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Glacial lake mapping with very high resolution satellite SAR data

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Abstract. Floods resulting from the outbursts of glacial lakes are among the most far-reaching disasters in high mountain regions. Glacial lakes are typically located in remote areas and space-borne remote sensing data are an important source of information about the occurrence and development of such lakes. Here we show that very high resolution satellite Synthetic Aperture Radar (SAR) data can be employed for reliably mapping glacial lakes. Results in the Alps, Pamir and Himalaya using TerraSAR-X and Radarsat-2 data are discussed in comparison to in-situ information, and high-resolution satellite optical and radar imagery. The performance of the satellite SAR data is best during the snow- and ice-free season. In the broader perspective of hazard management, the detection of glacial lakes and the monitoring of their changes from very high-resolution satellite SAR intensity images contributes to the initial assessment of hazards related to glacial lakes, but a more integrated, multi-level approach needs also to include other relevant information such as glacier outlines and outline changes or the identification of unstable slopes above the lake and the surrounding area, information types to which SAR analysis techniques can also contribute.

1 Introduction

Glacial Lake Outburst Floods (GLOFs) have repeatedly been the cause of major fatal events and damages in high mountain regions such as the Himalayas, Central Asia, Andes, Caucasus, and the European Alps (Kääb et al., 2005a; Mergili and Schneider, 2011). The related hazards may even increase due to current atmospheric warming as glaciers worldwide retreat and leave, under certain circumstances, glacier lakes behind. As a particularly far-reaching glacier-related hazard, GLOFs may have devastating impact on populated areas that are located far downstream of the source area. Glacial lakes are often located in remote areas and can only be accessed with a substantial effort and cost to investigate their condition. While, e.g. in Switzerland, a network is set-up to monitor glacier changes to help prevent glacial hazards (Swiss Glacier Monitoring Network, 2010), large and inaccessible areas in other mountain regions like the Pamir and Himalayas cannot be easily monitored from ground and air. Space-borne remote sensing data are therefore a valuable and important information source to collect information on glacier lakes.

So far, glacial lakes are mainly mapped and monitored using interpretation and manual mapping based on optical data, both air-photos and optical satellite data (Haeberli et al., 2001; Huggel et al., 2002; Kääb et al., 2005b; Quincey et al., 2005; Kääb, 2008; Bolch et al., 2008, 2011; Mergili et al., 2011, 2012; Tadono et al., 2011; Ukita et al., 2011). The accuracy and level of detail of such glacial lake maps mainly depends on the data source and acquisition conditions (including areas in shadow), the temporary or permanent charateristics of the glacial lake (e.g. turbidity), and the aim of the specific study. The latter may range from regional-scale overview maps, including low-detail lake outlines, to multitemporal maps of individual lakes or lake systems. A few studies based on optical data tested semi-automatic methods for classifying glacial lakes, like the Normalized Difference Water Index (NDWI) (Huggel et al., 2002). Thermal infrared analysis has also been used to investigate temperature differences in glacial lakes (Wessels et al., 2002). While these techniques work well under cloud-free conditions, data usability is hampered in bad and cloudy weather, a severe limitation for high mountains in general and for areas affected by monsoon in particular. This complicates a reliable, high-frequency, long-term monitoring of glacial lakes. Some

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glacial lake types develop slowly so that low-frequency monitoring is sufficient to track changes and detect hazardous developments. Other lake types, however, may develop rapidly, i.e. within some weeks or a few months (Kääb et al., 2003, 2005a; Narama et al., 2010), so that high-frequency monitoring would be highly valuable to early detect related hazards.

We propose use of very high resolution SAR data to complement information that can be retrieved by very high and high resolution optical data. The advantage of SAR is that data availability and usability is very predictable, a key requirement for monitoring. Currently, three sensors are available for SAR data at a very high spatial resolution of about 3 m: the German TerraSAR-X, the Canadian RADARSAT-2, and the Italian COSMO-SkyMed. In this paper we present results using TerraSAR-X and Radarsat-2 data for reliable and robust glacial lake mapping over test sites in the Alps, Pamir and Himalaya. In addition to very-high resolution SAR data with an acquisition strategy mainly driven by user requests, other satellite sensors, such as the European ERS-2 SAR and ENVISAT ASAR, and the Japanese ALOS PALSAR, provide SAR data at high spatial resolution on the order of 20 m and with a global acquisition strategy with corresponding archive holdings for historic analysis. A comparison of results obtained from high and very high resolution SAR systems is also presented in order to underline advantages and drawbacks of using one or the other SAR configuration.

2 Description of sites

Our study is focused on three different regions in Switzerland, Tajikistan and Nepal, where the requirements for glacial lake mapping were formulated by the Glacier and Permafrost Hazards in Mountains Working Group (GAPHAZ, 2011), Focus Humanitarian Assistance (FOCUS, 2007), and the International Centre for Integrated Mountain Development (ICIMOD, 2012), respectively. In all three regions glacial lake maps are required at 10 m spatial resolution (corresponding to approximately 1 : 25 000 scale), with a 10 m horizontal geocoding accuracy and a 90 % thematic accuracy. The requested updating frequency for the Swiss Alps and the Pamir mountains was at least one image per year in the peak of summer, even if a late spring acquisition is also of interest. In the Himalayas, a pre-monsoon (mid April to May) and a post-monsoon (October–November) map are requested by the users. Information should be provided in non-critical situations within a few weeks of the data acquisition. Additionally to the classification of water, mapping of the glacierized areas was of interest.

In the Swiss Alps a number of detail studies of selected regions and glacier lakes is available (Haeberli et al., 2001; Huggel et al., 2002) and regular map-updates are performed based on aero-photogrammetric flights. In addition, the Swiss Glacier Monitoring Network (2010) was set up in order to monitor glacier changes and early recognize glacier-related hazards. An inventory of hazardous glaciers (Naturgefahren Gletscher, 2011) has been compiled with regard to critical glacier fluctuations, glacier floods (both glacier lakes and subglacial water pocket outbursts) and ice avalanches (Raymond et al., 2003). Furthermore, live pictures of a few hazardous glaciers are available (live images from Swiss Glaciers, 2012). For our study we chose an accessible test area where our products could be validated insitu with a relatively small glacier lake of a typical extension of few hectares. The glacier lake in front of the Weingartengletscher (*gletscher* = glacier) with an extension of about 17 000 m^2 at an altitude of 3058 m a.s.l. (see Fig. 1) was selected for that purpose. The Weingarten glacier lake is of typical proglacial nature, though it lost direct glacier contact in recent decades, and has already produced an outburst flood on 25 June 2011 (Huggel et al., 2003). In a dedicated field campaign, the extension of the lake was mapped with a GPS in coincidence with a TerraSAR-X acquisition on 29 July 2009.

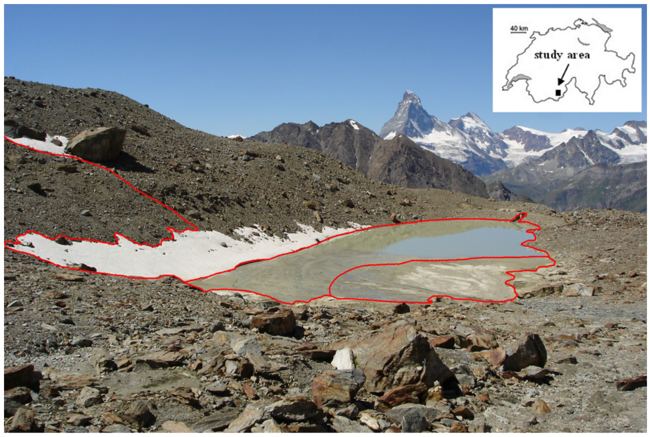


Fig. 1. Photograph of the Weingarten glacier lake on a field visit on 29 July 2009 with GPS path in red. The figure inset shows the location of the lake in Switzerland.

In the Pamir there is no systematic glacier lake monitoring concept available so far. Some unpublished hazard assessments and mitigation reports were produced by Non-Governmental Organizations (NGO) and development agencies, e.g. the Swiss Agency for Development and Cooperation (SDC), and a glacier lake inventory was published by Mergili et al. (2011) for the southwestern Pamir. Based on an assessment study (Schneider et al., 2004) conducted for FOCUS by the University of Natural Resources and Life Sciences (BOKU) of the Vienna University of Natural Resources and Applied Sciences, several areas were considered in Tajikistan to be at risk from GLOFs (see Fig. 2).

Glacial lake inventories and assessments exist for selected areas in the Himalayas (Mool et al., 2001a, b; ICIMOD 2012), although there is not yet a systematic glacial lake monitoring concept. In general, snapshots of varying time periods are available rather than regular time series. The latter

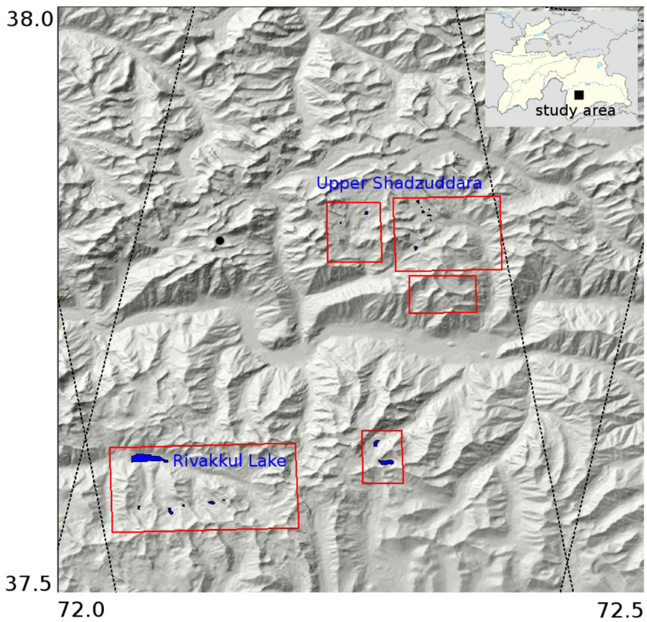


Fig. 2. Location map of the areas of interest in Tajikistan (red frames) with footprints of the TerraSAR-X acquisitions (black frames). Image background is a shaded relief of the SRTM DEM. The figure inset shows the location of the lakes in Tajikistan.

were produced only for a few selected small areas and hazard potential assessments (Ageta et al., 2000; Bolch et al., 2008; Bajracharja, 2009; ICIMOD 2012). ICIMOD indicated six glacial lakes to represent particular hazard potentials and that were planned to be surveyed in the field in 2009. In our analysis we retained four of the nominated lakes covered by two TerraSAR-X frames.

3 Satellite data and processing

The analysed SAR scenes are listed in Table 1. Over Switzerland we retained one TerraSAR-X, one ENVISAT ASAR and one ALOS PALSAR acquisition in the summer of 2009. For product validation we considered topographic maps and an in-situ map of the Weingarten glacier lake obtained using a GPS survey on 29 July 2009.

In order to cover an area in Tajikistan with as many as possible glacial lakes in one single TerraSAR-X frame, we limited our area of interest within latitude 37°30′–38°00′ and longitude 72°00′–72°30′. TerraSAR-X, ENVISAT ASAR, ALOS PALSAR and Radarsat-2 data were considered for the peak of summer 2009, early spring 2010, for a possible survey of the situation before the summer melt, and the peak of summer 2010 (see Table 1).

Also, our analysis in Nepal was limited to a narrow section within latitude 27.7°–28.0° and longitude 86.4°–87.2° in order to cover the area of interest with as many as possible glacial lakes in two TerraSAR-X frames. For the pre-monsoon (mid April to May) and post-monsoon (October–November) seasons of 2009 and 2010 TerraSAR-X, ENVISAT ASAR, ALOS PALSAR and Radarsat-2 data were selected (see Table 1). In addition, historical ALOS PALSAR and ERS-1/2 SAR images from 1992 to 2008 were considered for a reconstruction of the past evolution of the lakes.

Processing of the satellite radar images can be divided into several logical steps: SAR processing; SAR image registration, if relevant; SAR geocoding; and the generation of lake outlines. For each step quality control tests are introduced. Results of the SAR processing are images at the highest spatial resolution (single-look) in the original SAR geometry. Co-registration of SAR images is performed if two or more acquisitions from the same orbit configuration are considered. Co-registration can be achieved automatically with a very high precision on the order of 1/10-th of a pixel (Strozzi et al., 2002). For the terrain-corrected geocoding of satellite SAR data in the range-doppler geometry, a DEM is required. Considering that glacial lakes and their surroundings in high mountainous regions are exposed to large topographic relief and sometimes fast elevation changes (e.g. from ice melt), the quality, resolution and release date of the DEM nominally affects the final accuracy of the geocoding. Globally available digital elevation models include the SRTM DEM and the ASTER GDEM.

The SRTM DEM, derived from the Shuttle Radar Topography Mission (SRTM) carried out in 2000, is provided in geographic coordinates with a 3 arc sec (∼ 90 m) resolution for the Earth'2 land masses that lie between 60° N and 56° S latitude. The indicated absolute and relative 90 % vertical accuracies are ±16 m and ±6 m, respectively, whereas the horizontal positional accuracy is about ±20 m (Rodriguez et al., 2005). Version 3 of the SRTM DEM (SRTM3) shows large sections without data as a consequence of radar shadow, layover and insufficient interferometric coherence. In order to produce a DEM with larger coverage, version 4 of the SRTM DEM (SRTM4) has been processed using advanced interpolation algorithms and auxiliary DEMs to fill data voids. The ASTER GDEM (2012) was created by stereo-correlating the 1.3 million scene ASTER VNIR archive, covering the Earth's land surface between latitudes 83° north and 83° south. The GDEM is produced with 30 m posting and is a composite from images obtained between 1999 and 2008. Due to its dependency on the availability of suitable cloud-free optical ASTER stereo images and the need for visual contrast in the images sufficient for stereo-correlation, the quality and accuracy of GDEM varies significantly and artefacts are largely present. In addition, although provided at 30 m posting, it appears that version 1 of the ASTER GDEM, available at the time of our study, has in terms of topographic details a lower resolution than the SRTM4 and is affected by misregistrations between individual ASTER DEMs (Nuth and Kääb, 2011). These considerations lead us to use the SRTM4 for data analysis in Tajikistan and Nepal.

Table 1. Satellite SAR data considered in Switzerland, Tajikistan and Nepal.

Site	Sensor	Mode	Date
Switzerland	TerraSAR-X	Descending	29 Jul 2009
	ENVISAT	Descending	22 Jul 2009
	ALOS PALSAR	Ascending	21 Jul 2009
Tajikistan	TerraSAR-X	Descending	24 Aug 2009
			26 May 2010
	TerraSAR-X	Ascending	31 Aug 2009
			22 May 2010
			18 Aug 2010
	ENVISAT	Descending	19 Aug 2009
			26 May 2010
			08 Sep 2010
	ENVISAT	Ascending	8 Aug 2009
			15 May 2010
			28 Aug 2010
	ALOS PALSAR	Ascending	27 Jul 2009
			14 Sep 2010
	Radarsat-2	Descending	30 May 2010
			3 Sep 2010
	Radarsat-2	Ascending	25 May 2010
			29 Aug 2010
Nepal	TerraSAR-X	Descending	1 Jun 2009
			22 Oct 2009
			19 May 2010
	TerraSAR-X	Ascending	7 Jun 2009
			17 Oct 2009
			14 May 2010
	ENVISAT	Descending	25 Apr 2009
			17 Oct 2009
			15 May 2010
	ENVISAT	Ascending	30 Apr 2009
			22 Oct 2009
			20 May 2010
	ERS-1/2	Descending	20 May 1992
			11 Nov 1992
			11 Aug 1995
			12 Apr 1996
			21 Jul 2001
	ALOS PALSAR	Ascending	13 Dec 2007
			29 Apr 2008
			15 Dec 2008
			2 Aug 2009
			17 Sep 2009
			2 Nov 2009
			14 Nov 2007
			16 May 2008
			16 Nov 2008
			19 Aug 2009
			4 Oct 2009
			19 Nov 2009
	Radarsat-2	Descending	5 May 2010
	Radarsat-2	Ascending	13 May 2010

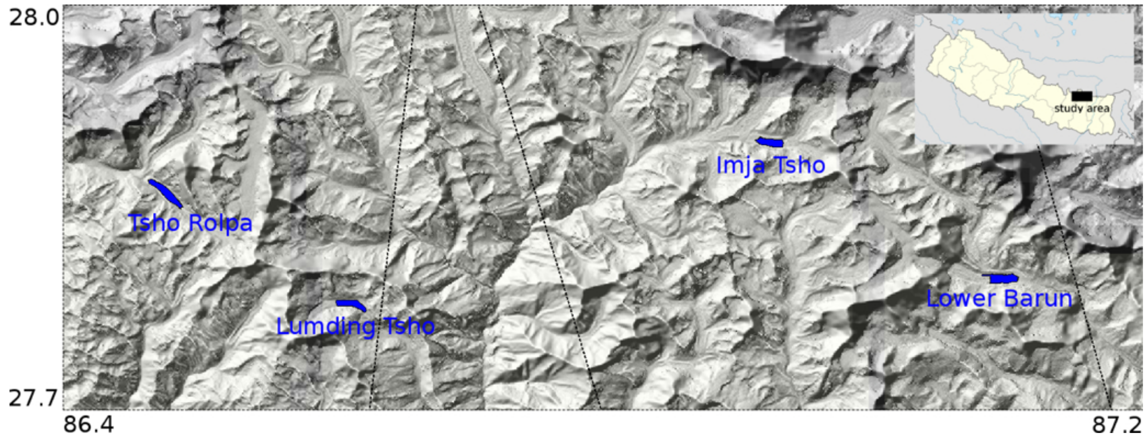


Fig. 3. Location map of the glacial lakes of interest in Nepal with footprints of the TerraSAR-X acquisitions (black frames). Image background is a shaded relief of the SRTM DEM. The inset shows the location of the lakes in Nepal.

The quality of the SRTM4 DEM for terrain-corrected geocoding was further assessed in Switzerland in comparison to the national-scale DEM derived from aerophotogrammetry with a spatial resolution of 25 m and an estimated vertical accuracy of 3 m. With both DEMs terrain corrected geocoding was accomplished at 10 m pixel spacing. We found that the horizontal geometric accuracy of the terrain-corrected geocoding of all satellite SAR images with SRTM4 is on the order of 30 m. Using the national-scale DEM, on the other hand, the horizontal geometric accuracy of geocoding very-high resolution TerraSAR-X data is on the order of 10 m, whereas the the accuracy of geocoding high resolution ERS-2 SAR, ENVISAT ASAR and ALOS PALSAR data is on the order of 20 m.

Lake outlines are produced in the requested projection as shape files from the SAR imagery at 10 m spatial resolution. Water surfaces are very well visible in SAR images because of the generally low backscattering intensity at all microwave wavelengths (Strozzi et al., 2000). We preferred to map the outlines manually because of the challenges and uncertainties using automatic methods as a consequence of the speckle of the radar images and of the wind and waves conditions of the lakes, which can increase locally the roughness of the water surface and thus the backscattering intensity. Supplementary geotiff's of the geocoded SAR images with a layover and shadow mask are also produced. The resulting information is thus in a form that can easily be integrated in the end-users' geographic information system (GIS) and used within the available infrastructure. Consistency tests based, e.g. on multiple independent results from different time periods or sensors, or validation with reference information of independent origin, are essential to better characterize the error and to estimate the reliability of the product.

4 Results in Switzerland

Figure 1 shows the Weingarten glacier lake. It represents a suitable test target as it is small (difficult to map), and has potentially confusing land classes such as wet snow and wet sand at the partially very shallow lake shore. During a field visit on 29 June 2009, in coincidence with a TerraSAR-X image acquisition, an in-situ lake map was obtained by a portable code-based GPS device with EGNOS mode enabled. The indicated horizontal positional accuracy of the GPS was on the order of ±5 m. The TerraSAR-X image of 29 July 2009 around the Weingarten glacier lake terrain-corrected geocoded at 2 m posting based on the Swiss national-scale DEM is presented in Fig. 4. The GPS path to and around the Weingarten lake acquired during the field visit is overlaid in red. The outline of the lake, determined in the SAR intensity image, is shown in blue. In the western part of the lake, the map derived from the TerraSAR-X image matches well with the GPS contour. Potential confusion was observed with the wet snow on the southern side of the lake and the wet sand areas to the north-east. Wet snow cover and sand have indeed a very low SAR backscattering intensity similar to that of water, introducing errors in the classification of glacier lakes.

With ENVISAT ASAR data we found that small lakes with an extension of a few hectares cannot be identified. In ALOS PALSAR images, glacier lakes have a sufficiently distinct signature that allows fairly accurate classification of ice free lakes. In addition, the larger incidence angle of ALOS PALSAR (35°) compared to ENVISAT ASAR (23°) results in smaller layover areas. For both sensors we expect better performance for larger lakes. This is of particular interest for historic analysis based on the satellite data archives.

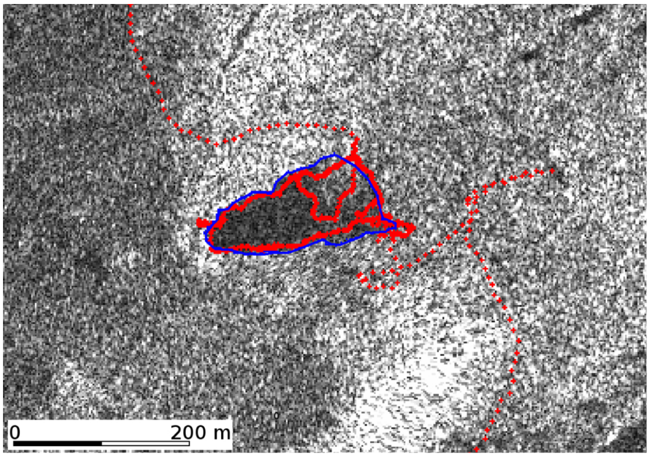


Fig. 4. Terrain-corrected geocoded TerraSAR-X image of 29 July 2009 around the Weingarten Lake in Switzerland. The GPS path to and around the Weingarten Lake acquired during the field visit is overlaid in red. The outline of the lake, determined in the SAR intensity image, is shown in blue.

5 Results in Tajikistan

The area of interest in Tajikistan (Fig. 2) includes one large lake (Rivakkul landslide-dammed lake with a maximum length is about 2.5 km) and many smaller, for the most part pro-glacial moraine-dammed, lakes with an extension of a few hectares. For all the satellite SAR data listed in Table 1, we produced geocoded SAR intensity images at 10 m pixel spacing as Geotiff's and lake outlines as shape files. In the interpretation of the results, it is important to note the different spatial resolutions of the considered satellite radar data. ENVISAT ASAR and ALOS PALSAR data have a ground resolution of about 25 m and for geocoding the images were oversampled to 10 m. TerraSAR-X and Radarsat-2 data have a ground resolution of about 3 m, and for geocoding the images were undersampled to 10 m.

Figure 5 shows the results over Rivakkul Lake from a TerraSAR-X, an ENVISAT ASAR and an ALOS PALSAR acquisition of almost the same period in the summer of 2009. The identification of the glacial lake and its mapping from the SAR backscattering intensity images was found to be quite straightforward and the results of ENVISAT ASAR and ALOS PALSAR data are not too different from that of TerraSAR-X, although with the latter the border of the lake is sharper due to the higher spatial resolution. A Landsat 5 TM scene of 25 August 2009, received in GeoTIFF format and converted to a RGB color composite of channels 5, 4 and 3, is used for validation. The glacier lake outline derived from the TerraSAR-X satellite image is overlaid to the Landsat 5 TM image. There is anagreement within ±30 m of the lake outlines derived from TerraSAR-X data with the Landsat 5 TM scene taking the lower resolution of 30 m of the Landsat data and the expected geocoding inaccuracies into account. In particular, the slight shift between the TerraSAR-X derived lake outlines and the Landsat 5 TM data is well expected from both the geolocation accuracy of Landsat orthoproducts, which is in the order of several tens to hundred meters, and use of the SRTM4 for the SAR data geocoding.

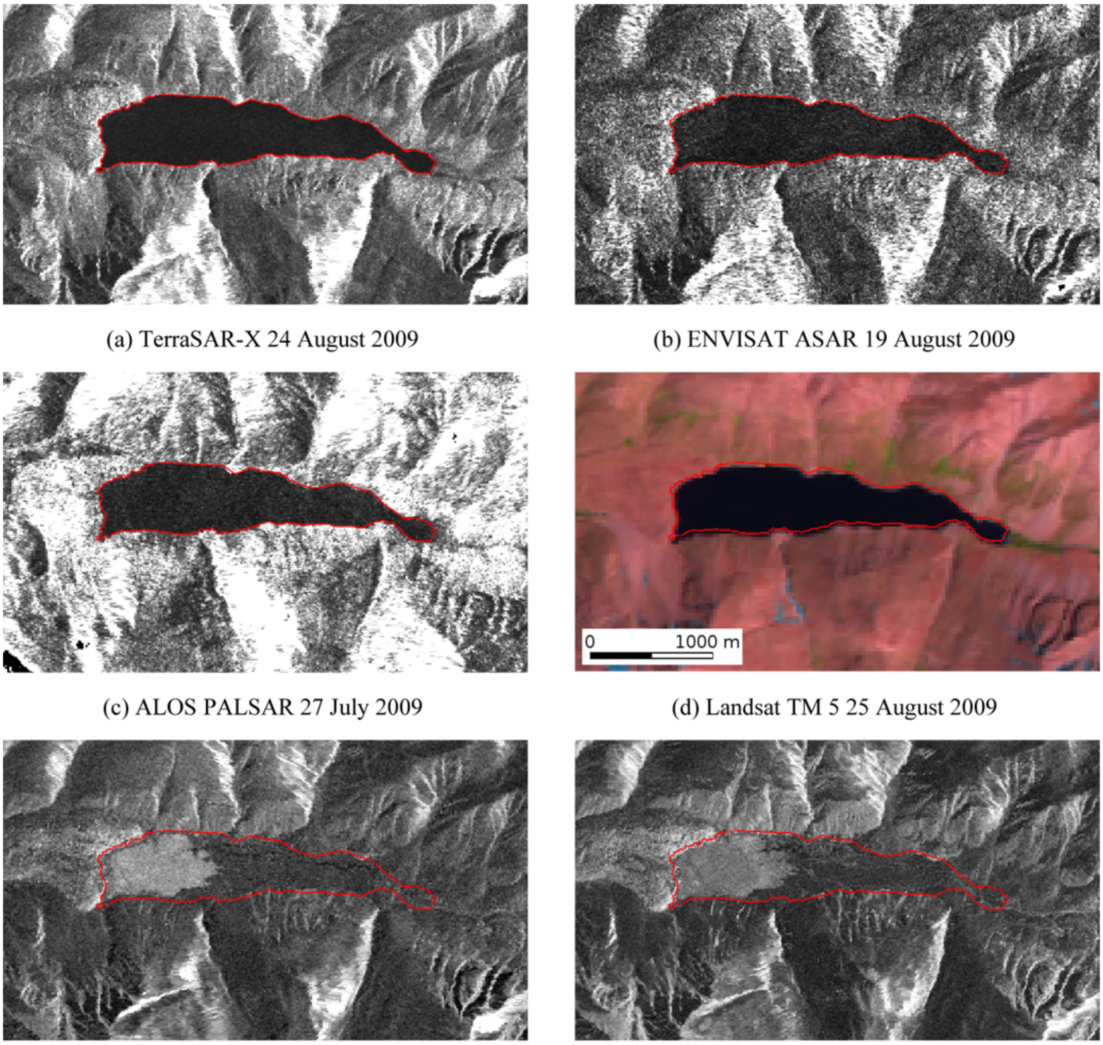
Also shown in Fig. 5 are a TerraSAR-X and RADARSAT-2 images acquired in the spring of 2010, which were analysed in order to survey the situation before the summer melt. With both sensors the glacier lake in spring cannot be completely identified because it is still frozen on the surface. Smaller lakes in spring images are even more difficult to identify than larger ones. In Fig. 5 we can furthermore see that images from the TerraSAR-X and RADARSAT-2 sensors are comparable despite the different frequencies because of the similar ground-resolution on the order of 3 m.

For the smaller lakes with an extension of a few hundreds of meters located in the upper Shadzuddara area, the identification and mapping of the outlines was more challenging. The higher spatial resolution of TerraSAR-X (Fig. 6a) and Radarsat-2 data make it easier to identify lakes as regions of low backscattering intensity than with ENVISAT ASAR (Fig. 6b) or ALOS PALSAR (Fig. 6c) data. In the interpretation of Fig. 6, layover and shadow masks, shown in black, should not be confused with low backscattering intensity. Between August 2009 and August 2010, the area of the potentially hazardous glacier lakes did not change significantly, as visible by the lake outlines determined in the summer of 2009. As shown in the Landsat scene of Fig. 6d, most of the lakes were correctly identified within ±30 m and the higher spatial resolution of TerraSAR-X is a great advantage for the precise delimitation of the lake shorelines. However, there is an outline derived from low TerraSAR-X backscattering intensity which does not correspond to a lake according to the Landsat image. As described in Sect. 4, possible reasons for this misclassification are wet snow cover and wet sand. However, as there is no ground information available, this cannot be verified.

With all SAR sensors, including TerraSAR-X, accurate and complete mapping of ice (i.e. glacier outlines) from the backscattering intensity is very hard. Best results are expected in mid summer, when ice and snow on the glacier surface are wet and thus characterized by a low backscattering intensity (Strozzi et al., 1997).

6 Results in Nepal

For the four prioritized glacial lakes Rolpa, Lumding, Imja and Lower Barun, outlines were produced – as indicated in Table 1 – for various time periods. In particular, the requirement of ICIMOD to have pre- and post-monsoon acquisitions could be satisfied for 2009 and 2010 with TerraSAR-X data of ascending and descending orbits. ERS-1/2, ALOS PALSAR, ENVISAT ASAR and Radarsat-2 images complement the data set with historical information on special time



(a) TerraSAR-X 24 August 2009

(b) ENVISAT ASAR 19 August 2009

(c) ALOS PALSAR 27 July 2009

(d) Landsat TM 5 25 August 2009

(e) TerraSAR-X 26 May 2010

(f) RADARSAT-2 30 May 2010

Fig. 5. Terrain-corrected geocoded TerraSAR-X, ENVISAT ASAR, ALOS PALSAR and Radarsat-2 images for summer 2009 and the early spring 2010 for Rivakkul Lake in the test-area in Tajikistan. The outline of the lake, determined in the summer TerraSAR-X intensity image, is shown in red. Layover and shadow are masked in black. A coincident Landsat 5 TM image is presented for validation.

periods. Geocoded SAR intensity images in Geotiff format were also computed to support the interpretation of the lake outlines at 10 m pixel spacing. Here, we concentrate on the results for Imja Tsho using ascending orbit SAR data. The length of the pro-glacial, moraine dammed Imja Tsho is according to the field base map of May 2009 2.03 km.

In general, the identification of the glacial lake and its mapping based on low backscattering intensity is straightforward for the TerraSAR-X data (Fig. 7a). With ENVISAT (Fig. 7b), the distinction of the shore line and of the glacier tongue is more difficult; also, depending on the presence of wind or ice, the precise delineation of the lake outline is more challenging. The performance of ERS-1/2 SAR data is similar to that of ENVISAT ASAR because these two sensors have similar ground resolution and operate at the same frequency. With ALOS PALSAR data (Fig. 7c), the distinction of the glacier lakes is less problematic than with ENVISAT ASAR data.

Historical ERS-1/2 SAR data of 1992, 1996 and 2001 and ALOS PALSAR acquisitions of 2007 and 2008 were employed, together with the TerraSAR-X scenes of 2009, to follow the temporal changes of the lake area. In Fig. 8 we observe for Imja Tsho between 1992 and 2009 a calving front retreat of more than 500 m and an increase in area from about 0.77 km^2 to about 1.07 km^2, similar to that reported by Bajracharya (2009) and Fujita et al. (2009).

Between October 2009 and May 2010, the area of Imja Tsho did not change significantly. A colour composite of the TerraSAR-X acquisitions of 17 October 2009 and 14 May 2010 in the original SAR geometry, presented in

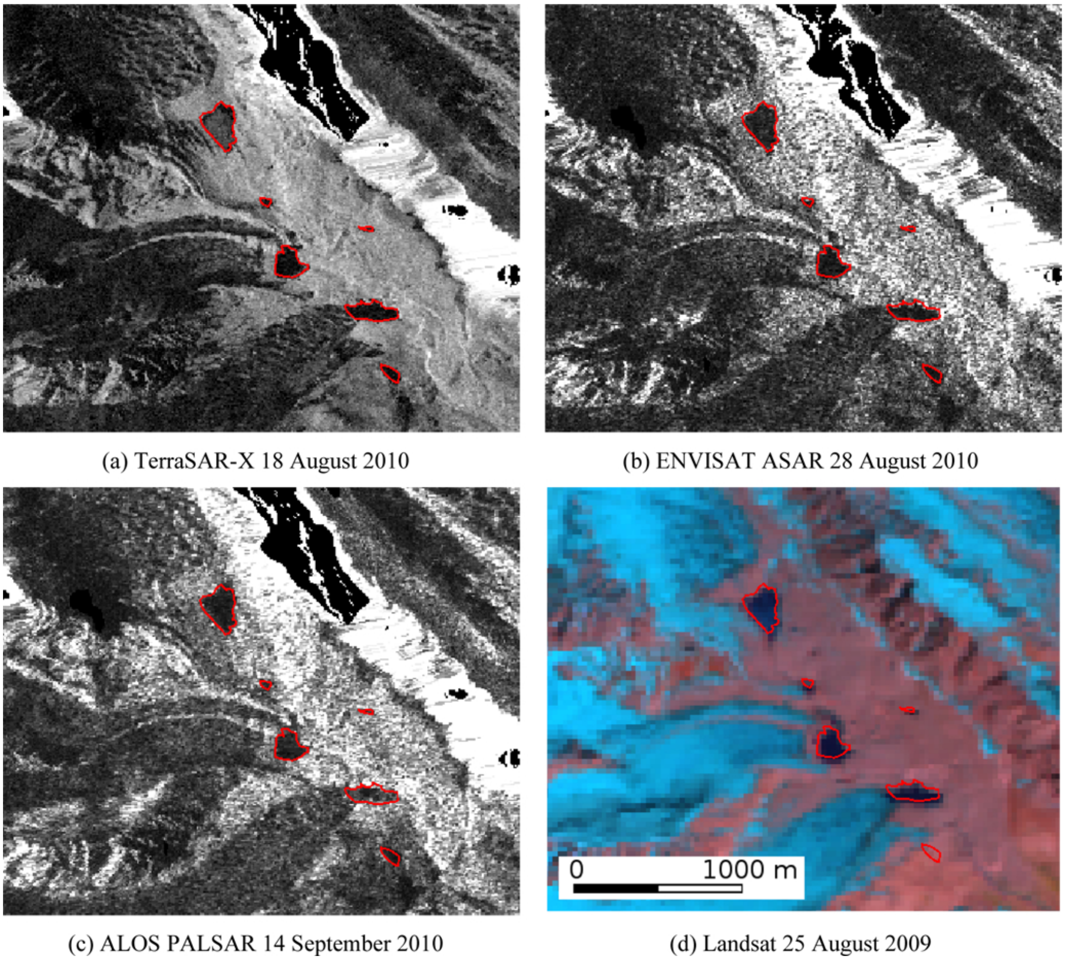
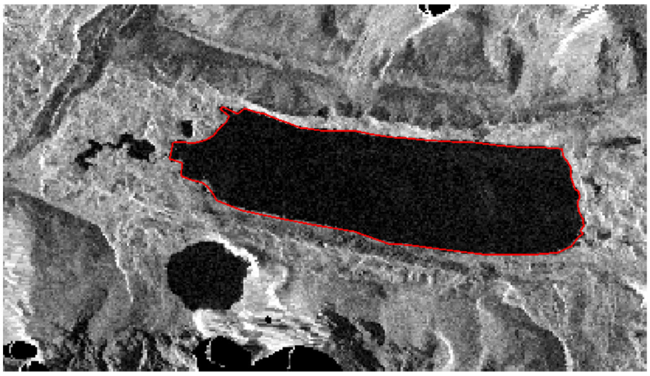


Fig. 6. Terrain-corrected geocoded TerraSAR-X, ENVISAT ASAR and ALOS PALSAR images for the summer of 2010 for glacial lakes with an extension of a few hundred of meters located in the upper Shadzuddara area in Tajikistan. The outlines of the lakes, determined in the TerraSAR-X intensity image of the summer of 2009, are shown in red. Layover and shadow are masked in black. A Landsat 5 TM image of the summer of 2009 is presented for validation.

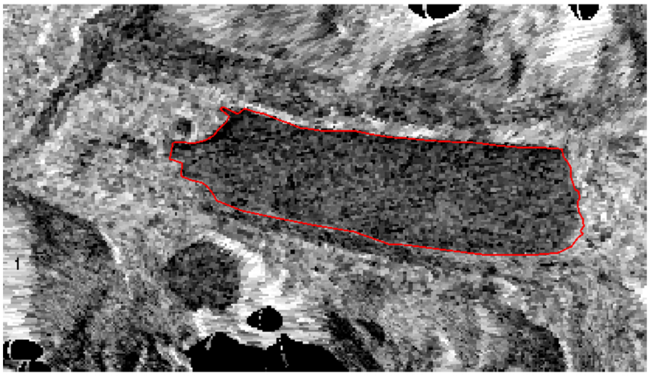
Fig. 9, highlights in detail this modest change. Considering that the precision of repeat-pass SAR image co-registration is on the order of a 1/10-th of a pixel (Strozzi et al., 2002) and that the ground-range resolution of TerraSAR-X data is on the order of 2 m, we can observe very small lake variations of less than 40 m.

Field observations of three lakes, including Imja Tsho, were provided by ICIMOD for validation. The detailed field investigations of Imja Tsho were performed in May 2009. For the topographic mapping, Sokkia and Pentax total stations were used with the additional support of benchmark networking and Leica SR20 GPS. In order to take the shore line of the lakes, a rubber boat was used and two persons with prisms were sent wherever possible to measure the shoreline at given distance intervals. In some cases near landslides, where it was too dangerous to get ashore, measurements were taken at about 5 to 10 m from the shoreline. The lake outlines delineated based on the survey data in the Modified Universal Transverse Mercator (MUTM) projection system with 3 degree zoning used in Nepal were converted to WGS84 coordinates. For integration into Google Earth, offsets varying from about 15 to 85 m, and different in each lake, were manually corrected.

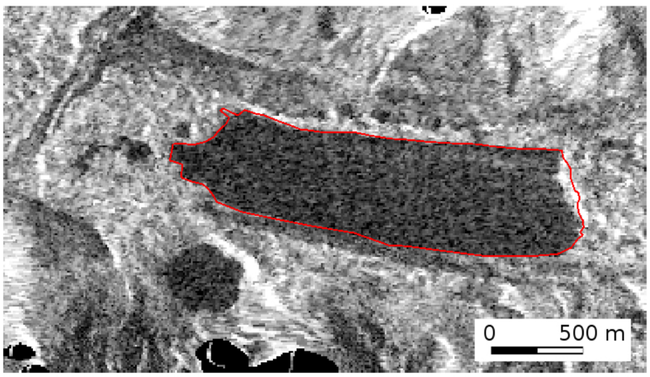
In Fig. 10, the glacial lake outlines derived from the TerraSAR-X satellite images of April and October 2009 and from the field survey in May 2009 are compared. The correspondence is generally very good with offsets within about 30 m, which are in line with the geocoding accuracy. Some water surfaces were mapped in the field also around the river outflow. Because floating icebergs from calving are not considered as lake area during the SAR image interpretation, the lake seems to be rapidly advancing during the season but in fact this might not be true. The RADARSAT-2 backscattering image of May 2010, used as background in Fig. 10, shows however an enlargement of the lake during one season. Usually, most of the glacier lakes in the valleys are extending



TerraSAR-X 17 October 2009



ENVISAT ASAR 22 October 2009



ALOS PALSAR 11 November 2009

Fig. 7. TerraSAR-X and ENVISAT ASAR images of October 2009 and ALOS PALSAR acquisition of November 2009 of Imja Tsho. Lake outline is derived from the TerraSAR-X data. Areas affected by layover and shadow are masked in black.

towards the glacial terminus while the lateral moraines are almost fixed, except for the changes in water level, which result in corresponding minor changes in the surface area of the lake. The fluctuation of the water level in winter and summer is around 1 to 2 m so that the shoreline of the lakes may vary up to 20 m (1–2 pixels) for shallow water depths. Thus, for monitoring changes in shoreline positions, pixel sizes of less than 10 m will be required.

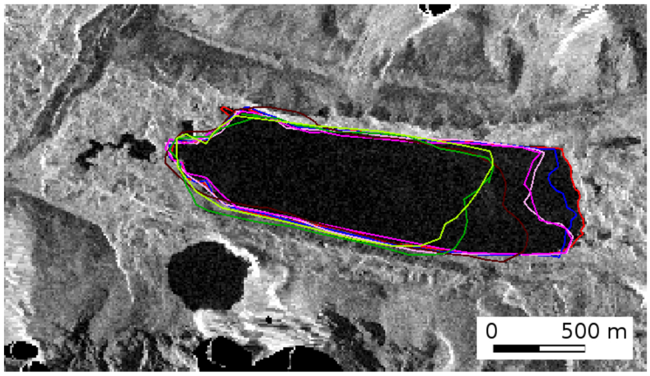


Fig. 8. Outlines of Imja Tsho derived from ERS-1/2 SAR data of May 1992 (light green), April 1996 (green), July 2001 (brown), ALOS PALSAR data of November 2007 (violet), May 2008 (pink), and TerraSAR-X data of April 2009 (blue) and October 2009 (red). Background image is the TerraSAR-X data of October 2009.

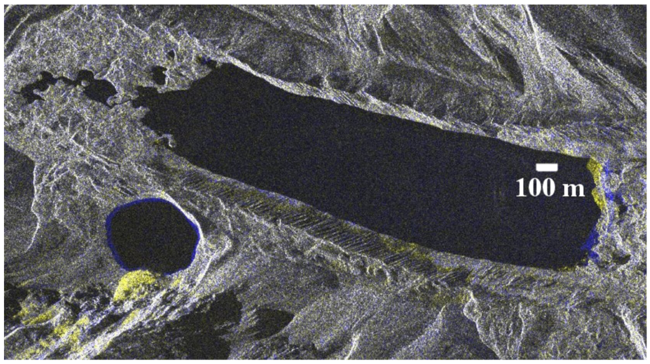


Fig. 9. Colour composite of the TerraSAR-X acquisitions of 17 Oct 2009 (red and green = yellow) and 14 May 2010 (blue) of Imja Tsho in the original SAR geometry. Ground-resolution (i.e. pixel spacing) is on the order of 2 m.

7 Discussion and conclusions

Glacial lake detection has to address the spatio-temporal behaviour of lakes, including appearance, disappearance and growing of known or unknown lakes threatening the population downstream. Glacial lake development to a dangerous level often occurs over years and optical remote sensing analysis is a useful tool to assess these potential hazards. But the development of glacial lakes may also happen within days or weeks (e.g. Narama et al., 2010), posing special challenges to frequent and area-wide monitoring. SAR sensors may be in particular useful, or in some regions even the only monitoring means, for such rapidly-developing lakes where the availability of cloud-free optical data is severely limited. In addition, satellite SAR acquisitions can be programmed well in advance and their use in rigorous planned surveying activities is assured independently of the weather providing a good timeliness of the data.

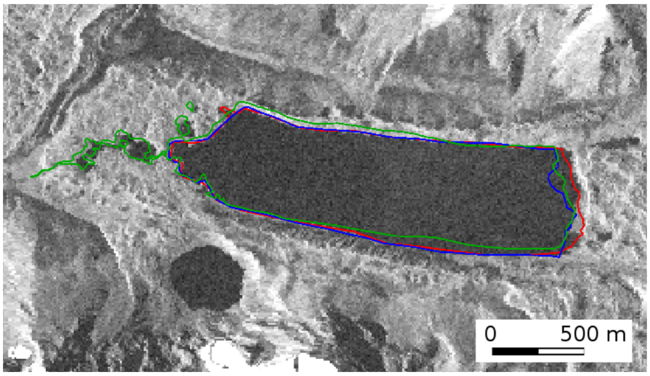


Fig. 10. Lakes outlines derived from TerraSAR-X data of April 2009 (blue) and October 2009 (red) and from field surveys (green) in May 2009 for Imja Tsho superimposed to the backscattering of the Radarsat-2 acquisition of May 2010.

We reported on the use of very high resolution satellite SAR data for reliable and robust glacial lake mapping. During the data interpretation, confusion with wet snow and wet sand areas has to be taken into account because of the very low backscattering intensity similar to that of water. Zones of icebergs and ice debris floating on the lakes, in particular at calving fronts, are confused with land if the interpretation is based on backscatter intensity only. In many cases, though not necessarily in all, multi-temporal analyses might hint to this type of misclassification. In addition, it is important to notice that ascending and descending orbits have different viewing geometries, especially into steep valleys, leading to different hidden areas. DEM quality and availability is crucial. We found that for the general use, SRTM4 proved to be the best large scale DEM available, but did not yet incorporate the ASTER GDEM version 2 in our tests. Visualisation of the data in Google Earth showed localisation errors between our SRTM4-based orthorectification with the Google Earth Landsat images of about 10 to 50 m. A drawback in the visual interpretation of satellite images applied in this study, compared to automated methods, is that the area of the lake may vary according to personal subjective interpretations. Another aspect which should be considered in the shoreline mapping with SAR data is shadow or layover of the lake's shorelines. But up to a 1 : 10 000 scale the produced outlines fit well with the in-situ validation data. Costs and processing effort of satellite SAR data are similar to that of satellite optical data, although interpretation, as explained before, might need more training. Thus, we envisage that the provided service is mature and complements well the more established optical remote sensing technology (Schneider, 2004; Kääb et al., 2005a; Quincey et al., 2005; Ukita et al., 2011; Mergili et al., 2012). The users involved in our study are developing more capacity in radar remote sensing analysis as part of ongoing and future risk management interventions in Tajikistan and the Himalayas. The huge archive of satellite SAR data dating back to the nineties allows for reconstruction of large lake historical data over the last 20 yr, and the high observation frequency with several commercial very high resolution sensors (TerraSAR-X, Radarsat-2, Cosmo-SkyMed) permits short reaction time to monitor rapid changes in all affected areas on the globe. With the upcoming Sentinel-1 satellites (Snoeij et al., 2011), additional SAR sensors will become available for monitoring the earth at very high temporal frequency.

GLOFs involve glacier lakes as the major source of water, but are usually part of a chain reaction or process combination, both before and after the lake outburst itself (Kääb et al., 2005a; Mergili and Schneider, 2011). For instance, glacial lake outbursts are not seldom, in particular in the Himalayas and the Andes, triggered by ice or rock masses falling into the lake and causing impact waves. Or, lake outbursts often cause debris flows when the flood wave entrains erodible sediments on its downstream valley path. Such debris flows have a much larger volume than the original water content of the flood and can thus have a much more devastating effect. Glacial lake outburst floods therefore have to be understood as part of a system of high-mountain processes around the lake of concern. That means that the surrounding of a potentially dangerous glacial lake and the (potential) processes in reach have to be considered too. For example, the stability of the surrounding moraines and their slopes and topography are of importance as potential source for events that may trigger a lake outburst. Mass movements, in particular, are more difficult to be detected than the lakes, since they only slightly differentiate in reflectance to stable rock (Schneider et al., 2004). A strong need for enhancing the presented glacial lake mapping service towards integrated hazard assessment was formulated by the user community. Immediate information needs related to glacier lakes are (i) slope stability above the lake and the valley below the lake, (ii) lake dam stability, and (iii) status and changes (size, mass balance, velocity) of the feeding or else connected glaciers. In this regard, apart from the detection of glacial lakes and their changes detected from very high-resolution satellite SAR intensity images investigated in this paper as a necessary first step, other products derived from SAR interferometric data may be considered in the near future. A more integrated, multi-level approach to tackle hazards related to glacial lakes with satellite SAR data may also include 46-day summer ALOS PALSAR coherence images for the mapping of glacier outlines (Strozzi et al., 2010a; Frey et al., 2012), in particular of debris-covered glacier outlines, and differential interferograms to identify areas showing displacements (e.g. Strozzi et al., 2004, 2010b). Due to the focus of this study, this discussion was limited to satellite SAR data, but satellite optical data, airborne imagery and ground data shall also be employed to derive similar or complementary information.

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