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Index for hazard of Glacier Lake Outburst flood of Lake Merzbacher by satellite-based monitoring of lake area and ice cover

Zunyi Xie, Donghui ShangGuan *, Shiqiang Zhang, Yongjian Ding, Shiyin Liu

State Key Laboratory of Cryospheric Science, Cold & Arid Regions Environmental & Engineering Research Institute, Chinese Academy of Sciences, Gansu 730000, PR China

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ABSTRACT

Previous studies show that the area of a moraine-dammed lake can provide a good indicator of the significance of its outburst. For a glacier-dammed lake however, because its area and depth fluctuates with the melting of its ice dam, it is difficult to predict the outburst of the glacier-dammed lake by using its area alone. A characteristic of the surface of Lake Merzbacher is a large amount of floating ice therefore, a method is proposed in this article to extract the area of floating ice on the lake and the area of ice free water in the lake by using Environment and Disaster Monitoring Small Satellite images respectively. Furthermore, based on the area of floating ice extracted through the image information of Lake Merzbacher in 2009 and 2010, we determined the relationship between the ice area and the outburst of the lake, then formulated the Index for hazard of Glacier Lake Outburst Flood (IGLOF) of Lake Merzbacher, which cannot only predict the flood outburst, but also determine the specific outburst period after the lake drainage had occurred. This can be shown in a recalculation of the lake drainages in the years 2009 and 2010. Research results indicate that when IGLOF is less than 0.5 and the lake area is larger than 3 km^2, the outburst process is in early-warning period and GLOF will occur in the next 5–8 days. Also, the successful outburst prediction of Lake Merzbacher in 2011 showed that the index described in this paper provides a quick methodology for forecasting and warning against Lake Merzbacher outburst floods. However as our research was based on a short observation period (2009-2011) and also cannot be supplemented by other images, it will still be needed to be checked and validated by continuous observation and improvement in future.

1. Introduction

It has been widely recognised that global climate change is causing the shrinkage or retreat of glaciers throughout the world (Cheng, 1996; Allison et al., 2001; IPCC, 2007). This has resulted in the number of glacier lakes decreasing while the area of glacier lakes is increasing (Wang et al., 2008). Glacier Lake Outburst Floods (GLOFs) are increasingly threatening the environment and the well-being of humans downstream, and this has drawn great attention from scientists(Huggel et al., 2002; McKillop and Clague, 2007; Dussaillant et al., 2009; Ives et al., 2010). The Merzbacher Glacial Lake in the source region of the Aksu River is the largest glacial lake in the Sary Jaz-Kumarik River Basin, and it suddenly outbursts nearly every year. During the period of 1932–2010, Lake Merzbacher glacial flash floods occurred 64 times of the 69 recorded years, amounting to more than 92.5% in frequency (Shen et al., 2009). With climate warming, glaciers provide more melt water into Lake Merzbacher thus increasing the volume of the lake, and also the ice dam of the lake became thinner and lower due to down wasting caused by regional warming. All of these changes tend to make Lake Merzbacher's outbursts tend to occur earlier and more frequently (Ng et al., 2007; Glazirin, 2010). This trend will increase the pressure of the need for greater flood control in the lower reaches of the Aksu River (Bohumir et al., 2009), therefore, intensive studies and administration on Lake Merzbacher are urgently needed.

Lake Merzbacher was discovered by Gottfried Merzbacher in 1903 during his expedition to Khan Tengri Peak and named by Progrebetskij in 1931 (Merzbacher, 1905; Pogrebetskij, 1935). In the 1930s, the outbursts of Lake Merzbacher began to be recorded by mountaineers (Demchenko, 1934; Zhavzharov, 1935). Some scientists evaluated the height of Pobeda Peak and the topographical maps of the Inylchek region were significantly improved in 1943 (Avsyuk, 1950; Ratsek, 1954). Then, in 1955, the first simple glaciological measurements were made near Lake Merzbacher. Ajrapet'yants and Bakov (1971a) tried to explain the outburst process of the lake in 1971 and Glazirin and Sokolov (1976) simulated the flood hydrograph of the lake by 1976. In the 1980s, Kuzmichenok (1984) mapped the lake bottom using aerial photographs after the drainage of the lake, Sokolov and Leonova (1981) and Konovalov (1990) attempted to predict the timing of the lake outbursts. Macheret et al. (1993) measured the depth of the lake at various points in the 1990s. After 2000, scientists started to research the lake by using the method of global positioning system (GPS) and remote sensing (RS). Helm et al.(2006) monitored the

* Corresponding author. Tel.: +86 13919104740.
E-mail addresses: dhguan@lzb.ac.cn, xiezunyigo2008@163.com (D. ShangGuan).

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2005 dam failure event of the Merzbacher Glacier Lake with reflected GPS signals. Furthermore, Liu et al. (1998) and Ng et al. (2007) analysed the relationship between Jokulhlaup characteristics of the lake and climate change in order to consider long-term change of the lake's flood behaviour. Huggel et al. (2002) assessed the hazards from glacier lake's outbursts based on the method of remote sensing. The remoteness and difficulty of access to the Lake Merzbacher region and scant suitable RS data available having the necessary repetition rates for Lake Merzbacher were among the reasons that previous research on the lake was mostly based on hydrological mechanisms (Ryzhov, 1959; Bakov and Dianmin, 1995; Liu et al., 1998) or long-term change of the lake (Mavlyudov, 1995; Shen et al., 2009; Glazirin, 2010). Until now, no-one really researched Lake Merzbacher glacial flash floods by dynamic monitoring or determined the early-warning index of the lake outburst based on remote sensing data. In fact, the dates of the outbursts of the lake were acquired by field observations every year. With the development of high temporal resolution disaster monitoring satellites, it is essential to utilise the remote sensing data to monitor and predict the outburst of the lake dynamically (Mool, 1998; Cenderelli and Wohl, 2001; Mergili et al., 2011).

In this paper, we utilised the images of Environment and Disaster Monitoring Small Satellite (HJ1-A, B) satellites with spatial resolution (30 m) and high temporal resolution (2d) to establish a high precision area automatic extraction procedure of Lake Merzbacher based on the characteristics of the floating ice covering the lake. As we found by analysing much previous RS data that the ice covering on Lake Merzbacher has a close relationship with the outburst of the lake. Through the area of floating ice information extracted from the images of Lake Merzbacher in 2009 and 2010, combining with the characteristics and regularity of the lake outburst, the formula of the Index for hazard of Glacier Lake Outburst of Lake Merzbacher (IGLOF) was proposed, and with this we mapped the outburst index graph. Research results showed that the IGLOF divided the whole outburst process of Lake Merzbacher into four periods: icefall, quick water storage, early-warning and post-drainage. When the IGLOF is less than 0.5 and the lake area is larger than 3 km^2, the lake is in its early-warning period and will outburst soon. In addition, according to the index map of the lake, we can forecast the outburst time of the lake when its drainage had occurred. However it is necessary to mention that until now either by the method of RS or field work, the exact date of Lake Merzbacher outbursts could not be narrowed to a single day but only expressed as a period (two or three days normally). The actual outburst period is monitored through field work by recording the maximum peak discharge at the downstream hydrological station. In recent years, the outburst times of Lake Merzbacher were mainly acquired by two institutes: CAIAG Central Asian Institute for Applied Geosciences and GFZ German Research Centre for Geosciences in Potsdam.

2. Study area

Lake Merzbacher (79°52′E, 42°13′N) is a large alpine glacier lake, which is located between the northern branch of the Inylchek Glacier (called Northern Inylchek Glacier) and the southern branch of the Inylchek Glacier (called Southern Inylchek Glacier) in the very heart of the Central Tien Shan mountain range, close to Khan Tengri (6995 m) and Pobeda Peak (7439 m) in Kyrgyzstan and Chinese border (Fig. 1). Southern Inylchek Glacier is the longest and largest glacier in central Tien Shan mountain region, with 63.5 km in length and 567.2 km^2 in area, followed by Northern Inylchek Glacier, with length and area at 41.1 km and 247.2 km^2 respectively. There are currently two lakes in the Northern Inylchek Valley, at an altitude of 3300 m and 3400 m above sea level. These two lakes are known as Lower Lake Merzbacher and Upper Lake Merzbacher. Lower Lake Merzbacher is dammed by the Southern Inylchek Glacier and has had regular outbursts since the beginning of the 20th century. There is a distance of 3–5 km between Lower Lake and Upper Lake, connected by the Merzbacher River. A large amount of floating ice covers the surface of the lower lake during its storage period. Research of the lake shows that the floating ice is produced by the ice split from the ice dam and marginal glaciers of the lake due to the constant collision brought by intense movement of lake water. Furthermore, the existence and movement of the floating ice may accelerate the outburst of the lake. After the drainage of the lake, there will be much a considerable amount of ice left in front of the ice dam (Fig. 2).

3. Data sources and methods

3.1. Data sources

Chinese Environment and Disaster Monitoring Small Satellites (HJ1-A, B double satellites) were launched in 2008, on which there are two CCD optical cameras, with spatial resolution of 30 m and temporal resolution of 2 days. The image produced by the satellites consists of 4 bands that are similar with Bands 1, 2, 3, and 4 of TM image including blue, green, red and near infrared bands. As the satellites have the advantages of high temporal resolution, it is adaptable for the research of glacial flash floods. Therefore, in this paper, we chose HJ1 images to do research on the IGLOF of Lake Merzbacher.

Considering that outbursts of Lake Merzbacher intensively occurred between June and August during these years, we chose 21 HJ1 images in 2009 and 2010 ranged from June to August, all of which were in good quality and has few clouds. In addition, three Landsat ETM+ images were picked (two were acquired in July in 2002, and the other was acquired on 31st September 2001) in order to do the geometry correction and the precision validation of the area extraction experiment. All of the experimental data are listed in Table 1 below.

3.2. Methods

Pre-processing of the images included removing the noise and enhancing the features of Lake Merzbacher. First we performed a geometric correction of the remote sensing data. One ETM+ image, with a 15 m pixel size, was used as the Geo-reference data (acquired 31st September 2001, Track no: path-147, row-31). Then, the geometric correction was performed for all of the experimental data based on the Geo-reference data, and an accuracy of 1 pixel was reached in the pre-processing. In the next stage, we achieved the atmospheric correction of the data by the FLAASH tool of the software ENVI. Eventually, we eliminated the haze in some images according to the algorithm of Zhang et al. (Zhang et al., 2002; Hu et al., 2009).

Below are the methods and procedure of this experiment.

3.2.1. Spectrum characteristic analysis of image

After the pre-processing, we clipped the Lake Merzbacher region along the northern Inylchek in ENVI in order to remove the interference of other ground objects in the images such as glaciers, snow, clouds and so on. This would ensure the later extraction process of the lake area to be quicker and more accurate (McFeeters, 1996).

Through the analysis of the clipped images of Lake Merzbacher region, we found that the lake is composed of two parts: the part of the lake which is clear of ice (such as the Upper Lake and some parts of the Lower Lake) and the other part of the lake covered by floating ice (such as some parts of the Lower Lake). Based on the characteristic of the surface of Lake Merzbacher, in this paper, we used a method to extract the area of floating ice on the lake and the area of ice free water in the lake. Before extracting the area, we widened the differences of spectral brightness value between floating ice and other ground objects by the method of Hue–Saturation–Value (HSV) Colour Transform and Inverse Colour Transform (Zhang et al., 2001). Fig. 4

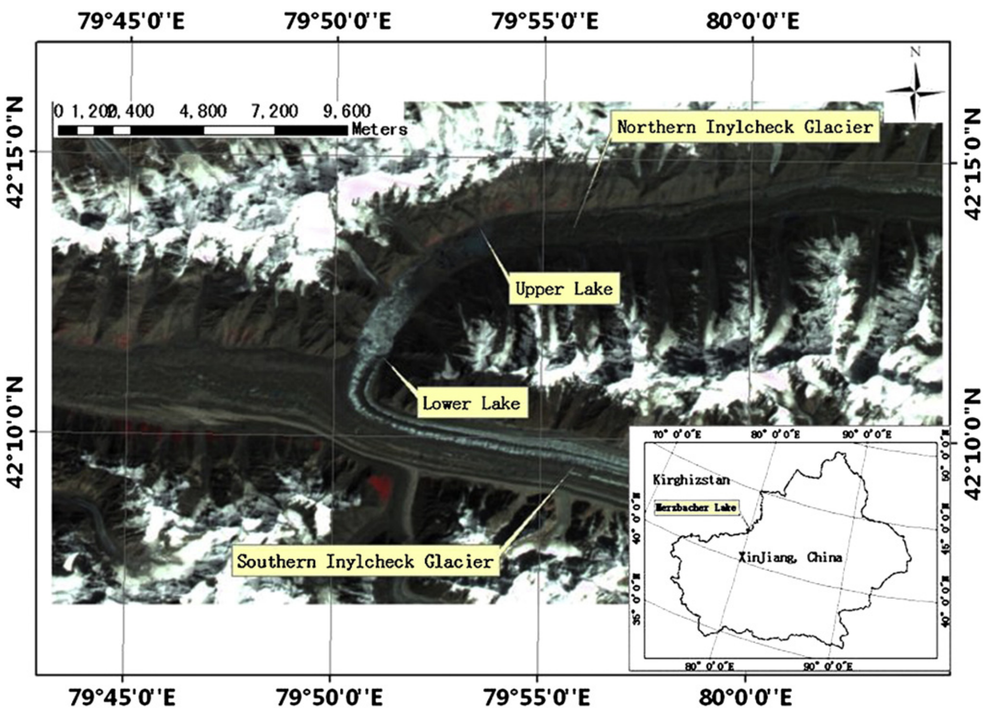

Fig. 1. The location of Lake Merzbacher.
(Source: 2009-08-07 HJ1B).

shows the comparison between the original image (acquired on 11th July 2009) and the enhanced image.

3.2.2. Area extraction

(1) Area extraction process of the lake which is clear of ice: This area was extracted by a Normalized Difference Water Index (NDWI) that was presented by Huggel et al. (2002). Specifically, it applied the idea of two spectral channels of the Environment and Disaster Satellite with maximum reflectance difference for the ice lake water; the blue channel (maximum reflectance of water) and the near-infrared (NIR) channel (minimum reflectance of water) were applied

$$NDWI = \frac{B_{NIR} - B_{Blue}}{B_{NIR} + B_{Blue}}$$

The NDWI can amplify the characteristics of Lake Merzbacher and inhibit the spectral information of other ground objects synchronously. Therefore, after several tests, we determined that when the NDWI value is between −0.35 and −0.55, the area of ice lake water can be extracted accurately in the NDWI images by applying threshold and mask technology.

(2) Area extraction process of the floating ice: based on the spectrum characteristic analysis of images mentioned above, after the method of HSV Colour Transform and Inverse Colour Transform was applied, we widened the differences of spectral brightness value between floating ice and other ground objects in images (if we did not do so some ground objects near the lake have similar spectrum information to that of floating ice, such as some glacial tills, it would have been difficult to exact the area of floating ice separately). Then, the near-infrared (NIR) channel and the red channel of the HSV image were chosen to do ratio (B_{NIR}/B_R). Through several tests, we found that when the ratio value is between 0.9 and 1.2, the area of floating ice can be extracted accurately from the ratio images by again utilising threshold and mask technology. All of the areas classified automatically by IDL programme and the area extraction graphs of Lake Merzbacher for the years 2009 and 2010 are shown by Fig. 5.

Fig. 2. Rudimental ice in front of the dam (shot by Dr. Shangguan in 25th August 2010).

3.3. Precision validation

In this paper, we utilised two Landsat7 ETM+ data as the references to detect the precise area of extraction (the two ETM+ data sets were acquired on 1st July 2002 and on 17th July 2002 respectively). The ETM+ data suffers from the SLC failure which occurred in 2003, though the stripe noise caused by SLC failure can be partly eliminated by some professional algorithm (for instance, previously we used the stripe noise elimination function from the website of the

Table 1
Remote sensing data used in experiments of 2009 and 2010.

Data of 2009	Sensors	Data of 2010	Sensor
2009-07-01	HJ1A-CCD2	2010-06-01	HJ1A-CCD2
2009-07-06	HJ1A-CCD1	2010-06-07	HJ1B-CCD2
2009-07-11	HJ1B-CCD2	2010-06-23	HJ1B-CCD1
2009-07-15	HJ1B-CCD2	2010-06-28	HJ1A-CCD2
2009-07-21	HJ1A-CCD1	2010-07-01	HJ1B-CCD1
2009-07-26	HJ1B-CCD2	2010-07-05	HJ1B-CCD1
2009-07-30	HJ1B-CCD2	2010-07-08	HJ1B-CCD2
2009-08-01	HJ1A-CCD2	2010-07-15	HJ1A-CCD1
2009-08-03	HJ1B-CCD2	2010-07-16	HJ1B-CCD2
2009-08-07	HJ1B-CCD2	2010-07-18	HJ1A-CCD2
2009-08-17	HJ1A-CCD2	2001-09-31	Landsat ETM+
2002-07-01	Landsat ETM+	2002-07-17	Landsat ETM+

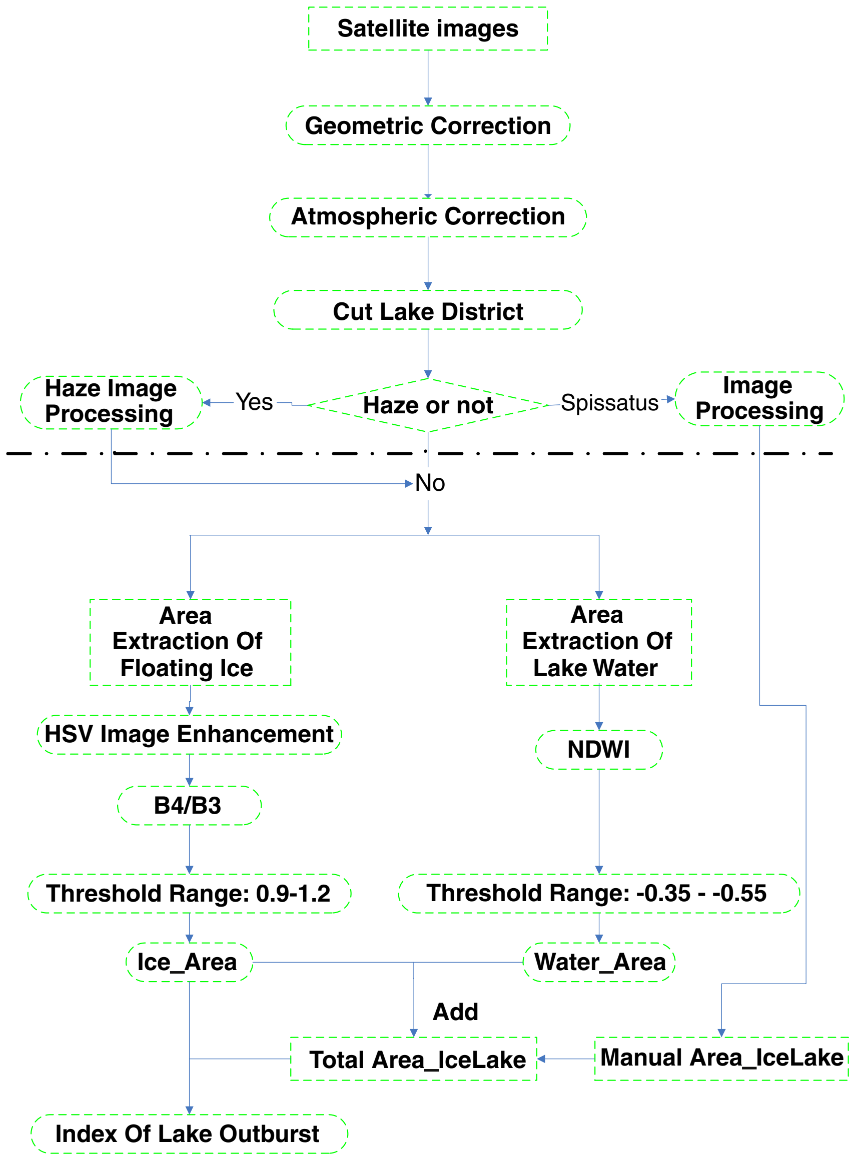

Fig. 3. Technology process for area extraction and outburst index of Lake Merzbacher.

International Scientific Data Service Platform to process the ETM+ data that were acquired after 2003), in order to improve the accuracy of our experiment, we decided to check the area extraction precision based on the 2002 ETM+ data, which have not been effected by the SLC failure. In calculating our experiment, we first integrated the green, red and near infrared bands of the ETM+ into multispectral image by image fusion (its spatial resolution is 30 m and has similar bands to the HJ1-A and B data, so it can be substituted). We next extracted the areas of floating ice and lake by the method proposed in this paper based on the multispectral image. Then we integrated the multispectral image and ETM+ panchromatic band into a higher spatial resolution image (15 m). This higher spatial resolution image can be the reference to detect the precision of the area of extraction. After accurate manual area extraction from the reference data was done, in comparison with the area calculated by our area extraction method based on multispectral image, we found that in the image of 2002-07-01, the total area of the lake we extracted from the multispectral image equalled 2.4 km^2. The floating ice extraction error was 0.1 km^2 while the water extraction error was 0.08 km^2, so the precision of floating ice area extraction is 90.5% and the precision of total area extraction is 93.0%. In the image of 2002-07-17, the total area of the lake we extracted was 2.65 km^2. The extraction error of floating ice and water were 0.17 km^2 and 0.06 km^2, so the precision of floating ice area extraction and total area extraction were 89.7% and 92.0% respectively (Table 2).

In conclusion, the errors in the area extraction of the lake mainly occurred in the parts that were incorrectly recorded. The reason for this is due to the fact that the ice floating at the junction between floating ice and water is immersed in water, which made the spectrum brightness of this floating ice different from both the floating ice wholly above water and water itself. However, the precision of the total area extraction and the floating ice area extraction was improved to more than 98% by later manual revision.

4. Results and discussion

4.1. Area changes of Lake Merzbacher

As can be seen from the figures of floating ice-water–total lake area for 2009 and 2010 (Fig. 6), the two lines' developments of floating ice area and total lake area saw the similar trends before and after the glacial lake breached. On the 1st of July of 2009, the

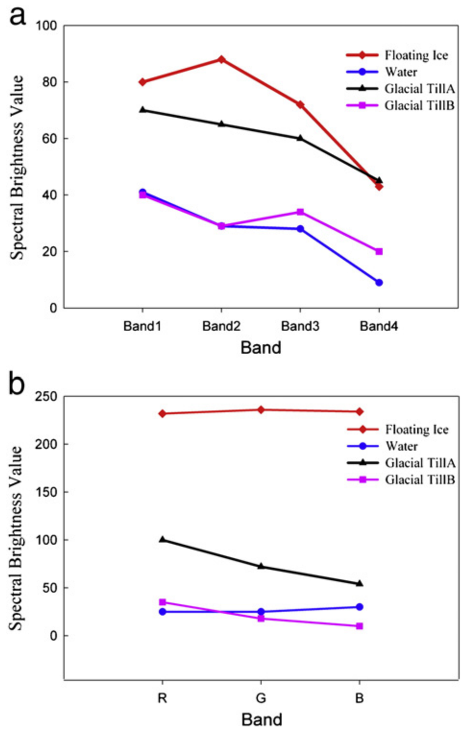

Fig. 4. The average pixel value of four kinds of ground objects before and after HSV enhancement.

area of floating ice stood at 0.97 km^2 and the area of total lake was 2.42 km^2. Then, both of the areas increased steadily until the 30th of July when the area of total lake reached its greatest area of 3.33 km^2, plunging dramatically after that time. The area of floating ice peaked at 1.89 km^2 after two days of the peak value of total lake area (1st of August) and it plummeted to 1.65 km^2 on the 3rd of August. Overall, the change processes of floating ice area and total area in 2009 can be summarised thus: since there was water injected into the lake, the areas of the floating ice and the total lake increased, then the area of the total lake would firstly reach the peak and plunge, subsequently, the floating ice area would reach its maximal area soon after and then plunge.

Comparing Fig. 6(a) Fig. 6 (b), it can be seen that the regularity of the area changes of the floating area and the total lake in 2010 was similar to those in 2009. On the 1st of June 2010, the area of floating ice and total lake were 1.10 km^2 and 1.78 km^2 respectively, then, the area of the total lake increased to its peak area of 3.83 km^2 on the 15th of July, and the next day saw the largest area of floating ice being at 2.39 km^2. In summary, the figure of floating ice-water–total lake area in 2010 has once again verified the regularity of the area changes of the floating ice and total lake mentioned above.

The increase of the total lake area is due to the glacial meltwater from the Northern and Southern Inylchek Glaciers (mainly from the Northern Inylchek Glacier), while the growth in the area of floating ice is because of the ice which is split from the ice dam and marginal glaciers of the lake due to the constant collision brought by intense movement of lake water. In considering the combination of field observation of Lake Merzbacher and the analysis of area change information extracted from the remote sensing images of the lake, we found that the lake shows two main characteristics before and after its outburst. Firstly, the whole outburst process of Lake Merzbacher includes four periods: icefall, quick water storage, early-warning and post-drainage. In probably about a week before the outburst of the lake, as the lake filled with water, the floating ice moves more slowly, the increase of its area becomes slower. However, at this moment, the increase of the total lake area tends to increase more quickly due to the faster supply of melt water. Secondly, on the day of the lake begins to discharge water, the area of the total lake plunges immediately whereas the floating ice will experience a slightly growth in area before it plunges.

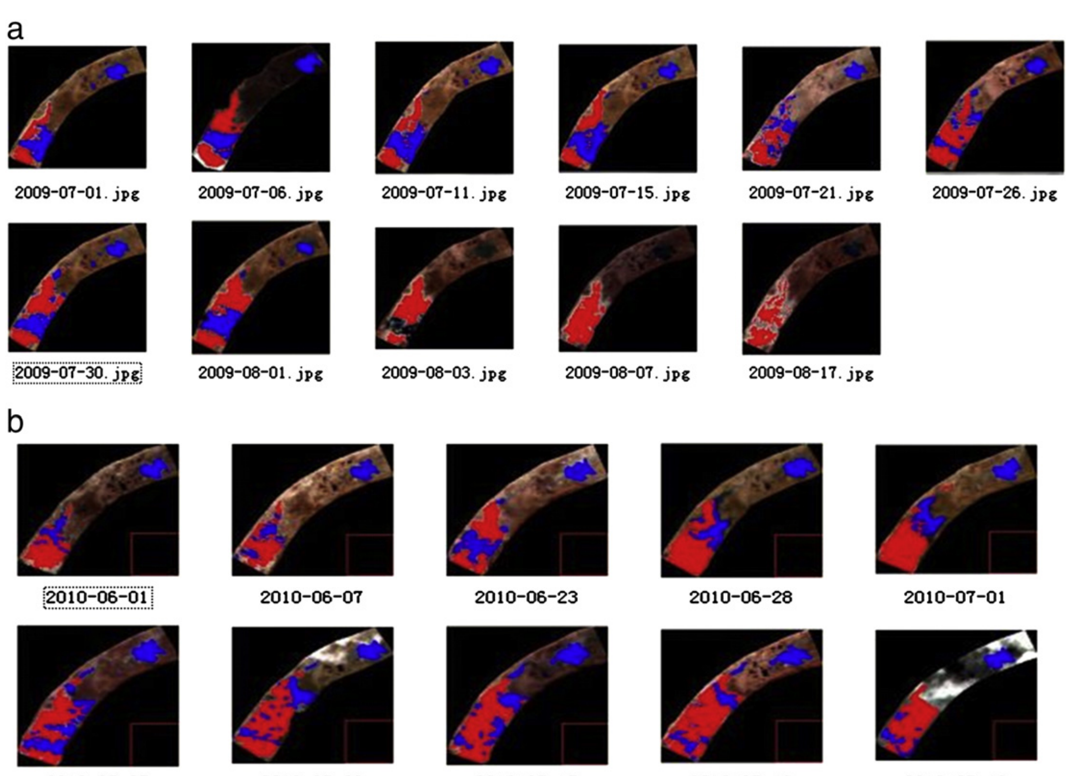

Fig. 5. Area extraction graphs of Lake Merzbacher for 2009 (a) and 2010 (b). (Red colour represents extracted floating ice, blue colour represents extracted water).

Table 2
Precision Percentages of the area extraction of Lake Merzbacher.

Date	Total area (/km^2)	Ice area (/km^2)	Water area (/km^2)	Ice precision (%)	Water precision (%)	Total precision (%)
01-07-2002 (30 m)	2.40	0.96	1.44	90.5%	94.5%	93.0%
01-07-2002 (15 m)	2.58	1.06	1.52			
17-07-2002 (30 m)	2.65	1.50	1.15	89.7%	95.1%	92.0%
17-07-2002 (15 m)	2.88	1.67	1.21			

4.2. Analysis of the index for outburst of Lake Merzbacher

Considering all things mentioned above in this paper, based on the characteristics of Lake Merzbacher, the regularity for area changes of the floating ice and total lake and their closely links with the outburst of the lake, an index named the "Index for hazard of Glacier Lake Outburst of Lake Merzbacher" is proposed. This index which is calculated by the ratio of the area change rates of floating ice and total lake, is aimed at alarming local residents downstream, and local authorities of the impending outburst of the lake and determining the approximate outburst time. The calculation formula of the index for hazard of outburst of Lake Merzbacher is below:

$$Index = \frac{X_{i+1} - X_i}{Y_{i+1} - Y_i} (X_i, X_{i+1} \textit{ are the day's and the next day's floating ice area}, Y_i, Y_{i+1} \textit{ are the day's and the next day's total lake area})$$

Fig. 7 shows the graphs of the outburst index in 2009 and 2010 which were acquired from the formula. In the graphs, the red line is the outburst flood index line, calculated by applying the formula of the outburst index. The green and blue lines are the areas of the change in the rates of floating ice and total lake, which were calculated by the formula: $(A_{i+1} - A_i)/A_i$ (A_i represents the day's floating ice area/total lake area, A_{i+1} represents the next day's floating ice area/total lake area). The multi-coloured line is the outburst early-warning line, which was determined by both experiments and experience. When the area of Lake Merzbacher reaches more than 3 km^2, the body of the lake is close to its holding capacity. At this moment the movement of the floating ice becomes much slower and also the supply of new floating ice is rare. As the outburst index is the ratio of the area of change of the rates of floating ice and total lake mass, it decreases over time. Through many tests and the experience of the researchers, we found that when the IGLOF is less than 0.5 and the lake area is larger than 3 km^2, Lake Merzbacher becomes very dangerous and will breach soon, therefore, we defined that 0.5 is the outburst critical value, which means that when the outburst index is smaller than 0.5, the lake has gone into the Early-warning period. The time for lake outburst determined by our method is in the period between two black vertical dashed lines.

4.3. Date determination of the outburst of Lake Merzbacher

The area of floating ice and total lake increases consistently before the outburst of Lake Merzbacher (Fig. 7), but on the day when there is water discharges from the lake, the area of the total lake decreases immediately whereas the floating ice will experience a slightly growth in area before it plunges. As a consequence, we can formulate a law reflected in the map of the outburst index that the value of the index is always being positive until the day when the lake starts to drain. Then the index will show an abnormal negative value, but will turn to positive again in the next one or two days, therefore, we determine the outburst time of Lake Merzbacher is in the period between the maximal negative value and the first positive value of the outburst index. According to the graph of outburst index in 2009 and 2010, we deduced that the outburst of the lake occurred between 29th July and 31st July in 2009, while that which occurred in 2010 was on the 15th of July or 16th of July. These assertions are proven by the field observations of 2009 and 2010 (through academic exchange with the specialists of Germany and Kyrgyzstan, the date of outburst monitored by field work fell in the period we speculated), which shows the feasibility of determining the outburst time of the lake by the outburst index graph of Lake Merzbacher.

4.4. Early-warning of outburst of Lake Merzbacher

The four periods of Lake Merzbacher are divided according to the graph of outburst index: icefall (light blue area), quick water storage (dark blue area), early-warning (red area) and post-drainage (yellow area). In the icefall period, water starts to be injected into the lake. Because of the intense movement of the lake water, a great deal of ice is split from the ice dam and marginal glaciers of the lake, which falls into the lake and also increases the area of floating ice. Some days later, the lake enters into the quick water storage period. During this period, the increase rate of the total lake area is quicker than that of the floating ice, which means the outburst index is going into decline. When the outburst index declines to below 0.5 (below the early-warning line) and the lake area is larger than 3 km^2, the lake goes into the early-warning period (it was for five days in 2009 and eight days in 2010). At this time, people in the area downstream

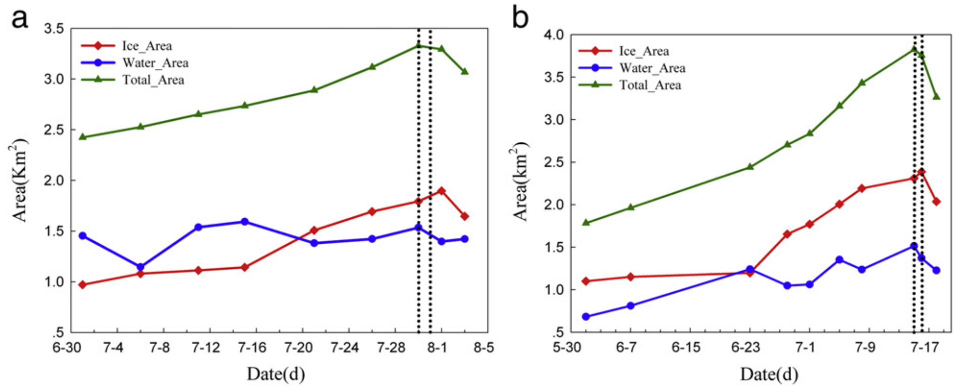

Fig. 6. Floating ice-water–total lake area for 2009 (a) and 2010 (b). (The time for lake outburst determined by our method is in the period between two black vertical dashed lines.)

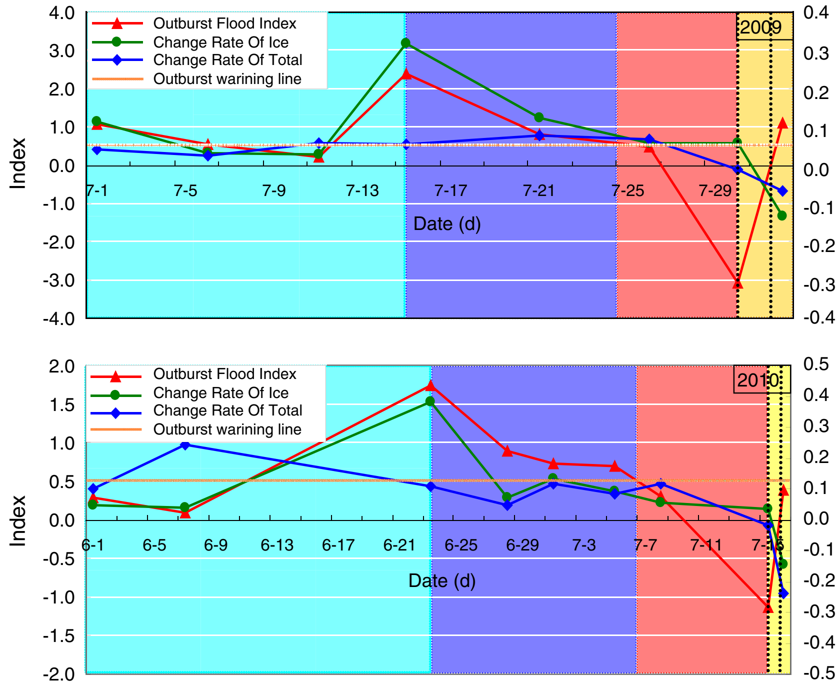

Fig. 7. Outburst index graph for hazard of Glacier Lake Outburst of Lake Merzbacher for 2009 and 2010.

of the lake should be warned as the lake is going to breach soon. This is because in the early-warning period, the lake is filled with water and the movement of water is very slow, therefore, the area change rate of floating ice tends to drop to 0, which is reflected in the graph of outburst index in that the outburst index tends to be 0 too. All of the above-mentioned points show the feasibility of predicting the outburst of Lake Merzbacher by the graph of outburst index. In addition, as the index is formulated by the ratio between the area change rates of floating ice and total lake, the features of the outburst of the lake are amplified, which makes the prediction and outburst date determination of the lake easier to calculate. The lake will take about one week to empty after the drainage (when there is no water in the lake, the IGLOF is constantly equal to 1), leaving icebergs to sink to the lake bottom and freeze to the ground during the winter. The whole outburst process of Lake Merzbacher will repeat nearly every year.

4.5. Validation

In order to verify the feasibility and validity of our experiments in the warning of the impending outburst of Lake Merzbacher, our research group monitored and issued a warning for the 2011 outburst event of Lake Merzbacher.

The data used in the 2011 experiment is in Table 3 and the methods and procedure for processing data is in Fig. 3, all of the extracted area information is in Table 4. The 2011 area extraction graph of Lake Merzbacher is also contained in Fig. 8 (as there is no floating ice on the surface of the upper Lake and when water flows into it, its area is always about 0.4 km^2. In order to extract the area information of lake more quickly, we skipped the area extraction of the upper lake in this experiment as this will not affect the results of warning).

Table 3
Remote Sensing data used in 2011.

Data of 2011	Sensors	Data of 2011	Sensor
2011-06-20	HJ1A-CCD1	2011-07-13	HJ1A-CCD2
2011-06-24	HJ1A-CCD1	2011-07-14	HJ1A-CCD1
2011-06-28	HJ1A-CCD1	2011-07-17	HJ1B-CCD1
2011-07-03	HJ1B-CCD2	2011-07-20	HJ1B-CCD1
2011-07-05	HJ1A-CCD2	2011-07-21	HJ1A-CCD2
2011-07-10	HJ1A-CCD1	2011-07-22	HJ1A-CCD1

During the experiment, we calculated the real-time outburst index of Lake Merzbacher by the outburst index formula based on the extracted area of floating ice and the total lake area and then drew and updated the 2011 outburst index graph over time in order to monitor the lake. Through the graph (Fig. 9), we could see clearly that on July 13, the area of the lake was 3.3 km^2 and the index was 0.4, which meant the lake had gone into the early-warning period (according to the definition of early-warning mentioned in previous paragraphs), therefore, according to the previous analysis and experience, the lake would breach in 5–8 days, which was July 18–July 21. Our research group sent early warnings to the flood control departments on the Aksu River which is located downstream from Lake Merzbacher.

Our research group continued to analyse the RS data of Lake Merzbacher and update the 2011 outburst index graph over the next 8 days. On July 22, we found from the index graph that the index reached the maximal negative value on July 17. According to the theory for how to define the outburst time of the lake in previous paragraphs (the outburst time of Lake Merzbacher is the period between the maximal negative value and the first positive value of the outburst index), we speculated the outburst time of Lake Merzbacher in 2011 fell within the period between July 17 and July 19. Shortly after, we got advice from Mr. Bolot Moldobekov, who is the Co-Director of CAIAG that his group monitored Lake Merzbacher over this time and that it breached during the July 18 and July 19 and was empty by July 21. In conclusion, the successful early-warning of GLOF in Lake Merzbacher in 2011 had verified the method proposed in the paper.

5. Conclusions

The release of Lake Merzbacher is a component of the annual hydrological cycle of the lake regime. Basically, the process can be described as follows: In the summer, melt water (predominantly from the Northern Inylchek Valley) fills up Lake Merzbacher. After filling, the lake bursts out. When the release of the lake water begins, the ice dam of the advancing Southern Inylchek Glacier buoys upwards.

Table 4
Area information of floating ice and total lake.

Date	6-20	6-24	6-28	7-3	7-5	7-10	7-13	7-14	7-17	7-20	7-21	7-22
Floating ice (km^2)	1.053	1.064	1.216	1.434	1.526	1.589	1.734	1.790	1.873	2.092	2.020	1.930
Water (km^2)	0.857	0.858	0.920	1.068	1.076	1.169	1.117	1.201	1.341	0.484	0.00	0.00
Lower lake area (km^2)	1.910	1.922	2.136	2.502	2.602	2.758	2.851	2.991	3.214	2.576	2.020	1.930

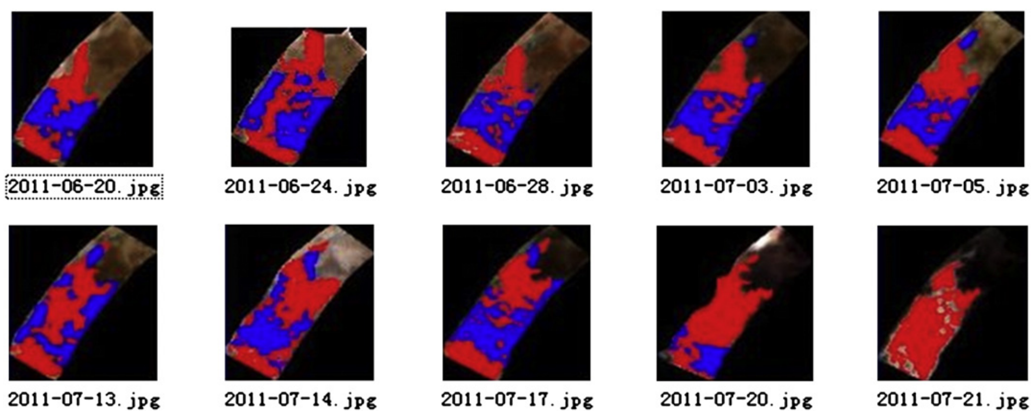

Fig. 8. Area extraction graph of Lake Merzbacher for 2011. (Red colour represents extracted floating ice, blue colour represents extracted water).

As a consequence, a system of englacial channels in the damming glacier opens and the lake water discharges through the main Inylchek Glacier westwards into the Inylchek Valley, and eventually leaves for the Aksu River in China, however, the flood water is not used in Kyrgyzstan (Glazirin, G.E., 2010).

According to the long-term record of outburst dates from Lake Merzbacher, figures reveal that outbursts have tended to occur earlier in the year since the 1930s, statistically shifting from October to August. There are two potential reasons for this fact: firstly, the gradual increase of summer air temperatures in high mountain regions results in an increase of ice and snow melt and thus accelerates the filling of Lake Merzbacher with water. Secondly, the Southern Inylchek Glacier became thinner due to down wasting caused by regional warming (Mool, P. K. et al., 2001; Felix Ng, 2007). The damming ice barrier of the still advancing part of the Southern Inylchek Glacier therefore melted faster and released the water of Lake Merzbacher earlier. As the extracted area of the lake in this paper shows, the maximum lake area in 2009 is 3.328 km^2 while that are 3.825 km^2 in 2010 and 3.614 km^2 in 2011. It indicates that the water storage of the lake has been increasing too. In addition, due to the increasing area of Lake Merbacher, its outburst occurred 15 days and 12 days earlier in 2010 and 2011 than in 2009.

This paper proposes the Index for hazard of Glacier Lake Outburst of Lake Merzbacher through arithmetic formula taking into account the area of floating ice and the total lake area. Results show that the index can predict the outburst process of the lake and determine the outburst period of the lake after its drainage had occurred. The whole experiment is achieved automatically by the IDL program, which ensures quick response in the event of an unexpected outburst of Lake Merzbacher. However, the automatic program is not so perfect due to the interferential factors such as snow or spissatus in images. Therefore, some work is still needed to be done in future to improve the whole experimental process in this paper so as to extract the area of Lake Merzbacher and to calculate the index automatically. As the time from the outburst of Lake Merzbacher to empty its body of water sometimes needs just 4–5 days, the research of glacial flash flood events of the lake requires high temporal resolution RS data. Therefore, many kinds of RS Data, such as Aster (the temporal resolution is 4–16 days), Spot(26 days), Landsat(16 days) and so on, do not have the necessary repetition rate needed for the research. The HJ1-A,

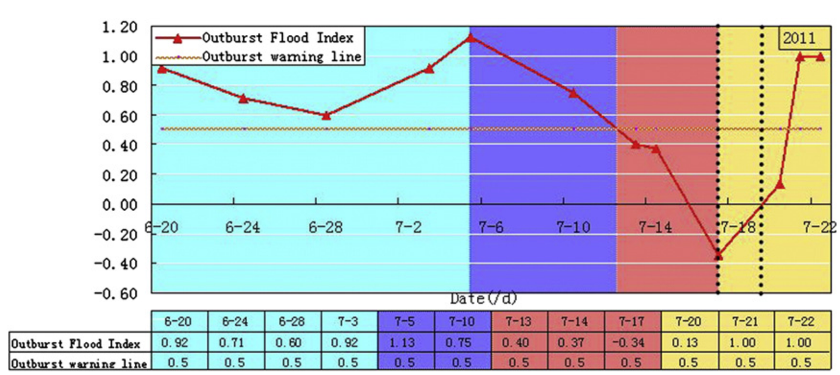

Fig. 9. Outburst index graph for hazard of Glacier Lake Outburst of Lake Merzbacher for 2011. (The red line is the outburst index line, the light blue area is the icefall period, the dark blue area is the quick water storage period, the red area is the early-warning period, and the yellow area is the post-drainage period. The time for lake outburst determined by our method is in the period between two black vertical dashed lines.)

B data, with the spatial resolution being 30 m and temporal resolution being of 2 days, is adaptable for the research of GLOF. Unfortunately, the image data of the Chinese Environment and Disaster Monitoring Small Satellites was commenced on March 2009, so our research was based on a short observation period (2009–2011) and also cannot be supplemented by other images. Consequently the result in this paper is based on our preliminary finding due to the short time series used, which represents the current limitations of our research. This means our experiment will still be needed to be checked and validated by continuous observation and improvement in order to provide more prefect warning systems for the forecasting of Lake Merzbacher outburst floods and reduce the Lake Merzbacher flood hazards for downstream settlements.

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