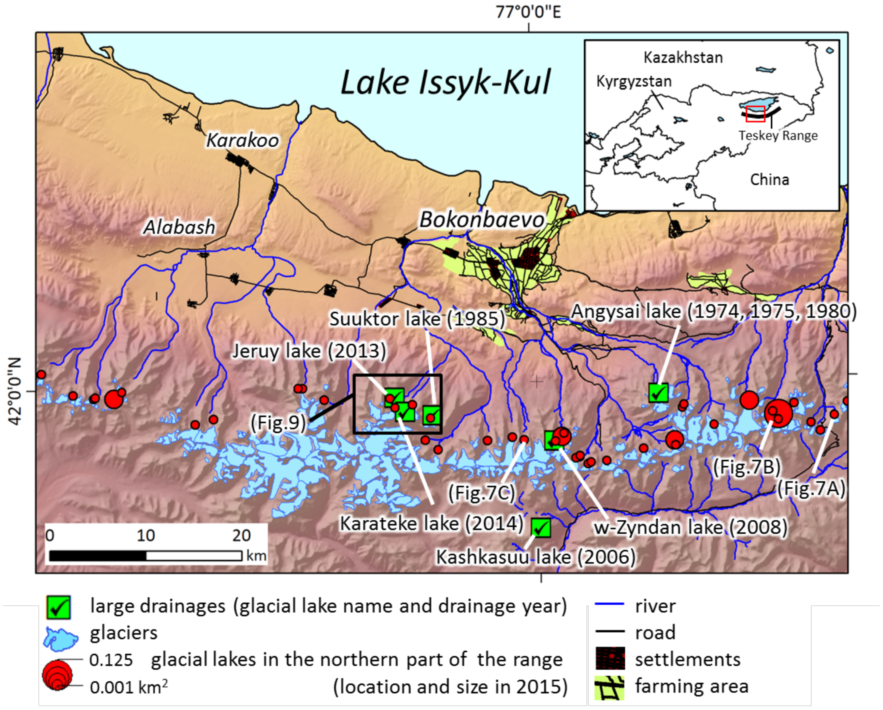

Fig. 1. The study area in the Tong region of the western part of the Teskey Range, Kyrgyzstan. Green boxes show the location of large drainage events with the name and year labeled. Location and size of red circles show locations and size of lakes in 2015.

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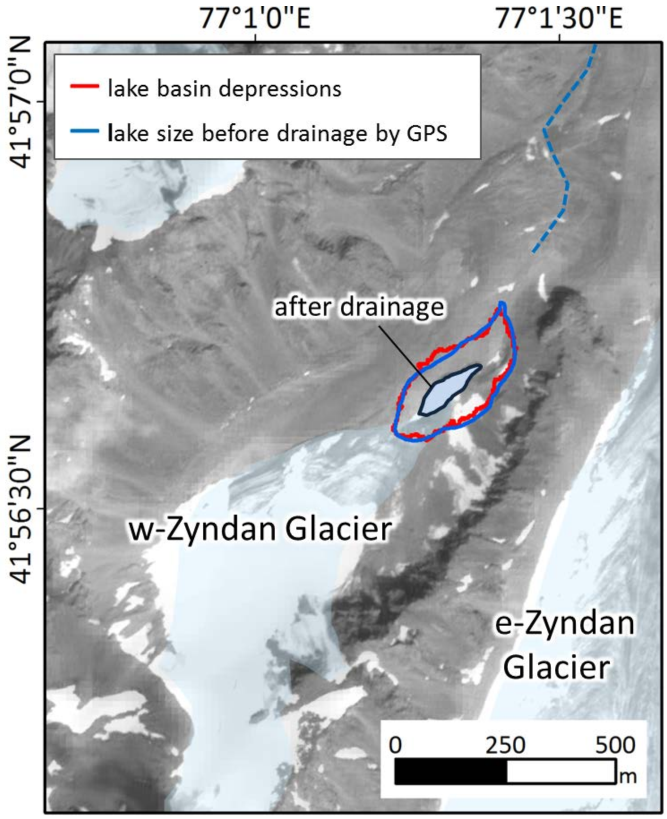

Fig. 2. Western Zyndan glacial lake at which a large drainage occurred in 2008 (location in Fig. 1). The blue line shows the lake perimeter before drainage according to GPS measurements in 2008. The red line shows the lake-basin depression according to ALOS PRISM DSM data.

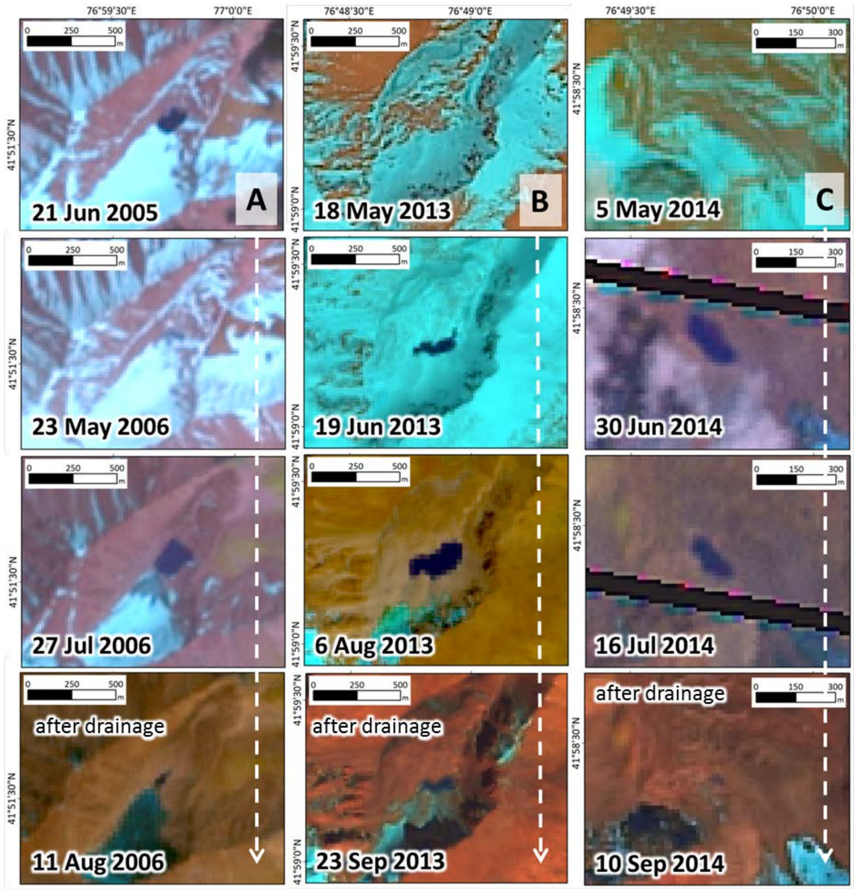

Fig. 3. Changes to three lakes. Left column (A) is Kashkasuu (26 Jul–11 Aug 2006), middle (B) is Jeruy (15 Aug 2013), and right (C) is Karateke (17 Jul 2014). Images are from Landsat7 ETM+ and ALOS AVNIR-2 and PRISM data. The locations are in Fig. 1.

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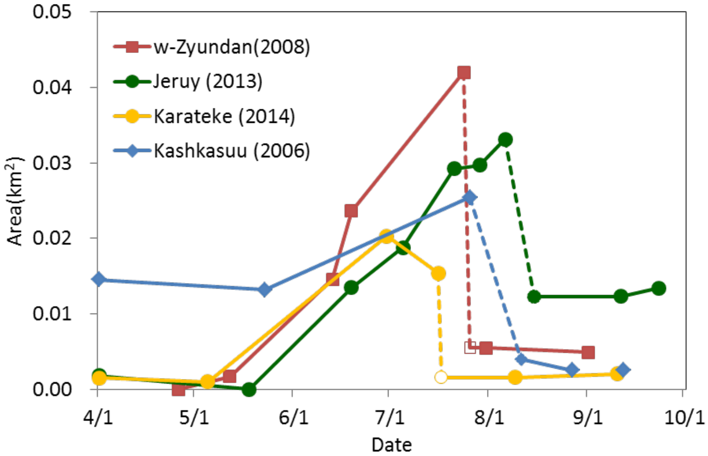

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659 Fig. 4. Seasonal area changes of four short-lived glacier lakes.

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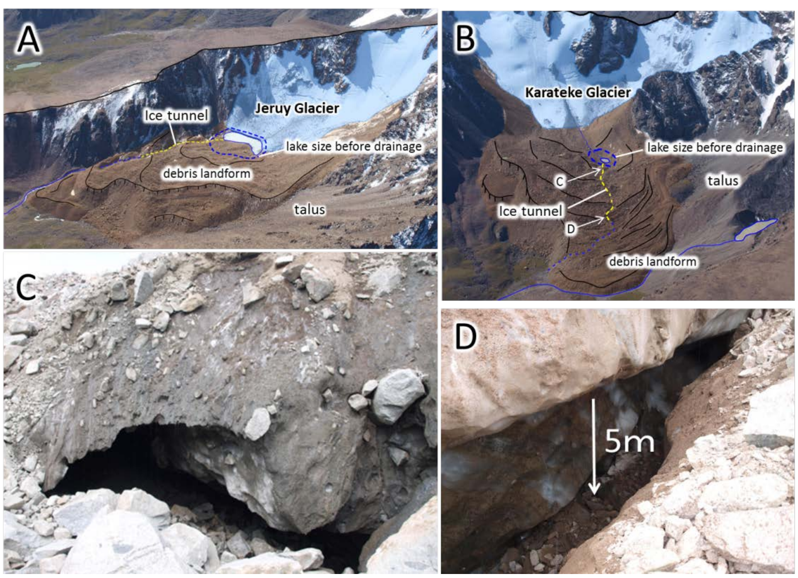

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662 Fig. 5. Surface details of Jeruy and Karateke Glaciers (locations in Fig. 1). In A) and B),
663 the blue dashed lines show the lake size before drainage. Yellow dashed lines locate
664 ice-tunnels. C) shows the ice tunnel at the middle point of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

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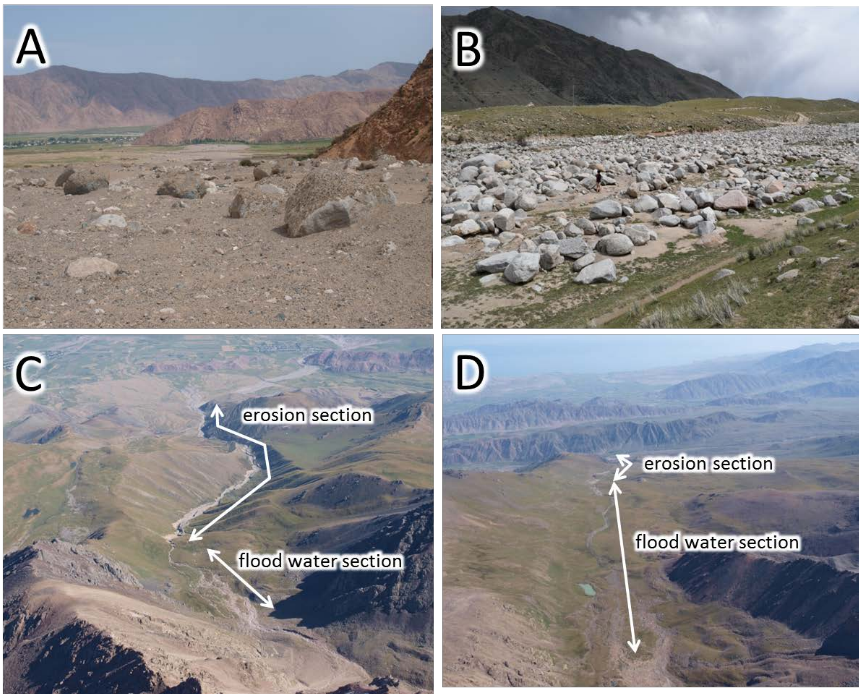

Fig. 6. Flood deposits and valley landforms in the Jeruy (left column) and Karateke (right column) Valleys. Top row shows the deposits, bottom row the landforms. The red arrows show the direction of flow, the dashed region is discussed in the text.

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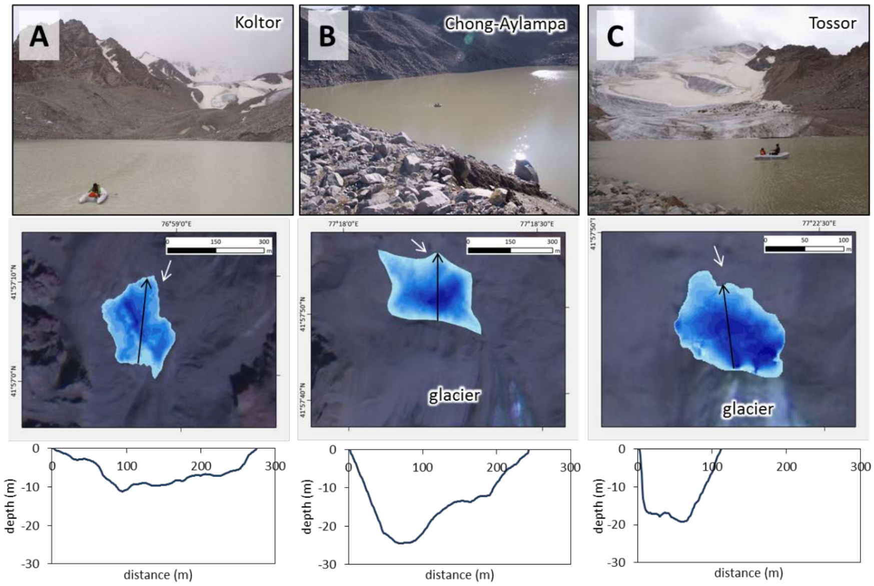

Fig. 7. Photos, lake-basin maps, and depth profiles of three glacial lakes. (A) Koltor, (B) Chong-Aylampa, (C) Tossor lakes (locations in Fig. 1). Black and white arrows on the lake-basin maps show each basin profile line and photo direction, respectively.

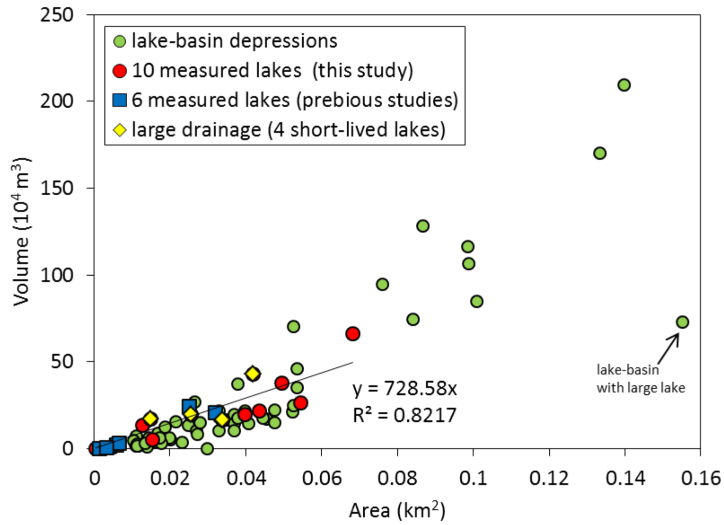

Fig. 8. Relationship between volume and area of directly measured lakes (this study, personal communication of I. Severskiy; Janský et al., 2010) and lake-basin depressions.

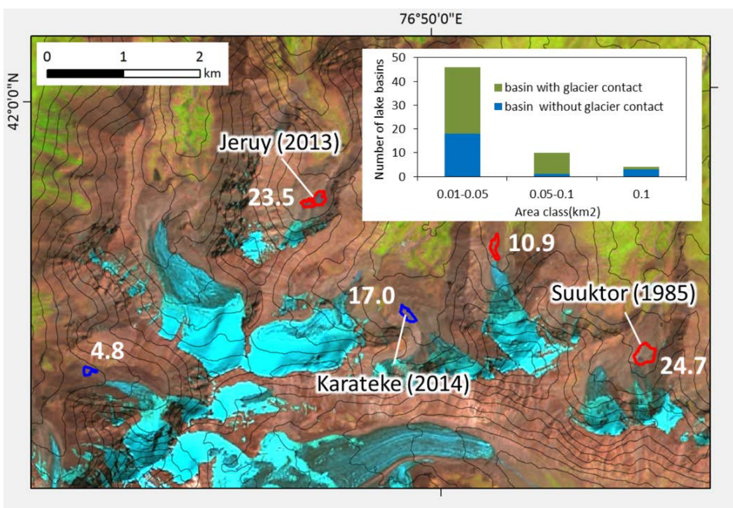

Fig. 9. Lake-basin depressions at glacier fronts in the study area (locations in Fig. 1). Units are 10^4 m^3. Blue lines of lakes are lake-basin depressions, and red lines lake-basin depressions with the lake in 2015. The box figure shows size, number, and type (with glacier contact or without glacier contact) of lake-basin depressions in the study area.

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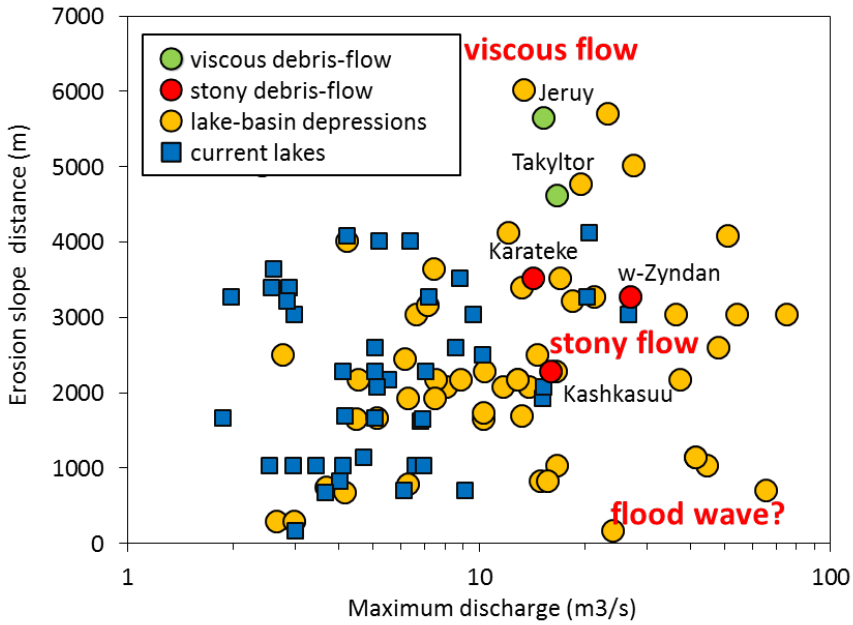

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717 Fig. 10. Debris-flow types in the study area.

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