Assessing the debris around glaciers using remote sensing and random sets

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Abstract

Glacier mapping from satellite multispectral image data is hampered by debris cover on glacier surfaces. Information on the spatial distribution and spatial-temporal dynamics of debris, however, bears various kinds of uncertainties. Debris exhibits the same spectral properties as lateral and terminal moraines and as bedrock outside the glacier margin. Multispectral classification alone is thus not suitable to properly assess its extent. Additional information has to be included, like the low slope angles and curvature characteristics. In this research we propose a random set method for uncertainty modelling of debris-covered glaciers extracted from remote sensed data. Here, we analyse the Fedchenko glacier situated in the Pamir mountains in Central Asia. Clean glacier ice and debris area are represented by random sets. Their statistical mean and median are estimated. The paper combines the advantages of an automated multispectral classification for clean glacier ice and snow with slope information derived from the digital elevation model (DEM). We use an SRTM3 DEM that is resampled to 30m. From a 1999 Landsat ETM+ image the results show that the mean area of clean glacier ice equals 841.87 km^2, and 94.39 km^2 for debris-covered area. Temporal analysis shows that the mean area of clean ice increased from 1992 to 1999 and is decreasing since 1999, in opposite to the debris covered area. We conclude that this method based on random set theory has the potential to serve as a general framework in uncertainty modelling of debris-covered glaciers and is applicable for mountainous glaciers.

Keywords: Random set theory, Uncertainty modelling, Glacier mapping, Debris cover, DEM analysis

1. Introduction

Due to the remoteness and inaccessible nature of mountain glaciers, remotely sensed data are an efficient tool for regular mapping of glaciers in a comprehensive and effective manner. A number of remote sensing techniques for automated mapping of clean glacier ice by means of multispectral classification are available. Commonly used techniques such as single band ratios and Normalized Difference Snow Index (NDSI) take advantage of the high brightness of snow and ice in the visible wavelength to separate them from darker areas such as rock, soil or vegetation. The greatest difficulty in glacier mapping from remote sensed data, however, is the presence of debris on glaciers. A debris-covered glacier area has a similar visible and near-infrared spectral signature to the surrounding terrain and thus complicates the mapping of glaciers (Bolch and Buchroithner 2007). Here, the traditional multi-spectral classification techniques are of limited value. A number of methods have been proposed to address this problem. These methods use additional information provided by topography (Bishop, Bonk *et al.* 2001), neighbourhood analysis (Paul, Huggel et al. 2004) and thermal radiation (Taschner and Ranzi 2002).

Information on spatial distribution of debris-covered glaciers from remote sensed data bears various kinds of uncertainties. Existing techniques for mapping debris-covered glaciers are crisp-based and have limitations in delineation of glaciers boundary where the transition between the debris-covered glacier and the adjacent terrain is gradual. A thresholding segmentation technique can be used in principle for identification of clean glacier ice from band ratio images and the debris-covered areas from glacier slope image (Paul, Huggel et al. 2004). Selection of a threshold value, however, is a critical task as a slight change can lead to overestimation or underestimation of the areal extent. The threshold value may be different for different satellite sensors and for different seasons (Dozier 1989; Hall, Riggs et al. 1995). Since it is arbitrary to choose a single-valued threshold, uncertainties exist in any segmentation results and can have a large effect on the subsequent spatial analysis (Lucieer and Stein 2002).

To investigate inherent uncertainties in observations of glaciers from satellite imageries, this study proposes a random set method for uncertainty modelling of debris-covered glaciers. A glacier with uncertainties can be treated as a randomly varying set, i.e. a random set. In this research we show that random sets can serve as a framework to model debris-covered glaciers with inherent uncertainties. Fedchenko glacier situated in the north-western part of the Pamir mountains, Tajikistan, was chosen as a study case for this research. The southern end of the glacier basin is located at 38º30´16´´N, 72º17´00´´E; the northern end at 39º05´10´´N, 72º18´52´´E.

In the following section we elaborate on the data used and the method proposed by this research. Section 3 presents results of the data processing for the Fedchenko glacier. Section 4 concludes the paper.

2. Data and method

2.1 Data used

Landsat images from the TM and the ETM+ sensors are used in this research due to their availability, and their moderate spatial and spectral resolution. For observations on glaciers it is important to work with images that have no cloud over the glaciated area and that have been taken at the end of the ablation season when the temporary snow cover is at its minimum and all the glacier zones can be clearly demarcated. These factors restrict the use of most available imagery. In total two orthorectified Landsat TM images (September 1992 and 2009) and one orthorectified ETM+ image (September 1999) were used.

A digital elevation model (DEM) is used to derive the slope information needed for identification of debris-covered area of a glacier. For the study area the only available DEM were a Shuttle Radar Topography Mission (SRTM3) DEM and an ASTER GDEM. The SRTM3 DEM is used in the research as it has a higher accuracy. A cubic convolution method of interpolation is used to resample the SRTM3 DEM to a 30 m resolution. Absolute vertical accuracies of DEMs were measured by comparison with ground control points (GCP) – elevation points extracted from Russian Topographic Maps (published data: 1979) distributed throughout the study area.

2.2 Method

The Normalized Difference Snow Index (NDSI) is employed for the identification of glacier snow and ice (GSI). Glacier surfaces that are covered by debris have a gentle slope, whereas at the contact edge of the glacier with the surroundings or bedrock, a distinct change in slope can be observed. This edge can be utilized for a delineation of debris-covered glaciers (Paul, Huggel et al. 2004). In this research we used this idea for the identification of plain areas, where potentially debris-covered areas of glacier might be situated. Plain areas are further processed for extracting the debris covered area (DCA).

For uncertainty modelling of debris-covered glaciers a random set model was applied. Thresholding approach of image segmentation was used to generate a random set. The idea of random set generation is that the extents of the two classes, GSI and plain areas, extracted from NDSI and slope images, respectively, are sensitive to the different thresholds. Therefore by slightly changing a threshold, a set of objects is generated. These form the focal elements of a random set.

To map a debris-covered glacier we use the NDSI and slope images. An NDSI image, which has values from -1 to 1, was segmented using a threshold value to obtain a binary image. A range of thresholds was selected combining values proposed in the literature and inspection of the images, as the human eye can estimate the correct values by using textural features. The range of threshold values was divided into n equal intervals, resulting into $n+1$ thresholds to produce the binary images. Slope information is used to delineate the plain areas where potentially DCA is situated. The minimum threshold value is defined from the mean value of slope calculated from the cross-profiles to glacier body, whereas the maximum threshold value is set equal to 24°, being an upper limit for the steepness that a glacier might have (Paul, Huggel et al. 2004).

The covering functions of the generated random sets give the probability of an image pixel to be GSI or to be situated on plain areas. Suppose, ξ is an image pixel in Euclidian space $\mathbb{R}^2$: $\xi \in I \subset \mathbb{R}^2$ with pixel size r and a slope value d, and $\mathcal{A}_\mathrm{i}$, $\mathrm{i}=\{1,2, \ldots,\mathrm{n}\}$ and $\mathcal{B}_\mathrm{j}$, $\mathrm{j}=\{1,2, \ldots,\mathrm{m}\}$ are the focal elements of random sets $\mathcal{A}$ and $\mathcal{B}$ generated from the NDSI and the slope image, respectively. The covering function Γ of the random set $\mathcal{A}$ gives the probability for every pixel to be covered by the set $\mathcal{A}$. The probability of pixel ξ to be in the random set $\mathcal{A}$ is calculated as (Molchanov 1993),

$$\mathrm{Pr}_{\Gamma}(\xi)=\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}} I_{\mathcal{A}_\mathrm{i}}(\xi)$$

where $I_{\mathcal{A}_i}$ is the indicator function of $\mathcal{A}_\mathrm{i}$ defined as

$$I_{\mathcal{A}_i}=\begin{cases}1, & \xi \in \mathcal{A}_i \\ 0, & \xi \notin \mathcal{A}_i\end{cases}$$

Due to the rough mountainous terrain the identification of debris-covered areas requires additional analysis to slope bounding. Because plain areas ($0° < d < 24°$) occur everywhere in the study area, it is necessary first to eliminate plain areas that are not a part of the glacier. Only plain areas connected to GSI can be part of the debris cover. The covering function Π of plain areas is calculated from the focal elements of the random set $\mathcal{B}$ in the same way as Γ. The support set $\Pi_s=\{\xi \in \mathbb{R}^2\colon \mathrm{Pr}_\Pi(\xi) > 0\}$ describes the possible part of the debris-covered area. It consists of N detached components, $\Pi_s=\bigcup_{\mathrm{j}=1}^{\mathrm{N}} \Pi_\mathrm{j}$. We exclude those areas that are not connected to the possible part of clean glacier ice: $\Gamma_s \cap \Pi_\mathrm{j} = \emptyset$, and recalculate Π accordingly.

The second step is calculation of the covering function Δ of DCA. The GSI area of glaciers occurs in plain areas along with DCA, there is no DCA on a plain area but GSI. In other words, for a pixel that is possibly covered by plain areas, its probability to be covered by DCA depends whether the pixel has been classified as GSI or not. If the probability of an image pixel being covered by plain areas is greater than 0 and its probability to be GSI is positive: $\mathrm{Pr}_\Gamma(\xi)>0$ and $\mathrm{Pr}_\Pi(\xi)>0$, then the probability to be in DCA is $\mathrm{Pr}_\Delta(\xi) = \min\{\mathrm{Pr}_\Pi(\xi), 1 - \mathrm{Pr}_\Gamma(\xi)\}$, otherwise $\mathrm{Pr}_\Delta(\xi)= \mathrm{Pr}_\Pi(\xi)$.

The level sets ($\Gamma_p = \{\xi \in \mathbb{R}^2\colon \mathrm{Pr}_\Gamma(\xi) \geq p\}$) are used to reflect the spatial distribution of the varying sizes of the random sets to quantify the extensional uncertainty of segmented objects. The mean area EA of the random sets Γ (GSI) is determined by

$$\mathrm{EA}(\Gamma) = \mathrm{r} \times \sum_{\xi \in I} \mathrm{Pr}_\Gamma(\xi).$$

The Vorob'ev expectation as an estimation of the mean is different from the median set of Γ, defined as the 0.5-level set. The mean of the random set Γ is estimated by first determining the mean area EA(Γ), and then finding a p-level set for Γ which has the area equal to EA(Γ) (Zhao, Stein *et al.* 2010).

The set-theoretic variance of a random set Γ is defined as:

$$\Gamma_{\mathrm{var}}(\xi) = \sum_{i=1}^{N} \left(I_{\mathcal{A}_i}(\xi) - \mathrm{Pr}_\Gamma(\xi)\right)^2,$$

whereas the sum of the Γ_{var}, denoted as SD, as:

$$\mathrm{SD} = \mathrm{r} \times \sum_{\xi \in I} \Gamma_{\mathrm{var}}(\xi)$$

and the coefficient of variation (CV) as CV=SD/EA, being a normalized and dimensionless measure. The CV summarizes the dispersion of the distribution of a random set. A high CV indicates a larger proportion of objects with a high Γ_{var} or Δ_{var} and thus points to a large extensional uncertainty (Zhao, Stein *et al.* 2010). Extensional uncertainty for GSI and DCA is identified by

$$\frac{\sum_{\xi \in \mathrm{I}} \Gamma_{\mathrm{var}}(\xi)}{\sum_{\xi \in \mathrm{I}} \mathrm{Pr}_\Gamma(\xi)} \text{ and } \frac{\sum_{\xi \in \mathrm{I}} \Delta_{\mathrm{var}}(\xi)}{\sum_{\xi \in \mathrm{I}} \mathrm{Pr}_\Delta(\xi)}.$$

3. Results

The mean area of GSI and DCA in 1999 equals 841.87 km^2 and 94.39 km^2, respectively. Debris cover amounts to around 10% of the total glaciated area. The differences between the areas of support set and core set (Γ_1, Δ_1) indicate the extensional uncertainty. These are 50.78 km^2 and 33 km^2 for GSI and DCA, respectively, constituting 6% of GSI and 35% of DCA areas respectively. The higher uncertainty corresponds to a higher variance of random sets (Bandishoev 2011).

Due to the rough mountainous terrain, each terrain aspect has specific properties. For example, there is more snow accumulation in the north aspect due to less solar illumination in comparison with the south. We use the aspect information derived from DEM to quantify the uncertainty of GSI and DCA. The results are given in Figure 1.

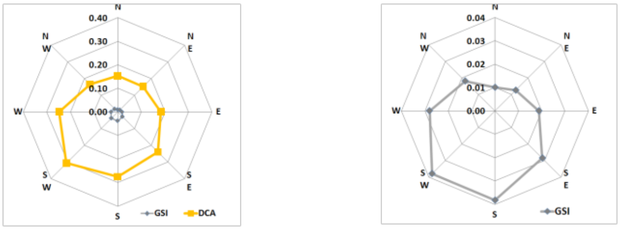

Figure 1. Coefficient of variation of GSI and DCA areas versus aspect.

A large extensional uncertainty of GSI occurs on the south-western and southern aspects of the terrain (CV=0.038) and to a lesser degree on the northern aspect (CV=0.01). With the sun azimuth (143.55) and sun elevation (51.93) of ETM+ image used in this research, the reason of relatively large extensional uncertainty might be saturated pixels on southward aspects. The total CV for GSI equals 0.021, being an indicator of a smaller extensional uncertainty. For DCA a rather large extensional uncertainty occurs (CV=0.2), and most of it occur on the south-western and southern aspects. The reason of such a large uncertainty is the rough mountainous terrain.

For the temporal analysis we use three images (date of acquisition: 1992, 1999, 2009) from Landsat TM and ETM+ sensors. The idea is to show the change in the debris-covered glacier extents and to quantify the uncertainties. The temporal DEM for the study area is only available for February 2000. Thus, to perform temporal analysis we assume that the DEM did not changed from 1992 to 2009. The support set, mean and core set areas of GSI and DCA, together with the coefficient of variance (CV) are calculated, and results are shown in Figure 2.

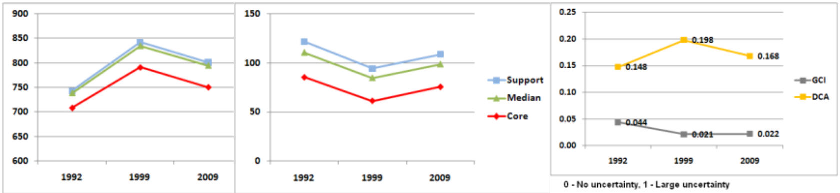

Figure 2. Mean, median and support areas for GSI (left) and DCA (middle) per year. The variation of uncertainty in term of CV per year (right).

To validate the method we use digitized glacier boundaries as a reference. As the study area covers a wide glaciated area we use two different areas in order to account for the location variation of the terrain and roughness where we focus on the core set of debris-covered areas. The overall accuracy equals 87.58% for the smooth area and 73.5% for the rough area.

4. Discussion and conclusion

This study applies a random set model for uncertainty modelling of a debris-covered glacier. Uncertainties are modelled for glacier snow and ice and for debris-covered areas of a glacier separately. This partitioning allows us to quantify the uncertainty for both constituent parts of a glacier. This is important as in some cases glacier areas covered by debris compose a large part of the glacier surface, and ignoring them will lead to misclassification. For example, in this research we found that about 10% of Fedchenko glacier is covered by debris.

By using the statistical parameters of random sets (support, mean, median, variance) the study demonstrates that the randomness of segmentation thresholding parameters has different effects on extracted snow and ice and debris-covered areas. Taking into account the rough mountainous terrain of the glacier these parameters quantify the uncertainty versus aspects. We find that, for both components of the glacier, the extensional uncertainty into southward direction of the terrain is twice as large as in the northward direction.

The temporal uncertainty modelling shows that the mean area of snow and ice increased from 1992 to 1999 and it is decreasing since 1999, as opposed to the pattern for the debris-covered area. The correlation between ice and debris-covered glacier area can be interpreted as the occurrence of debris where ice or snow melts.

The result of the uncertainty modelling for debris-covered glaciers proves that a random set approach is an effective tool for modelling and quantification of uncertainties. This method can thus be used for the assessment of debris-covered glaciers and their changes in time, being of a vital importance for planning and management of water resources as in the IPCC studies.

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