Remote sensing for glacial hazards monitoring in the Caucasian Mountains, Russia

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Abstract -The glaciation of Caucasian Mountains has been decreasing for the past few decades, leading to increased hazard of events, connected with glacier melt. We analyse a glacier collapse, a series of catastrophic debris flows, and the potential for outburst glacial floods in several river valleys of the central Caucasus. A wide variety of remote sensing data exist for these areas, including ground and aerial images, imagery from Corona, Landsat ETM+, Terra ASTER, IRS LISS/Pan, and QuickBird sensors. We assess the potential uses of the satellite imagery for monitoring immediate and long-term consequences of glacial disasters, and compare it against the aerial imagery and ground surveys.

Keywords: Debris flow, glacier collapse, remote sensing

1. INTRODUCTION

1.1 Aims of this paper

The increased availability of various satellite imagery means that it is more widely involved in the monitoring of glacial hazards (such as glacial debris flows and glacier collapses). We investigate the potential uses of satellite imagery depending on the scale and type of the hazard phenomena and on image properties.

1.2 Background

Although airphotos have been used in the debris flow research for a number of decades (Golubev and Labutina, 1966; Jätzold, 1971; Sadov, 1972, Vinogradov, 1976), satellite imagery was not actively utilised until recently. However, it is used for study of glacial catastrophes, analysis of their consequences and for forecasts (Alsdorf&Smith, 1999, Kääb *et al.*, 2003).

Even though satellite images usually have coarser spatial resolution than images from airborne platforms, they have many advantages such as smaller geometric distortions due to greater heights of flight, and the ease of repetitive surveys. Most recent satellite remote sensing systems, such as QuickBird, have the spatial resolution analogous to the airphotos and allow to study details of the debris flow objects. We have been developing techniques to integrate satellite imagery into the research of debris flows and glacial catastrophes (Chernomorets, 1990, Kolka…, 2002, Popovnin *et al.*, 2003).

1.2 The study region, methods and data

The study region is situated in the centre of the Caucasian Mountains, north of the Main Caucasus Range, where currently the glaciation is decreasing. We looked at glacial hazards in three river valleys: Adyl-Su, Gerkhozhan-Su and Genaldon (Figure 1). These sites allow to study a whole range of glacial hazards, from small, potentially dangerous periglacial lakes in the Adyl-su valley, to the gigantic glacial collapse in the Genaldon valley.

Figure 1. Location of the study region in the Central Caucasus. River valleys: 1 - Adyl-Su, 2 - Gerkhozhan-Su, 3 - Genaldon.

In order to assess the usefulness of remote sensing data we have compared materials of large-scale (1:3,000) geodetic surveys, airborne imagery, satellite images from Corona KH-4B, Landsat 7 ETM+, Terra ASTER, IRS LISS/Pan and QuickBird sensors. Subsets of a Corona KH-4B photo and of a multispectral MSK-4 airphoto were scanned with sufficient detail to preserve the resolution of the photos (about 2 and 1 m correspondingly). The images were georeferenced to the Gauss-Krüger projection and, where possible, orthocorrected. We have derived ground control points from 1:25,000 topographic maps, GPS measurements and in some cases from digital terrain models, created from digitized 1:25,000 maps. Georeferencing and orthocorrection were carried out in ERDAS Imagine software. Overlay and analysis of the georeferenced imagery was performed in ArcView software.

2. RESULTS AND DISCUSSION

2.1 The Adyl-Su valley

Catastrophic debris flows occurred in this popular mountaneering valley in 1958 and 1959. Currently a series of periglacial lakes (Figure 2) is developing by the edge of Bashkara Glacier and threatening to produce an outburst debris flow which can destroy sports camps and settlements downstream. The small size of lakes (50-300 m in diameter) is more suited for ground observations, however, they are also well visible in air and satellite imagery.

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The larger lake appeared in 1940s due to retreat of Bashkara Glacier and was the source of debris flows in 1958/59. According to our field measurements, the current volume of water in the lake is about 800,000 m^3.

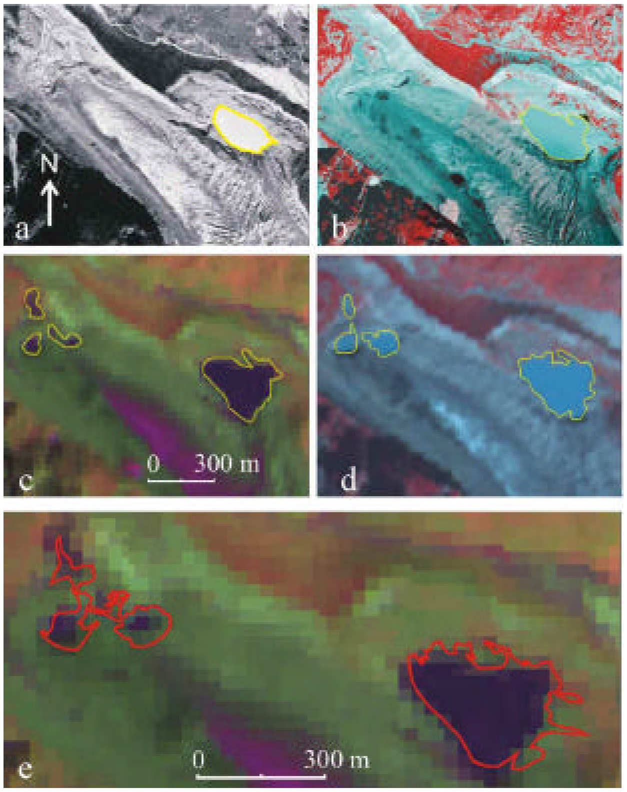

Figure 2. Lakes in the Adyl-su valley by Bashkara Glacier (lake boundaries are outlined): a – Corona KH-4B satellite photo, 20.09.1971; b – MSK-4 airphoto, 23.08.1990; c – Landsat 7 ETM+ image, 9.08.1999; d – Terra ASTER image, 15.09.2001; e – lake boundaries from ground survey of July 2001 overlaid on the Landsat 7 ETM+ image.

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Figure 2 shows the growth of the larger lake from 1971 to 2001 and change of its shape. In the Corona photo of 20 September 1971 one could still see a channel along the right edge of the Bashkara Glacier in place of catastrophic flows of 1958/59, which was later destroyed due to the movement of the glacier. In the group of three other small lakes the two closest to the glacier formed in the end of 1980s. They contained about 60,000 m^3 of water in total in 2001, and this volume grows constantly. This is enough to trigger a catastrophic debris flow (a comparable water volume initiated the flows in 1958/1959). We conducted field geodetic and GPS surveys of the lakes in 2001. However, here we determine the accuracy of spatial measurements achievable with various satellite images: this would be extremely useful if a debris flow occurs and the area becomes inaccessible. We measured selected distances between stable objects, such as old morainic ridges and rock ridges in three types of satellite imagery. In the absence of a detailed topographic map, the MSK-4 orthocorrected airphoto (Figure 2 b) with the spatial resolution of about 1 m was taken as a reference. The results are summarised in Table 1.

Table 1. Accuracy of Distance Measurements for Various Satellite Images

No	Data source	Airphoto MSK-4	Corona KH-4B	Landsat 7 ETM+	Terra ASTER
	Date	23.08.1990	20.09.1971	9.08.1999	15.09.2001
1	length, m	768.2	740.2	772.4	764.9
	d[a], m	0.0	-28.0	4.2	-3.3
	d[a], %	100.0	96.4	100.5	99.6
2	length, m	284.7	267.3	300.6	294.9
	d[a], m	0.0	-17.4	15.9	10.2
	d[a], %	100.0	93.9	105.6	103.6
3	length, m	751.5	710.6	-	-
	d[a], m	0.0	-40.9	-	-
	d[a], %	100.0	94.6	-	-
Average d, %		100.0	94.9	103.1	101.6

[a] d is the difference in distance relative to the MSK-4 airphoto.

As we see in Table 1, the least accurate distance measurements (5-6% error) were derived from the Corona satellite photo. This is probably best explained by the fact that the Adyl-Su area was almost on the edge of the Corona panoramic frame, and as there were only a few ground control points, we were not able to perform an accurate orthocorrection of the scanned subset of the frame. However, even in this case the estimated accuracy of area measurements is within 10-12%. For the ETM+ image the accuracy of distance measurements is about 3%, and of area measurements within 6%. For the ASTER images the accuracy of distance measurements is about 2% and of area measurements is within 4%. With the increase of the lake size the accuracy would grow further.

Having estimated the accuracy of measurements, we measured the area of the larger lake (also known as Lake Bashkara) and the total area of the three small lakes in the satellite images and compared it against the results of our geodetic survey in 2001.

Table 2. Lake Area Measurements for Adyl-Su Valley

Object	Data source	Corona KH-4B	ÌÑÊ-4	Landsat 7 ETM+	Geodetic survey	Terra ASTER
	Date	20.09. 1971	23.08. 1990	9.08. 1999	Jul-Aug 2001	15.09. 2001
Larger lake	area, m^2	32783	51351	64484	63996	67885
	area, %[a]	51.2 ±12	80.2	100.8 ±6	100	106.1 ±4
Three small lakes	area, m^2	-	-	20213	21431	22623
	area, %	-	-	94.3 ±6	100	105.6 ±4

[a] in relation to results of the 2001 geodetic survey

As follows from Table 2, Lake Baskhara has significantly grown since 1971, when it was about half of the present size. The other lakes are small in size and have complicated coastline: although this limits the possibilities of area estimates from the ETM+ imagery (resolution 30 m or 15 m pan-sharpened) and ASTER imagery (15 m resolution), the areas show the right tendency of constant increase, confirmed by ground observations.

2.2 Gerkhozhan-Su valley

Catastrophic debris flows in the Gerkhozhan-Su valley in late July 2000 destroyed part of the town of Tyrnyauz, killing at least 8 people. We have studied the post-catastrophic changes both in the field and with remote sensing methods.

Satellite imagery from Landsat 7 ETM+ and Terra ASTER proved useful for detection of large-scale changes in the lower part of the valley. Even though it was not possible to distinguish small details, visible in airphotos (Figure 3 a), the comparison of the satellite images before and after the debris flows of 2000 shows a number of key features, such as a fan of debris flow deposits which temporarily blocked the Baksan River in the main valley (Figure 3 c, top-centre). Thickness of the deposits reached 15-18 m (surveyed in the field). As a result, the Baksan River formed a temporary lake upstream, which reached 0.55 km^2 in area (measured from aerial images) and existed for two months, until September 2000. Comparison of the November 1997 airphoto and digital aerial images taken in September 2000 showed that 42 buildings and some minor constructions were flooded. It was necessary to dig a special channel (shown by a black arrow in Figure 3 c) for the Baksan River to release the accumulated water. Images such as the Terra ASTER subset in Figure 3 c can be used to assess the effectiveness of anti-flooding measures.

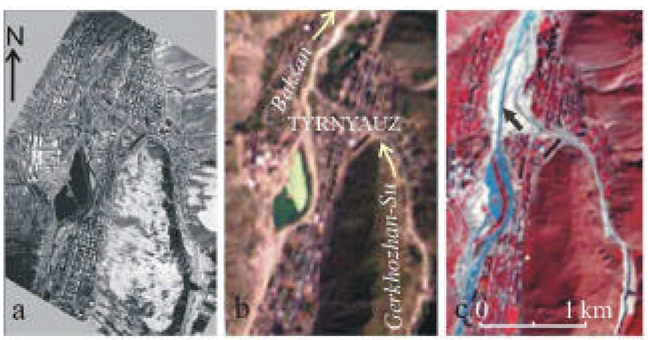

Figure 3. Lower part of the Gerkhozhan-Su valley: a - airphoto of November 1997; b – Landsat 7 ETM+ image (bands 3, 2, 1 pan-sharpened), 9.08.1999 (before the catastrophic debris flows); c – Terra ASTER image (bands 3, 2, 1), 15.09.2001 (after the catastrophic debris flows). The black arrow in (c) shows a new channel, digged for the Baksan River after the catastrophic debris flows in July 2000.

The upper part of the Gerkhozhan-Su valley area has smaller features and has been more successfully studied with the help of digital aerial helicopter-based) imagery due to the necessary level of detail, despite difficulties with orthocorrection of oblique imagery. In Figure 4 we compare a ETM+ image taken before the catastrophe and an aerial image taken two months after it (resolution about 0.5 m). The debris flows of 2000 started from the edge of the Western Kayaarty Glacier (1). The main source of debris was the debris flow channel (2) which became significantly larger and deeper after the flows of 2000. The debris flow accumulation field (4) has also increased.

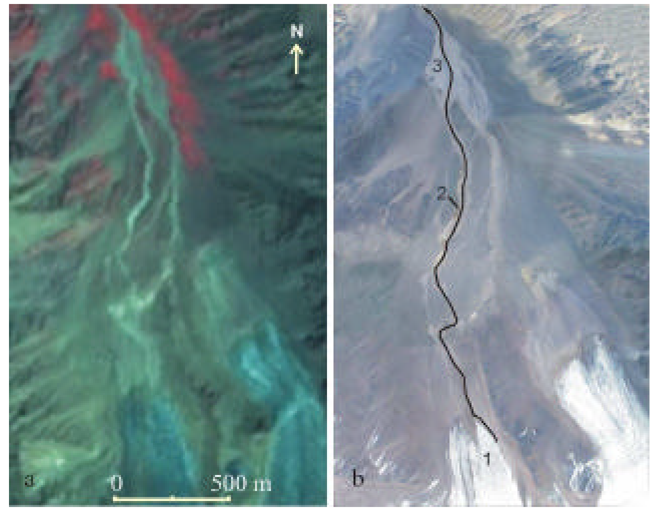

Figure 4. Upper part of the Gerkhozhan-Su valley: a – Landsat 7 ETM+ image (bands 4, 3, 2 pan-sharpened), 9.08.1999; b – orthocorrected aerial digital image, September 2000. The black line shows the way of catastrophic debris flows in 2000. Numbered features are explained in the text.

2.3 Kolka Glacier/Genaldon valley

Kolka glacier collapse on 20 September 2002 has moved over 115 million m^3 of ice and debris by 19 km in several minutes and took away over 120 lives. Some background information and imagery can be found in (Kolka…, 2002, Popovnin *et al.*, 2003, Kääb *et al.*, 2003). The total disaster area is over 15 km^2 and includes a 2 km^2 body of displaced ice and debris with over a dozen of highly dynamic meltwater lakes, threatening outburst floods for the following years during the warm season. Satellite imaging proved the most efficient for this area, since the disaster area is large, still dangerous, partly inaccessible and spans a great range of altitudes (from 1500 to over 4000 m), making complete aerial survey difficult. We measured areas of temporary lakes from Terra ASTER imagery for two dates after the catastrophe (Table 3).

Table 3. Areas of temporary lakes in the Genaldon valley after the glacial catastrophe of 20.09.2002, as derived from ASTER imagery

Lake No.	Location relative to the Genaldon River	Area, 10^3 m^2	
		27.09. 2002	06.10. 2002
1	Along the right bank, near the former village of Genal	-	4
2		-	3
3		-	12
4	Lake Saniba, along the right bank, in the mouth of the Kauridon R.	218	262
5	Along the right bank, near the village of Karmadon	10	7
6		5	5
7	Above the ice body by the village of Karmadon	50	36
8	Lake Kolka on Kolka Glacier	-	24
9	Along the left bank, near the village of Kani	57	36
10		50	32
11		9	5
12		9	5
13	Along the left bank, at the confluence of the Genaldon R. and the Gizeldon R.	13	6
Total area		421	437

As we see from Table 3, in 10 days after the catastrophe four more lakes appeared and their total area has slightly increased.

For the vicinity of Lake Saniba, the largest of the temporary lakes, we have also compiled a map of lake area changes between 22 September 2002, when the lake was created by debris flow, and 19 October 2002, on the basis of aerial and satellite imagery (Figure 5).

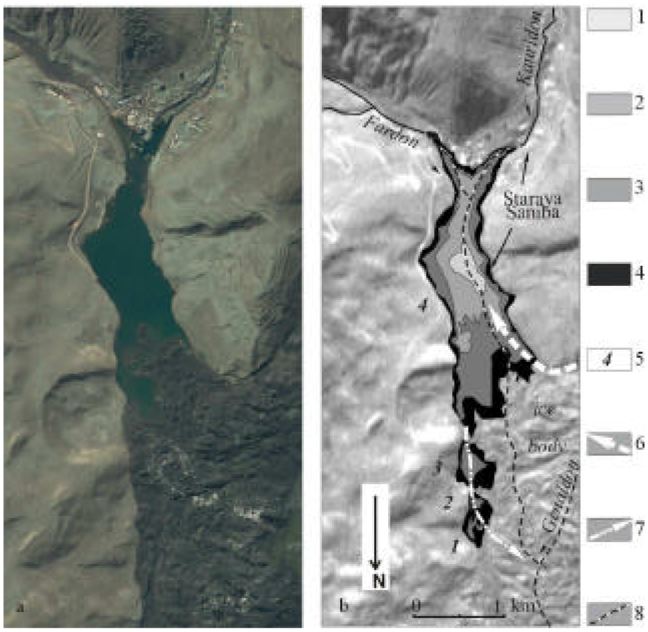

Figure 5. Changes in size of temporary lakes near Staraya Saniba village: a – QuickBird image of 25.09.2002 (courtesy of www.digitalglobe.com), b – map of the lake area changes: 1 – area on 22 September 2002 (from an aerial image before an outburst debris flow), 2 - 24 September 2002 (aerial image), 3 - 6 October 2002 (Terra ASTER), 4 - 19 October 2002 (IRS LISS/Pan), 5 - numbers of lakes (see Table 3), 6 - direction of the outburst debris flow on 22 September 2002, 7 - direction of flow from Lake Saniba, 8 - location of river channels before the catastrophe.

The map shows a consistent picture of the lake area increase. We are continuing to monitor the state and areas of the temporary lakes on the basis of the IRS image acquisitions which are ongoing.

3. CONCLUSIONS

We conclude that remote sensing methods are particularly efficient for immediate action after large-scale glacial disasters due to:

- very quick rate of environmental change which makes other types of survey not feasible, while study of these quick changes is essential to improve the disaster forecast;
- lack of ground access (destroyed infrastructure, unstable ground, continued ice melt etc);
- sufficient accuracy (distance and area measurements within a few percent);
- increased availability of various imagery due to efforts of local disaster response agencies, as well as national and international space agencies and receiving stations.

The latter calls for the development of an improved technology for fast integrated processing of heterogeneous imagery with varying geometry, spatial and spectral resolution. For example, real-time imagery from automatic digital cameras on monitoring sites can be georeferenced to a more general map of the area, derived from satellite and aerial imagery, and be used for assessment of the glacial hazard level and its changes.

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