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Glacier-Related Hazards and Their Assessment in the Tajik Pamir: A Short Review

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Abstract

This paper reviews contemporary glacial features, characteristics of documented glacial hazards, and the status of hazard assessment studies in the Pamirs of Tajikistan (hereafter the Tajik Pamir). The review found detachment of a hanging glacier, glacier-surging, and outburst discharge of a glacial lake to be major potential causes of glacial hazards in the Tajik Pamir, especially in the western area (west from approx. 73° E). Guerrilla glacial lakes, which are characterised as glacial lakes on the ice-core moraine that "appear repeatedly," "enlarge rapidly (within less than one year)," "disappear within less than two years," "are superficially closed," and "are of relatively small size (approx. $< 10^6$ m^2)" should hereafter be paid special attentions. Preparation of appropriate hazard-mitigation activities should require early detection of not only the large crack in the hanging-glacier terminus, surge behaviour, and the glacial lake and guerrilla glacial lake, but also regular monitoring of these hazard factors. One of the most suitable monitoring techniques is to use earth observation satellite images with a relatively short repetitive cycle (ideally once every few days) and a high spatial resolution (ideally several meters). These criteria may be satisfied in the near future by using images captured by many sets of microsatellites, such as the 50-kg class microsatellite SPRITE-SAT (RISING).

Key words: glacier surge, guerrilla glacial lake, glacial lake outburst floods, hazard assessment, microsatellite, Tajik Pamir

Ⅰ. Introduction

Glaciers in high mountain regions benefit human activities by serving as sources of drinking water, irrigation, and energy generation, but they also pose occasional hazards such as glacial lake outburst floods (GLOFs) and ice avalanches, causing human casualties and economic losses in downstream areas. Accordingly, various assessments and mitigations of the glacier-related hazards have been undertaken in many glacierized mountain regions of the world (e.g., Huggel et al., 2002; Iwata et al., 2002; Quincy et al., 2007; Watanabe et al., 2009; Bosch et al., 2011; Fujita et al., 2012).

The Pamir is one of the high mountain regions in Asia, comprising parts of Tajikistan, Afghanistan, Kyrgyzstan, and China (Fig. 1). In very recent years, the threat of glacier-related hazards in the Pamir of Tajikistan (the Tajik Pamir) has been reported by various media (e.g., Makhmadaliev et al., 2008; Asia Plus, 2011; NASA Earth Observatory, 2011; Shodomonov, 2012). Simultaneously, assessment investigations of glacier-related hazards have been conducted in the Tajik Pamir (Schneider et al., 2010; Mergili and Schneider, 2011).

This situation suggests that action is required to reduce the potential risks of glacial-related

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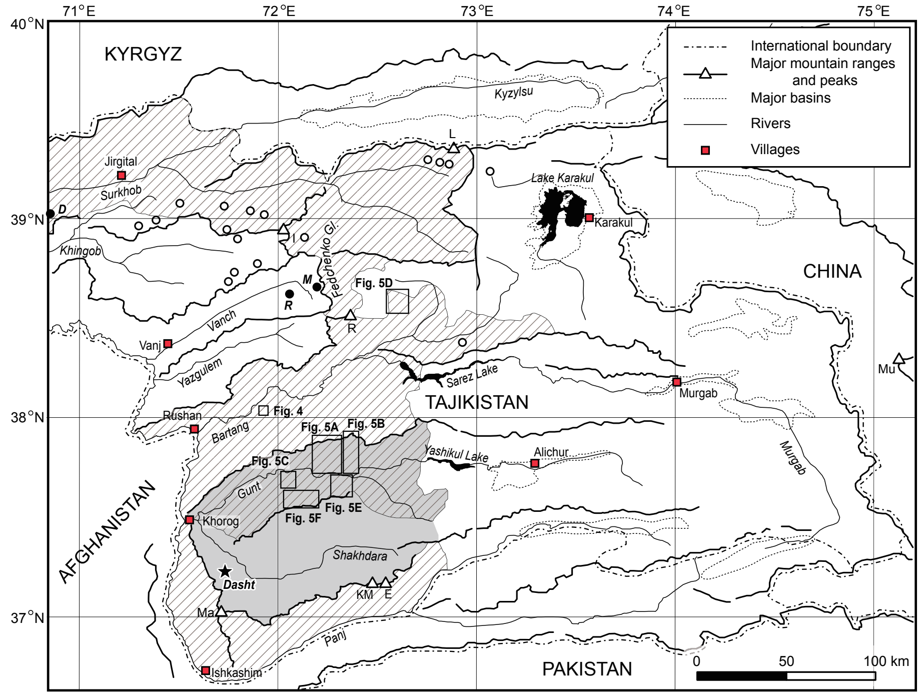


Fig. 1. Overview map of the Pamir
Hatch lines on the Jirgital and GBAO (Gorno-Badakhshan Autonomous Oblast) areas represent the area where Schneider et al. (2010) conducted hazard assessment investigations in the Tajik Pamir. Shaded area in the southwestern Tajik Pamir covers the Gunt and Shakhdara valleys, where the hazard assessment of alpine lake outburst floods was carried out by Mergili and Schneider (2011). Solid star: location of the Dasht Lake, which caused a catastrophic outburst flood on 7 August 2002. Open and solid circles: distribution of glaciers listed in Kotlyakov et al. (2010b) as 'the largest observed surges of glaciers in the Pamir from 1960 to 2003'; three glaciers with solid circles (D, Didal Glacier, M, Medvezhiy Glacier, and R, Ravak Glacier) caused hazardous surges in the past. Peaks: L, Lenin (7,143 m); I, Ismoli Somoni (7,495 m); R, Revolution (6,940 m); Ma, Mayakovskiy (6,095 m); KM, Karl Marx (6,723 m); E, Engels (6,507 m); Mu, Muztag Ata (7,546 m). Boxes: locations and areas of Figs. 4 and 5.

hazards in the Tajik Pamir. However, the basic information needed for such action has not been sufficiently available until now. The primary goal of this paper is to provide such information by reviewing the following topics: (1) contemporary glacial features, (2) characteristics of documented hazards associated with glaciers, and (3) the current status of the hazard assessment. The secondary goal of this paper is to discuss the preferred hazard mitigation measures based on the review.

Ⅱ. The Pamir and the present glaciation

1. Geographical configuration and climate

The Pamir is one of the central Asian highlands, and is characterized by a rough mosaic terrain consisting of high-mountain ranges and high basins (Iwata, 2008; Fig. 1). It occupies a quasi-square area 300 km from north to south and 300–400 km from west to east, between 36–40°N and 70–76°E, largely comprising the western part of Tajikistan.

The terrain of the western part of the Tajik Pamir is very different from the eastern part (Fig. 1). The western Tajik Pamir (west of approximately 73°E) is distinguished by a combination of the predominantly west-east trending mountain ranges with altitudes of 5,000–7,000 m, and deep, narrow valleys. In contrast, the eastern Tajik Pamir (east of approximately 73°E) consists of broad valleys and basins bordered by more subdued mountain ranges with altitudes of 5,000–6,000 m.

The climate of the Pamir is represented by sub-continental and arid continental climates. The moisture delivered to the Pamir is mainly from the Westerlies, although Indian monsoons also reach southeastern Pamir occasionally (Aizen et al., 2009). Two-thirds of the annual precipitation occurs during the winter and spring seasons (Aizen, 2011). The precipitation map of Tajikistan (UNEP, 2002) shows that: (1) the western Tajik Pamir generally receives greater amounts of mean annual precipitation (200–2,000 mm/y) than the eastern Tajik Pamir (<100–200 mm/y), which belongs to the area influenced by the orographic rain shadow effect, and (2) within the western Tajik Pamir, the area situated north of the Bartang valley receives higher mean annual precipitation (400–2,000 mm/y) than the area south of the Bartang river (200–800 mm/y).

The settlements in the Tajik Pamir are concentrated in the valley floors of the western Tajik Pamir, except for some cases (e.g., Alichur, Murgab, and Karakul), and most residences, infrastructure, and arable fields in the western Tajik Pamir are situated on the alluvial fans/cones developing on the tributary mouths (Watanabe, 2000), making the western Tajik Pamir more vulnerable to geohazards (e.g., GLOF and seasonal high flow flood).

2. Glaciers

In the Tajik Pamir, 6,730 glaciers, covering a total area of 7,493 km^2, have been identified by the Institute of Geography, the USSR Academy of Sciences (now the Russian Academy of Sciences) (Kotlyakov et al., 2010a). The distribution and types of these glaciers are roughly explained as follows. The westward area from approximately 73°E (western Tajik Pamir) is dominated by scattered cirques and small valley glaciers, which are gradually replaced by larger valley glaciers toward the northeast of the main valleys. In the most northeastern portion of the western Tajik Pamir, large glacier complexes consisting of two or more individual valley glaciers can often be found; for instance, the Fedchenko Glacier, which is recognized as the largest glaciers in the Asian High Mountains (Iwata, 2009; Fig. 1). In contrast to the western Tajik Pamir, the leeward area more eastward across the mountain ranges at approximately 73°E (eastern Tajik Pamir) has an arid climate due to the strong rain-shadow effects, and therefore is largely occupied by the smaller valley glaciers or slope niche glaciers.

A notable feature of the Pamirian glaciers is that some of them have shown dynamic instability, which can be regarded as 'surging.' As of 1991, a total of 630 surge-type glaciers have been identified in the Tajik Pamir (Kotlyakov et al., 2010b); among them, 51 glaciers have shown one or more observed surges, and 215 glaciers exhibit signs of periodic activity (Kotlyakov et al., 2008 and 2010b). The important point to note is that these surge-type glaciers are mainly situated in the northeastern part of the western Tajik Pamir, where the majority of the 20 largest surging glaciers from 1960 to 2003 were also identified (Fig. 1). Regarding the types of surges in the Tajik Pamir, Kotlyakov et al. (2010b) states that many of them have been accompanied by the advance of the glacier snout toward ice-free valleys with velocities of up to 100 m/day.

3. Glacial lakes

Systematic investigations to clarify the distribution, types, and development of glacial lakes have been conducted only in the southwestern Tajik Pamir (the Gunt and Shakhdara valleys; Fig. 1) by Mergili and Schneider (2011) and Mergili et al. (2012). These studies were performed for 1968–2009 using multitemporal satellite images (Corona, Landsat ETM+, ASTER), and define the proximal lake, which is either directly embedded in the exposed ice, or dammed by debris-covered glacier tongues, rock glaciers or fresh moraines, as the glacial lake. These studies identified 172 glacial lakes (covering an area of ≥2,500 m^2) in the 2007/2008 images. Most of these lakes were already formed by 1968, and may have grown larger since then.

The 172 glacial lakes are mostly located at 4,400–4,700 m a.s.l. (Mergili et al., 2012). This altitudinal zone is significantly higher than the altitudes ranging from 3,810–4,000 m a.s.l., which are calculated as the lower boundary of the discontinuous permafrost (permafrost probable) by Müllebner (2010). This situation in the southwestern Tajik Pamir is at least a favorable factor for the stability of the ice core (dead ice) underneath the lake-dammed moraines in this region.

Fig. 2. The Medvezhiy Glacier in the most recent surge
The location of this glacier is shown in Fig.1. The satellite image (from the Advanced Land Imager on NASA's Earth Observing-1 satellite) was acquired on 23 July 2011. Both the satellite image and the information of the glacier terminus positions on 2 May and 3 June 2011 are cited from NASA Earth Observatory (2011).

Ⅲ. Glacier-related hazards in the Tajik Pamir

The report published by the Department of Hydrometeorology in Tajikistan (Figure 3.7 in Makhmadaliev et al., 2008, p35) indicates that 9 GLOFs and 1 glacier-related debris-flow have occurred in the western Tajik Pamir. On the other hand, only 7 GLOFs are confirmed by the website of MNV Consulting Ltd., which shows the historical records of major floods in Tajikistan during the period 1894–2000. However, detailed information about the cause and location of these glacier-related hazards has been obtained for only five events. These hazardous events are closely associated with either glacier surges or glacial lakes on moraines.

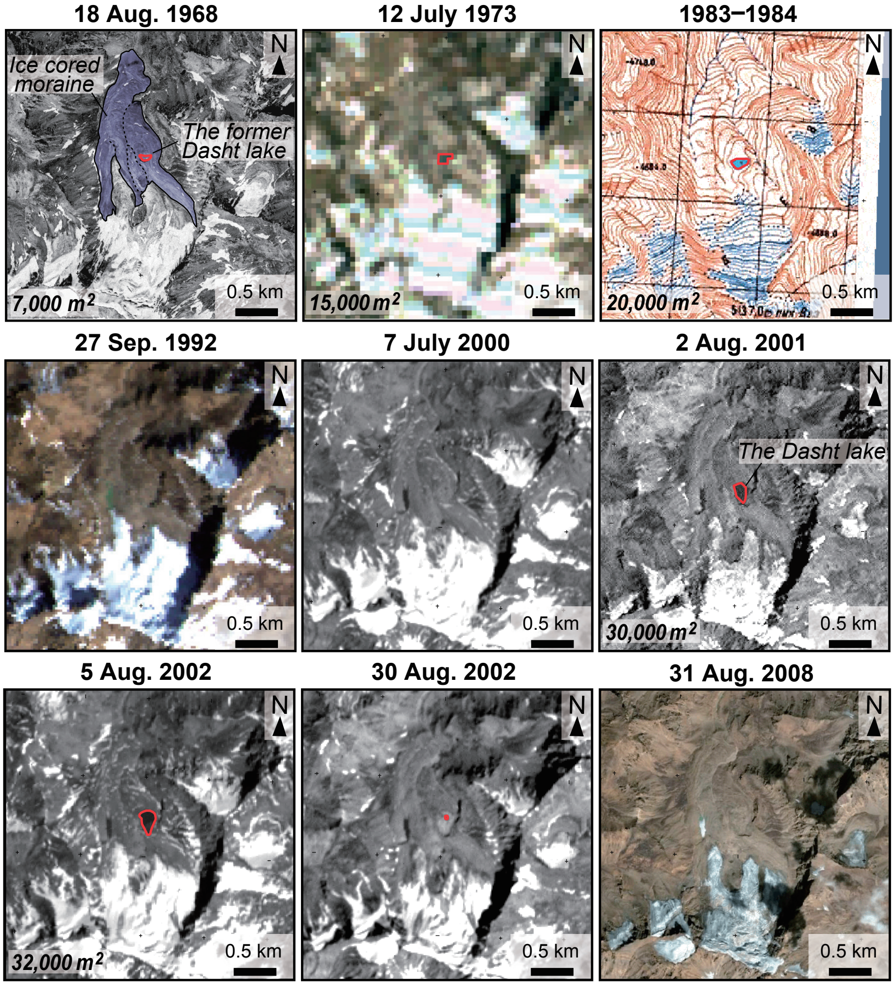
1. Hazard related to glacier surge

A well-known case of surge-related hazard in the Tajik Pamir is the outburst of a glacial-dammed lake, which occurs when the tributary glacier advances into the ice-free trunk valley and blocks the main river. Such a surge took place at the Medvezhiy (Bear) Glacier (N38°39', E72°09'37"), located in the upper reaches of the Vanch Valley in the western Tajik Pamir (Fig. 1). Six surges of this glacier have been identified, with a recurrence time of approximately 10 years (1951, 1963, 1973, 1989, 2001, and 2011) (Novikov, 2002; Kotlyakov et al., 2010b). Among these surges, the events of 1963, 1973, 1989, and 2011 have induced the glacier terminus to block the main valley, and closed the Abdukagor River (Fig. 2). Eventually, in both the 1963 and 1973 events, ephemeral ice-dammed lakes with as much as 100 m in depth (volumes of more than 20 million m^3) have formed, followed by outburst floods (Novikov, 2002; NASA Earth Observatory, 2011). These outburst floods brought about significant damage to infrastructures downstream, but did not produce any casualties (NASA Earth Observatory, 2011). The latest 2011 surge event suggests potential hazard risk for the next several years because the glacier front has advanced 800–1000 m downstream, far enough to block the Abdukagor River from 6 June to 23 June. As a result, a small ice-dammed lake has emerged, as shown in the satellite image taken on 23 July 2011 (Fig. 2). At present, the destruction of a bridge across the river downstream due to the increased river water has been reported (NASA Earth Observatory, 2011).

Ice-water debris-flow, which originates from the glacier tongue, itself collapsed by surge, is known to be another surge-related hazard in the Tajik Pamir. For example, the surge of the Ravak Glacier (N38°39', E72°04') on 20 July 1967 and that of the Didal Glacier (N38°59'20", E70°43'04") in 1974 caused this type of hazard (Kotlyakov et al., 2010b; Fig. 1).

2. Hazard related to glacial lake on moraines

Only one event has been recognized as a hazard related to a glacial lake on moraines in the Tajik Pamir up to now. The hazard was a debris flow named 'the Dasht 2002 event,' which occurred in the tributary headwaters of the Shakhdara Valley (the southwestern Tajik Pamir) on 7 August 2002 (Fig. 1). This hazardous debris flow originated from a glacial lake (the Dasht lake; N37°13'12", E71°44'03", 4,400 m a.s.l.), which had formed on the ice-cored end moraine and increased in size to an area of 32,000 m^2 (Fig. 3). The volumes of the water released from this lake and that of the entrained debris into the water were estimated to be 32,000 m^3 and 1.0–1.5 million m^3, respectively (Mergili and Schneider, 2011). This debris flow traveled 10.5 km downstream into the valley, and


18 Aug. 1968

12 July 1973

1983–1984

27 Sep. 1992

7 July 2000

2 Aug. 2001

5 Aug. 2002

30 Aug. 2002

31 Aug. 2008

Fig. 3. Developments of the Dasht Lake between 18 August 1968 and 31 August 2008
The location of this lake is shown in Fig.1. Solid lines: boundary of ice-cored terminal moraine. Dashed lines: channels. Italic numbers at the bottom left corner indicate the area of the lake. The lake outburst flood occurred on 7 August 2002. The following datasets were used: Corona satellite photo (1968), Landsat MSS (1973), 1: 50,000 Russian topographic map (1983~1984), Landsat TM (1992), Landsat ETM+ (2000, 2001, and 2002), and Google Earth images (2008). All data were geo-referenced to the WGS 84 UTM 43°N horizontal coordinate system, using Arc GIS 9.2. Orthorectification of the Corona satellite photos was not performed here.

inundated the Dasht Village (2,620–2,600 m a.s.l.), situated on the alluvial fan. Its travel time to the village was estimated to be at least 45 minutes based on reports from the local population (Mergili and Schneider, 2011). Eventually, this event destroyed a large part of the village and killed approximately 25 people.

The changes of the Dasht Lake before and after the event can be traced from the observation of the multitemporal satellite images covering the years 1968, 1973, 1992, 2000, 2002, and 2008, and a 1:50,000 Russian map compiled in 1983–84 (Fig. 3). The notable observations are shown below along the timeline.

(a) Appearance: the Dasht Lake has been visible as a re-appeared lake on the ice-cored end moraine since 7 July 2000. The former Dasht Lake had occurred as a thermokarst lake (with an area of 7,000 m^2) without any spillways by 18 August 1968. The lake had expanded to 15,000 m^2 by 12 July 1973, and continued to expand to 20,000 m^2 in 1983–84, then, had disappeared by 27 September 1992. The maximum size of the former Dasht Lake was much smaller than that of the Dasht Lake in the 2000s.

(b) Expansion to outburst: the expansion of the Dasht Lake to almost the same size as before the outburst occurred within less than a year, between 7 July 2000 and 2 August 2001. The expanded lake had discharged catastrophically within one year of 2 August 2001. Any pronounced spillways from the Dasht Lake were not observed during the period between its appearance and outburst.

(c) Post-outburst: a satellite image taken in 2008 (Google Earth Image) shows that no lake/pond formed in the former extent of the Dasht Lake after the outburst.

From the development history described above, the Dasht Lake can be characterized as having repeated appearance, rapid enlargement, no surficial outlet, and being a short-lived lake on the ice-cored end moraine. The appearance and expansion of this glacial lake can most likely be attributed to the temporal blockage of the drainage channel through or beneath the dead-ice/till complex, caused by ice deformation and/or ice-debris collapse into the channel, as was observed in the Tien Shan (Narama et al., 2010). The sudden discharge (outburst) from the lake is probably because of the blockage failure due to increasing water pressure and/or the atmospheric warming in the summer.

One significant feature of the Dasht debris flow is, as Mergili and Schneider (2011) suggests, that the debris flowed approximately 6.0–1.0 km beyond the travel distance calculated using various existing empirical models such as those by Corominas et al. (2003), Haeberli (1983), and Rickenmann (1999). This indicates the possibility that subglacial waters were involved in the debris flow, and/or the backwater effects of the flow (Mergili and Schneider, 2011).

Ⅳ. Applied hazards assessment

In the Tajik Pamir, assessments of geohazards (including GLOFs, mass movements, and seismicity) have been carried out continuously by an Austrian research group since 2002 (Schneider, 2005). The main results of these assessment activities were summarized in Schneider et al. (2010) and Mergili and Schneider (2011). There are significant differences in the assessments (e.g., research areas, focused hazards, methods, and final outputs) of these two investigations, which we review in this section.

1. Assessment by Schneider et al. (2010)

Schneider et al. (2010) was published as an assessment report of 342 pages. The focus of this assessment was to show the potential risk rating of geohazards for each of the 209 selected villages in the Jirgital and Gorno-Badakhshan Autonomous Oblast (GBAO) areas (Tajik Pamir) and the Zarafshan Range, and to provide proper hazard mitigation recommendations to the respective villages. The study areas in the Tajik Pamir are shown in Fig. 1.

(1) Methodology of assessment

First, the basic information for the assessment is acquired from the following three works: (1) remote sensing surveys at regional scales using GIS, medium-resolution datasets (SRTM digital elevation model, Landsat and ASTER images), Google Earth, and geological maps, (2) field observations at several key areas (including observations from helicopter), and (3) estimates of hazard impacts from computer modeling. Next, the evaluation of the hazard risks is conducted for each village based on the obtained information. In this assessment stage, the occurrence probability for each of four different hazard intensities (I for low intensity, to IV for very high intensity) is firstly defined from five classes (0 for zero probability to 4 for very high probability). Then, the probability class assigned to each hazard intensity is summed up according to the rating scheme. Finally, the potential hazard risk to each village is rated to be one of six levels (1 for very low hazard, to 6 for very high hazard), depending on the calculated score. The confidence levels (A for vey high confidence, to E for no information), showing the quality of the assessment work, is given for each rating.

(2) Results of assessment

The assessment by Schneider et al. (2010) showed that 34 villages in the Tajik Pamir (the GBAO and Jirgital areas) and 23 villages in the Zarafshan Range were rated to have ‘medium hazard’ (Class 4). It is worth noting that regional differences can be found in the hazard types threatening these villages. Specifically, major threats from glacier related hazards are restricted to the villages in the GBAO area, Tajik Pamir. On the other hand, hazards related to mass movements are the predominant risk for villages in the Jirgital area, Tajik Pamir, and the Zarafshan Range.

Regarding the significant glacier-related hazards in the GBAO area, the following three cases can be extracted from the assessment report: (1) ice avalanches caused by detachment of a glacier, (2) GLOFs, and (3) compounded-GLOFs induced by the cascade effect. The potential of

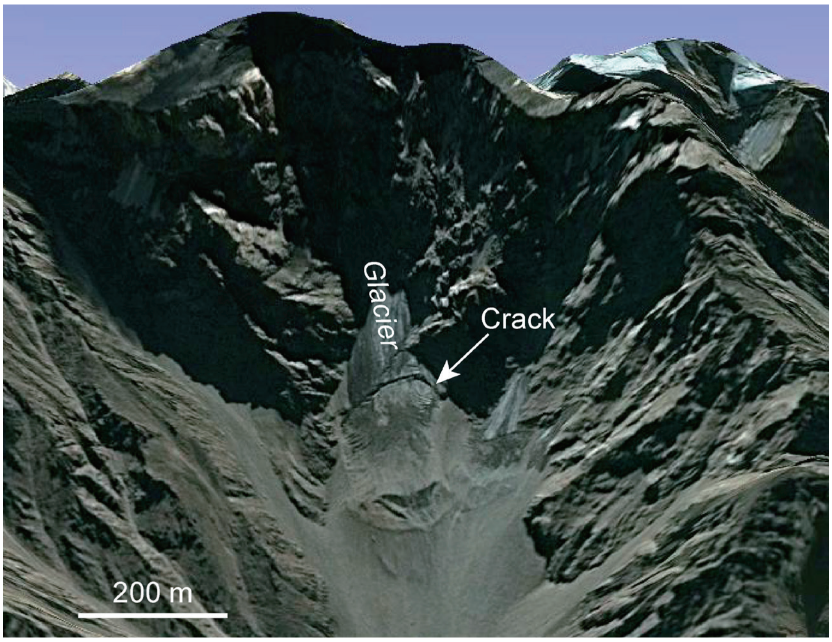


Fig. 4. Google Earth view of a crack emerging in a hanging glacier, the Bartang Valley (see Fig. 1 for location)
The original image was captured on 31 August 2008.

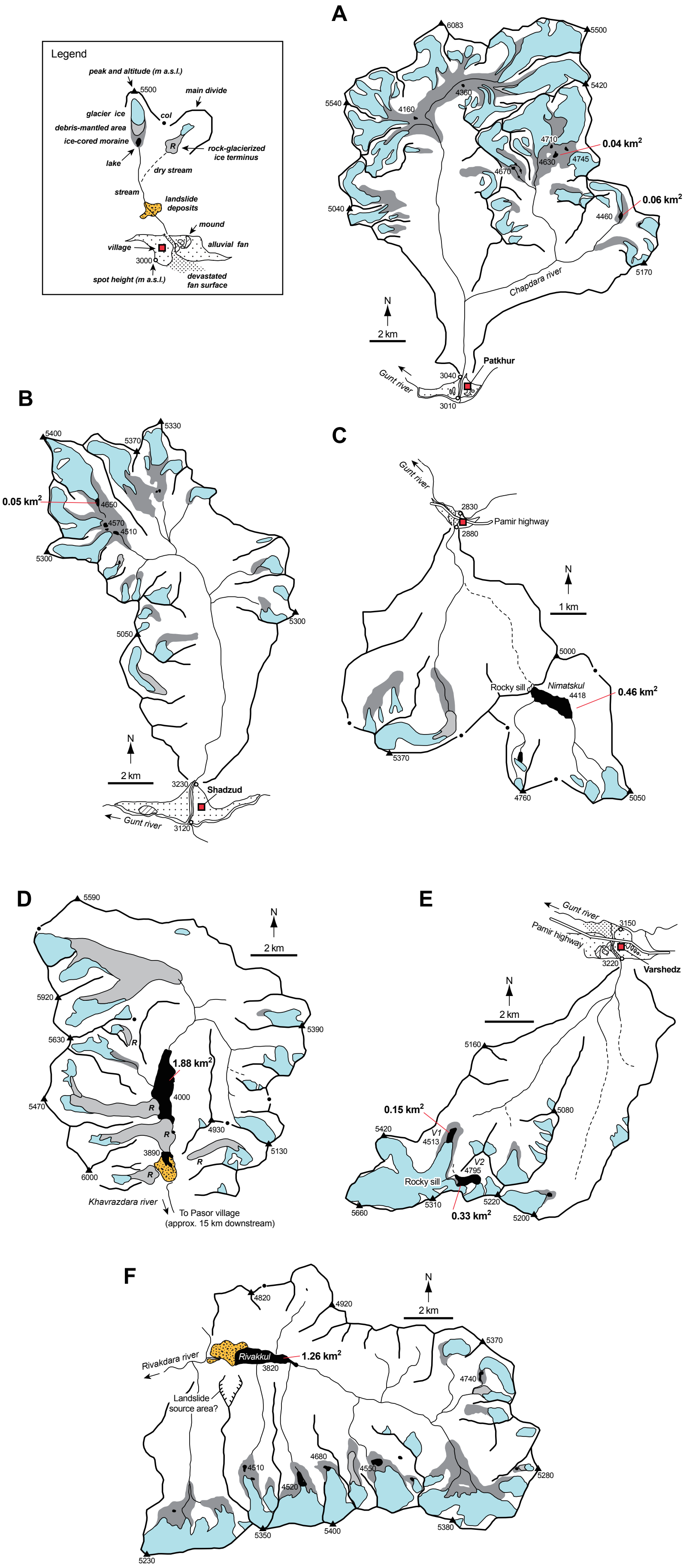


Fig. 5. Drainage basins associated with the lakes, which either Schneider et al. (2010) or Mergili and Schneider (2011) assessed potential sources of hazardous outburst floods, the Tajik Pamir (see Fig. 1 for location) A: Patkhurdara basin. B: Shadzudara basin. C: Nimatsdara basin. D: Upper reaches of Khavrazdara basin. E: Varshedzdara basin. F: Upper reaches of Rivakdara basin. Geomorphic and glacial configurations in these maps were identified from the Google Earth observations, and were subsequently delineated on the ortho-images with contour lines, which were constructed from SRTM-3 DEM and Landsat 7 ETM+ images (p151r034; captured on 22 August 2005). The altitudes shown in these maps are mainly derived from Google Earth.

(1) occurring was detected in a hanging-glacier (N38°01', E71°55'), which occupies the uppermost reaches of a tributary valley in the Bartang Valley (Fig. 1), where a transverse crack has been formed near the glacier tongue (Fig. 4). Both of Bartang and Ravivd villages, located near the mouth of the tributary, were rated to have 'medium hazard' (Class 4).

The risk of the (2) occurring has been pointed out particularly in the following glacial lakes:

(a) glacial lakes proximal to glacier snouts (e.g., supraglacial lakes and moraine-dammed lakes), distributed in the headwaters of Patkhur village (N37°42'26", E72°12'34"; Fig. 5A) and Shadzud village (N37°42'45", E72°21'40"; Fig. 5B), the Gunt valley.

(b) the distal glacial lake Nimatskul (N37°40'30", E72°04'07"; Fig. 5C), located in a tributary of the Gunt Valley.

(c) the lake dammed by a rock-glacierized glacier-terminus (N38°34', E72°36'30"; Fig. 5D), located in the headwaters of Pasor Village, the upper Bartang Valley.

Villages downstream of these glacial lakes were assigned rates up to 'medium hazard' (Class 4).

Case (3) can occur when a GLOF triggers one or more cascading outburst floods of the downstream lakes. Such cases have been assumed in two glacial lakes in the headwater of Varshedz village (N37°42', E72°20'50"; Fig. 5E) and the landslide-dammed lake Rivakkul (N37°36'55", E72°04'40"; Fig. 5F), and the glacial lakes upstream of it. In particular, the lakes in the headwaters of Varshedz village have been assessed as the most hazardous glacial lakes in the GBAO, and therefore, Varshedz village, located at the valley mouth, was rated as having 'high hazard' (Class 5).

2. Assessment by Mergili and Schneider (2011)

Mergili and Schneider (2011) focused on assessing each of the identified alpine lakes (including both glacial and non-glacial lakes) for the potential and impact of lake outburst hazard. The study area of this assessment covers the Gunt and Shakhdara valleys, the southwestern Tajik Pamir (Fig. 1), and does not overlap that of Schneider et al. (2010), except the Gunt Valley.

(1) Methodology of assessment

The hazard assessment of Mergili and Schneider (2011) was carried out based on GIS and Remote Sensing approaches, part of which was established in e.g., Reynolds (2003) and

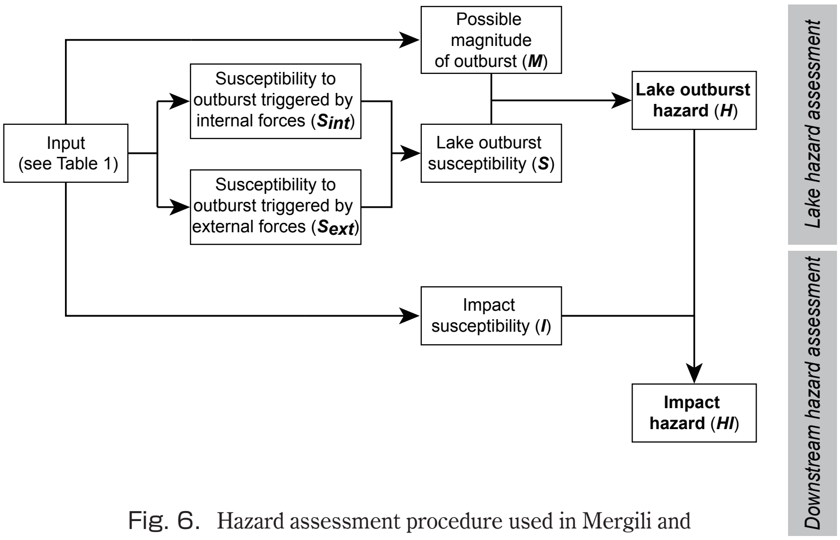


Fig. 6. Hazard assessment procedure used in Mergili and Schneider (2011)
Modification of the original figure in Mergili and Schneider (2011).

Huggel et al. (2004). In this assessment, 408 alpine lakes were first identified in the study area. Then, both of the potentially hazardous lakes and possible hazard-impact areas were evaluated through the rating and scouring systems. The input parameters and workflow used in this analysis are shown in Table 1 and Fig. 6, respectively.

As shown in Fig. 6, the ratings of the potentially hazardous lake ('Lake outburst hazard' *H*) are derived from a combination of the 'lake outburst susceptibility' rating *S* and the 'potential magnitude of outburst' rating *M*. Subsequently, the 'impact susceptibility' rating *I*, expressing the potential risk of outburst floods along the area downstream from lakes, is evaluated for each pixel of the study area. Finally, the rating for the possible hazard-impact area (the impact hazard rating *H*), is proposed through the integration of the *H* rating with the *I* rating, and the results are output as a hazard indication map. The detailed procedures for estimating each rating of *H* and *HI* are briefly described below.

a. Evaluation of potentially hazardous lakes

In order to evaluate the potentially hazardous lakes, firstly, the definition of the 'lake outburst susceptibility' rating *S* is required. The *S* ratings are built on the combined ratings of internal and external factors (S_{int} and S_{ext}) that could potentially trigger a lake outburst. The ratings of the internal factors (S_{int}) are initially determined from the five types of dam materials, and are subsequently adjusted more or less depending on the values of the following three criteria: 'existence of spillway from lake,' 'development of lake area,' and 'dam geometry' (the tangent of the average downstream slope of the dam). The ratings of the external factors (S_{ext}) are initially set based on the 'topographic susceptibility index,' and are then increased or decreased depending on the values of the following three criteria: 'possibility of ice calving into lake,' 'effect of seismic hazard,' and 'freeboard.'

Next, the 'possible magnitude of outburst' rating *M* is determined according to the lake area, which is considered to be one of the best surrogates for the indicator of outburst magnitude, e.g., 'volume of a lake' or 'expected peak discharge of outburst flood.' Finally, the ratings of the potentially hazardous lakes (0 for negligible, to 6 for extremely high) are derived by combing the *S* rating with the *M* rating.

b. Evaluation of possible hazard-impact area

The 'impact susceptibility' rating *I* is the last analysis to define the rates of the 'possible

Table 1. Input parameters used in hazard assessment of Mergili and Schneider (2011) (see Fig. 6) Simplification of the original table in Mergili and Schneider (2011).

Parameter	Unit	Source
Lake drainage	boolean	Qualitative interpretation of satellite imagery
Dam type	nominal	
Possible calving into lake	boolean	
Elevation (m a.s.l.)	m	Computed from lake centroid and DEM
Freeboard	m	
Lake area	m^2	Derived from mapped lake
Average lake depth	m	Empirical relationship with lake area
Lake volume	m^3	Derived from lake area and average lake depth
Lake area development 1968–2007/2008	ratio	Comparison of lake area derived by multitemporal analysis of satellite imagery
Lake area development 2001/2002–2007/2008	ratio	
Maximum Peak Ground Acceleration	ms^{-2}	Map of active faults and published relationships

hazard-impact area (*HI*)' (0 for negligible, to 6 for extremely high), as mentioned above. The rating *I* denotes the tendency of a lake outburst flood to affect a certain area, and is assigned to one of 7 classes (0 for negligible, to 6 for extremely high) according to the evaluation of the following two factors: (a) relation to the existing four empirical relationships (Haeberli, 1983; Rickenmann, 1999; Huggel, 2004; Huggel et al., 2004) for estimating the travel distance of outburst flood to the area downstream from lakes, and (b) the average slope angle in the area from the lake to the estimated extent of outburst flood. For instance, a pixel corresponding to any one of the four empirical relationships among 3 classes (1 for low, to 3 for medium), is determined to be one of those classes based on the average slope angle to this pixel from a lake. In contrast, a pixel that corresponds to all four empirical relationships (e.g., the area just below a lake) is instantly determined to be class 6 'extremely high.'

(2) Results of assessment

In the 'lake outburst hazard' (*H*) assessment, among the 408 identified alpine lakes in the southwestern Tajik Pamir, 122 lakes were evaluated as 'egligible' (Class 0), 35 lakes as 'low hazard' (Class 1), 124 lakes as 'moderate hazard' (Class 2), 87 lakes as 'medium hazard' (Class 3), 34 lakes as 'high hazard' (Class 4), 6 lakes as 'very high hazard' (Class 5), and no lakes as 'extremely high hazard' (Class 6). Moreover, three lakes were highlighted as the potentially most hazardous lakes, based on overlaying the possible impact areas of lake outburst floods (Impact Hazard *HI* pixels) with areas of settlements and agriculture/pasture fields. All of these lakes were already mentioned in Schneider et al. (2010), and were found in the upper reaches of the tributaries of the Gunt Valley. To be specific, two of the three lakes are located in the headwaters of the Varshedz village (Fig. 5E): Lakes *V1* (N37°37'39", E72°16'16") and *V2* (N37°36'40", E72°16'45") are assigned to 'very high hazard' and 'high hazard,' respectively. The third lake is the Nimatskul (Lake *N1*; Fig. 5C), and is ranked 'high hazard.'

On the other hand, the Dasht Lake in 2002 (just before causing the GLOF) was ranked 'medium hazard' (Class 3), which we deem to be an underestimation of its actual impact downstream. The main reason for the low *H* rating is that the limited size of the Dasht Lake (its *M* index) downgraded the score of the lake outburst susceptibility '*S*,' which is ranked 'very high' (Class 5) in the definition of the *H* rating. Therefore, it is difficult or impossible to appropriately assess the potential risks for outburst flooding from a small glacial lake such as the Dasht Lake using this approach. This must be taken into consideration when applying this method of assessment to hazard-mitigation.

Ⅴ. Remarks on the Tajik-Pamirian glacier-related hazards

1. Assumed glacier-related hazards

Considering both past hazardous events (see Chapter III) and the assessment results (see Chapter IV), the following three matters: detached glaciers, surge glaciers, and glacial lakes (in particular 'guerrilla glacial lakes'), appear to be responsible for major hazards in the Tajik Pamir, especially in the GBAO area. Detailed descriptions on each of these are given below.

(1) Detached glaciers

A hanging glacier, located in a tributary of the Bartang Valley, has shown signs of glacier detachment along a transverse crack (Schneider et al., 2010; Fig. 4). If the detachment actually occurs, the ice avalanche caused by the falling ice bodies will cause serious damage to the villages downstream.

(2) Surge glaciers

One of the major features of the Pamirian glaciation is the existence of many surge glaciers, occurring mainly in the northwestern Pamir, as mentioned in Chapter III. Some of them terminate their snouts at the valley confluence, potentially blocking the ice-free main valley after the surge-induced advance, and subsequently forming a temporary glacier-barriered lake, which is prone to cause outburst floods (e.g., the Medvezhiy Glacier). Furthermore, it has been reported that surge movement by a collapsed glacier-tongue can cause an ice-water debris flow. Therefore, the surging behaviors of such glaciers pose a potentially disastrous threat in the Tajik Pamir.

(3) Glacial lakes (in particular ‘guerrilla glacial lakes’)

Potentially hazardous glacial lakes were identified through hazard assessment studies (Schneider et al., 2010; Mergili and Schneider 2011) in most areas of the Tajik Pamir, as discussed in Chapter IV and shown in Fig. 5. However, it should be noted that although an outburst flood from a relatively small-size glacial lake (e.g., 32, 000 m^2) can cause serious damage downstream, as exemplified by the Dasht 2002 event, its potential risk could not be appropriately evaluated by these hazard assessment studies.

To analyze the Dasht 2002 event, this type of glacial lake should be distinguished as a ‘repeatedly appearing,’ ‘rapidly enlarged (within less than one year),’ ‘short-lived (within less than two years),’ ‘superficially closed,’ and ‘relatively small sized’ glacial lake on the ice-core moraine, and can be appropriately designated as a guerrilla glacial lake. Such guerrilla glacial lakes can discharge unexpectedly, when the blockage to the drainage channels beneath/through the ice-core moraine fails (e.g., Narama et al., 2010; Mergili and Schneider, 2011). Because both the blockage and failure are likely to be dependent on invisible factors in the sub/intra-moraine conditions, it would be impossible to predict the timing of the lake appearance, ot the lake outburst.

In summary, in the Tajik Pamir, not only are glacial lakes assessed as dangerous lakes, but some also display the features of guerilla glacial lakes, and should be assumed to pose a serious potential hazard downstream. Early detection of the emergence of the guerrilla glacial lakes is key to reducing the GLOF hazards in this region, because the unpredicted outburst discharge from such a lake can potentially occur within less than one or two years of its appearance.

2. Recommended action to mitigate glacier-related hazards

As mentioned above, the Tajik Pamir still faces the hazards associated with the detachment of a hanging glacier, glacier surging, and the outburst discharge of glacial lakes (particularly guerrilla glacial lakes). Accordingly, early detection of large cracks in the hanging-glacier terminus, surge movements, and glacial lakes or guerrilla glacial lakes, as well as regular monitoring of such identified hazard factors are needed to prepare appropriate hazard-mitigation actions. In other words, frequent and routine monitoring of all glaciers and glacial lakes should be conducted continuously to fulfill these demands. In terms of cost and efficiency, one of the best ways to perform such monitoring is to use earth observation satellite images, which can be captured with a relatively short repetitive cycle and medium to high spatial resolution, at relatively low cost. At present, these requirements are barely satisfied with the satellite images of Landsat ETM+ and Terra/ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) with a 16-day repeat cycle and a >15 m spatial-resolution. In the near future, however, observation of a certain area with much more frequent repetition may be practicable by launching many sets of microsatellites such as the 50-kg class microsatellite SPRITE-SAT (RISING) (Sakamoto et al., 2010; Yoshida et al., 2010).

Finally, it should be noted that although the risk assessments of glacier-related hazards in the Tajik Pamir have been accomplished in two different ways (Schneider et al., 2010; Mergili and Schneider, 2011), the assessment areas of these two studies barely overlap each other, and do not cover the whole area of the Tajik Pamir (Fig. 1), as mentioned in Chapter IV. Assessment investigations using both approaches are urgently needed in the Tajik Pamir, in order to fill in assessment blanks such as that in the Vanch Valley (Fig. 1). Furthermore, adequate warning based on the updated results of monitoring and assessment should be provided to the hazard-affected local populations.

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