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Estimating glacier volume loss using remotely sensed images, digital elevation data, and GIS modelling

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Glacier retreat has received much attention in the public and scientific community as a sensitive indicator of global warming. Parameters for changes in glacier size include length, area, volume, and mass balance. While measurement of changes in glacier length and area is relatively straightforward using remotely sensed data, estimating changes in volume and mass balance remains a major challenge. The objectives of this research are to (1) develop a new model to describe the nonlinear thinning process of a glacier surface headward from the terminus position and (2) reconstruct historical glacier longitudinal profiles and 3D surfaces based on current glacier longitudinal profile and thinning rate, and estimate glacier volume loss. Using historical terminus positions and Landsat Thematic Mapper (TM), IKONOS, and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global digital elevation model (GDEM) data for the Gangotri Glacier in the Himalayas, longitudinal profiles and 3D surfaces of the glacier for 1900, 1935, and 1971 were reconstructed, and the amount and rate of volumetric losses during 1900–1935, 1935–1971, and 1971–2005 were derived. The methods can be used for more detailed study on estimating volume loss of the Himalayan glaciers and other glaciers.

1. Introduction

A glacier is made up of fallen snow that compresses into large, thickened ice masses over many years. Ice, snow, and glaciers have important effects on land-surface temperature and air/soil moisture. They are also important freshwater resources through surface runoff. As a sensitive indicator of global climate change, glacier retreat has received great attention in recent decades (Kargel et al. 2010; Owen 2009; Yao et al. 2007; Ding et al. 2006; Gupta, Haritashya, and Singh 2005; Haerberli et al. 1999; Oerlemans 1994). Because of its unique capabilities in acquiring spatial, spectral, and temporal information on Earth's surface features and phenomena, satellite remote sensing has become an important method for studying glaciers that often have accessibility and cost constraints (Racoviteanu, Williams, and Barry 2008; Kulkarni et al. 2007; Gupta, Haritashya, and Singh 2005; Kargel et al. 2005, 2010).

Parameters for changes in glacier size include length, area, volume, and mass balance. Glacier length is relatively easy to obtain from satellite images once the terminus position (the front end of the glacier) is identified. Although termini of some debris-covered glaciers may be difficult to see from medium-resolution satellite images such as

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Landsat Thematic Mapper (TM), they can be readily identified from high-resolution images such as IKONOS. Measurement of debris-covered glacier areas can be difficult due to the spectral similarity of debris and other surface features near the glacier, but additional data such as digital elevation models (DEMs) can be used to support more accurate mapping of debris-covered glaciers (Paul, Huggel, and Kääb 2004). While many studies have been carried out on measuring glacier length and area changes, and changes in glacier length have been used as a common measure for glacier retreat (Bahuguna et al. 2007; Kulkarni et al. 2007; Paul, Huggel, and Kääb 2004), it should be noted that changes in glacier length may or may not be related to changes in glacier volume or mass because some glaciers change length with little or no change in mass, and others show changes in thickness and mass but not length (Kargel et al. 2010).

While glacier mass balance is difficult, sometimes impossible, to obtain by remote-sensing methods (Kargel et al. 2005), estimation of glacier volume loss is a challenging question that may be explored by integration of remote sensing and spatial modelling in geographic information systems (GISs). In addition to its crucial role for estimation of water storage as glacier ice and contribution of glaciers to sea level rise (Meier 1984; Kaser et al. 2006), glacier volume is also related to the time-scale required for glaciers to complete their response to climate change (Paterson 1981; Jóhannesson, Raymond, and Waddington 1989a, 1989b). The objectives of this research are to (1) develop a new model to describe the nonlinear thinning process of a glacier surface headward from the terminus position and (2) reconstruct historical glacier longitudinal profiles and 3D surfaces based on current glacier longitudinal profile and thinning rate, and estimate glacier volume loss of the Gangotri Glacier in the Himalayas in different time periods from 1900 to 2005.

2. Study area and data

2.1. Study area

The Gangotri Glacier (Figure 1) of the Indian Himalayas was selected as the study area for the following reasons: (1) due to the low level of human activity in the Himalayas, the glacier provides a unique environment for studying global climate change; and (2) as one of the largest glaciers in the Himalayas (about 25 km by 30 km) and of high elevation, the Gangotri Glacier is difficult to access by traditional means and many important parameters of glacier behaviour (especially volumetric changes) are absent. Sharma and Owen (1996) and Owen (2009) reconstructed the ice positions and thickness of the Gangotri Glacier throughout the Late Quaternary based on historical and optically stimulated luminescence dating methods. Their work presents an excellent picture of the Late Quaternary glacial history of the Gangotri Glacier. However, estimation of volumetric changes in the Gangotri Glacier was not possible due to the lack of accurate profile data and 3D shape of the glacial valley.

2.2. Data

Landsat TM images (30 m resolution) acquired on 2 September 2001, IKONOS images acquired on 31 August 2005, and 30 m-resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global DEM (GDEM) data released by the Ministry of Economy, Trade, and Industry (METI) of Japan and NASA in June 2009 were used in this study (Figure 2). A pan-sharpened image was created by merging the



Figure 1. Location of the Gangotri Glacier (A) in the Himalayas. The blue line is the approximate location of the Ganges River. The glacier is bound between $N 30^{\circ} 43' 22'' - 30^{\circ} 55' 49''$ and $E 79^{\circ} 4' 41'' - 79^{\circ} 16' 34''$. The top side of the map is north.

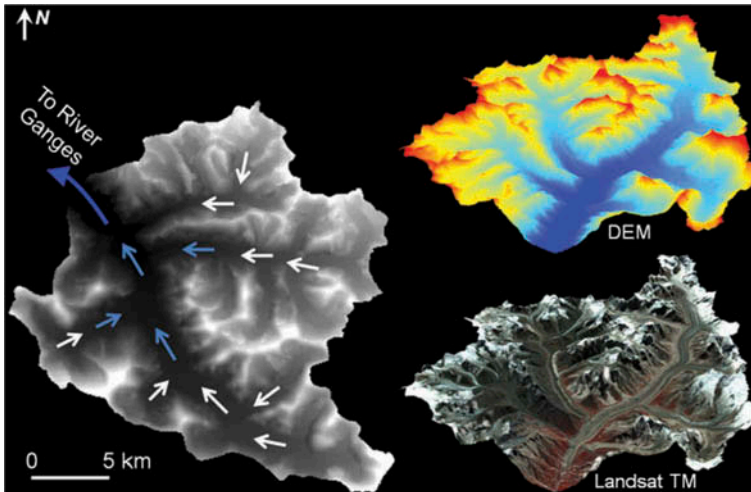


Figure 2. Digital elevation model (DEM) of the Gangotri Glacier derived from ASTER global DEM (GDEM) data. The arrows show flow direction of snow and melting water. The image in the lower right is a perspective view of Landsat TM imagery (acquired on 2 September 2001) draped over the DEM (ASTER GDEM is a product of METI and NASA).

IKONOS 4 m-resolution multispectral bands with the 1 m-resolution panchromatic band to output a final image with both spectral information and spatial details (Figure 3). Figure 3 also shows the terminus positions of the Gangotri Glacier for 1780,

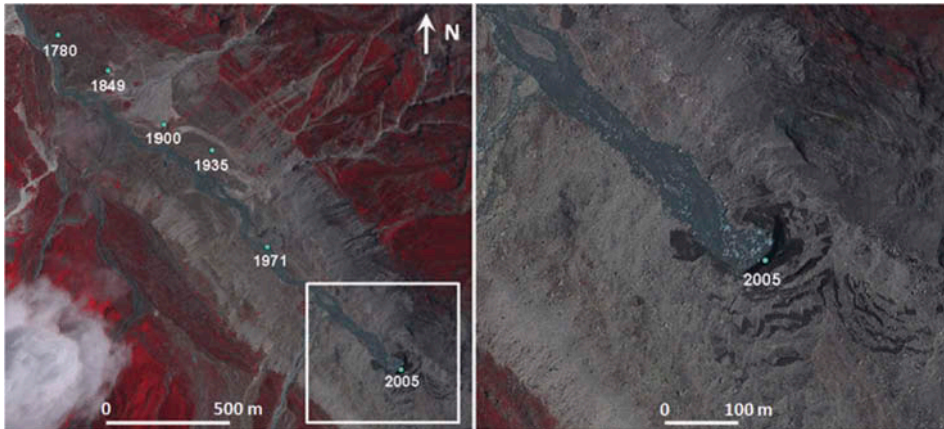


Figure 3. High-resolution IKONOS satellite image acquired on 31 August 2005. The points and numbers on the left-hand image represent terminus positions of Gangotri Glacier in 1780, 1849, 1900, 1935, 1971, and 2005. The right-hand image shows the 2005 terminus. This pan-sharpened image was created by merging 4 m-resolution IKONOS multispectral images with 1 m-resolution panchromatic IKONOS images. The terminus positions were obtained from the NASA Earth Observatory website (<http://earthobservatory.nasa.gov/IOTD/view.php?id=4594>).

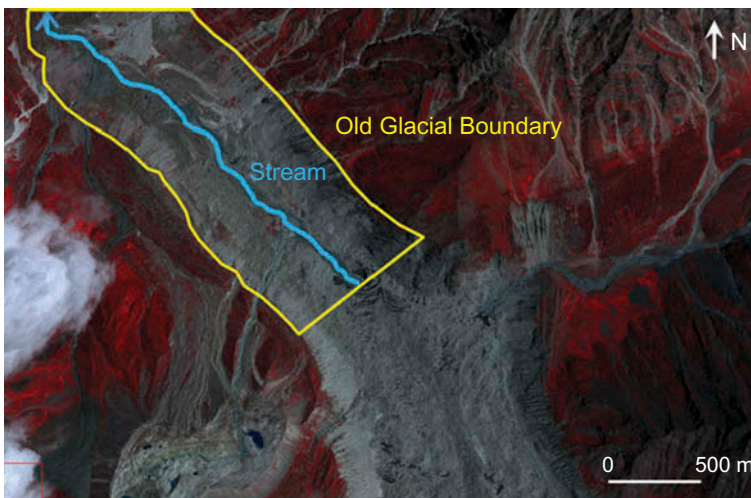


Figure 4. Old glacial boundary and stream from the terminus shown on a pan-sharpened IKONOS satellite image acquired on 31 August 2005.

1849, 1900, 1935, 1971, and 2005 provided by NASA. The old glacial boundary and current stream from the terminus can be seen on the pan-sharpened IKONOS image (Figure 4). The GDEM data were used to visualize snow and melt-water flow directions as shown in Figure 2, and to reconstruct longitudinal glacier profiles and 3D glacier surfaces.

3. Methods

3.1. Reconstruction of glacier profiles

There are two main approaches to glacier surface reconstruction: (1) empirical approaches that require geomorphic evidence such as terminal and lateral moraine, melt-water channels, and trimlines (Nesje and Dahl 2001; Rea and Evans 2007); and (2) theoretical approaches that use mathematical and physical models (Schilling and Hollin 1981; Rea and Evans 2007; Benn and Hulton 2010). Nye (1951, 1952) proposed a parabolic ice-surface profile model based on the perfect-plasticity assumption of ice flow mechanics. The model can be expressed as $h(x) = C\sqrt{x}$, where $h(x)$ is the profile elevation, x is distance to the terminus, and C is a constant describing the overall 'stiffness' of the flow. The Nye model has been frequently cited in the literature (Macgregor, Anderson, and Waddington 2009; Benn and Hulton 2010; Ng, Barr, and Clark 2010). Ng, Barr, and Clark (2010) analysed data derived from the surface profiles of 200 modern ice masses from various parts of the world and investigated four attributes including two parameters derived from Nye's theoretical parabola. Inspired by the Nye model and glacier/ice thinning results from other parts of the world (Motyka et al. 2002, Alaska; Berthier et al. 2007, Western Himalaya; Brown and Rivera 2007, Chile; Bolch et al. 2008, Eastern Himalaya; Moholdt et al. 2010, Arctic), we propose a new model to incorporate thinning rate and current longitudinal profile for glacier surface reconstruction.

If collection of geomorphic data is problematic, the snowline on remotely sensed images acquired at the end of melting season (September) can be used to estimate the equilibrium line altitude (ELA) (Kulkarni, Rathore, and Alex 2004). In this study, the Landsat TM imagery from 2 September 2001 and the snowline elevation of 5000 m on the north-facing slopes was used as the ELA. As reported in Berthier et al. (2007) and Bolch et al. (2008), the thinning of Himalayan glaciers is evident. Given a current longitudinal profile from the terminus to the ELA, the historical terminus positions, and the maximum thinning rate of a glacier, a new method was developed for reconstructing historical glacier profiles.

The reconstructed profile elevation at year t (z_t) can be expressed as a function of the horizontal distance (d) from the current location to the terminus position along the centre line:

$$z_t = f(d) = z_0 + r_{\max}(t_0 - t) \left(1 - \sqrt{\frac{d}{d_{\max}}} \right), \quad (1)$$

where z_0 is the elevation of year t_0 , r_{\max} is the maximum thinning rate (m year^{-1}), and d_{\max} is the maximum length of the profile from the terminus to the ELA. At the terminus where $d = 0$, Equation (1) becomes

$$z_t = z_0 + r_{\max}(t_0 - t). \quad (2)$$

At the ELA where $d = d_{\max}$, Equation (1) becomes $z_t = z_0$. For any location between the terminus and the ELA, Equation (1) represents a nonlinear thinning process of the glacier: significant thinning at low altitudes (lower part of the ablation zone) and only slight thinning at high altitudes (upper part of the accumulation zone). In addition to reconstruction of historical glacier longitudinal profiles, it should be noted that Equation (1) can also be used to predict future glacier longitudinal profiles.

3.2. Reconstruction of 3D glacier surfaces

Once the glacier longitudinal profiles are reconstructed, the next logical step is to reconstruct 3D glacier surfaces so that volumetric changes can be estimated. Figure 5 is a diagram showing the reconstruction of a 3D glacier surface based on the longitudinal profile and terminus position. The process is described below.

To construct 3D glacier surfaces, random points (x_i, y_i) ($i = 1, 2, 3, \dots, n$) can be generated on the glacier surface in GIS. Although the random points may or may not be on the curved glacier centre line (Figure 5), the distance d from the terminus to the random point (x_i, y_i) along the curved centre line can be obtained. In Esri's ArcGIS (Redlands, CA, USA), this is implemented through computer programming using the ICurve interface in ArcObjects. Once d is calculated, the glacier surface elevation z_i at location (x_i, y_i) can be calculated using Equation (1). With a series of 3D points (x_1, y_1, z_1) , (x_2, y_2, z_2) , (x_3, y_3, z_3) , ..., (x_n, y_n, z_n) on the glacier surface (Figure 5), a 3D glacier surface can be reconstructed using spatial interpolation methods such as inverse distance-weighted (IDW) interpolation. Subsequently, glacier volume loss can be obtained from multiple 3D glacier surfaces.

4. Results

Based on the interpretation of Landsat TM imagery acquired on 2 September 2001, which was near the end of melting season, the snow-line elevation of 5000 m above sea level was used as the ELA. This ELA position is similar to that of 5100 m obtained by Berthier et al. (2007) in the Bara Shigri glacier of the Himalayas – a glacier similar to the Gangotri Glacier in regards to length and geographic location. According to the study by Berthier et al. (2007) for the Bara Shigri glacier (approximately 200 km northwest of the Gangotri Glacier), a maximum thinning rate of 2.0 m year^{-1} for the period 1971–2005 was applied to the Gangotri Glacier. Assuming that glacier thinning rate in this area is proportionally related to glacier retreating distance between 1900 and 2005 (Figure 3), the estimated maximum annual thinning rates for the periods of 1900–1935, 1935–1971, and 1971–2005 are 0.5, 1.0,

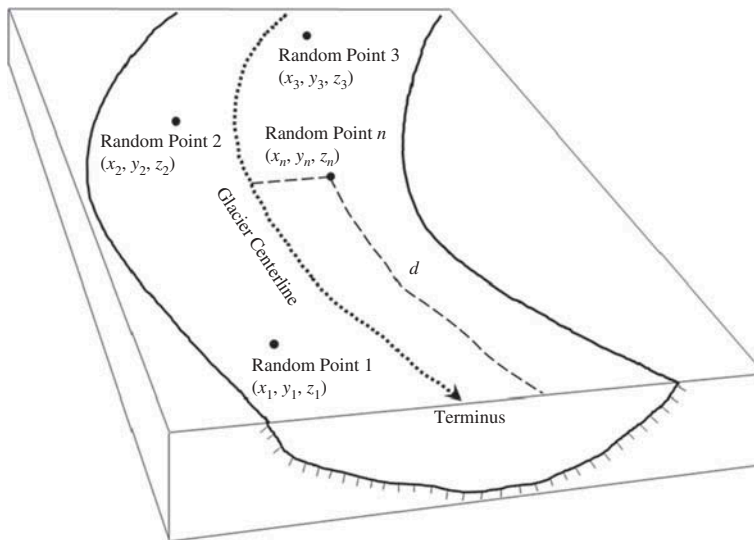


Figure 5. Reconstruction of a 3D glacier surface based on longitudinal profile and random points.

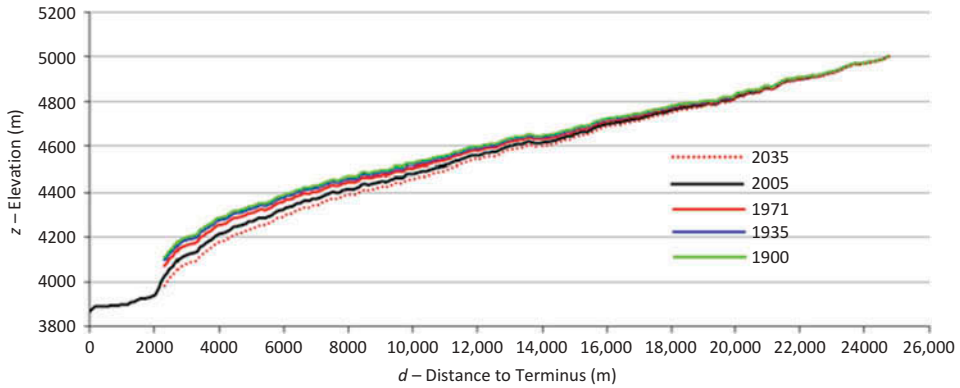


Figure 6. DEM-derived 2005 profile (black line) and reconstructed and projected profiles of the Gangotri Glacier. The projected 2035 profile (red dotted line) was obtained based on a maximum annual thinning rate of 2.0 m.

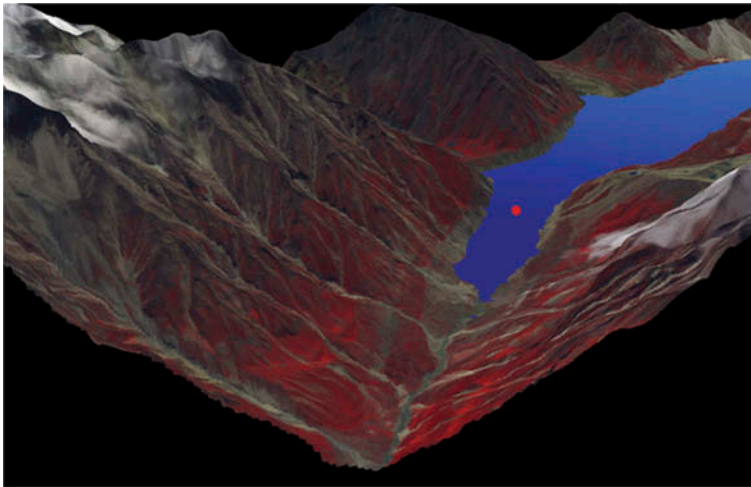


Figure 7. Perspective view of the reconstructed 1900 glacier surface (blue) and pan-sharpened IKONOS satellite imagery draped over the digital elevation model (DEM) derived from ASTER GDEM data. The red dot is the 2005 terminus position (the front end of the glacier). Traces of earlier glacier features are also visible. This picture shows not only the retreating distance but also the volumetric changes in the Gangotri Glacier from 1900 to 2005.

and 2.0 m, respectively. Figure 6 shows the 2005 longitudinal profile of the Gangotri Glacier (black line) derived from DEM, reconstructed profiles for 1900, 1935, and 1971, and the projected 2035 profile (dotted red line) calculated using Equation (1).

From the reconstructed surface profiles, 3D glacier surfaces of 1900, 1935, and 1971 were reconstructed using the method described in Section 3. Figure 7 shows the reconstructed 1900 surface (blue) and the pan-sharpened IKONOS imagery draped over the DEM derived from ASTER GDEM data. The red dot is the terminus position in 2005. Traces of earlier glacier features are also visible in Figure 7 (also refer to Figure 3).

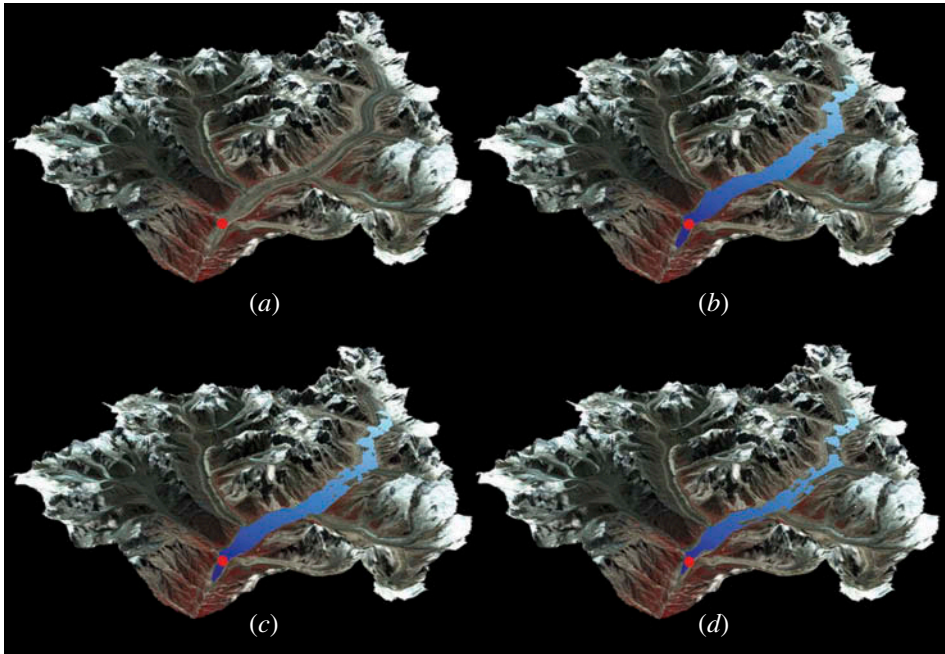


Figure 8. Perspective view of volume loss (shaded blue) in the Gangotri Glacier. Landsat TM imagery acquired on 2 September 2001 was draped over a digital elevation model (DEM). The debris-covered Gangotri Glacier is clearly visible in Figure 8(a), and the red dot is the 2005 terminus position (the front end of the glacier). It will be seen that the glacier was retreating while losing volume. (b) Volume loss (shaded blue), 1900–2005. (c) Volume loss (shaded blue), 1935–2005. (d) Volume loss (shaded blue), 1971–2005.

Figure 7 shows not only the retreating distance but also the volumetric changes of the Gangotri Glacier from 1900 to 2005. More perspective views of glacier volume loss for 1900–1935, 1935–1971, and 1971–2005 are shown in Figure 8. The amount and rate of glacier volume loss are listed in Table 1.

Supposing the maximum thinning rates are relatively reliable, the results in Table 1 suggest that the annual rate of glacier volume loss in the Gangotri Glacier is increasing and has doubled since the early twentieth century, from 0.0041 km^3 to 0.0085 km^3 . Such results are important in gaining a better understanding of the behaviours of Himalayan glaciers, and for quantifying the effects of global warming and sea level rise (Meier 1984; Oerlemans 1994).

Table 1. Volume loss in Gangotri Glacier, 1900–2005.

Time period	Glacier volume loss (w.e.*)	Volume loss rate (w.e.*)
1900–1935	0.1421 km^3	$0.0041 \text{ km}^3 \text{ year}^{-1}$
1935–1971	0.2589 km^3	$0.0072 \text{ km}^3 \text{ year}^{-1}$
1971–2005	0.2885 km^3	$0.0085 \text{ km}^3 \text{ year}^{-1}$

Note: *Water equivalent – glacier volume loss was converted to equivalent water volume loss.

5. Discussion

Unlike many studies that use distance or area as the major measure for glacier retreat or advance, this study focused on a more challenging question – how to estimate volumetric changes of glaciers. Glacier volume loss can be converted to equivalent water volume loss, which is an important parameter for gaining a better understanding of glacier behaviour and the effects of global climate change. Remote sensing and GIS played an important role in this study. Landsat TM images allowed us to delineate the centre line of the Gangotri Glacier, which was used to derive the longitudinal profile from ASTER GDEM data released by METI and NASA in June 2009. High-resolution IKONOS images provided important details on the terminus position and related glacier features, which were used for the reconstruction of glacier longitudinal profiles and 3D surfaces. GIS provided a powerful tool for spatial analysis and spatial modelling, which is essential for the reconstruction of glacier longitudinal profiles and 3D surfaces. Thousands of random points were generated in GIS, and the elevation of each point was calculated using the proposed nonlinear model. Without the support of remotely sensed data and GIS, it would be almost impossible to obtain all these (x, y, z) points in a difficult terrain such as the Himalayas.

A new model was proposed in this study to reconstruct historical glacier longitudinal profiles and 3D surfaces and to predict future glacier longitudinal profiles and 3D surfaces. From Equation (1), it can be seen that z_t is controlled by the maximum thinning rate r_{\max} if both d and z_0 are known. In this study, the maximum annual thinning rate of 2.0 m for 1971–2005 was determined following the results reported by Berthier et al. (2007) for the Bara Shigri glacier. Since the Bara Shigri and Gangotri glaciers are both located in the Western Himalaya region and are of similar length, it is believed that this maximum thinning rate is appropriate for the Gangotri Glacier. It is possible that r_{\max} can be obtained through linear regression if a series of z_0 and t_0 values is available, but detailed field investigation and dating evidence would be needed. Also it would be interesting to test the performance of Equation (1) using glacier/ice thinning results from other parts of the world, such as Alaska (Motyka et al. 2002), Western Himalaya (Berthier et al. 2007), Eastern Himalaya (Bolch et al. 2008), Chile (Brown and Rivera 2007), and the Arctic (Moholdt et al. 2010). Schwitter and Raymond (1993) found that, in almost all cases, the thickness change in glaciers decreases more strongly than linearly with distance from the terminus position. They used a profile factor f in the range of 0.1 to 0.4 to describe the shape of the longitudinal profile of thickness change, with $f = 0.5$ corresponding to a variation in thickness change that is linear with longitudinal distance. It would be interesting to investigate whether the profile factor f is related to the maximum thinning rate r_{\max} in the proposed model. It is hoped that more data from the Gangotri Glacier and other glaciers can be used for further evaluation of the model.

6. Conclusions and future work

Among the four major parameters (length, area, volume, and mass balance) of changes in glacier size, changes in volume and mass balance are more difficult to quantify using remotely sensed data. In this study, a new model to describe the nonlinear thinning process of a glacier surface headward from the terminus position is proposed. Methods for reconstructing longitudinal profiles and 3D surfaces of glaciers are described and implemented in GIS. Using historical terminus positions and Landsat TM, IKONOS, and ASTER GDEM data for the Gangotri Glacier in Western Himalaya, longitudinal profiles

and 3D surfaces of the glacier for 1900, 1935, and 1971 are reconstructed. The amount and rate of volumetric losses of the Gangotri Glacier for the periods 1900–1935, 1935–1971, and 1971–2005 are estimated for the first time. Total volume loss in the Gangotri Glacier was approximately 0.6895 km^3 (water equivalent) from 1900 to 2005. If glacier thinning rate is proportionally related to glacier retreating distance in this area, the results suggest that the annual rate of glacier volume loss in the Gangotri Glacier is increasing and has doubled since the early twentieth century, from 0.0041 km^3 between 1900 and 1935 to 0.0085 km^3 between 1971 and 2005. These results are important for gaining a better understanding of behaviours of Himalayan glaciers, and for quantifying effects of global warming and sea level rise.

Future work includes the possibility of integration with physical models and other models of glacier thickness changes for gaining a better understanding of glacier behaviours and the effects of global climate change. In addition, the proposed models can be further evaluated with new data from the Gangotri Glacier and other glaciers. It is also possible to develop a free software tool using ArcObjects and computer programming in ArcGIS that can be used by glaciologists, hydrologists, and environmental scientists for studying volumetric changes in glaciers. A user-friendly interface can be designed to allow convenient selection of input and output data and processing parameters. Software may be installed on mobile computers to support scientists working in the field. This would facilitate data collection, analysis, and model evaluation in support of research activities in glaciology, hydrology, and environmental science.

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