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Spatio-temporal development of high-mountain lakes in the headwaters of the Amu Darya River (Central Asia)

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ABSTRACT

The sources of the Amu Darya, one of the major Central Asian rivers draining to the Aral Sea, are located in the glacierized high-mountain areas of Tajikistan, Kyrgyzstan and Afghanistan. There, climate change and the resulting retreat of glaciers have led to the formation of numerous new glacial lakes. Other lakes in the area are embedded in older glacial landscapes (erosion lakes) or retained by block or debris dams (e.g., Lake Sarez). A multi-temporal lake inventory is prepared and analysed, based on remotely sensed data. Corona images from 1968 are used as well as more up-to-date ASTER and Landsat 7 scenes. 1642 lakes are mapped in total, 652 out of them are glacial lakes. 73% of all lakes are located above 4000 m a.s.l. Glacial lakes, abundant in those areas where glacier tongues retreat over flat or moderately steep terrain, have experienced a significant growth, even though changes are often superimposed by short-term fluctuations. The analysis results also indicate a shifting of the growth of glacial lakes from the south western Pamir to the central and northern Pamir during the observation period. This trend is most likely associated with more elevated contribution areas in the central and northern Pamir. The lakes of the other types have remained constant in size in general. The lake development reflects changes in the state of the water resources in the study area on the one hand and determines the level of lake outburst hazards on the other hand.

1. Introduction

The Amu Darya is one of the most important rivers in the lowlands of Central Asia. Its sources are located in the glacierized high-mountain areas of Tajikistan, Kyrgyzstan and Afghanistan (Pamir, Alai and Hindukush mountains). They include the upper catchments of the Surkhob River, the Khingob River and the Panj River (Fig. 1). The Surkhob and Khingob Rivers, after their confluence, continue as Vakhsh River, a tributary to the Panj River forming the Tajik–Afghan border. After the confluence of Panj and Vakhsh, the river continues as Amu Darya all the way to the Aral Sea. Controlling of the water flow of the Vakhsh River in Tajikistan for hydropower generation has led to political tensions with Uzbekistan and Turkmenistan where the water is extensively used for irrigation, and inappropriate water management practices have led to the shrinkage of the Aral Sea (e.g., Micklin, 1988; Micklin and Aladin, 2008). The runoff regime of the Amu Darya and other Central Asian river systems, and the contribution of glacial melt water, have been the subject of comprehensive research (e.g., Agaltseva et al., 1997; Aizen and Aizen, 1997; Aizen et al., 2007a). Particularly in the valleys of those arid mountain areas, melt water is highly important for the livelihood of the people (e.g., irrigation, hydropower generation), whilst its importance diminishes in humid areas and with increasing distance from the glaciers (Hagg and Braun, 2005; Kaser and Grosshauser, 2010).

High-mountain environments are highly dynamic and sensitive systems. Therefore they serve as early indicators for climate fluctuations, including snow, glaciers, permafrost, ecosystems and the water cycle (e.g., Beniston, 2003; Huber et al., 2005; Harris et al., 2009). There is overwhelming evidence for a worldwide accelerated retreat of glaciers over the last few decades (WGMS, 2008), involving the tropics (e.g., Kaser, 1999), arid and humid mid-latitudes (e.g., Aizen et al., 2007b; Lambrecht and Kuhn, 2007) and the polar regions (e.g., Cook et al., 2005). Much of this retreat has been attributed to the evident atmospheric temperature rise (IPCC, 2007). However, glacial retreat is not occurring at the same rates and with the same characteristics worldwide.

Locally, the dynamics of the glacial and periglacial environment disturb the equilibrium of the system and therefore lead to an increased level of hazard (Evans and Clague, 1994; Huggel et al., 2004a,b; Kääb et al., 2005; IPCC, 2007; Quincey et al., 2007; Harris et al., 2009; Dussaillant et al., 2010; Haeberli et al., 2010a). One particular aspect is the formation of glacial lakes, dammed by moraines or by the glaciers themselves. Such lakes often occur in areas influenced by permafrost. Tweed and Russell (1999) distinguished nine types of ice-dammed lakes. On the one hand, glacial lakes mirror the state of the glaciers as source of fresh water. On the other hand some lakes are prone to sudden outbursts (Glacial Lake Outburst Floods or GLOFs) and pose a potential threat to the downstream communities. Most studies

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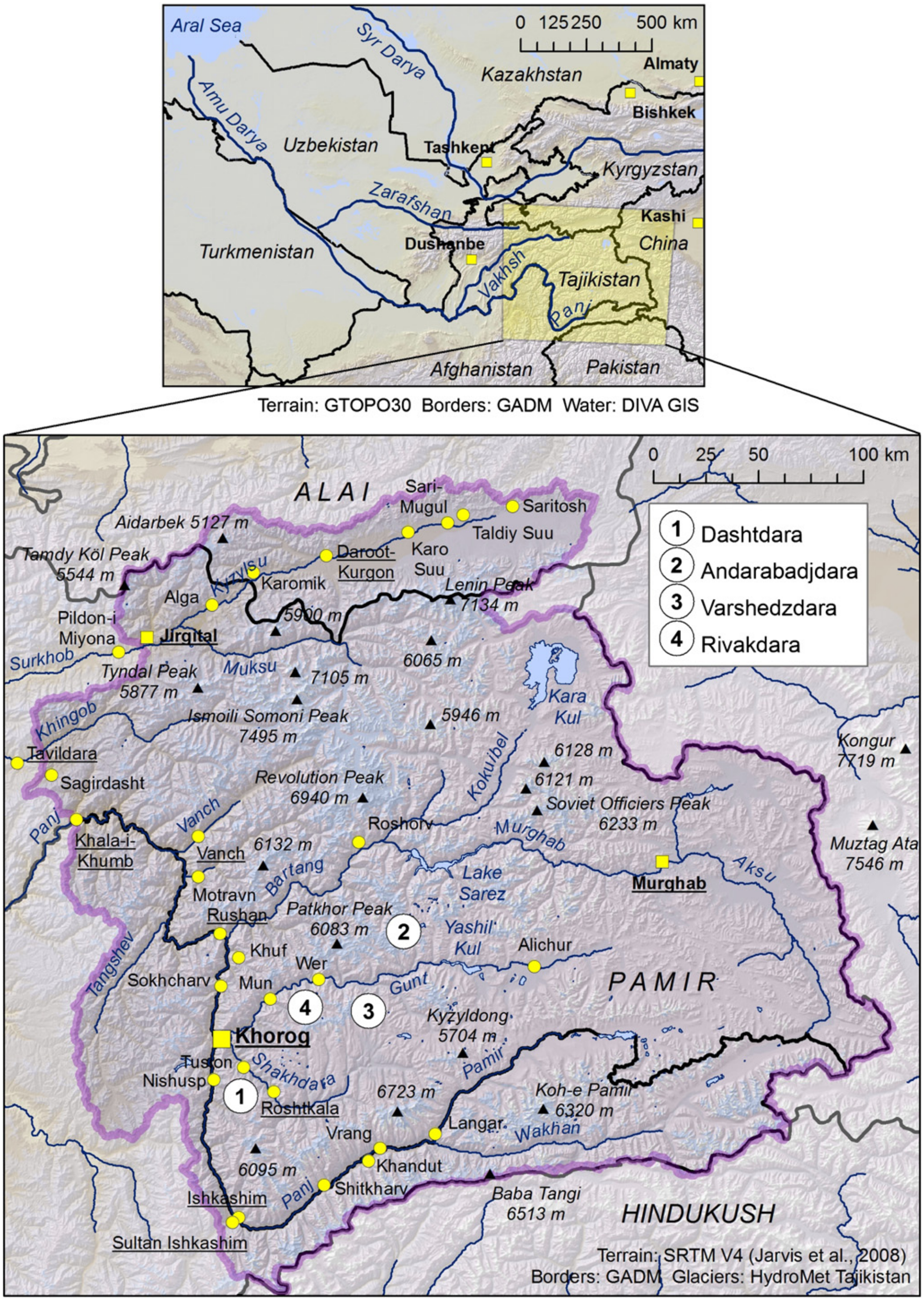


Fig. 1. Study area, including the headwaters of the Amu Darya in the Pamir, Alai and Hindukush (Tajikistan, Kyrgyzstan and Afghanistan).

published on glacial lakes are related to GLOF events or GLOF hazard. Studies cover most glacierized mountain areas in the world, e.g., in the Himalayas of Nepal and Bhutan (Watanabe and Rothacher, 1996; Richardson and Reynolds, 2000; Bajracharya et al., 2007; ICIMOD, 2011), the Karakorum (Hewitt, 1982; Hewitt and Liu, 2010), the Pamir (Mergili and Schneider, 2011), the Tien Shan (Narama et al., 2010; Bolch et al., 2011), the Andes (Vilímek et al., 2005; Harrison et al., 2006; Haeberli et al., 2010b), the North American mountains (Clarke, 1982), the Norwegian mountains (Breien et al., 2008) and the western Alps (Haeberli, 1983; Tinti et al., 1999; Huggel et al., 2002, 2003). The anticipation of possible glacial lake development is seen as a first important step of hazard assessment (Frey et al., 2010). GLOFs can evolve in different ways, for example by rock/ice avalanches or ice fronts calving into lakes, rising lake levels leading to overflow, progressive incision, mechanical rupture or retrogressive erosion of a dam, hydrostatic failure or degradation of glacier dams or ice-cores in moraine dams (Walder and Costa, 1996; Richardson and Reynolds, 2000). Peak discharges are often some magnitudes higher than in the case of "normal" floods (Cenderelli and Wohl, 2001). Entrainment may considerably increase the event magnitude and convert the flood into a destructive debris flow.

Also other types of lakes are relevant from a hazard perspective (Evans, 1986; Costa and Schuster, 1988; Walder and O'Connor, 1997). Landslide dams are of particular interest as most of them fail within the first year after their formation (Costa and Schuster, 1988). In the seismically active Central Asian mountains, recent and former landslide-dammed lakes are common. There is still controversy about the safety of Usoi Dam, the highest landslide dam worldwide, impounding Lake Sarez since its formation during a major earthquake in 1911 (e.g., Schuster and Alford, 2004; Risley et al., 2006). On the other hand, there are discussions on the use of Lake Sarez – and other lakes – for hydropower generation. In general, the use of high-mountain lakes for hydropower generation is a subject of increasing interest (Terrier et al., 2011).

The aspects outlined above highlight the importance of up-to-date-knowledge on high-mountain lakes. Whilst the level of information is considerable in some mountain areas of the world, the knowledge about the spatial distribution, and even more the temporal development, of high-mountain lakes in the Pamir is still limited.

The present article attempts to fill this gap by focusing on the analysis of the distribution and the temporal development of lakes in the headwaters of the Amu Darya catchment. For this purpose, a multi-temporal lake inventory is prepared and the spatial distribution of the lake characteristics is analysed as well as the patterns of lake development. It is attempted to link the findings to observed glacier dynamics. The results shall serve as a baseline for the assessment of lake outburst hazards and for studies on the potential of the lakes for hydropower generation.

Next, the study area is introduced (Chapter 2). Then, the methods applied to explore the spatial distribution and the temporal development of high-mountain lakes in the study area are outlined (Chapter 3). The presentation of the results (Chapter 4) is followed by a discussion (Chapter 5) and the conclusions (Chapter 6).

2. Study area

Here, a 98,300 km^2 study area is considered, extending from 1670 m a.s.l. near Khala-i-Khumb to 7495 m at the top of Ismoili Somoni Peak (see Fig. 1). The northern and southern limits of the study area are the Alai and Hindukush ranges in Kyrgyzstan and Afghanistan, respectively. They largely extend in east-west direction. In between, the Pamir in the Gorno-Badakhshan Autonomous Oblast of Tajikistan represents the largest share of the study area. The western Pamir is characterized by glacierized mountain ranges exceeding 6000 m a.s.l. and deeply incised, fairly densely populated valleys. The eastern Pamir represents an arid highland above 3500 m a.s.l. with glaciers covering only the highest peaks. The northern Pamir with the Academy of Sciences and Transalai ranges carries three peaks exceeding 7000 m a.s.l. and is extensively glacierized. The Fedchenko Glacier extends over a length of >75 km and covers a surface area >700 km^2. Many glacier tongues in the study area are covered by debris, making it hard to delineate their extent from satellite imagery or superficial field surveys. Even though a general retreat of the areas of exposed ice was identified for several mountain ranges within the study area (e.g., Khromova et al., 2006; Haritashya et al., 2009; Mergili et al., 2012), melting of ice within decaying debris-covered glacier tongues may contribute a significant share of the total loss of ice volume on the one hand and favours the development of lakes in the subsiding areas on the other hand.

The climate in the study area is temperate semi-arid to arid and continental with hot summers and cold winters. Most meteorological stations in the study area have recorded a positive trend of the mean annual air temperature (MAAT) for the period 1940–2000 (Makhmadaliev et al., 2008). The increase of the MAAT did not exceed +1 °C for any of the station. One station even displayed a negative trend. However, the most recent data available are from the valleys, which deviate considerably from the conditions in the high-mountain areas. The state of information suffers from a lack of up-to-date high-altitude meteorological data. The Fedchenko station does not provide reliable data since 1995. According to the 4th IPCC report (IPCC, 2007), the median of the projected increase of the MAAT from 1980–1999 to 2080–2099 for Tajikistan is 3.7 °C.

The changing temperature regime impacts the livelihood of the local communities in both a positive and a negative way (Kassam, 2009). Much of these impacts concern water resources related to the numerous glaciers and lakes in the headwaters of the valleys.

3. Materials and methods

3.1. Lake identification and classification

The study presented relies primarily on the analysis of medium-resolution satellite imagery. In order to obtain the most recent state of the lakes in the study area in a consistent way, ASTER images of 2009 are used as the primary source of information (raster cell size: 15 m). However, since it is not possible to cover the entire area with cloud- and snow-free scenes from one single year, let alone day, also ASTER images and pan-sharpened Landsat 7 scenes from 2007, 2008 and 2010 are used. Verification and the collection of additional information for each lake are supported by high-resolution Google Earth scenes.

The manual delineation of the boundaries of each single lake in the study area is preferred to an automatic procedure. Even though automatic lake identification procedures from optical or radar satellite imagery are well introduced (e.g., Huggel et al., 2002; Kääb et al., 2005; Strozzi et al., 2012) it turned out that, in this specific case, the amount of manual post- processing required would most likely more than offset the advantages of an automated lake detection.

Three lake types are distinguished. The classification scheme chosen is kept as simple as possible, constrained to criteria identifiable from the remotely sensed data used (Table 1 and Fig. 2). The approach can be considered reproducible as the visual image interpretation is based on clear, largely objective criteria. A more detailed lake classification could only be done at the cost of higher uncertainties and poor reproducibility. Particularly in the case of glacial lakes (Type 3), no further distinction into pro-glacial, supra-glacial etc. (e.g., Tweed and Russell, 1999; ICIMOD, 2011) lakes is applied. The transition between the various types of glacial lakes is rather gradual than sharp and their identification requires at least high-resolution imagery (Kääb et al., 2005) or even geophysical methods not applicable at the regional scale.

The elevation a.s.l. of each lake is extracted from the SRTM V4 digital elevation model (Jarvis et al., 2008; approx. 90 m raster cell size) using the location of the lake centroid as reference. The lake area A (m^2) is computed from the mapped polygons. All lakes with $A < 2500$ m^2 are disregarded.

3.2. Lake area development

The lake evolution or lake area development is expressed as the change of lake surface area during the observation period both in absolute and relative terms,

$$D_A = A_2 - A_1, r_A = \frac{A_2}{A_1}, \quad (1)$$

Table 1
Lake types as distinguished in the mapping and analysis.

Lake type	Criterion
1 Erosion lake	Impounded by pronounced rock barriers or embedded in undulating landscapes most likely formed during the Pleistocene, at some distance from the recent glaciers, but often still above 4000 m a.s.l. The term erosion lake follows ICIMOD (2011).
2 Block or debris-dammed lake	Impounded by dams dominated by coarse blocks, debris, or a combination of both, most commonly representing Pleistocene terminal moraines, landslide deposits, or talus or debris cones.
3 Glacial lake	Either directly embedded in the exposed ice or retained by debris-covered glacier tongues, rock glaciers, or fresh moraines.

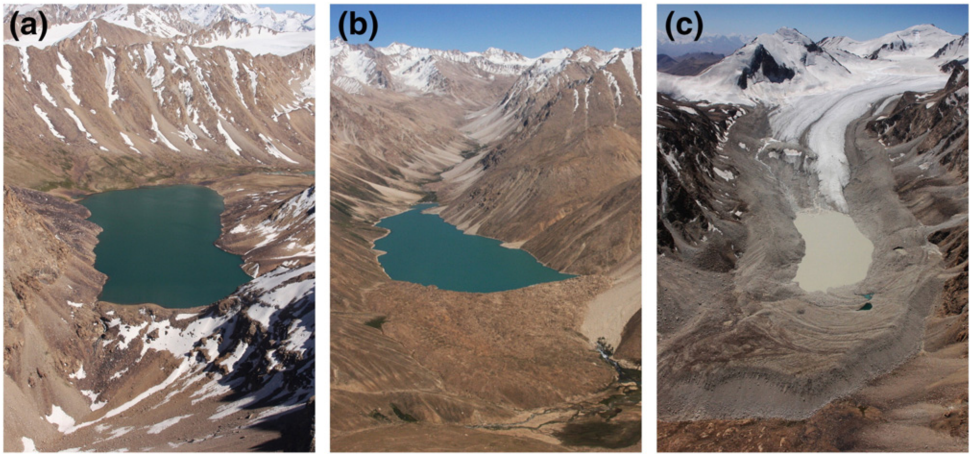


Fig. 2. Examples for lakes of the various types — a Erosion lake (Type 1) b Lake impounded by block or debris dam (Type 2) c Glacial lake (Type 3).

where D_A is the absolute lake area development (m^2), r_A is the relative lake area development (ratio) and A_1 and A_2 are the lake areas (m^2) at the beginning and at the end of the observation period. In addition to the entire period from 1968 to 2009, two sub-periods are considered: Period 1 from 1968 to 2002 and Period 2 from 2002 to 2009. Scanned and georectified declassified Corona images (raster cell size <5 m) are used for 1968, ASTER and pan-sharpened Landsat 7 images for 2001 and – as already explained above – for 2009. Since appropriate ASTER and Landsat scenes are not available for the entire area from one single year, scenes are also taken from up to two years earlier or later. Only lakes with a surface area $A \geq 2500$ m^2 in 2009 are considered in the analysis.

The accuracy of lake polygons mapped from medium-resolution satellite imagery suffers from uncertainties related to the subjectivity of polygon construction and to the geometric distortion of the imagery, which cannot always be completely removed with reasonable effort. Since lakes are always flat, the problem of distortion is supposed to be less significant than for mapping efforts on inclined slopes. However, the distortion uncertainty u_c still exists and is tested using Landsat scenes as reference. u_c quantifies the absolute value of the relative difference between the lake area mapped from the Landsat scene and the lake area mapped from the ASTER or Corona scene. For Corona scenes, $u_c \leq 14\%$ with 75% confidence, $u_c \leq 20\%$ with 90% confidence and $u_c \leq 27\%$ with 95% confidence. For the ASTER scenes, the uncertainty of the mapped area $u_c \leq 4\%$ with 75% confidence, $u_c \leq 6\%$ with 90% confidence and $u_c \leq 13\%$ with 95% confidence. Also the effects of mapping uncertainty are supposed to be significant at the image resolution used and are therefore analysed. Empirical tests show that the manual definition of lake boundaries on ASTER images, based on subjective interpretation, is subject to a mapping uncertainty in the order of one raster cell (i.e., 15 m). Corona scenes have a higher resolution, but are only available as greyscale images, making mapping more difficult and uncertain. The mapping uncertainty is set to $u_m = 5$ m for Corona imagery. The degree of the effects of distortions and uncertain polygon boundaries on the derived lake area depends on the lake area itself. Assuming a circular lake,

$$A_{\max} = (1+u_c)\cdot\left(\sqrt{\frac{A_m}{\pi}}+u_m\right)^2\pi, A_{\min} = (1-u_c)\cdot\left(\sqrt{\frac{A_m}{\pi}}-u_m\right)^2\pi, \quad (2)$$

where A_{max} and A_{min} are the maximum and minimum possible lake areas (m^2), A_m is the mapped lake area (m^2) and u_m is the mapping uncertainty (m). Growing and shrinking lakes are therefore defined as

$$D_{A,g} = A_{2,\min}-A_{1,\max}, D_{A,g} > 0, r_{A,g} = \frac{A_{2,\min}}{A_{1,\max}}, r_{A,g} > 1, \quad (3)$$

$$D_{A,s} = A_{2,\max}-A_{1,\min}, D_{A,s}<0, r_{A,s} = \frac{A_{2,\max}}{A_{1,\min}}, r_{A,s}<1, \quad (4)$$

where the subscripts *s* and *g* stand for shrinkage and growth. This procedure gives a minimum number of growing and shrinking lakes, only considering those where the trend of evolution can be determined with a certain degree of confidence. The real number of growing or shrinking lakes and the absolute values of D_A and r_A may be higher.

4. Results

4.1. Spatial distribution of lakes

1642 lakes are identified in the study area: 885 erosion lakes (Type 1 in Table 1; see Fig. 2), 105 lakes impounded by block or debris dams (Type 2) and 652 glacial lakes (Type 3). Table 2 summarizes some statistical key features of the lakes of the various types.

The distribution of lakes of different types and size classes is shown in Fig. 3. The southern Pamir is a hot spot for erosion lakes, whilst the glacial lakes obviously group together very close to glacierized areas (Fig. 4). However, whilst the density of glacial lakes is comparatively high in the ranges of the south western Pamir and also in the extensively glacierized central Pamir, almost no glacial lakes exist in some parts of the western Pamir. These patterns are a consequence of the topographic characteristics of the various mountain ranges as illustrated by Fig. 5: the ROC (Receiver Operating Characteristic) curves indicate the degree to which the distribution of a binary target variable (in this case, raster cells with a density of glacial lakes ≥20 are set to 1, all other raster cells are set to 0) is explained by a predictor variable (density of glaciers and density of areas with moderate topography, respectively). The true positive rate (fraction of true positive predictions out of all positive observations) is plotted against the false positive rate (fraction of false positive predictions out of the negative observations) at certain threshold levels, i.e., a straight diagonal line would represent a

Table 2
Lake statistics, organized by lake type. n = number of lakes, A_{med} and A_{max} = median and maximum lake area, z_{med}, z_{max} and z_{min} = median, maximum and minimum elevation a.s.l.

Lake type	n	A_{med} (km^2)	A_{max} (km^2)	z_{med} (m)	z_{max} (m)	z_{min} (m)
1 Erosion lake	885	0.015	404.55	4294	5131	1716
2 Block or debris dam	105	0.018	88.51	4265	4956	2314
3 Glacial lake	652	0.007	1.89	4505	5109	3057
Total	1642	0.010	404.55	4395	5131	1716

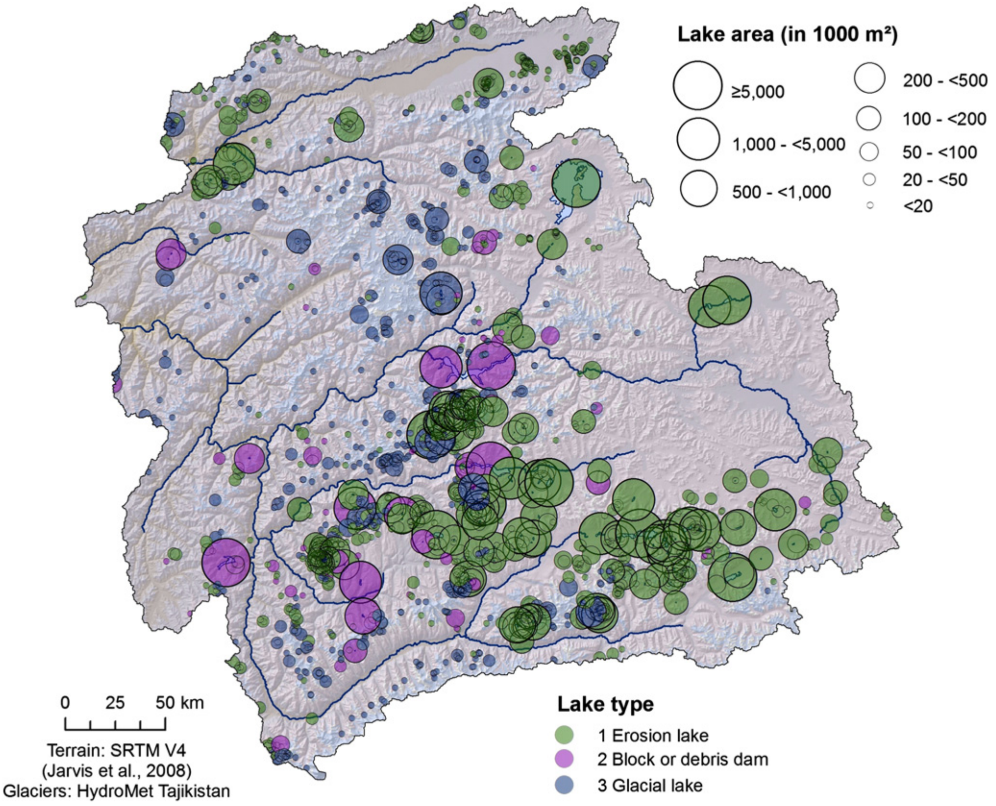


Fig. 3. Distribution of lakes in the study area according to types and size classes.

random distribution. Here, all raster cells with a slope <10° are considered as areas with moderate topography, the density of such areas as well as of glaciers is computed with a search radius of 10 km, analogous to the lake density. Not surprisingly, there is a strong positive correlation between glacial lake density and glaciers (area under curve $AUC = 0.833$, 0.5 would represent a random distribution). Using the product of glacier density and the density of areas with moderate topography, the *AUC* rises only slightly to 0.852, illustrating the dominance of glacier density as a predictor (see Fig. 5a). When removing all areas with a distance >10 km to the next glacier from the analysis, the clear preference of the occurrence of glacial lakes in areas with moderate topography becomes more obvious ($AUC = 0.659$; see Fig. 5b).

Fig. 6 plots the distribution of the dam types and the lake areas vs. elevation. Only 26.7% of all lakes, but 80.6% of the lake area are below 4000 m a.s.l. Out of the total lake area of 727 km^2, the Kara Kul – located at approx. 3900 m a.s.l. – accounts for 405 km^2 or 55.7%. Also most of the other large lakes in the area occupy areas between 3000 and 4000 m a.s.l., many of them are retained by block dams at the bottom

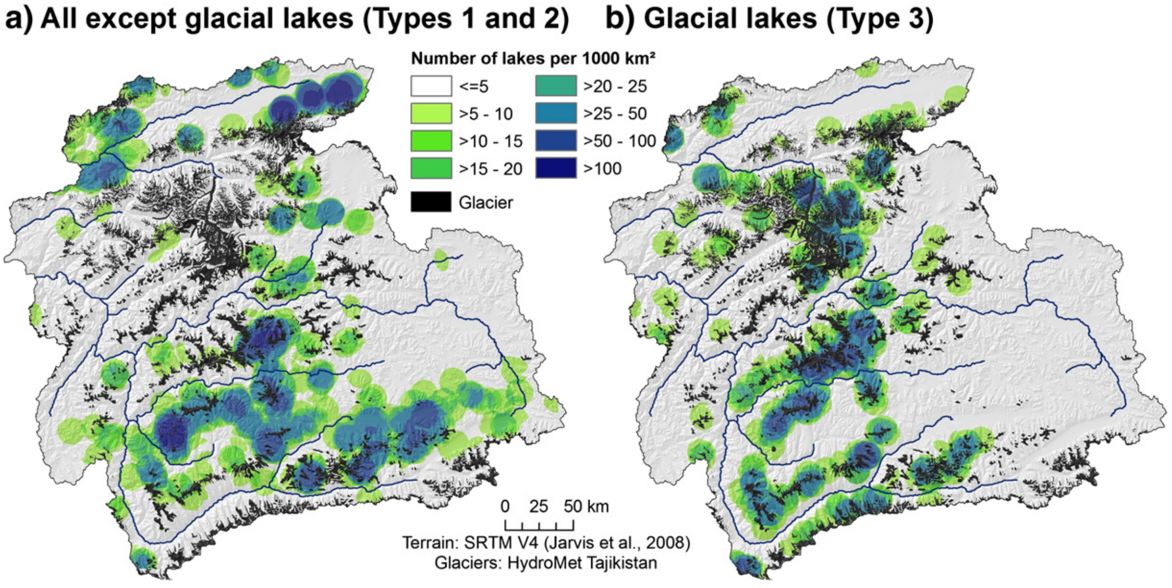


Fig. 4. Density of a all except glacial lakes and b glacial lakes, circle radius = 10 km.

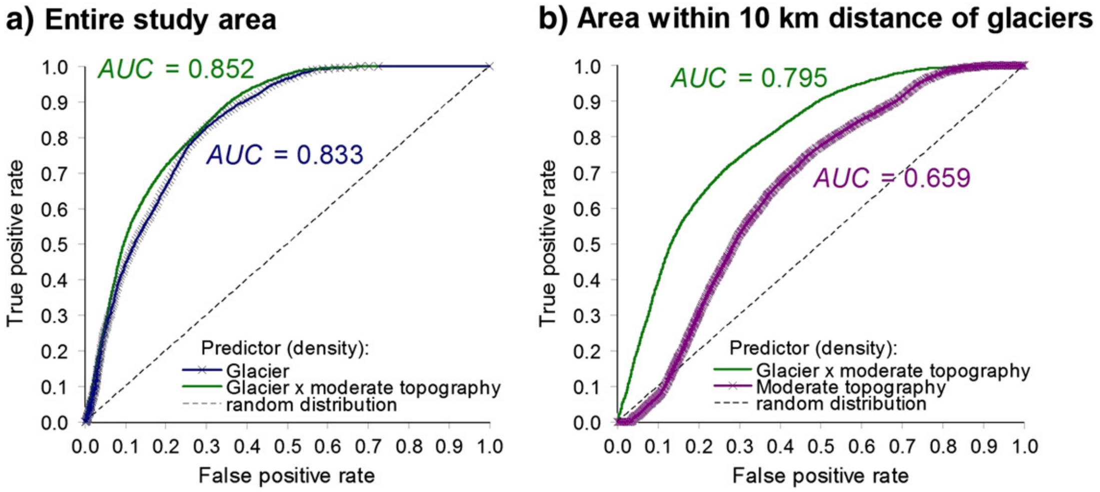


Fig. 5. ROC plots of the prediction rate of the location of the glacial lakes depending on the location of the glaciers and areas with moderate topography – densities within a radius of 10 km are used for all variables (see Fig. 4) a for the entire study area b constrained to areas within a 10 km distance from the next glacier – *AUC* = area under curve.

of large valleys (Type 2; e.g., Lake Sarez and Yashil Kul). Above the steep valley flanks Pleistocene glaciers have shaped undulating plains. This environment favours the occurrence of Type 1 lakes (Fig. 7). Above 4500 m a.s.l., in the zone of recent glaciers and fresh moraines, lakes of Type 3 become more abundant. The highest lakes are identified above 5100 m a.s.l. Most of the lakes below 4000 m a.s.l. are in the northern part of the study area whilst less than 10% of all lakes in the south western Pamir are located below this threshold.

The high elevation of many lakes leads to the assumption of a certain influence of permafrost, possibly affecting the stability of the dams themselves as well as the stability of adjacent slopes and rock walls (Haeberli et al., 2010a). No detailed and up-to-date permafrost investigations are available for the study area, but national or even global datasets of the potential permafrost distribution become increasingly available (e.g., Gruber, 2012). Here, a map of the potential present and future distribution of discontinuous and sporadic permafrost in Tajikistan (Mergili et al., 2012) is used. It was derived by adapting the scheme developed by Haeberli (1975) for Switzerland to the conditions in Tajikistan. Four scenarios of atmospheric temperature increase were assumed, using the IPCC scenarios until the year 2100 (IPCC, 2007) as reference.

Table 3 illustrates that 95.6% of all glacial lakes are located in areas with at least sporadic permafrost, and more than 92.2% are found in areas with discontinuous permafrost. Since the lakes of the other types are, in average, found at a lower elevation, 90.6% of all lakes are located in areas with at least sporadic permafrost, whilst 81.5% are found in areas with discontinuous permafrost.

Increasing atmospheric temperatures, leading to permafrost retreat, could substantially change this situation and therefore alter the stability of the dams (see Table 3). With +4 °C, 79.8% of all glacial lakes would be found in areas of at least sporadic permafrost and only 66.4% would be located in discontinuous permafrost areas. For all lakes, the percentages would assume 66.5% and 52.3%, respectively.

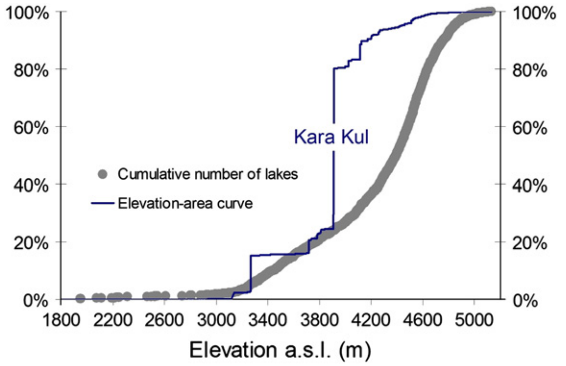


Fig. 6. Cumulative hypsographic curves of lake number and area.

4.2. Lake evolution 1968–2009

The minimum number and percentage of growing and shrinking lakes are summarized in Table 4, with the results yielded with the 90% confidence taken as reference and the results yielded with the 75% and 95% confidence values given in brackets. Fig. 8 illustrates the absolute and relative patterns of lake evolution.

A highly significant growth of glacial lakes in the observation period can be confirmed, whilst lakes of the other types do not display such clear signals and have obviously remained largely constant in size in average. The tendency of glacial lakes to grow is much more pronounced in relative than in absolute terms since the lakes are in average smaller than those of the other types (see Table 2). 40.8% of all glacial lakes in the study area are confirmed as growing during the observation period with a 90% confidence. In contrast, a shrinking trend can be confirmed for very few glacial lakes only (see Table 4).

Out of the 266 growing glacial lakes, 214 (80.5%) were smaller than 2500 m^2 in 1968 or did not exist at all. It has to be considered that lakes <2500 m^2 are not regarded in the 2009 dataset, resulting in the neglect of disappearing lakes. Even so, a clear trend of growth can be confirmed since the remaining number of 52 lakes clearly exceeds the number of 12 shrinking lakes.

Erosion lakes show moderate trends in both directions. Only 6.6% of the lakes of Type 1 are confirmed as growing, 4.6% as shrinking. Given the confidence of 90%, at least part of these changes may be interpreted as noise. Furthermore, short-term fluctuations of the lake level are most likely involved. Also the magnitude of growth of these lakes is much smaller than that of glacial lakes, both in absolute and in relative terms (see Fig. 8). The trends observed for lakes impounded by block or debris dams (Type 2; 5.7% growing, 2.9% shrinking with 90% confidence) are not considered significant due to the small number of lakes of this type in general.

A significant growth over both of the observation periods 1 and 2 (continuity) can be confirmed for very few lakes only (see Table 4 and Fig. 8b and f). Most of them are glacial lakes (12 out of 13). This initially surprising finding may be related to less significant trends being covered by the mapping uncertainty (the confidence interval is relatively broad) and to short-term fluctuations blurring the long-term trends. However, it also reflects the dynamics of high-mountain geosystems, where changes on various time scales are superimposed. Some glacial

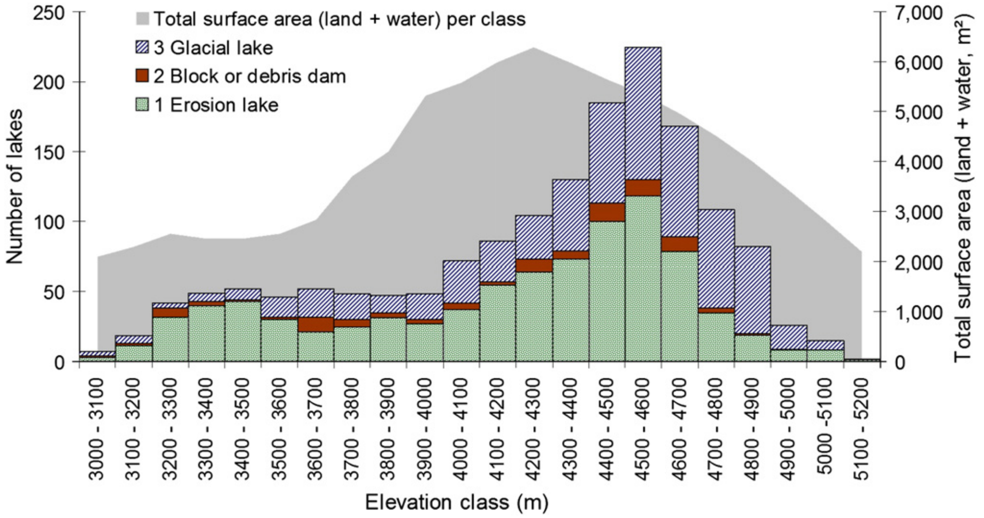


Fig. 7. Distribution of lakes of the various types according to the elevation — only those lakes above 3000 m a.s.l. are shown, the total surface area for each elevation class (land + water) is shown as reference.

lakes appear and grow within a short time window (sometimes less than one year), whilst others grow ± continuously over years and decades.

One of the most striking examples of a rapidly developing lake is located in the headwaters of the Dashtdara Valley (see Fig. 1; referred to as Lake Dasht). Lake Dasht developed probably in spring or early summer 2001 on the tongue of a debris-covered glacier. None of the older satellite images indicated the existence of a lake in that place. The lake only slightly increased in area until it drained suddenly on August 7, 2002 (Fig. 9). The resulting GLOF caused major damage and dozens of fatalities in the village of Dasht 11 km downstream (Mergili and Schneider, 2011; Mergili et al., 2012). Only a small pond remained in the former lake bed which did not fill up again. Since the drainage occurred beneath the glacier surface, the most likely interpretation of the observations is that a drainage channel within the glacier was suddenly blocked at the end of 2000 or in the beginning of 2001, allowing the development of the lake. With increasing lake size and therefore pressure, the blockage failed and the lake drained suddenly. Lake Dasht is not included in the analysis presented here as it did not exist in 2009. However, in general it is likely that very few lakes have disappeared during the observation period. The Dasht event was the only major GLOF recorded, and the disappearance of lakes due to sedimentation usually extends over longer periods.

One of the dominant lake evolution processes in the study area is the ± continuous growth of lakes in the forefield of retreating glaciers. Two unnamed lakes in the headwaters of the Andarabadjdara Valley (see Fig. 1; referred to as Lake Andarabadj) and the Varshedzdara Valley (see Fig. 1; referred to as Lake Varshedz) are among the largest glacial lakes of this type in the study area. Both drain to the Gunt Valley (see Fig. 1) and were much smaller in summer 1968 than in 2008 and 2007, respectively (Fig. 10). Table 5 quantifies the absolute and relative evolution of the size of the two lakes. Whilst there is no indication for a stabilization of the size of Lake Andarabadj, it seems that the growth rate of Lake Varshedz has reached its maximum earlier and slowed down considerably at least since the beginning of the 21st century. This is confirmed by helicopter surveys in 2009 and 2011, indicating a stable lake size comparable to that of 2007. The glacial lakes in the Rivakdara Valley (see Fig. 1), another tributary of the Gunt valley, show a similar behaviour as shown for Lake Varshedz.

Despite the low number of lakes with confirmed growth in both of the periods, the trends shown for Lake Varshedz and Lake Andarabadj reflect the situation in the study area: in average, glacial lakes have increased in size in both observation periods, a trend that is confirmed for 28.4% of them in Period 1 and for 13.2% in Period 2 (see Table 4). The more prominent trend in Period 1 can partly be explained by the longer duration. On the other hand it confirms the general deceleration of lake development in the south western Pamir – with many glacial lakes, including Lake Varshedz and the lakes in the upper Rivakdara mentioned above – during the first decade of the 21st century. Fig. 11 shows a comparison of growing non-glacial and glacial lakes for the two investigation periods. In Period 1, an increase in size is confirmed for 60 (22.0%) out of the 273 glacial lakes in the south western Pamir, whilst this number has decreased to 25 (9.2%) in Period 2. In the central and northern Pamir, 52 (34.0%) out of 153 glacial lakes are confirmed growing in Period 1, 45 (29.4%) in Period 2. Whilst the decrease of the rate of growing glacial lakes in the south western Pamir is in line with the trend observed for the entire study area, the minor negative trend in the central and northern Pamir is most likely a consequence of the

Table 3
Number and percentage of lakes located in areas with a potential for discontinuous and sporadic permafrost for various assumptions of increasing air temperature.

Lake type	*n*	+0 °C	+1 °C	+2 °C	+3 °C	+4 °C
Discontinuous permafrost						
1 Erosion lake	885	660 (74.6%)	604 (68.2%)	541 (61.1%)	476 (53.8%)	382 (43.2%)
2 Block or debris dam	105	77 (73.3%)	67 (63.8%)	60 (57.1%)	52 (49.5%)	43 (41.0%)
3 Glacial lake	652	601 (92.2%)	575 (88.2%)	538 (82.5%)	494 (75.8%)	433 (66.4%)
Total	1642	1338 (81.5%)	1246 (75.9%)	1139 (69.4%)	1022 (62.2%)	858 (52.3%)
Sporadic permafrost						
1 Erosion lake	885	779 (88.0%)	730 (82.5%)	641 (72.4%)	571 (64.5%)	514 (58.1%)
2 Block or debris dam	105	86 (81.9%)	81 (77.1%)	72 (68.6%)	66 (62.9%)	58 (55.2%)
3 Glacial lake	652	623 (95.6%)	612 (93.9%)	595 (91.3%)	557 (85.4%)	520 (79.8%)
Total	1642	1488 (90.6%)	1423 (86.7%)	1308 (79.7%)	1194 (72.7%)	1092 (66.5%)

Table 4
Confirmed (90% confidence) number of growing and shrinking lakes in absolute terms and as percentage of the total number of lakes of each type — the numbers in brackets represent the results yielded with 95% and 75% confidence (see text for details).

Lake type	Growing lakes	Percentage of growing lakes	Shrinking lakes	Percentage of shrinking lakes
Entire period				
1 Erosion lake	58 (55–64)	6.6 (6.2–7.2%)	41 (22–54)	4.6 (2.5–6.1%)
2 Block/debris dam	6 (5–6)	5.7 (4.8–5.7%)	3 (3–5)	2.9 (2.9–4.8%)
3 Glacial lake	266 (251–278)	40.8 (38.5–42.6%)	12 (6–16)	1.8 (0.9–2.5%)
Total	330 (311–348)	20.1 (18.9–21.2%)	56 (31–75)	3.4 (1.9–4.6%)
Entire period (continuity)				
1 Erosion lake	1 (1–2)	0.1 (0.1–0.2%)	0 (0–0)	0.0 (0.0–0.0%)
2 Block/debris dam	0 (0–0)	0.0 (0.0–0.0%)	0 (0–0)	0.0 (0.0–0.0%)
3 Glacial lake	12 (7–16)	1.8 (1.1–2.5%)	1 (0–1)	0.2 (0.0–0.2%)
Total	13 (8–18)	0.8 (0.5–1.1%)	1 (0–1)	0.1 (0.0–0.1%)
Period 1				
1 Erosion lake	46 (42–50)	5.2 (4.7–5.6%)	58 (39–79)	6.6 (4.4–8.9%)
2 Block/debris dam	6 (5–7)	5.7 (4.8–6.7%)	6 (0–6)	5.7 (0.0–5.7%)
3 Glacial lake	185 (178–188)	28.4 (27.3–28.8%)	34 (26–41)	5.2 (4–6.3.0%)
Total	237 (225–245)	14.4 (13.7–14.9%)	98 (65–126)	6.0 (4–7.7.0%)
Period 2				
1 Erosion lake	23 (19–27)	2.6 (2.1–3.1%)	4 (3–5)	0.5 (0.3–0.6%)
2 Block/debris dam	2 (0–3)	1.9 (0.0–2.9%)	0 (0–0)	0.0 (0.0–0.0%)
3 Glacial lake	86 (78–91)	13.2 (12.0–14.0%)	12 (9–13)	1.8 (1.4–2.0%)
Total	111 (97–121)	6.8 (5.9–7.4%)	16 (12–18)	1.0 (0.7–1.1%)

shorter observation period only. The higher ratio of growing glacial lakes in the central and northern Pamir in general reflects the more dynamic high-mountain environment there. 47.1% of all lakes observed in 2009 did not exist in 1968 (south western Pamir: 10.3%).

Since the peaks in the central and northern Pamir are in general higher than those in the south western Pamir, the northward shift of glacial lake growth is reflected in – or is a consequence of – the elevation patterns. Among those glacial lakes with a vertical extent of their catchment >200 m, lakes growing in Period 2 are in average found at a lower elevation (4225 m a.s.l.) than those growing during Period 1 (4470 m a.s.l.). In contrast, the catchments of the lakes growing in Period 2 peak higher up (average maximum elevation for Period 1: 5196 m; for Period 2: 5433 m). With more elevated accumulation areas of the glaciers and therefore larger ice reservoirs, the termini of the tongues – and consequently also most of the glacial lakes – are found at a lower elevation, compared to those glaciers with a more limited accumulation area.

The number of growing lakes of the remaining types is too small to allow for the derivation of robust spatial trends. In contrast to the glacial lakes, several erosion lakes were slightly shrinking in Period 1, a trend that was not observed in Period 2 (see Table 4 and Fig. 8). This phenomenon is interesting insofar as it counters the trend of the glacial lakes, displaying a more pronounced growth in Period 1 than in Period 2. It is most likely a consequence of intra- or short-term inter-annual variations of the lake level as well as of the neglect of lakes <2500 m^2 in the 2009 dataset.

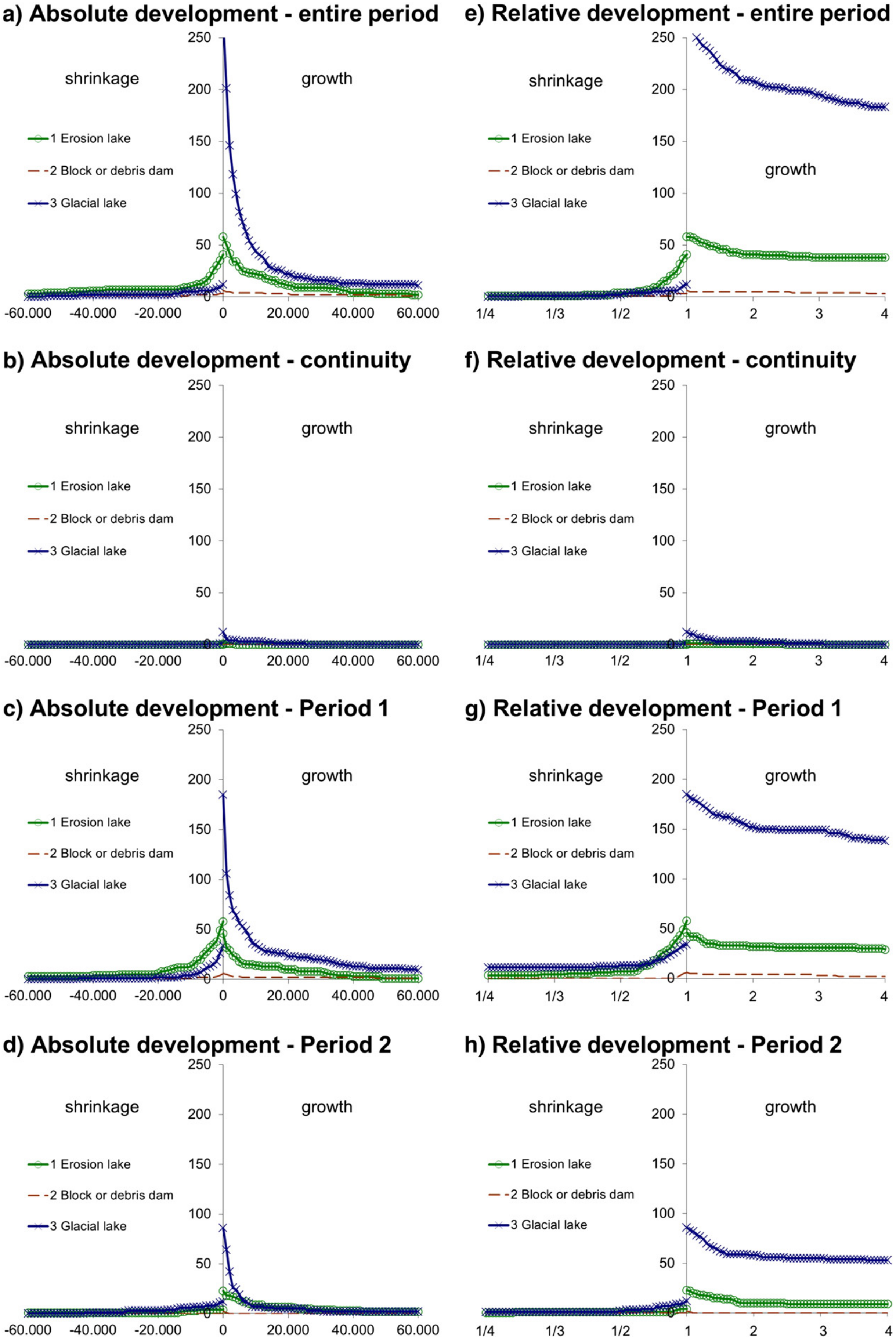
5. Discussion

The study illustrates the existence and characteristics of high-mountain lakes in the headwaters of the Amu Darya River, Central Asia. The evolution of each lake in the period 1968 – 2009 is quantified. Despite the uncertainties connected to the multi-temporal mapping from medium-resolution satellite imagery and to short-term fluctuations of the lake level, it can be confirmed that glacial lakes are the most dynamic type, with a strong trend of growth. Even though the existence of a relationship between glacier retreat and the formation or growth of glacial lakes seems obvious (see Fig. 10), the quantification of this relationship is hampered by the complexity of the issue as well as by the relative scarcity of detailed information on the recent glacier development in the study area. Numerous measurements were discontinued in the early 1990 as a consequence of the political and economic transformations in Central Asia (IAHS/UNEP/UNESCO, 1998). Compared to the Tien Shan (e.g., Khromova et al., 2003; Aizen et al., 2006; Surazakov and Aizen, 2006; Aizen et al., 2007b), less detailed recent data are available for the Pamir. Haritashya et al. (2009) analysed the development of 30 glacier tongues in the Wakhan Pamir (Afghanistan) in the period 1976 – 2003, 28 of which were retreating (maximum rate: 36 m per year). They highlighted the relationship of this retreat to the formation of a number of glacial lakes. Khromova et al. (2006), for the eastern Pamir, found a decrease of the glacier area by 11.6% (corresponding to 1.05% per year) for the period 1990–2001, compared to a 7.8% decrease (0.65% per year) for the period 1978–1990. Mergili et al. (2012) investigated a set of 118 glaciers in the south western Pamir which, in the period 2002–2007, decreased in area by 1.15% per year in average (1969–2002: 0.48%). The quantification of the retreat of debris-covered glaciers requires detailed investigations at the local scale. Furthermore, the evolution of lakes as documented in Fig. 8 and Table 4 and shown in Fig. 10 is not only related to changes of glacier length or area, but also to the subsidence of the glacier surface and the specific topographic conditions. Clusters of glacial lakes can only develop on comparatively flat terrain at the elevation of the retreating glacier tongues. An extremely simple but efficient way of a first-order assessment is to define all areas with a low surface slope. Frey et al. (2010) used an upper threshold of 5°, a threshold of 10° is applied here. Such conditions were given over large areas of the south western Pamir during the observation period. The deceleration of lake development observed there during the last decade may be connected to changing patterns of glacier dynamics, but also to the retreat of the glacier tongues over steeper terrain. More detailed research on the conditioning of the basal topography beneath the glaciers will be required in order to predict the future trends for the various parts of the study area (e.g., Linsbauer et al., 2012; Paul and Linsbauer, 2012).

The moving centre of the growth of glacial lakes from the south western Pamir to the central and northern Pamir may reflect the trends of glacier dynamics. It is hypothesized that the process of glacier retreat has started later there than in the south western Pamir. Mergili et al. (2012) have found indicators for such a trend, but more definitive up-to-date information is still needed. The climate in the high-elevation areas of the central and northern Pamir is comparably humid, possibly leading to more favourable accumulation patterns than in other parts of the study area and consequently to a delayed response to the increase in atmospheric temperature. Given the uncertainties and the comparatively short duration of Period 2, the significance of the derived trends has to be re-evaluated in one or two decades.

The hazard connected to the formation and existence of lakes strongly depends on the dam type. The dams of glacial lakes (Type 3) commonly contain ice (glacier, ice-cored moraine, rock glacier) and melting of this ice may drastically change the static equilibrium of the dam. Even though many glacial lakes are located on or in front of retreating glacier tongues and display a ± continuous growth, also those lakes quickly appearing or disappearing are highly relevant from a hazard perspective (2002 Dasht event). There is a potential for

Fig. 8. Lake evolution for the entire investigation period as well as for the periods 1 and 2 a–d in absolute terms (x axis: m^2 growth or shrinkage; y axis: number of lakes beyond the x value) and e–f in relative terms (x axis: factor of growth or shrinkage), b and f (continuity) include all lakes displaying the same tendency (either growth or shrinkage) in both periods.


a) Absolute development - entire period
e) Relative development - entire period
b) Absolute development - continuity
f) Relative development - continuity
c) Absolute development - Period 1
g) Relative development - Period 1
d) Absolute development - Period 2
h) Relative development - Period 2
shrinkage
growth
1 Erosion lake
2 Block or debris dam
3 Glacial lake
0
50
100
150
200
250
-60.000
-40.000
-20.000
0
20.000
40.000
60.000
1/4
1/3
1/2
1
2
3
4

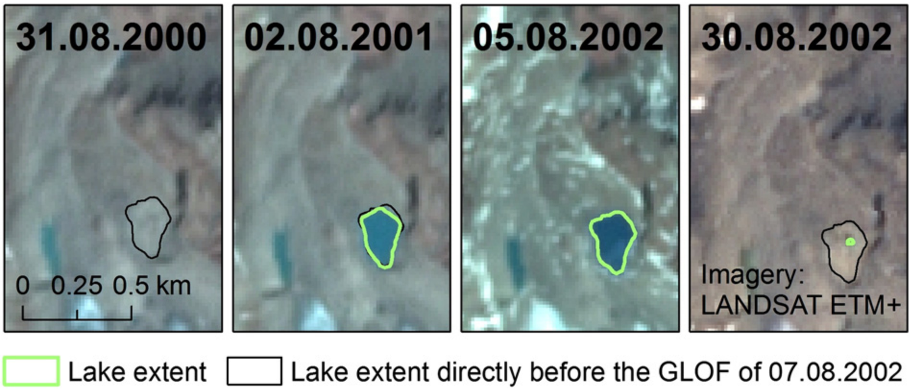


Fig. 9. Temporal development and sudden drainage of Lake Dasht.

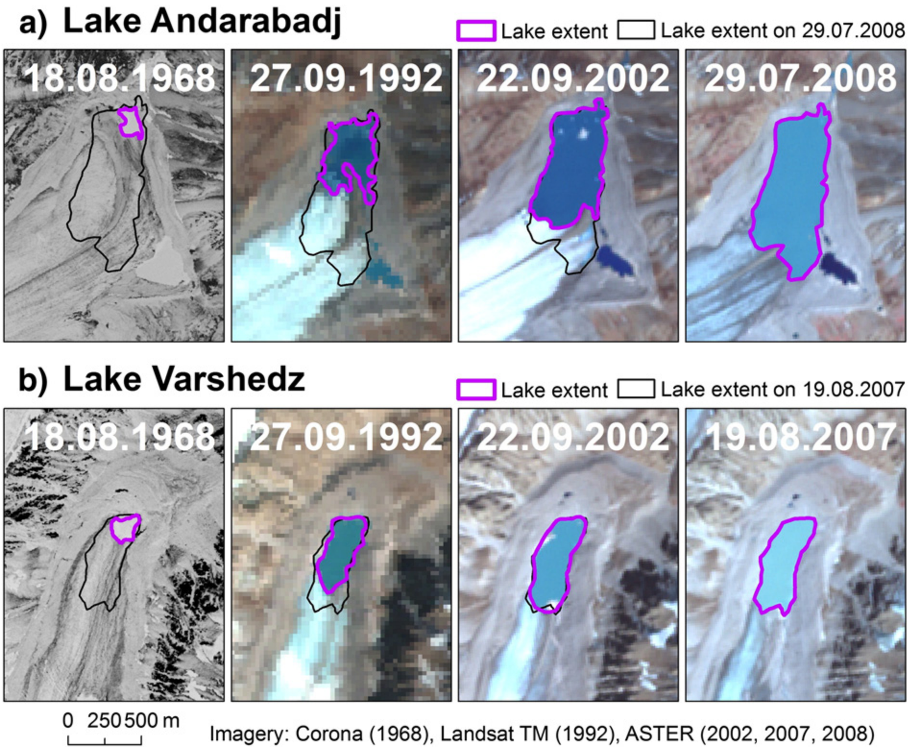


Fig. 10. a Lake Andarabadj and b Lake Varshedz — both lakes have shown a continuous increase in surface since 1968.

the formation of such lakes due to the presence of numerous surging glaciers which may temporarily block valley outlets (Kotlyakov et al., 2008). Landslide-dammed lakes of Type 2, in contrast to glacial lakes, are commonly short-lived and often drain within a few days or weeks after their formation (Costa and Schuster, 1988). However, they may also remain constant in size for decades and centuries. The findings presented shall be used as input for analysing the susceptibility of mountain communities and infrastructures to lake outburst floods in the study area, based on the work of Mergili and Schneider (2011) and Mergili et al. (2011). The regional-scale analysis scheme developed and applied to the south western Pamir by Mergili and Schneider (2011) shall be further improved and extended, and applied to the entire headwater region of the Amu Darya River.

Table 5
Development of the surface areas of Lake Andarabadj and Lake Varshedz in absolute and relative terms, the percentages relate to the lake area in 2008 (Lake Andarabadj) and 2007 (Lake Varshedz), respectively.

	1968	1992	2002	2007/2008
Lake Andarabadj	20,636 m^2	136,492 m^2	296,477 m^2	407,872 m^2
	5.1%	33.5%	72.7%	100.0%
Lake Varshedz	23,327 m^2	98,869 m^2	147,048 m^2	152,413 m^2
	15.3%	64.9%	96.5%	100.0%

6. Conclusions

A multi-temporal lake inventory was prepared for the study area. Altogether, 1642 lakes >2500 m^2 were detected from remotely sensed data. A clear growing trend was observed among the 652 glacial lakes, which does not apply to lakes of other types (erosion lakes and such lakes retained by block or debris dams). The long-term lake development is most likely blurred by intra- and short term inter-annual variations of the lake area. Glacial lake growth is related to glacier retreat or decay in rather flat areas. A shift of glacial lake growth towards more elevated catchments is observed. However, more data and a longer observation period will be required to confirm this trend. The lake inventory

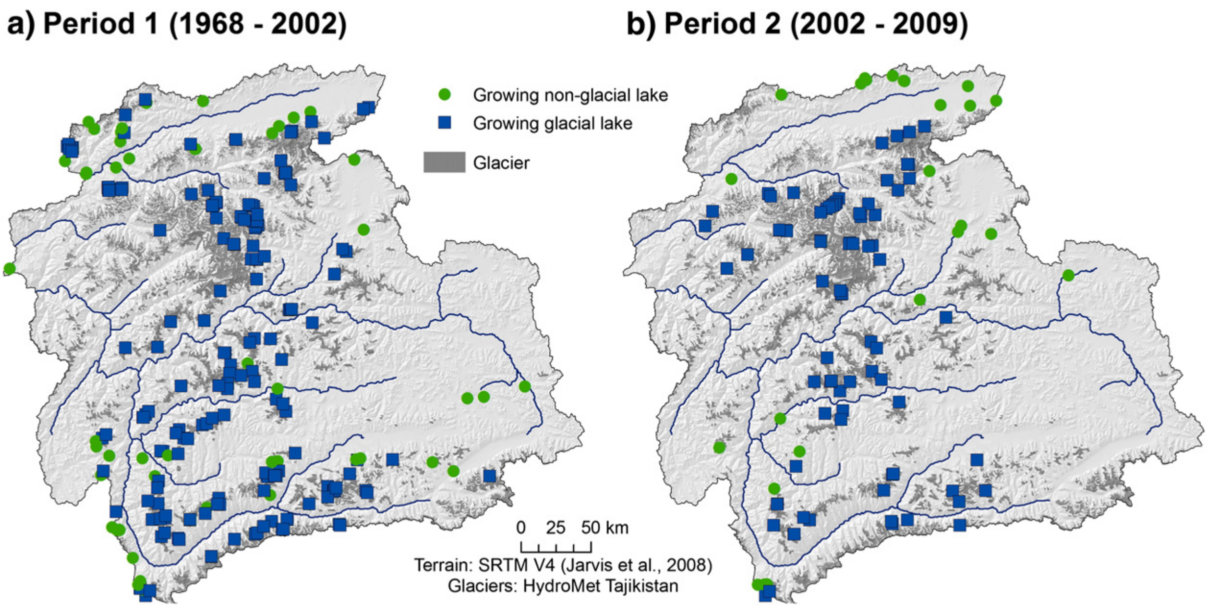


Fig. 11. Location of non-glacial lakes (Types 1 and 2) and glacial lakes (Type 3) growing a in Period 1 and b in Period 2.

will be an essential input for analysing the hazards related to possible lake outburst floods. More data on the glacier development are needed to better analyse the relationship between glacier retreat and lake evolution.

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