Glacier area and volume changes of Hidden Valley, Mustang, Nepal from ~1980s to 2010 based on remote sensing

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Abstract Glaciers are one of the important natural resources of freshwater and sources of water for hydropower, agriculture and drinking whenever the water is scarce. This mapping and change analysis helps to understand the status and decadal changes of glaciers in Hidden Valley, Mustang district, Nepal. The investigation is carried out using Landsat images of the years 1977 (~1980s), 1990, 2000 and 2010. We mapped 10 glaciers of the Hidden Valley covering an area of 19.79 km^2 based on the object-based image classification method using an automatic method and manual delineation by a Geographic Information System (GIS), separately. The glacier outlines for 2010, 2000, 1990 and 1980s in both methods are delineated from the multispectral Landsat images of the respective years. The total area losses of the glaciers from the automatic method are 1.713 and 0.625 km^2 between 1990−2000 and 2000−2010 and from manual delineation are 2.021, 1.264, 1.041 km^2 between ~1980s−1990, 1990−2000 and 2000−2010. The amount of average estimated glacier ice reserves lost is 0.326 km^3 (26.26 %) and the total glacier area loss is 4.33 km^2 (21.87 %) from the 1980s to 2010 based on manual delineation. The glaciers of Hidden Valley are shrinking and fragmented due to decrease in glacier area and ice reserves.

Key words Hidden Valley, Nepal; glacier; remote sensing; GIS

INTRODUCTION

Glaciers are significant natural resources in the Himalaya and the Himalayan glaciers contribute considerably to river runoff in South Asia. The Himalayan glaciers have retreated remarkably in the past two decades (Fujita *et al.*, 2001; Bajracharya *et al.*, 2007). The retreat of glaciers in the Himalaya is due to decrease in precipitation and warmer temperature (Ren *et al.*, 2006). Due to the mass changes of a glacier, there are direct and undelayed responses to the atmospheric conditions in the respective year. It is difficult to continuously monitor Himalayan glaciers due to the rugged terrain surface. Remote sensing techniques provide multi-sensor and multi-temporal data for monitoring glacier properties such as glacier area, length, surface elevation, albedo, equilibrium line altitude (ELA), terminus position, volume, accumulation/ablation rates, and accumulation area ratio (AAR), from which glacier mass balances can be inferred. Such tools are particularly useful for inaccessible areas. In previous studies around the world, temperature has been shown to be one of the major controlling factors for glacial change (Berthier *et al.*, 2007; Kulkarni *et al.*, 2007; Kulkarni *et al.*, 2011; Wagnon *et al.*, 2007; Bhambri *et al.*, 2011). The glaciers of Hidden valley have been studied since 1974 (Fujii *et al.*, 1976; Nakawo *et al.*, 1976; K, 1977; Fujita *et al.* 1997, 2001; Fujita and Nuimura, 2011). Previous studies have shown that the glacier area of Hidden Valley is 18.5 km^2 (Nakawo *et al*., 1976). It is, however, unclear what factors influence the glacier melting and to what extent glaciers change in this valley because of the lack monitoring data. Therefore, the aim of this study is to examine changes in glacier area, length and ice reserves of Hidden Valley from ~1980s to 2010 and long-term analysis for continuous glacier monitoring.

STUDY AREA

Hidden Valley is a small valley located at 28°77′−28°83′N and 83°49′−83°61′E on the northern side of the Nepal Himalaya, in Kagbeni VDC of Mustang district, Nepal (Fig. 1). This valley lies in the Sangda River watershed, which is one of the main tributaries of the Kaligandagi River. This watershed falls in the rain shadow area and is characterized by a dry, arid climate and desert type landscape (Bhusal, 2001). There are ten glaciers in this valley among which KaTHgr_5 is the largest

(Nakawo *et al.*, 1976) and most of the glaciers are of clean type except glacier KaThgr_2 which is a debris covered glacier. The altitude of Hidden Valley ranges from 5111 to 6515 m a.s.l. and its area is 432.6 km^2.

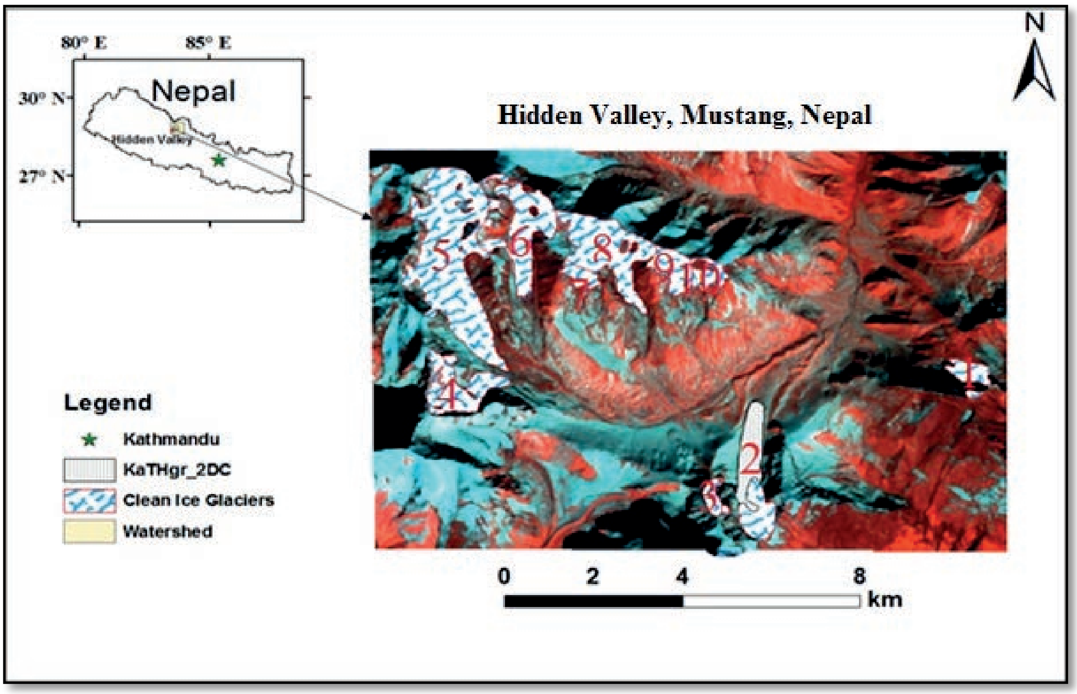

Fig. 1 Location map of study area showing Nepal.

DATA AND METHODS

Data sources

The Landsat images with least snow and no cloud cover, and ASTER DEM are downloaded from the United States Geological Survey (USGS) website (http://glovis.usgs.gov/) to analyse the glacier changes of Hidden Valley for the years ~1980s, 1990, 2000 and 2010.

Methods

ERDAS Imagine (ver. 2011) and ArcGIS (ver. 9.3) software are used to generate the digital database and for pre-processing of satellite data. In this study, current glacier distribution and glacier changes of Hidden Valley from ~1980s to 2010 are mapped using remote sensing data from the Landsat series using two different methods:

i) Manual delineation method Glacier outlines are delineated by applying cursor tracking on images in combination with false colour composites of the years between ~1980s and 2010 in ArcGIS. A manual delineation method for glacier mapping would be preferred for this Valley since there are few glaciers.

ii) Automatic method An automatic methodology is used for delineation of clean ice (CI) glaciers using an object based image classification (OBIC) approach (Bajracharya and Shrestha, 2011; Bajracharya *et al.*, 2014). First, the 2010 image is segmented using multi-resolution segmentation that creates the image object based upon spectral, shape, orientation and textural characteristics. Rule sets are created to classify the image objects based on spectral and spatial characteristics. All the classified Clean Ice image objects are merged and the products are exported to a .shp file. The methodology for automatic glacier mapping is illustrated in Fig. 2.

Mapping of clean ice glacier

Previous studies have shown that normalized difference snow index (NDSI) and band ratio methods could not differentiate debris-covered glacier ice from surrounding moraines/rocky surface due to similar spectral signatures (Bolch *et al.*, 2007). However, when compared with manual delineation, thresholding of NDSI is a time efficient and robust approach for mapping clean ice glacier (Paul *et al.*, 2002; Bolch and Kamp, 2006; Racoviteanu *et al.*, 2008). NDSI = [Mean Band 2 − Mean Band 5 / [Mean Band 2 + Mean Band 5] >= 0.64 is used to divide up the image into separated regions represented by basic unclassified image objects called image object primitives/segmentation. Then the image object level classified using NDSI >= 0.26 to delineate the clean ice part of the glaciers based on the visual inspection and shaded relief map. However, the NDSI value alone is not sufficient to get the exact boundary of the clean ice glaciers. Therefore, different filtering parameters are used to remove the mis-classified polygons such as normalised difference vegetation index (NDVI = [Mean Band 4 − Mean Band 3 / [Mean Band 4 + Mean Band 3]) with threshold value <= −0.35 for vegetation, a land and water mask (LWM = ([Mean Band 5/Mean Band 2] + 0.0001) × 100) with threshold value of >= 32 for water bodies. Also, mean slope with a threshold value of >54°, mean elevation <= 5400 m, brightness < 760 are used to remove the misclassified image objects from the clean ice glacier.

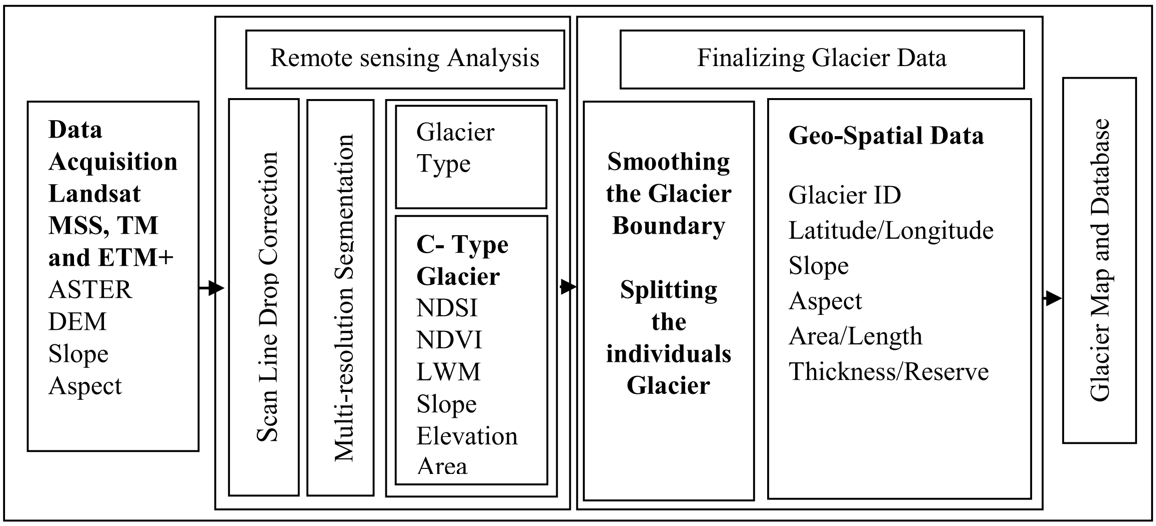

Fig. 2 Flow diagram of methodology for automatic glacier mapping using satellite images (Bajracharya and Shrestha, 2011).

Methodology for glacier length

First clip of the DEM is done by individual glacier boundary and reclassify each clip DEM in such a way that gives the highest and lowest point of the glacier. Then centreline is drawn from the highest point to lowest point based on the contour line, Google Earth map, direct manual judgement, and by snapping the glacier boundary to get the glacier length.

Methodology for mean ice thickness

Glacial mean ice thickness is estimated using a relationship with area, specifically developed for the Himalayan glaciers (Chaohai and Sharma, 1988):

$$H = -11.32 + 53.21F^{0.3}$$

where, H is Mean glacier ice thickness (m) and F is Glacier area (km^2). Ice reserves are estimated by mean ice thickness multiplied by the glacial area.

Mapping uncertainty

Typically, the accuracy of the glacier outlines depends on the resolution of the images used, the conditions during image acquisition (seasonal snow, shadow) and the contrast between the glacier and its surroundings (DeBeer and Sharp, 2007). Previous studies reported a mapping uncertainty of ± 2–3% for clean-ice glaciers (Paul *et al.*, 2002, Bolch and Kamp, 2006). In this study, RMSE values are calculated for both methods using:

$$\text{RMSE}=\sqrt{\sum_{i=1}^{n}\frac{(Am-Aa)^2}{n}}$$

where *Am* is manual area (km^2) and *Aa* is automatic area (km^2).

RESULTS AND DISCUSSION

All the glaciers of Hidden Valley are mapped manually using Landsat images of the years from ~1980s, 1990, 2000 and 2010. The total area is 19.79 km^2 based on ~1980s, which is 4.57% of Sangda watershed (432.6 km^2). The total area losses of the glaciers derived by the automatic method are 1.713 and 0.625 km^2 between 1990−2000 and 2000−2010 and from manual delineation are 2.021, 1.264, 1.041 km^2 between ~1980s−1990, 1990−2000 and 2000−2010. This study shows that Rikha Samba Glacier (KaTHgr_5) is the largest glacier and Glacier KaTHgr_3 is the smallest, with areas of 5.54 km^2 and 0.26 km^2, respectively, based on manual delineation. The RMSE values between the two methods are small 5.01%, 4.75% and 4.33% for the years ~1980s−1990, 1990−2000 and 2000−2010. Therefore, all the results are analysed based on the manual delineation method. The glacier area of Hidden Valley has a decreasing trend. Previous studies have shown that total glacier area loss of Bhutan Glacier from ~1980s to 2010 is 27.3±0.9% (206.6 km^2) (Bajracharya *et al.*, 2014). Ye *et. al*; (2009) reported ~10.41% (~0.3% year^{-1}) glacier area loss from 1974 to 2008 in 34 years at the northern slope of Mount Everest. The glacier KaTHgr_5 and glacier KaTHgr_4 are integrated up to the years 2000 and due to the melting and retreating, these two glaciers separated from year 2000 onwards. The overall loss in glacier ice reserves for the years ~1980s to 2010 is −0.326 km^3 (26.26%).

Decadal glacier area change in different elevation zones

The mapped glaciers of Hidden Valley are at elevations ranging from 6515 to 5225 m a.s.l with most of the glacier area distributed at elevations of 5600–6200 m a.s.l. (Fig. 3). The hypsography of all glaciers of Hidden Valley shows that most of the glacier area retreating in the elevation range 5600−6200 m a.s.l., from the 1980s to 2010, by 4.42 km^2 (22.46%). While at the upper part of the glaciers, there are least changes in glacier area.

Table 1 Changes in glacier area and ice reserves from ~1980s−2010.

Year	Glacier	Elevation (m a.s.l.)			Area (km^2)		Ice reserves (km^3)	
	number	Highest	Lowest	Diff.	Total	Diff.	Total	Diff.
2010	10	6507	5317	92	15.46	−4.33 (21.87%)	0.915	−0.326 (26.26%)
2000	10	6507	5312		16.50		0.993	
1990	9	6507	5312		17.77		1.088	
~1980s	9	6515	5225		19.79		1.241	

Glacier length changes

Overall, all the glaciers terminuses of Hidden Valley are retreating (Fig. 4). This study shows that KaTHgr_5 glacier is the longest glacier with a total length of 5.54 km based on 2010 Landsat data. The largest glacier KaTHgr_5 and smallest glacier KaTHgr_3 have retreat rates of 13.83 and 3.86 m year^{-1}, respectively from ~1980s to 2010. The higher retreat rate of KaTHgr_5 glacier is because of its aspect.

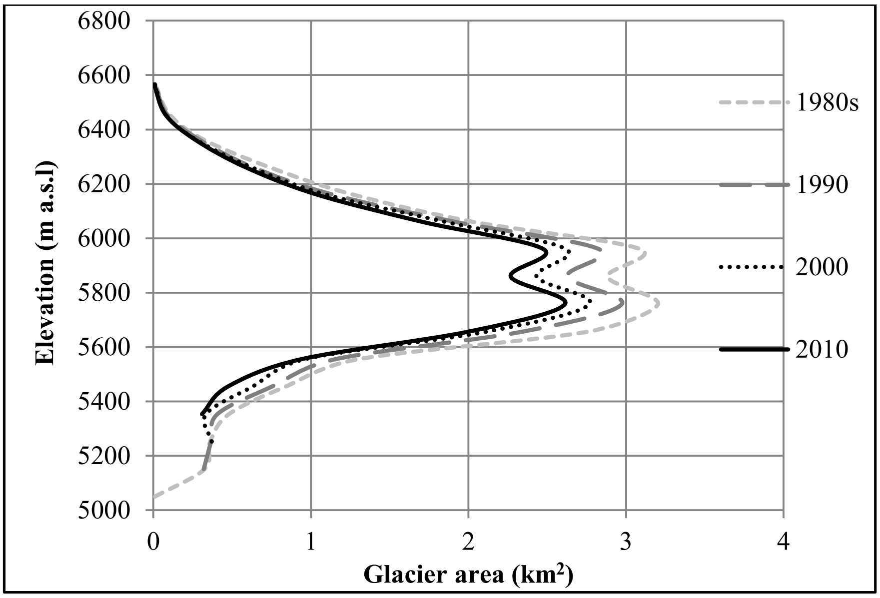

Fig. 3 Hypsography of all glaciers of Hidden Valley in ~1980s, 1990, 2000 and 2010.

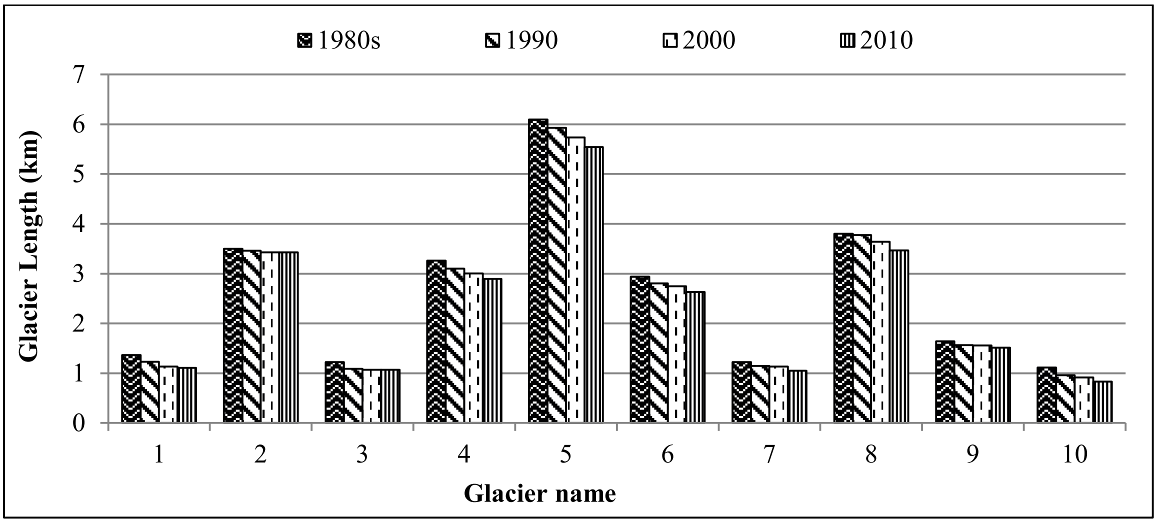

Fig. 4 Variation of glacier length in ~1980, 1990, 2000 and 2010 and its trend.

Thickness changes

The resulting ice thickness for the entire Hidden Valley ranges from (27.31−82.44 m) based on 1980s Landsat data and (24.12−77.59 m) based on 2010 Landsat data. To obtain accurate data, it is necessary to know more about the glacier attributes, such as measurements of the thickness of the glacier by surveying campaigns, and to know the mass balance of the glacier, which is useful for evaluating the water resources for the future. The mean estimated ice thickness of KaTgr_5 glacier decreased by 4.85 m between ~1980s and 2010.

CONCLUSIONS

The GIS and Remote sensing techniques are important tools for the analysis of acquired Landsat images, mapping and continuous monitoring of glaciers. It is better to use direct manual delineation method for a small number of glaciers, such as in Hidden Valley. Further, the automatic method with some manual editing in ArcGIS is useful if large numbers of glaciers are to be analysed. Analysis of the glacier data of Hidden Valley over ~1980s−2010 shows that the overall loss in glacier area is 21.87% and of estimated ice reserves is 26.26%. Most of the glacier area is distributed at an elevation of 5600−6000 m. Average length of the glaciers of Hidden Valley has decreased by 12.10%. The estimated average ice thicknesses of the glaciers are in the range 27.31−82.44 m in the 1980s and decreased to 24.12−77.59 m in 2010.

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