# EVALUATION OF QUICKBIRD AND IKONOS IMAGERY FOR ASSESSMENT OF HIGH-MOUNTAIN HAZARDS

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## ABSTRACT

The potential of satellite remote sensing for high-mountain hazard assessments has been increasingly recognized in recent years. So far, mainly satellite sensors such as Landsat-5/7, SPOT-3/4, or ASTER have been used for investigating glacial hazards. The recent emergence of commercial satellite sensors with very high spatial resolution in the sub-metre range opens new perspectives for applications in the area of natural hazards. Satellite sensors such as IKONOS, QuickBird or Orbview-3 provide imagery comparable to aerial photography. Presumably due to the recent emergence of these satellite sensors and the high image acquisition costs, studies on the application of QuickBird and IKONOS data for high-mountain hazards are largely missing yet. This contribution therefore aims at evaluating the potential of QuickBird and IKONOS imagery for high-mountain, in particular glacial, hazard assessments. QuickBird imagery was used in relation with a major rock-ice avalanche in the Northern Caucasus in 2002 for detailed analysis of avalanche formation and dynamics, for assessment of ice dam, lake and related flood hazards, and for mass movement model support. IKONOS imagery was used in the Swiss Alps for identification of potentially unstable debris slopes and debris flow formation in combination with digital terrain modelling. Limitations of this type of satellite data for high-mountain hazard studies are related to the high acquisition cost, and problems to collect sufficiently accurate ground reference data for geocorrection. However, this study shows that for the demonstrated applications in remote areas the achieved absolute ground positional error of 20-30 m allows of reasonable results. It is concluded that the QuickBird and IKONOS imagery are powerful tools for high-mountain hazard assessments with a high potential in the future.

**Keywords:** High-mountain and glacial hazards, IKONOS, QuickBird.

## INTRODUCTION

High-mountain areas are strongly affected by natural hazards due to their steep topography and related mass movement processes. The situation is aggravated by the sensitivity of high-mountain areas, and in particular of the glacial environment, to climate change. High-mountain areas are generally remote areas where ground-based collection of data and monitoring is difficult, prohibitive or impossible. Such reasons have prompted the application of airborne and spaceborne remote sensing techniques for monitoring and assessing high-mountain hazards (1,2). The analysis of aerial photographs has played an important role for glacial hazard research for several decades, e.g. for ice avalanche or glacial lake studies (3,4,5). It was, however, only in recent years that satellite remote sensing started to be increasingly used in this field of research owing to improved spatial resolution and a growing recognition of the potential of such studies. Applications have thereby focused on detection and assessment of hazardous glacial lakes (6,7,8), evaluation of ice avalanche potentials (9) or identificaion of debris flow initiation zones in periglacial environments (10). These studies were mainly based on optical satellite sensors such as ASTER, Landsat or SPOT. Most recent developments in optical satellite remote sensing have now led to a limited number of very-high resolution sensors, presently represented by IKONOS, QuickBird, OrbView-3, and SPOT-5 which has a slightly reduced resolution (11). Because of the recent emergence and the high acquisition cost, studies using these types of sensors for high-mountain hazards are yet largely missing. Therefore, it is the purpose of this paper to evaluate the technical aspects of QuickBird and IKONOS image processing and correction with a special focus on their use in remote high-mountain areas as well as to demonstrate their potential for related hazard applications. For QuickBird data, applications are shown in relation with a major ice-rock avalanche disaster in the North Caucasus in 2002. Applications for IKONOS imagery are demonstrated using debris slope instability problems and related debris flow formation in the Swiss Alps as an example.

## TECHNICAL SPECIFICATIONS

Successful launches of commercial very-high resolution satellites include IKONOS in 1999, QuickBird in 2001 and OrbView-3 in 2003, all of them having metre or sub-metre spatial resolution. SPOT-5 with a 2.5 m resolution has been in operation since 2002. Table 1 summarizes the main technical specifications of these sensors.

*Table 1: Technical specifications of very-high resolution satellite sensors (information from (12), DigitalGlobe, ORBIMAGE, Space Imaging and Spot Image).*

| Satellite sensor; Provider | Spectral bands | Spatial resolution / swath width (at nadir) | Average revisiting time; off-track viewing angle | Price per km$^2$ (USD) |
|---|---|---|---|---|
| IKONOS<br>Space Imaging | Panchromatic:<br>450-900 nm<br>445-516 nm<br>506-595 nm<br>632-698 nm<br>757-853 nm | 0.81 m / 11 km<br><br>3.2 m<br>3.2 m<br>3.2 m<br>3.2 m | 2-3 days<br>±30° | ~ 18 |
| QuickBird<br>DigitalGlobe | Panchromatic:<br>450-900 nm<br>450-520 nm<br>520-600 nm<br>630-690 nm<br>760-900 nm | 0.61 m / 16.5 km<br><br>2.44 m<br>2.44 m<br>2.44 m<br>2.44 m | 1-3.5 days<br>±30° | ~ 24 |
| OrbView-3<br>ORBIMAGE | Panchromatic:<br>450-900 nm<br>450-520 nm<br>520-600 nm<br>625-695 nm<br>760-900 nm | 1 m / 8 km<br><br>4 m<br>4 m<br>4 m<br>4 m | < 3 days<br>±50° | ~ 20<br>(unconfirmed) |
| SPOT-5<br>Spot Image | Panchromatic:<br>480-710 nm<br>500-590 nm<br>610-680 nm<br>780-890 nm<br>1580-1750 nm | 2.5, 5 m / 60 km<br><br>10 m<br>10 m<br>10 m<br>20 m | 5 days<br>±27° | ~ 1.2 |

The three commercial, US-based satellite systems have all very similar technical characteristics in terms of spectral band ranges, spatial resolution and revisiting times. For application in the field of natural hazards it is of importance that thanks to the pointing capabilities of the sensor the revisiting period can be decreased to less than three days. SPOT-5 has a slightly reduced spatial resolution and cannot produce real-colour images but disposes of an along-track stereo sensor and is a significantly more economic option than the commercial competitors.

## IMAGE PROCESSING AND GEO-CORRECTION

This section resumes the working steps of image acquisition, georectification and topographic correction for both QuickBird and IKONOS.

**QuickBird**

Image acquisition: DigitalGlobe, the provider of QuickBird data, offers different image data products with varying corrections applied. 'Basic' imagery may be the preferred choice for research purpose since the least system correction, in particular no topographic pre-correction, is applied to this data type. However, financial expenses can be a limiting factor, because this data type is only delivered for entire scenes. The 'Ortho Ready Standard' format can be a feasible alternative since a user-defined image size can be acquired and a topographic pre-correction is not applied, either. With the 'Standard' format the original image geometry cannot be replicated due to a coarse topographic correction previously applied by DigitalGlobe. Here, QuickBird panchromatic and multispectral images in 'Ortho Ready Standard' format from 25 September 2002, five days after the avalanche catastrophe (see section below), were acquired.

Georeferencing: QuickBird imagery has a number of specific characteristics and requirements which are new and challenging in comparison to satellite imagery with more conventional ground resolution. The main issues are related to

- handling of unusually large image files
- accuracy requirements related to the very high spatial resolution (1 m and better), particularly related problems in remote or badly documented regions.

The first point involves problems of computing power and software processing time. The largest image files (0.6 m ground resolution) are up to 2 GB in size and thus 1-2 orders of magnitude larger than most remote sensing image files. Secondly, highly accurate ground control points (GCPs) are required in order to achieve a high absolute accuracy (in accordance with the high spatial resolution of QuickBird imagery). Such high-precision GCPs are usually not extractable from standard topographic maps and must be taken by geodetic surveys (including differential GPS techniques). However, in high-mountain areas, and particularly in remote regions, field surveys are often not possible or too time-consuming. In North Ossetia, 1:25,000 maps have been used to extract GCPs. These Russian maps, however, are not very accurate and often out of date.

PCI Geomatica 9.02 was used for the geometric correction. For the images covering the glacierized areas, accurate GCPs were difficult to find and mainly mountain summits or river/torrent confluences had to be used. About 15-25 GCPs per image scene (with scene sizes of about 300-400 $km^2$) were collected. Once the GCPs were defined, the DEM derived from ASTER along-track stereo imagery (e.g. (13)) was used to calculate the orthorectified image. The ASTER DEM had a resolution of 30 m, which is theoretically not adequate to correct a satellite image in the range of 0.6-2.5 m. For nadir images, a DEM of roughly one order of magnitude higher resolution may be used. The QuickBird images used here were not taken at nadir position but with a pointing angle of ca. 25° and therefore a DEM with a resolution better than 30 m should be used. However, for such very-high resolution images, DEMs of comparable resolution are mostly missing, especially in high-mountains or less developed countries. Where the ASTER DEM lacked elevation values (e.g. due to cloud coverage) or large errors were present, a DEM derived from the Shuttle Radar Topography Mission (SRTM) was integrated instead (for details see (14,15)). The vertical RMSE of the ASTER DEM was around 60 m for the Kolka-Karmadon area with maximum errors of up to 500 m (15). A maximum vertical error of 500 m of the ASTER DEM translates into a horizontal position error for the orthoprojection of ca. 90 m for the 8.5° across-track pointing of the ASTER sensor, a 60 m vertical error into a 10 m position error (13). For the QuickBird ortho-image, the resulting ground RMSE was between 10 and 30 m. Maximum vertical errors of several hundred metres of the ASTER DEM, however, were only found for mountain peaks and thus did not strongly affect the analysis of the QuickBird image. The error was hence acceptable for the applications performed here. When a significantly higher accuracy would be requested, e.g. for detailed planning issues, the raw image files could be re-corrected using more accurate GCPs and DEMs.

Briefly summarised, unusually large image files, maps and thus GCPs with insufficient accuracy, and a DEM with limited resolution were the main problems encountered with the geometric correction of the QuickBird images in the Caucasus. In addition, very few experiences with QuickBird image processing were available at the time of the study performed, in particular with regard to high-mountain areas.

### IKONOS

Image acquisition: Similar to QuickBird, IKONOS provider Space Imaging offers different data products with different corrections applied. Here, a least correction format was chosen with the image tied to the UTM coordinate system but with no topographic correction applied. The panchromatic image was taken on September 17, 2000 in the central Swiss Alps (Grimsel region).

The geometric correction was also performed with PCI Geomatica. Ten GCPs were used for the image with a size of ca. 180 km$^2$. The resulting ground RMSE was ca. 3.5 m. For the topographic correction, the 25 m-gridded DEM available from the Swiss Federal Office of Topography was used (Swisstopo). Though the geometric image correction process was performed with standard reference data (topographic maps of 1:25,000 scale) and no specific GPS-supported GCPs were collected, the accuracy achieved was very reasonable and acceptable for the objectives aimed at.

## QUICKBIRD AND THE 2002 CAUCASUS ROCK-ICE AVALANCHE

### The 20 September 2002 avalanche disaster in the Caucasus

A massive rock-ice avalanche of about $100 \cdot 10^6$ m$^3$ volume took place on the northern slope of the Kazbek massif, North Ossetia, Russian Caucasus, on September 20, 2002 (16,17). The avalanche started as a slope failure, that impacted and almost completely entrained Kolka glacier, travelled down the Genaldon valley for 20 km, was stopped at the entrance of the Karmadon gorge, and was finally succeeded by a distal mudflow which continued for another 15 km (18), Figure 1. In Karmadon, the ice-rock avalanche deposits formed an enormous dam of ca. 2 km length, 0.5-1 km width and 100 m thickness. The event caused the death of approx. 140 people and massive destruction. Lakes which formed at the margin of the dam rapidly grew during the days and weeks after the avalanche and threatened the downstream area (8). An up-to-date ground reference was required for disaster management and hazard analysis. Recent aerial photographs were not available and a special campaign for taking aerial photographs was not feasible due to the political situation (North Caucasus conflict). Physical access to the avalanche starting zone was very difficult. QuickBird imagery could provide the necessary details of the area. The following sections demonstrate QuickBird applications for high-mountain hazards shown with examples from the Caucasus case.

### Avalanche analysis

The analysis started at the initial slope failure zone in the Kazbek massif between 3,500 and 4,300 m a.s.l. With the geocorrected QuickBird images and pre-event photographs, the volume of the failure mass including the amount of ice and rock involved could be estimated by measuring the area of the ice shear-off zones and estimating the related shear depth in the satellite image. Also the main geological structures could be identified. With respect to the eroded Kolka glacier, the analysis of the images concentrated on the total mass lost. The high spatial resolution of QuickBird allowed textural image characteristics to be used to identify morphological structures on the remnants of the glacier and thus to derive conclusions about the nature of the mass impact. In the same way, erosion structures and trim lines of ice shear-off zones were detected on the QuickBird images.

In the avalanche track and transition zone various parameters were calculated or estimated on the base of the QuickBird satellite images. Flow depth and width, and a number of cross sections were derived with the aid of a DEM. Avalanche superelevations were measured to calculate the maximum flow velocity (Figure 2). Such parameters were used to reconstruct the processes and for computer models of mass movements. The QuickBird images were highly useful to analyse the flow process, i.e. the detailed direction of the flow, more fluid and solid flow phases, etc. The near-infrared band of QuickBird was used to distinguish between vegetated and non-vegetated areas (high reflectance of vegetation in the near-infrared spectrum). Specific flow processes such as overjumping of the avalanche of ridges could thus be detected. The sharp trim line between areas affected and not affected by the avalanche, which were detectable on the QuickBird images, indicated that the avalanche was a rather liquid flow type without a significant dust part.

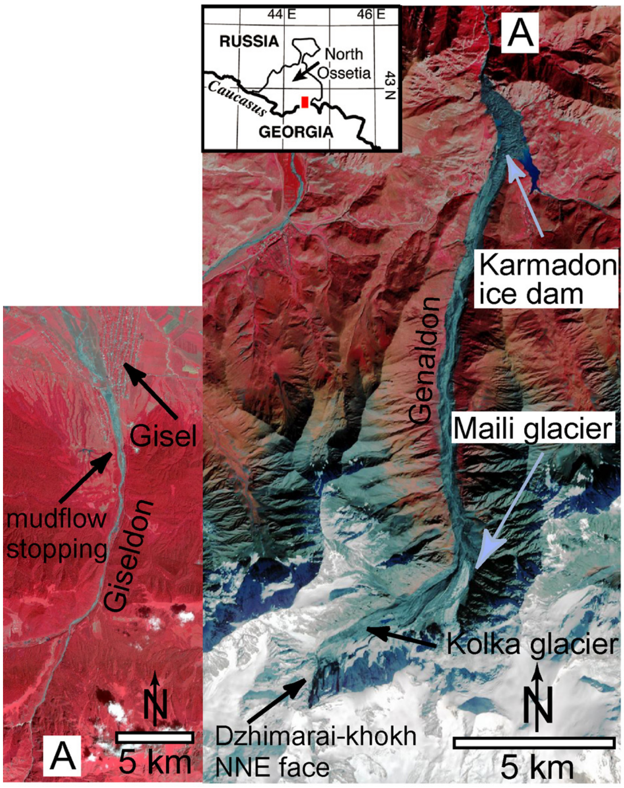


*Figure 1: Overview of the 2002 Kolka-Karmadon rock-ice avalanche in the Northern Caucasus starting from the Kazbek massif (Dzhimarai-khokh). The left image shows its continuation to the north (ASTER image from October 6, 2002).*

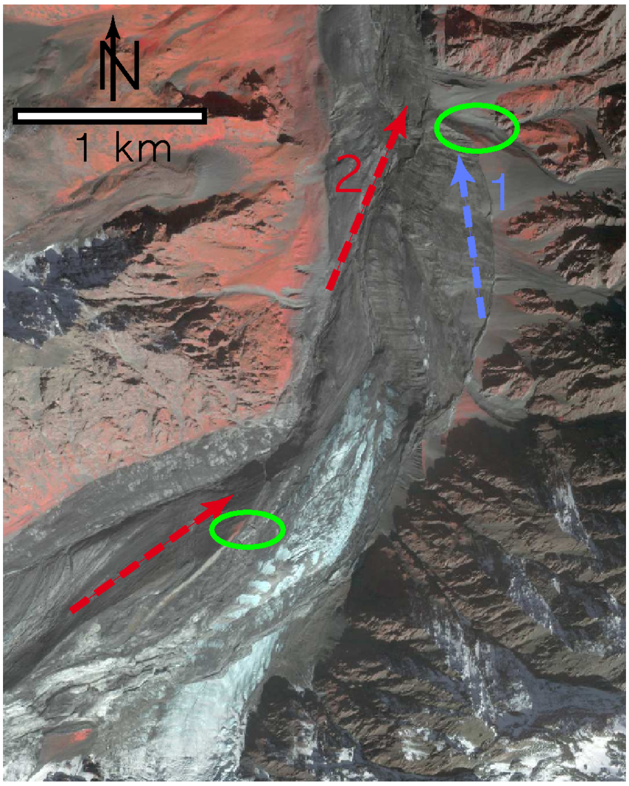


*Figure 2: Near-infrared QuickBird image of the superelevation zone of the ice-rock avalanche in the Caucasus. Arrows indicate avalanche flow direction as visible on the image. The blue arrow represents the first more liquid surge, while the red one points to deposits from the second surge. The green circles are evidence of unaffected vegetation (in red), the upper one indicating overjump processes.*

### Ice dam assessments

The QuickBird images were also used for studies of the ice dam and the marginal lakes (Figure 3). The areal extension of the ice dam was mapped on the ortho-image. Geodetically measured topographic profiles across the dam in combination with terrain information of pre-avalanche conditions from map-derived DEM yielded the dam depth, and together with dam surface information, volume estimates could be made. Similar calculations of ice dam depth and volume were made using the post-avalanche ASTER DEM and the pre-avalanche DEM yielding maximum ice dam depths of 150 m (15). Errors involved in these calculations can be assessed from a RMSE of 11 m of the ASTER DEM in the ice dam area. It was important to know the ice dam volume in order to reconstruct the avalanche mass volume and to consider the stability of the ice dam. Based on the images, the morphological characteristics of the ice dam were analyzed as well as possible zones of instability indicated, for instance, by dam collapse processes. With simultaneously taken ASTER images, the spatial resolution was a drawback to perform a similar analysis. Drainage channels and the general hydrology of the ice dam were investigated in order to estimate possible related hazards. Likewise, the areas of the different ice-dammed lakes were calculated and stored water volumes estimated. Comparison of QuickBird and ASTER images allowed an assessment of the ice dam development over time (8). Based on these studies, potential water outburst scenarios were defined and impacts on downstream areas anticipated.

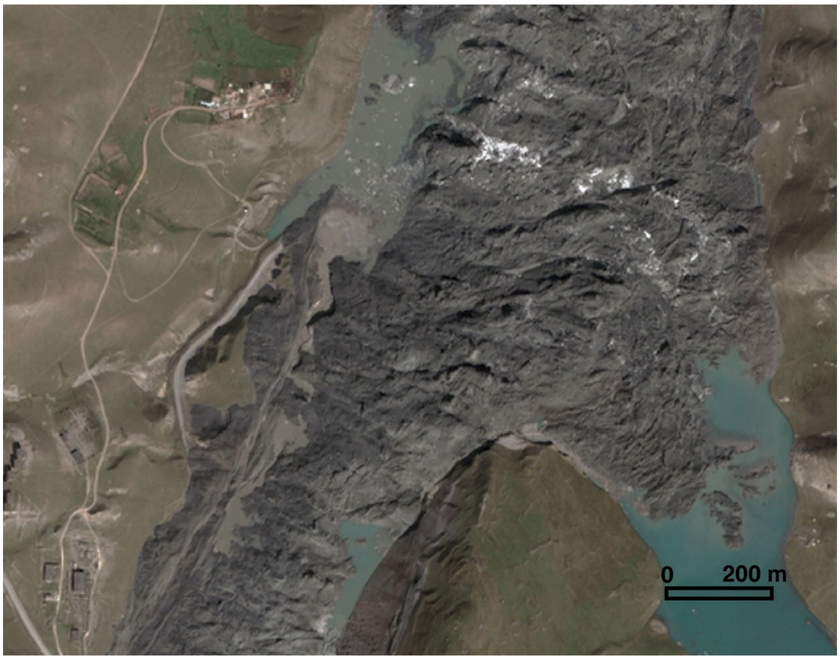


*Figure 3: QuickBird image of the upstream part of the ice dam at Karmadon showing well the marginally dammed lakes.*

### Visualization and hazard mapping

The QuickBird images were used as a cartographic basis necessary for projection, evaluation and verification/adjustment of computer models, since an up-to-date cartographic basis was missing (for details on the flow models, cf. (19,20)). The model results could thus be projected on the satellite images and directly verified (back-analysis of 2002 event) and evaluated (simulation of potential hazards). This allowed us to detect where buildings or traffic routes could be affected. Endangered areas were thus designated. Generation of a hazard map for the Karmadon area was based on concepts developed in Switzerland which differentiate between the two categories intensity and probability of occurrence of a dangerous event (21). Each category is rated 'low', 'medium' or 'high'. In case of Kolka-Karmadon, generation of the hazard map is complicated by the high complexity of the natural processes. The 2002 event and smaller ones in 1835 and 1902 were used to derive a probability of occurrence of 0.45 (corresponds to a medium rating), whereas the intensity of the events is clearly high (inundation heights >2 m). These considerations result in a high danger rating (red zone). Delineation of the areal extent of the red zone was based on the 2002 event and on the simulations with computer avalanche and debris flow models (Figure 4). The hazard map is preliminary so far and shows only the high-danger zone. Other hazardous processes such as snow avalanches are not included in this version. For mapping the endangered zones, the satellite images were an excellent means and visualization tool. They can replace topographic maps in the range of 1:10,000.

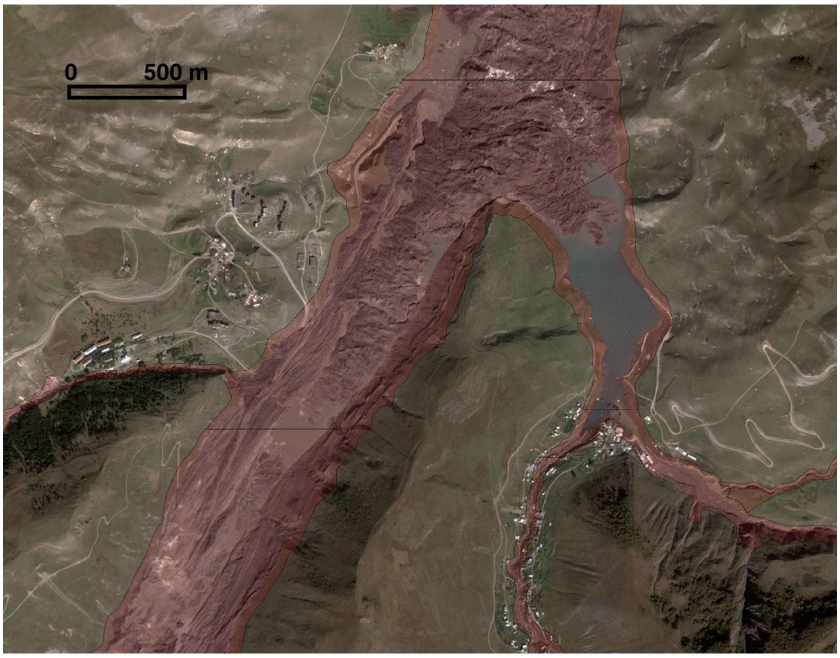


*Figure 4: Hazard map for the area of Karmadon/Saniba (North Ossetia), showing the high-danger zone in red, based on hazard modelling and assessment, and using QuickBird satellite imagery mapping.*

**Disaster management and response**

Very-high resolution satellites such as IKONOS or QuickBird are currently the only satellite sensors actually suitable for evaluating damages caused by mass movements or floods. The ground resolution is thereby a critical factor. Damage assessment with QuickBird images was possible down to individual buildings (Figure 5). The satellite images were best used to evaluate the number of inundated or destroyed buildings. Precise damage characteristics of single buildings, however, could not even be recognised with QuickBird images. Minor or major traffic routes affected could also be designated.

In emergency situations, time is of critical importance. The minimum of about 60 hours for rapid data delivery with QuickBird can result in an essential delay depending on the type of disasters. New satellite constellations are being planned which are dedicated particularly to disaster management/response and have data providing times of a few hours (22). In fact, the overall cost of a disaster often depends on how quickly the event is responded to, and how efficiently response activities are managed. This requires a synoptic overview of the affected area. Satellite images of 15-30 m resolution have been recognised not to completely fulfil these needs. QuickBird images do have the capabilities for emergency applications, for example assessment of critical lifelines such as roads, telecommunications or power supplies.

In North Ossetia, the QuickBird images were not intended for immediate emergency applications. The days following the catastrophe were mostly characterised by recovery actions. A rapid image supply could indeed have helped assessing the viable access routes. The lack of experience with QuickBird data acquisition and processing at that time, however, would have prevented a rapid image acquisition.

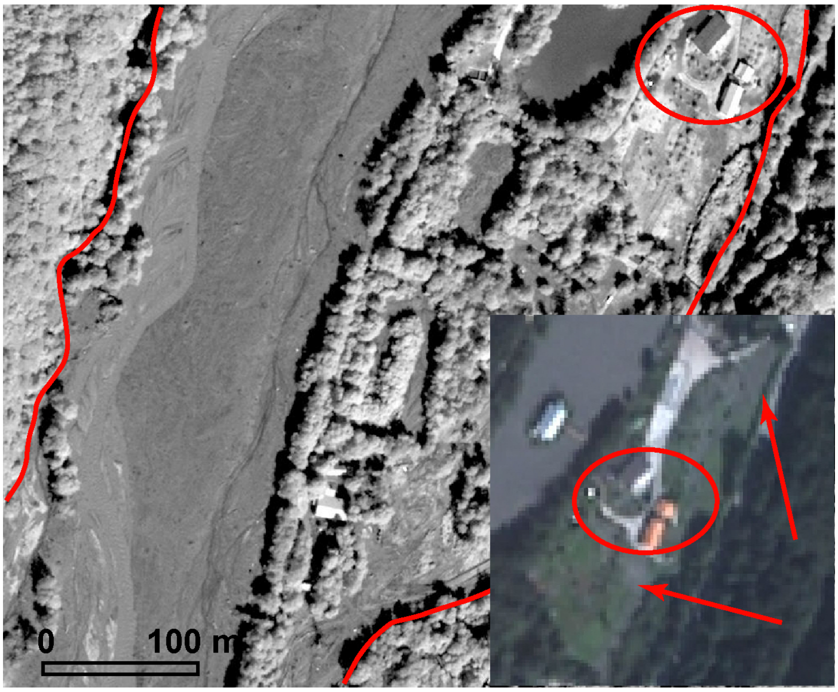


*Figure 5: Panchromatic 0.6 m QuickBird satellite image of an area affected by the mudflow in the Giseldon river. The image shows private property affected by the mudflow deposits. The lower right inset is the corresponding multispectral image with inundated areas indicated by arrows. Red circles depict the same buildings in the panchromatic and multispectral images.*

## IKONOS AND PERIGLACIAL DEBRIS SLOPE INSTABILITY IN THE SWISS ALPS

### Periglacial slope instability and debris flow initiation

Debris flows are a widespread hazard in the Alps and regularly cause severe damages and occasionally casualties. In the Swiss Alps, many of the debris flows have their origin in periglacial areas. Investigations of severe and repeated debris flow disasters in the Swiss Alps have shown that more than 50% of debris flows greater than 1,000 $m^3$ originated in zones which were still covered by glaciers 150 years ago (23,24). Steep areas of morainic, unconsolidated sediment which have been uncovered by glaciers since the Little Ice Age maximum around 1850 are particularly prone to debris flow formation (25) due to hydrogeological processes reducing the mechanical stability (10). It is found that debris flows originating in large and steep debris reservoirs such as talus or scree slopes have typical starting slope inclinations between 27° and 38° (26). Hydrological conditions related to the permeability, grain size and structure, or possible permafrost occurrence are further components of critical importance for debris flow formation (10,24). In the Alps, large areas in the glacial and periglacial environment consist of unconsolidated debris reservoirs potentially prone to debris flow initiation. Detection of possibly critical areas on a regional basis could contribute to the assessment of related debris flow hazards.

### Remote sensing of potentially unstable debris slopes

Optical high-resolution sensors basically have the potential to identify periglacial debris slopes on a regional scale. However, in practice, the detection of steep sediment reservoirs from remote sensing imagery is a major challenge. A main problem is the spectral similarity of bare rock and debris (27). Therefore, classification algorithms considering spectral information only are unlikely to yield satisfactory results. Recent research efforts directed to map debris-covered glaciers were confronted with similar problems, and stressed the importance of including digital elevation information for classification (27,28). Further studies have shown that classification methods (artificial neural network) based on multispectral imagery with a spatial resolution of about 20-30 m (e.g. Landsat-TM) did not yield satisfactory results in mapping debris slopes (10). It has been found that the spatial resolution played a crucial role in the distinction between rock and debris material, since debris accumulations show a uniform surface structure in contrast to exposed bedrock as a function of spatial resolution. Such uniform structures are not recognized by satellite sensors with spatial resolution of 20 to 30 m, spatial resolution thus being a limiting factor.

**IKONOS-based detection techniques**

The aforementioned studies gave reason to start investigation with the very-high resolution sensor IKONOS. The following methods were developed for automatic detection of potentially unstable debris slopes. An edge detection filter was found to be able to detect the structural uniformity of debris accumulations and to discriminate them from the irregular structure of bedrock (Figure 6). The filter calculates the average of the grey value difference between the central pixel and each of its surrounding neighbours and assigns the value to the central pixel. More uniform areas have smaller grey value differences and are thus assigned lower values. The number of neighbours is defined by a moving window of specified dimensions. An appropriate window size basically depends on the scale of the structure to be detected. Here, best results were obtained by an 11×11 window. The resulting grey value image was then segmented into debris and bedrock according to a threshold value of 47. A 5×5 median filter was finally applied to smooth the classification and avoid small isolated pixels.

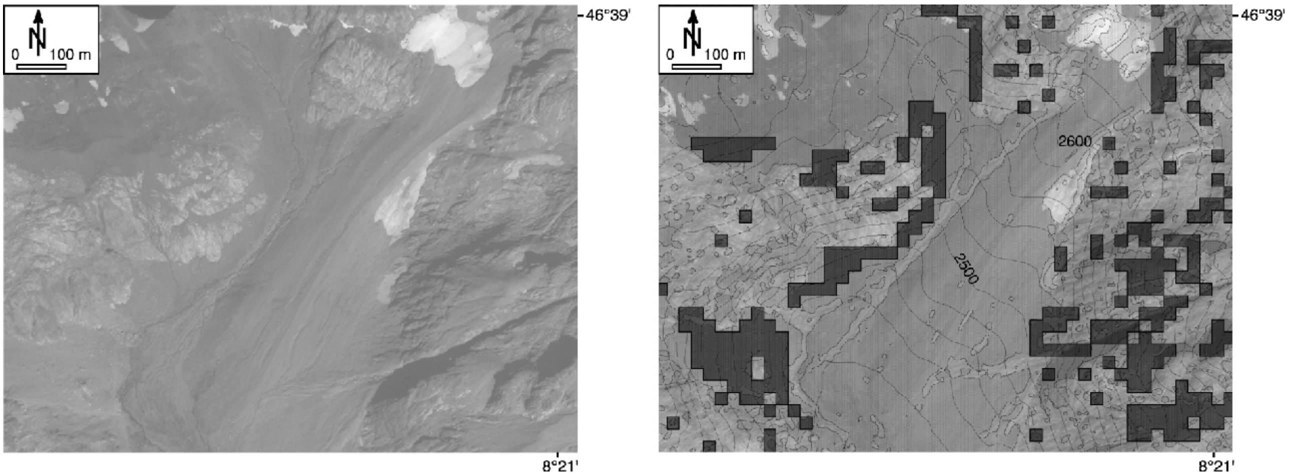


*Figure 6: IKONOS panchromatic image of September 17, 2000 with 1 m spatial resolution of a periglacial area in the Grimsel region (Swiss Alps) with mixed presence of large talus slope, debris and bedrock (left). Potential debris flow initiation zones (black) based on the classification of debris reservoirs (grey) and bedrock/sporadic debris (light grey).*

For detection of potential debris flow initiation zones, areas with a slope range between 27° and 38° (using the official Swiss 25 m-gridded DEM) were selected from the previously classified debris accumulation areas. The areas thus identified could then be used as an input to a GIS-based model simulating the potential debris flow and delineating areas likely to be affected (10). As outlined in greater detail in (10), the model computes the downstream propagation of the debris flow based on the topography. The travel distance is constrained by a threshold ratio of vertical drop to horizontal run-out distance of 0.19 (i.e. average slope). Several studies have shown that this slope value encompasses debris flow events in the Swiss Alps (23,26) and is thus suitable for a worst-case scenario.

## CONCLUSIONS

Very-high resolution sensors such as QuickBird, IKONOS or Orbview-3 have significantly pushed forward the limits of application set by more conventional sensors with a resolution of about 20-30 m. Due to its recent emergence and high acquisition cost, the potential of this new type of imagery has not yet been fully exploited, particularly not in high-mountain areas. Here, applications with respect to high-mountain hazards were demonstrated. QuickBird imagery was used for detailed analysis of avalanche formation and dynamics, for assessment of ice dam, lake and related flood hazards, and for mass movement model support. Once geocorrected, QuickBird images can represent an excellent cartographic basis, e.g. for hazard mapping. In remote mountain areas, similar reference data are often far from being available. IKONOS imagery was used in this study for identification of potentially unstable debris slopes in combination with digital terrain modelling. The same applications previously failed with satellite imagery of reduced resolution.

Given the high spatial resolution, QuickBird or IKONOS imagery could also be used for disaster response such as rapid damage assessment or assessment of critical lifelines in order to quickly and efficiently manage response activities. The critical factor thereby is, however, how fast satellite images can be delivered. The 2-3 days currently necessary for QuickBird data are often not feasible. If, for a specific hazard situation, repeated acquisition of images is needed, e.g. for continuous hazard monitoring, or for pre-/post-event analyses, QuickBird or IKONOS may often be too expensive and sensors such as ASTER or SPOT 5 may be the more appropriate tools.

Image processing and geocorrection for QuickBird and IKONOS may require costly ground reference data when highest precision is pursued. In remote high-mountain areas the accuracy of the image geocorrection process must be reduced. However, the current study has shown that an absolute ground positional error of 20-30 m allows of reasonable results for the applications performed.

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