Separating snow, clean and debris covered ice in the Upper Indus Basin, Hindukush-Karakoram-Himalayas, using Landsat images between 1998-2002

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Abstract

The Hindukush Karakoram Himalayan mountains contain some of the largest glaciers of the world, and supply melt water from perennial snow and glaciers to the Upper Indus Basin (UIB) upstream of Tarbela dam, which constitutes greater than 80% of the annual flows, and caters to the needs of millions of people in the Indus Basin. It is therefore important to study the response of perennial snow and glaciers in the UIB under changing climatic conditions, using improved hydrological modeling, glacier mass balance, and observations of glacier responses. However, the available glacier inventories and datasets only provide total perennial-snow and glacier cover areas, despite the fact that snow, clean ice and debris covered ice have different melt rates and densities. This distinction is vital for improved hydrological modeling and mass balance studies. This study, therefore, presents a separated perennial snow and glacier inventory (perennial snow-cover on steep slopes, perennial snow-covered ice, clean and debris covered ice) based on a semi-automated method that combines Landsat images and surface slope information in a supervised maximum likelihood classification to map distinct glacier zones, followed by manual post processing. The accuracy of the presented inventory falls well within the accuracy limits of available snow and glacier inventory products. For the entire UIB, estimates of perennial and/or seasonal snow on steep slopes, snow-covered ice, clean and debris covered ice zones are 7,238 ±

724, 5,226 ± 522, 4,695 ± 469 and 2,126 ± 212 km^2 respectively. Thus total snow and glacier cover is 19,285 ± 1,928 km^2, out of which 12,075 ± 1,207 km^2 is glacier cover (excluding steep slope snow-cover). Equilibrium Line Altitude (ELA) estimates based on the Snow Line Elevation (SLE) in various watersheds range between 4,800-5,500 m, while the Accumulation Area Ratio (AAR) ranges between 7-80%. 0^{o}C isotherms during peak ablation months (July and August) range between ~ 5,500-6,200m in various watersheds. These outputs can be used as input to hydrological models, to estimate spatially-variable degree day factors for hydrological modeling, to separate glacier and snow-melt contributions in river flows, and to study glacier mass balance, and glacier responses to changing climate.

Key words: ELA,AAR, Glacier Inventory, Upper Indus Basin, Snow and Glaciers

1. Introduction

The Hindukush-Karakoram-Himalaya (HKH) and Tibetan Plateau (TP) glaciers supply snow- and glacier-melt to more than 1.4 billion people (one fifth of the world's population) in the Indus, Ganges, Brahmaputra, Yangtze and Yellow River basins (Immerzeel et al., 2010; Schaner et al., 2012; Minora et al., 2013).A major river basin originating from the HKH – TP region where cryospheric contributions to river flows are highly significant and hence river flows are highly susceptible to climate change is the Upper Indus Basin (UIB). In recent years, this basin has received considerable attention of researchers providing information related to hydro-meteorology (e.g. Archer, 2003, 2004; Fowler and Archer, 2005, 2006), water resources management and planning (e.g. Archer et al., 2010; Mukhopadhyay and Dutta, 2010; Mukhopadhyay, 2012), and climate change impacts on river flows (e.g. Sharif et al., 2013; Cook et al., 2013; Mukhopadhyay and Khan, 2014a,b; Mukhopadhyay et al., 2014). These studies not only provide useful information about cryospheric conditions in this data-limited region but also provide evidence that potential future changes to the hydrology will have important socio-economic implications for this region.

There are more than 20,000 glaciers in the entire HKH, including the UIB, of which 5,000 glaciers are in the Karakorum (Inman, 2010) and more than 12,000 are in the Himalayas (Thayyen and Gergan, 2010), covering an area of about 60,000 km^2(Kaab et al., 2012). Of these thousands of glaciers, fewer than 37 glaciers (both in the Himalayas and Karakoram) have been measured in the field (e.g. Young and Hewitt, 1988, 1990;Young and Schmok,1989; Hewitt, 2005, 2007, 2011, 2013; Inman, 2010). Considering the difficulties involved in field surveys in the rugged terrain of the HKH and the absence of long-term historical data, an alternative method is to use remotely sensed data which can provide information on glacier area, snowline changes, surface elevation and terminus position (Racoviteanu et al., 2009).

The latest glacier inventories using satellite imagery in the UIB provide extents and information of total perennial snow and glacier areas (Mool et al., 2005; Bajracharya and Shrestha, 2011, Arendt et al., 2013; Pfeffer et al., 2014).So far the area covered by different glacier facies within a glacier system are either not estimated or unavailable for researchers in this region. The hydro-climatic conditions in glacierized basins of the UIB change significantly with altitude and topography and the response of glaciers to climate changes may be different at higher elevation than lower elevation, particularly for large glaciers where thick/thin debris cover can suppress/increase the melting rate (Hewitt, 2005, 2011, 2013; Kaab et al., 2012; Gardelle et al., 2012; Reid and Brock, 2010). In such a complex system, it is therefore important to monitor glacier changes separately for distinct perennial snow and glacier zones such as perennial and/or seasonal snow on steep slopes, snow-covered ice, clean and debris-covered ice. Snow has a lower degree-day melt-factor than clean ice (4.1 mm/day/^{o}C vs. 7.1 mm/day/^{o}C) (Zhang et al., 2006). On the other hand thin debris covered snow and ice have about 12 and 9% greater melt rate than clean snow and ice, respectively in the HKH region (Singh et al., 2000).Thick debris covered ice has a melt rates about one third that of clean ice (The Batura Glacier Investigation Group, 1979; Mihalcea et al., 2006,2008; Mayer et al., 2006), while in some glaciers in the Karakoram region a difference of one half has been noticed (Hewitt, 2013). Previous hydrological modeling studies have neither considered snow, ice and debris covered ice separately (such as Tahir et al., 2011; Immerzeel et al., 2009) nor used separate enhanced/reduced melt rates for thin/thick debris covered ice (e.g. Immerzeel et al., 2012a,b, 2013; Lutz et al., 2014), and hence their results may contain biases. Additionally, estimates of the areal extents of different perennial snow and glacier surfaces are useful for the derivation of other important attributes such as degree day factors, changes in Equilibrium Line Altitude (ELA), Accumulation Area Ratio (AAR) and 0^{o}C isotherms (Altitude of 0^{o}C temperature) and consequently, glacier mass balance.

The aim of this study is therefore to provide baseline information for hydrological modeling, climate change studies and glacier mass balance analysis. The specific objectives of current study are to provide: (1) separate estimates of perennial and/or seasonal snow on steep slopes, snow-covered ice, clean and debris covered ice areas, and (2) ELA, AAR and $0^{o}C$ isotherms at the sub-watershed level for the entire UIB, using a combined dataset of Land Remote-Sensing Satellite (Landsat) images and DEM-derived surface slope information. The semi-automated classification used in the current study is first developed for one Landsat scene which covers an extensive glacierized area in the central Karakoram region and then applied to the entire region of the UIB, while the ELA and AAR have been extracted after classification, using standard methods.

2. Study Area

The study area selected is the UIB, upstream of Tarbela dam. The UIB extends across portions of Pakistan, India and China in mountainous regions of the western Himalaya, Karakoram and Hindu Kush ranges (Figure 1a,b) and has a total drainage area of about 172,000 km^2 (Khan et al., 2014; Ali and De Boer, 2007). The origin of the Indus River lies north of the Himalaya and starts at an elevation of about 5,300m from Kailash in Tibet, near Mansarovar Lake and ends in the Arabian Sea, as shown in Figure 1b (Jain et al., 2007; Inam et al., 2008). The total length of the Indus River (see Figure 1a) is about 3000 km, and runs from the north to the south of Pakistan (Inam et al., 2008; Akhtar, 2009). However, this study is confined only to the area between the source of the Indus River and upstream of Tarbela dam (i.e the UIB).Major watersheds in the UIB are shown in Figure 1c.

In the UIB, approximately 13% of the area is covered by perennial snow and glacier in summer, while in winter more than 70% of the basin area is covered with snow (Hewitt, 1988). Many glaciers in this region range in altitude from approximately 2,500 m to over 7,000 m above mean sea level and have average lengths more than 10 km (The Batura Glacier Investigation

Group., 1979). Most of the glaciers are in the high altitude mountain basins (above 4000 m), such as the Hunza, Shigar and Shyok basins, and are nourished by avalanches, re-distribution by wind, and seasonal snow (Akhtar, 2009; Hewitt, 2011, 2013). In general, these mountain glaciers can be divided into snow accumulation areas located at higher elevations, and ablation areas located at lower elevations of the glacier (Hewitt, 1989). The zone of accumulation of glaciers in the study area ranges from 3000 to 7000m (Young and Hewitt, 1988; Young and Schmok, 1989; Hewitt, 2005, 2007).In the accumulation zone, the annual accumulation from snowfall and avalanching is not entirely removed by ablation and the zone is covered by snow throughout the year. The mid- to upper ablation areas between 3,500 and 5,200 m in elevation can be categorized as clean ice area where ice is exposed after melting of the seasonal snow in the summer. The glacier ice in the lower ablation zone below 3,500m (near to tongue mantles) is mostly covered with thick debris that retards the ablation (The Batura Glacier Investigation Group., 1979; Mihalcea et al., 2006, 2008; Benn and Lehmkuhl, 2000), while debris covers in the mid-ablation zone are generally thin and accelerate ablation during summer (Mattson et al., 1993; Nuimura et al., 2011; Benn and Lehmkuhl, 2000). Most of the thick debris covered glaciers are located in Karakoram mountain region (Hewitt, 2011, 2013).

The climatic pattern of the UIB is highly influenced by both monsoon and westerlies. The trajectories of monsoon and westerlies are shown in Figure 1a. In the UIB most of the annual precipitation (snowfall) occurs in winter. The central Karakoram receives about 67% of annual precipitation in winter and the remaining 33% in the summer monsoon (Young and Hewitt, 1988, 1993;Young and Schmok,1989;Hewitt, 2005,2007).

The Upper Indus River stream flow can be characterized by significant seasonal variability. Inflow to Tarbela Dam is measured at Besham Qila gauging station (about 80 km upstream of Tarbela dam), with a mean annual flow of 2384 m^3/s between1970 and2010. The average monthly discharge at Besham Qila (1970-2010) and monthly precipitation over the study area (average of all stations' monthly precipitation over the available data record for each station) is provided in Figure 2-a. This figure shows that maximum precipitation occurs in April and maximum flow occurs in the month of July. October through March are low flow months, and more than 70% of the annual stream flow occurs in two to three months (June to August). The monthly snow cover variation during 2000-2010 in the study area has been extracted fromModerate Resolution Imaging Spectro-radiometer (MODIS)data, and are provided in Figure 2-b, which shows a maximum snow cover of 50-80% in March, and minimum snow cover of 10-15 % during July to September. The seasonal snow and glacier-melt contribute significantly to peak summer river flows. Thus, seasonal snowfall and glaciers have significant importance in the Indus River stream flow variation.

3. Data

3.1. Landsat and MODIS Data

Ideally, the classification of multiple Landsat scenes taken on the same date and time can provide most the accurate estimate of snow-glacier cover over large areas. However, due to non-availability of Landsat images taken on the same date for the entire UIB, and significant cloud cover in some images, images with minimum snow and cloud cover from the end of the ablation period (July to September) have been acquired. To minimize the effect of seasonal snow cover on the mapping of glacierized areas, the 8-day Moderate Resolution Imaging Spectro-radiometer (MODIS) snow product (MOD10A2) was first used to determine the dates with minimum snow cover during the years from 2000-2010.

The snow cover data from MODIS images with a cloud cover greater than 20% were not included in the analysis. As shown in Figure 2b, the average minimum snow cover extent within the UIB occurs between July to September, on average, for the period 2000 – 2010. Based on this information, cloud-free Landsat images between 1998 and 2002 were selected at the end of the melting season (i.e. July, August and September), however, to cover the whole UIB an image from 2009 has also been included. Furthermore, to maintain consistency in the identification of glacier zones in overlapping areas between adjacent scenes, we compared the transient snowline near clean ice/snow margins on the same glacier in both scenes and selected the images with the greater clean ice area. Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM +), 7 band images with 30m resolution are available for free from the U.S Geological Survey (USGS). Details of these images are shown in Figure 3 and Table 1.

3.2. Topographic data

The Shuttle Radar Topography Mission (SRTM) obtained a near-global high-resolution database of the Earth's topography by the single-pass Interferometric Synthetic Aperture Radar (IFSAR) technique in February, 2000 (Mukhopadhyay and Dutta, 2010). Due to shadow, layover, and poor signal return over some regions, the SRTM raw Digital Elevation Models (DEMs) contain voids (Tachikawa et al., 2011). However, pre-processed void free SRTM DEM 90m data are available for free covering 60^{o} N to 56^{o} S from the International Centre for Tropical Agriculture (CIAT). The SRTM DEM has linear vertical absolute altitude error less than 16m, and linear vertical relative altitude error less than 10m at 90% confidence level (Farr et al., 2007). The SRTM DEMs from CGIAR has been downloaded, mosaicked, projected and used in the current study. Watershed delineation has been carried out according to the methodology explained in Khan et al. (2014).

3.3. Climatic data

To compute 0^{o}C isotherms within each individual watershed, and to compare high summer months' 0^{o}C isotherms with Equilibrium Line Altitudes (ELAs), discussed in Section 4.4 and 5.3 respectively, temperature data from twenty five climatic stations have been collected. Station locations are shown in Figure 1-c, while their location details, period of record and sources are provided in Table 2. The valley-based stations are maintained by the Pakistan Meteorological Department (PMD) and have a long period of record (> 55 years) and the high altitude stations are maintained by the Water and Power Development Department (WAPDA), Pakistan for its snow and ice project with shorter period of record. We have obtained daily maximum and minimum temperatures from PMD and WAPDA. PMD collects climatic data in accordance with the guidelines prescribed by the World Meteorological Organization (WMO). WAPDA has auto-recording climatic stations and the data are collected in accordance with WMO guidelines. In addition, we have collected monthly average temperature values from two stations: Leh and Srinagar, maintained by the Indian Meteorological Department and used in Archer (2003,2004).Data from another station (Demchok) maintained by the Chinese Meteorological Department was obtained from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn).

3.4. Other datasets

To assess the quantitative accuracy of the snow-glacier inventory, other glacier and snow-cover products have also been used in the current study. Details of these datasets are as follows. (i) Digital Chart of the World (DCW): based on data collected between 1960-1980 (Danko, 1992; DMA, 1992). Since the latest data for this snow-glacier product was collected in 1980, therefore the inventory is referred to as DCW 1980. From DMA's (1992) assessment of the positional accuracies of the features represented in the DCW, 10% error is assigned to the estimates of the Snow Cover Area (SCA) derived from the DCW. (ii, iii) Two sets of global land cover (GLC) data, are used to quantify snow-cover/glacier area for post 1980 conditions. The first set of GLC data, produced from the data collected by the Advanced Very High Resolution Radiometer (AVHRR) instruments on board the NOAA polar-orbiting satellites is considered to represent global land cover characteristics for the years 1992-1993 (Loveland et al., 2000). The overall area-weighted accuracy of this GLC dataset is estimated as 66.9% (Scepan, 1999), while snow cover user accuracy is 98%. Data was collected over a period of 14 months, and therefore may contain seasonal snow cover along with glacier areas. The second set of GLC data are obtained from the data acquired by the VEGETATION instrument on board the SPOT 4 satellite. These data, known as GEM GLC 2000, are considered to be the internationally standardized land cover data, producing the land cover information of the earth for the years around 2000. The overall accuracy of the GLC 2000 land cover areas is 68.6% (Mayaux et al., 2006). (iv) The Randolph Glacier Inventory version 3.0 (Pfeffer et al., 2014) is a combination of the above mentioned DCW, the World Glacier Inventory (WGI, 1989) and glacier inventory by Cogley (2009). RGI data is available for free, using the website: (http://www.glims.org/RGI/). The reported uncertainty in RGI data is +/- 5% (Pfeffer et al., 2014) (v) MODIS snow-cover products are based on an automated snow mapping algorithm, which uses MODIS band 4 (0.545 – 0.565 µm) and band 6 (1.628 – 1.652 µm) to calculate the Normalized Difference Snow Index (NDSI) (Hall and Riggs, 2007). The MODIS global snow-cover products are available on daily, 8-day, and monthly interval and at 500m resolution.

The MODIS products have an accuracy of more than 90% in clear sky conditions (Wang et al., 2009; Gao et al., 2010). Therefore, the MODIS Terra 8 -day product has been acquired and used for Landsat data selection, while Terra and Aqua monthly snow-cover products have also been acquired to quantify minimum snow cover in a month (annual minimum snow cover can be considered perennial snow and glacier cover). Either the Terra or Aqua product with the fewest missing values in a month was selected. Additionally, for comparison of our estimated glacier-cover with manually digitized boundaries, glacier outlines were acquired through the Global Land Ice Measurements from Space (GLIMS) database (GLIMS and National Snow and Ice Data Center, 2005). According to the GLIMS documentation, these glacier outlines have been manually digitized following GLIMS guidelines (see Raup et al., 2007) in GLIMS View using two ASTER scenes acquired on 09/30/2001. However, there is no quantitative accuracy estimate of GLIMS data available, though in fact, as GLIMS glaciers outlines are manually digitized, they can be expected to be of very high accuracy.

4. Methods

Currently, ASTER is used extensively by the GLIMS project for monitoring of glacier parameters and mass balance estimations because of its high spatial (15m) and spectral resolution (Raup et al., 2007). A major limitation of ASTER is its small swath width of 60km, which means that many ASTER images are needed for glacier monitoring over large glacierized areas such as the HKH region. Landsat images, which have a relatively large swath width of 185 km and which have been available since the 1970's, are more useful for glacier mapping studies over extensive areas. An additional advantage of Landsat images is that these are available in Ortho-rectified format, which saves analysis time and minimizes rectification errors (as compared to ASTER images and their classification). Paul and Kaab (2005) showed that glacier area estimated using ASTER and Landsat images is within ± 5%.

Commonly used techniques, such as the calculation of Landsat band ratios (for example, Band 3/ Band 5 and Band 4/ Band 5) and the NDSI, have proven successful in delineating total glacier area as reported by previous studies (see e.g. Hall et al., 1987; Sidjak, 1999; Kääb et al., 2002; Paul et al., 2002; Paul and Kaab, 2005; Kaab et al., 2012; Pandey et al., 2012; Gardelle et al., 2013). Racoviteanu et al. (2009) reviewed mapping studies of glacier cover using single-band ratios and NDSI algorithms and illustrated the effectiveness of these algorithms in mapping glacier cover over large areas. These studies have found that while empirically determined thresholds of band ratios can distinguish debris-free glacier ice from non-glacierized portions, these methods fail to distinguish exposed ice from snow cover, exposed ice from water bodies, and debris cover from surrounding terrain (Racoviteanu et al., 2009).

Automated delineation of the debris-covered areas using multispectral remotely sensed data alone may not provide accurate delineation due to the absence of a clear spectral boundary between debris-covered ice and its adjacent rocks and/or the dominance of debris pixels over ice (Bolch and Kamp, 2005). Earlier studies have shown that in addition to high resolution multispectral data such as Landsat, ASTER or SPOT, other techniques such as the combination of morphometric, thermal bands and/or surface slope information can improve the automated delineation of debris-covered areas, because of the differences of topographic and physical characteristics between debris-covered areas of the glaciers and relatively steep surrounding areas (e.g. Bishop et al., 1998, 2001; Sidjak and Wheate, 1999; Paul et al., 2004; Bolch and Kamp, 2005; Bolch et al., 2008). Despite these important advances, automated mapping of debris-covered glaciers from satellite data remains a challenge because of the uncertainty involved in identifying the boundary of debris-covered glaciers (Racoviteanu et al., 2009). Manual digitization of debris-covered glaciers may provide a more accurate estimate of glacier extent (Veettil, 2012), but its application is time-consuming over large regions. However, the combination of Landsat band 5 and slope information provides more precise results for debris covered ice than using Landsat band 5 data alone (Veettil, 2012, 2014).

Therefore in the current study, we used a semi-automated method for delineation of glacierized areas into three zones: snow-cover, exposed ice and debris-covered ice that can be applied to areas with extensive ice cover. Snow-cover has further been divided into perennial and/or seasonal snow-cover on steep slopes and snow-covered ice (mild slopes $<25^{o}$). Initial trials of classification of the UIB using thresholds of band ratios such as Band 3/ Band 5, Band 4/ Band 5 and NDSI showed that the ratio of Band 3 to Band 5 provided better classification of snow/ice areas on glaciers, particularly in shadowed regions, as also indicated by other studies (Paul and Kaab, 2005; Bolch et al., 2010). Overall, these methods were not successful in differentiating perennial snow-cover from exposed ice and/or debris cover from surrounding terrain. We therefore adopted a supervised maximum likelihood (ML) classification for mapping of glacier zones. The ML algorithm assigns each unclassified pixel in the image to the most probable class based on the probability of that pixel occurring within each class given a Gaussian probability density function calculated for each class using training data (Lillesand et al., 2007).To improve the accuracy of classification, in particular for the identification of debris-cover areas, all visible and infrared bands of Landsat TM and ETM + images were combined with a surface slope information layer derived from the SRTM DEM (Table 3). The data values of each layer were normalized by the variance of each layer, because the surface slope values had a larger range than the spectral reflectance values. The areas under thick clouds were also masked out.

4.1. Snow-Glacier zone classification

The methodology adopted in the following steps was applied to a single Landsat scene (row/path: 149/35) acquired on August 13, 1998 to determine the classification accuracy and to select a set of input bands that can be used in the mapping of glacier cover for the entire area of the UIB.

4.1.1. Selection of training samples

Training samples for six classes (perennial snow-covered ice, exposed ice, debris covered ice, water, shadow, terrain) were identified prior to classification and selected through screen digitization. The selection of training data was based on visual observation of the Landsat image as shown in Figure 4. The selected training data were evaluated using a confusion matrix to produce a reliable training set with higher accuracy. The confusion matrix compares the results of the maximum likelihood classification with the training classification in selected training areas. If the percentage of incorrectly classified pixels was high for a particular class, the histograms related to those training areas were analyzed and those with uni-modal distribution were retained. This evaluation also demonstrated that the surface slope layer combined with the Landsat layers is essential for separating debris from terrain and snow under shadowed areas from exposed ice (see Figure 5). Debris and terrain show the greatest contrast with other zones in the infrared bands of the Landsat image (i.e. Band 5 and Band7) combined with the surface slope layer but have similar brightness values in the visible bands (i.e. Band 1, Band 2 and Band 3), while ice and water are easily distinguishable in the visible bands but similar in the infrared bands.

4.1.2. Spectral separability analysis for optimal band selection

To improve the classification accuracy and to increase the between-class separability in training data with fewer data layers, we used the Jeffreys-Matusita (JM) distance (Bruzzone et al., 1995) to select bands with the least amount of redundant spectral information. The values of the JM distance ranged between 0 and 1414. If the JM distance between two classes for any band combination is close to the upper limit, then the training samples of these classes are very different in the selected bands. Initially, the signature separability analysis was performed using the training data for all possible pairs of classes. Because of the band saturation problem in the visible bands of Landsat images over snow-covered areas (Hall et al., 1988) and the resulting higher brightness variance of the perennial snow-covered areas, the ML algorithm has the tendency to over-represent the dominant classes. This also resulted in higher average separability for band combinations that include the snow class in the separability analysis. In an effort to reduce this effect and minimize the dominance of perennial snow-cover in the classification process, a mask was generated and applied to the mosaic of images to exclude the perennial snow-covered ice areas from further analysis of signature separability and from the classification process. The unsupervised RGB clustering algorithm available in Erdas Imagine (see more details in Erdas Imagine Field guide, 2010) was used to map perennial snow cover areas using a three band composite (RGB 345) of the Landsat image as shown in Figure 6b. The perennial snow areas were then masked out from the combined dataset of all layers of the Landsat image with slope (SLP) information (Figure 6c). The signature separability analysis was further performed with no perennial snow cover areas in the image using the training areas of five classes (exposed ice, debris covered ice, water, shadow, terrain). Based on this analysis, five input datasets of different band layers (i.e. (i) 1-5-SLP; (ii) 1- 4-5-SLP; (iii) 1-3-4-5-SLP; (iv) 1-

3- 4-5-7-SLP and (v) 1-2- 3- 4- 5- 7-SLP) were found to have the highest average JM distances for all possible pairs of classes and provide greater separability among classes.

4.1.3. Supervised multispectral classification

The maximum likelihood classification was performed to create thematic maps of glacier zones using selected input datasets with different band combinations based on the separability analysis. The final classification map was selected based on an accuracy assessment of these maps. The accuracy assessment used a confusion matrix to calculate the percentages of correctly or incorrectly classified pixels for selected testing samples for all selected maps. Ideally, the testing sample should be determined from ground reference data and compared with randomly selected individual pixels from the thematic map (Richards and Jia, 2006). Due to the lack of available ground reference data in the study area, another set of testing areas was selected and labeled at the same time as the training areas. Classification trials using selected input band combinations showed quite high percentage accuracies for each class ranging between 91 and 93% (Figure 5). The overall classification accuracy for the band combination of Band 1, Band 3, Band 4, Band 5, Band 7 and SLP was higher but the individual classification accuracy for the ice class was lower, while the band combination Band 1, Band 2, Band 5 and SLP had higher accuracy for the ice class and lower for the debris class. From the visual interpretation of the thematic maps using each of these band combinations, it was concluded that the input band combination of Band 1, Band 2, Band 5 and SLP provided better results for exposed ice and debris cover areas.

To delineate the glacierized area into different glacier zones for the entire UIB, the selected set of input bands Band 1, Band 2, Band 5 and SLP was used in the ML classifier to identify five regions: (1) exposed ice, (2) debris covered ice, (3) water, (4) shadow, and (5) other terrain, using the methodology as described in Sections 4.1 to 4.3 for the Landsat image 149/35. Training areas collected for this image were used in the classification of the mosaic image. However, the training areas for the 'shadow' class were adjusted based on the overlapping areas between adjacent scenes because different acquisition times of neighboring scenes affected the shadow conditions. The step by step classification process is shown in Figure 6 (a-f).

After classification of the mosaic image, the snow areas were combined with other classes (Figure 6e). A median 3 x 3 filter was applied to the glacier zone map to reduce noise in the map, mostly in shadowed regions and misclassified debris areas (Figure 6f).The overall visual accuracy of the glacier classification was determined by comparing the results with glacier outlines available through the GLIMS database for the central Karakoram region (see Figure 7). The accuracy for the individual glacier zones was also assessed through visual interpretation of the Landsat images. Based on the accuracy assessment, we further refined the identified glacierized regions using post-classification processing which included masking of problem areas, application of the Band 3/ Band 5 mask, median filter, and manual editing as described below.

4.1.4. Post classification processing

Visual interpretation of the glacier zones map shows that the shadowed areas that result from the very complex topography are the most problematic and can be partially responsible for errors in classifying the snow-covered ice and exposed ice. For this reason, all shadowed regions (i.e. glacier and non-glacier areas) were classified into a separate "shadow" class during classification. These areas were not included in the final glacier map which resulted in underestimation of mostly perennial snow cover areas (Figure 6d). To avoid this problem, we further delineated the glacier cover using the Band 3 to Band 5 ratio method which is particularly useful to identify glacier areas under shadow condition, as reported by previous studies (Paul and Kaab, 2005; Bloch et al., 2010). The perennial snow areas under shadow classified by the Band 3/ Band 5 ratio method were then extracted and added to the perennial snow cover class in the final glacier zones map (Figure 6e).

The clean ice areas were successfully mapped for most glaciers except for a few glaciers where clean ice areas were classified as water. Small water bodies were also misclassified as ice in some cases. Classifying water as a separate class, however, minimized this misclassification by accurately classifying water pixels in many other areas. Comparison of the classification accuracy for individual classes using selected band combinations with higher JM distances also showed that inclusion of the visible bands (i.e. Band 1 and Band 2) in the final selected input band combinations provided better results in distinguishing water bodies from exposed ice areas. Water areas misclassified as ice were manually deleted from the final glacier cover map. After this editing, the clean ice areas misclassified as water pixels were combined with the 'exposed ice' class.

Misclassification also occurs in transition areas between glacier and non-glacierized areas, and for bare surfaces along rivers located on lower slopes with similar spectral response as debris cover. For our final glacier map, we therefore first deleted all mapped glacier areas below 2,000 m elevation. The misclassified isolated debris-covered ice areas above the elevation threshold were then manually deleted. Given the extensive debris cover in the study areas and difficulty in identifying the boundary of the debris-cover glacier on the scene, extensive manual deleting of isolated artifact debris covered areas was performed to provide a more precise estimate, however, no manual boundary adjustment of glacier outlines has been adopted.

Furthermore, snow is not stable on steep slopes under its own weight, and falls to lower altitudes either by avalanches or aerial distribution, and any snow on these slopes is not actually part of the glaciers (Hewitt, 2011, 2013; Immerzeel et al., 2013). Meierding (1982) has used a 60^{o} slope for separation of steep slope rock-wall areas from glaciers, while Bajracharya and Shrestha (2011) have reported that most of the glaciers (not snow-cover areas) in the UIB have slopes <25^{o}. Immerzeel et al (2013) used a minimum slope value of 20^{o} for separation of steep slope snow from glaciers on mild slopes in their hydrological modeling study of two glaciers in the Karakoram and western Himalayas. The minimum slope at which gravitational slope transport occurs is about 22° (Immerzeel et al., 2013). Therefore, for separation of perennial and/or seasonal snow from snow-covered ice and clean ice, we have adopted a slope threshold of 25°. The threshold slope criteria means that any snow-cover at slopes greater than 25° has been considered as perennial and/or seasonal snow, while below this threshold value snow-cover is assumed to be snow-covered ice. There could also be some small percentages of steep sloped hanging glaciers, and seasonal snow (re-distributed by wind) at mild slopes but that cannot be separated further. Interestingly, the snow depth at slope 25° could be up to 10m (Immerzeel et al., 2013), and density up to 100-350 kg/m^3 depending on type of snow/firn (fresh snow has lower density than settled snow or saturated snow or firn) (Cuffey and Paterson, 2010; Thakur et al., 2013). The separate area of perennial and/or seasonal snow zones is thus an important input for glacier mass balance analysis. Estimates of perennial and/or seasonal snow on slopes> 25° is also important to assess long-term snow-cover dynamics, using snow-cover products, such as MODIS.

4.2. Sources of Errors and Accuracy Assessment

4.2.1. Sources of Error

Image classification errors can be induced by: (i) Co-registration of DEMs and Landsat images, (ii) Classification of individual image separately and edge matching of classified perennial snow and glaciers boundaries, and (iii) Available resolution of data (Landsat data in current study). Care has been taken to minimize these errors in the current study, as follows:

(i) To avoid co-registration errors between the SRTM DEM and Landsat images, pre-geo-referenced datasets have been obtained and projected to the WGS 84, UTM Zone 43N coordinate system, prior to mosaicking. All datasets have been re-sampled to the same resolution (i.e. 30 m).

(ii) To avoid extensive post-classification edge matching of the classification output (Homer et al., 1997), mosaic of 18 Landsat images has been classified. To ensure consistent radiometric characteristics between multiple scenes, an atmospheric correction was applied to all 18 Landsat images used in the creation of a mosaic image for the UIB. The correction was determined using an improved image-based Dark Object Subtraction (DOS) model developed by Chavez (1996).

(iii) The resolution of available data also induces error in estimation of areal extent, and is normally taken as one half the pixel size of data times the perimeter of digitized/classified boundaries(O'Gorman, 1996;Minora et al., 2013). We have estimated error due to resolution using the overall perimeter of the final classified perennial snow and glacier boundaries and multiplied it with 15m (half pixel size of the Landsat images used).

4.2.2. Accuracy Assessment

The accuracy of the perennial and or seasonal snow- and glacier-cover classification has been evaluated using four different methods: (i) Accuracy of classification using training samples and final classified images has been analyzed using a confusion matrix of training samples and the classified image, (ii) Visual accuracy of the classified snow- and glacier-cover has been conducted using manually digitized GLIMS data for the western and central Karakoram, (iii) Computation of error due to resolution, as explained in section 4.2.1, and (iv) Quantitative comparison of current delineated snow- and glacier-cover with other available snow and glacier-cover datasets (details of these datasets are provided in section 3.4).

4.3. Equilibrium Line Altitude (ELA) and Accumulation Area Ratio estimation

The Equilibrium Line Altitude (ELA) is the elevation at which the annual net mass of the glacier remains zero, and is an important altitude for climate impact studies of glaciers and water-resources (Cuffey and Paterson, 2010). The area above the ELA is known as the zone of accumulation, while the area below is known as the zone of ablation. The ratio of the zone of accumulation area to total glacier area is known as the Accumulation Area Ratio (AAR). A number of various methods have been used for estimation of ELA and AAR, including: Area x Altitude (AA), Area x Altitude Balanced Ratio (AABR), Maximum Elevation of Lateral

Moraines (MELM), Toe-to-Headwall Altitude Ratio (THAR), fixed Accumulation Area Ratio (AAR), Toe-to-Summit Altitude Method (TSAM) and Snow-Line-Elevation Method (SLEM) (Osmaston, 2005; Benn and Lehmkuhl, 2000; Owen and Benn, 2005; Kulkarni, 1992; Pandey et al., 2012). The AA, AABR, AAR methods are not suitable for the UIB due to the fact that they require repeated topographic surveys of the glacier surface, and these methods were developed for low-relief mountain glaciers and need modification before use in high mountain regions (Benn and Lehmkuhl, 2000). THAR and TSAM require less topographic data (the minimum altitude of moraine and the altitude of the highest summit in the glacier catchment), however, may produce biases in high Asian glaciers due to avalanches and moraine formation (Benn and Lehmkuhl, 2000).

In temperate glaciers, usually the Snow Line Elevation (SLE) and ELA are assumed to be the same (Lliboutry, 1971;Kulkarni, 1992;Pandey et al., 2012; Rabatel et al., 2005, 2008, 2012). Due to limited available information about separate glacier faces, previous studies have adopted different methodologies to estimate SLE and ELA, for example, use of snow cover areas with basin's hypsometric information (Kaur et al., 2009), use of ice cover boundaries and DEMs (Kulkarni, 1992; Pandey et al., 2012), and manual digitization (for very few glaciers) of SLEs (McFadden et al., 2011; Gardelle et al., 2013). Thus, in the current study ELA has been estimated in each watershed, using the average SLE.

To estimate ELAs, steps followed are: i) extraction of snow and ice altitudes from the DEM using the snow and ice cover (both debris and clean ice) boundary, ii) preparation of separate snow and ice cover hypsometric curves, iii) demarcation of the lower and upper limits of SLEs in each watershed. The upper limit has been selected as the upper altitude of clean ice, below which 100% of the clean ice exists, while the lower altitude has been selected from where snow cover is greater than 0% (i.e. an altitude above which 100% of perennial and or seasonal snow exists), and iv) computation of area average altitude (ELA): the average of total snow-glacier area within lower and upper SLE limits. Ideally, the SLE and ELA should be estimated at the end of the ablation period, therefore all the data should be from the same date, month and year. In the current study the available images are not for the same date, month and year, as discussed previously. Therefore, some underestimation in the lower SLE limits could be due to fresh avalanches at low altitudes, redistribution by wind and seasonal snow (which was still present on the date of image acquisition), and/or overestimation in the highest SLE limit due to misclassification of saturated wet snow and ice (Sidjak and Wheate, 1999). As both the upper and lower limits have slight under- and over-estimation at the same time, the significance on the estimated SLE and ELA should be negligible. Almost all of the selected images are during the 1998-2002 period with July to September minimum snow covers, and therefore may not have significant variation in the SLE and ELA. Additionally, AARs (Accumulation Area/Total Glacier Area) have been estimated for each watershed based on the glacier area above the ELA and total snow-glacier area (excluding steep slope snow-cover).

4.4. 0° C isotherm estimation

The 0° C isotherm can be defined as the altitude of 0°C temperature for a selected time (e.g. day, month or year). 0° C isotherms at the end of the ablation period have close relationship with SLE and ELA (see discussion in Section 5.3). Archer (2004) has used valley based in combination with a few high altitude climatic stations to estimate monthly 0° C temperature altitudes for the entire UIB, however, no such estimates are available for individual sub-watersheds. Pairs of low and high altitude stations within each watershed have been selected (based on maximum altitude difference), and1999-2002 monthly mean temperature data were used (for consistency with Landsat data) for temperature lapse rate and 0°C isotherms estimation. For comparison, we have also estimated 0°Cisotherms during 1999-2010. However, the results provided in the current study are based on 1999-2002 data for consistency with the Landsat data.

5. Results and Discussions:

5.1. Results validation:

To assess the accuracy of the glacier cover map, the total snow-glacier area derived using our semi-automated method was compared with glacier outlines that have been manually digitized in GLIMSView using two ASTER scenes for the western and central Karakoram region. Visual comparison of manually digitized glacier outlines with the glacier outlines based on Landsat scene shows good agreement for most glaciers (Figure 7). About 90% of the classified snow-glacier intersects with the GLIMS glacier inventory, while most of the remaining 10% is perennial and/or snow at steep slopes. Snow-covered ice areas under shadows and/or on steep slopes were substantially underestimated using the supervised classification alone. These areas were separately mapped using the band ratio method and added to the perennial snow-covered ice class. A confusion matrix was used to determine the level of agreement between the manually digitized outlines and our estimates of total glacier areas with and without the inclusion of snow-covered ice under shadowed areas. As summarized in Table 4, total glacier areas in both cases (i.e. total glacier areas with and without the inclusion of snow-covered ice under shadowed areas) have overall accuracy of 91.7 %, while the kappa coefficient (Cohen 1960) values increased from 0.61 to 0.71 when the snow-under shadowed areas in perennial snow-covered ice were added (Table 4). However, in some areas the addition of the shadowed areas to the perennial snow-covered ice resulted in an over-estimation of the snow-covered glacier surfaces compared to the manually delineated outlines. Based on a visual inspection of the GLIMS outlines on the Landsat scene, this higher estimate of glacier cover represents a more realistic upper boundary of the glacier cover, particularly for small tributaries of the glacier. The producer's accuracy of the total classified glacier cover inside the manually digitized outlines increased to 83% of the digitized area with the inclusion of the snow-covered ice areas under shadow. The 17% of the areas that were not identified by this method consist mostly of debris-covered glacier areas for smaller glaciers. Areas where lateral moraines do not exist for glaciers in the transition zones between glacier and non-glacier regions were also not identified by our classification. Similarly, the surrounding areas with similar spectral response as glacier debris were misclassified into the debris class. However, these misclassified area in debris class were manually deleted in the post-classification process. The 'exposed ice' areas compare well with the Landsat scene except for wet snow areas which were mostly classified as clean ice. Due to the existence of mixed pixels of wet snow and exposed ice, particularly at the snow line location, the difference between exposed ice and wet-snow/firn is difficult to discern (Sidjak and Wheate, 1999). Using a separate class of wet snow/firn in the classification algorithm may reduce the uncertainty in identifying the boundary between accumulation and ablation zones. Error due to resolution of Landsat data has been computed as one-half the pixel size (15m in current study) times the perimeter of classified snow- glacier-area, and found to be less than 9% of the total area, and is nearly the same as the overall accuracy (91.7%) determined from the confusion matrix.

Additionally, the quantitative accuracy of the classified snow- glacier area is compared with the available snow-glacier inventories and land-cover products. The difference between various available snow-glacier cover products and current study's total snow-glacier area are ~0.1 %, 5%, 5.6%, 7.3%, and 13% with Kaab et al. (2012), RGI v 3.0, GLC 1992, GLC 2000 and DCW 1980 respectively. These errors are well within the accuracy limits of the various products (see Table 5). Slight differences are also expected due to the fact that all of these inventories are based on different time intervals, where both seasonal snow and long-term changes in glacier area can produce large uncertainties.

5.2. Estimated snow-glacier inventory in the UIB:

The semi-automatic method for the entire UIB showed promising results in mapping snow-glacier zones (perennial and or seasonal snow, snow-covered ice areas, clean and debris covered ice areas) for areas with extensive glacier extent (Figure 8), and details are provided in Table 5. The total glacier area within the UIB above Tarbela reservoir is estimated at about 19,285 km^2, while total perennial snow is 7,238 km^2, perennial snow-covered ice is 5,226 km^2, exposed ice areas and debris covered ice areas are estimated at about 4,695 km^2, and 2,126 km^2, respectively (see Table 5). Previous studies (e.g. Hewitt, 2011, 2013; Bajracharya and Shrestha, 2011; Minora et al., 2013) noticed that debris covered glaciers in the UIB are in the range of 10-15 % of total perennial snow and glacier cover area, while our results also lie in the same range (~11%). The method of combining of Landsat bands (i.e. Band 1, Band 2 and Band 5) with surface slope information showed promising results in distinguishing debris covered areas from surrounding bare rocks, and is consistent with the earlier studies of Veettil (2012,2014). However, both these studies are based on very limited debris-cover glaciers in the central Karakoram (Shigar watershed).

We also summarize the total glacier area covered by glacier zones within sub-watersheds of the UIB for the major tributaries to the Upper Indus River. The Shigar, Hunza and Shyok River basins have higher percentages of perennial snow and glacier cover of 38.9, 30.4 and 25% of watershed area respectively, while the sub-basins to the south (Kharmong, Astore, Gilgit and UIB**: area between Tarbela Dam and Kharmong gauging station, excluding all other watersheds) river basins have relatively lower glacier cover (see Table 5).

The analysis of hypsometric curves for each glacier zone within the sub-basins indicates large differences in glacier elevation ranges and their distribution among sub-basins (Figure 9-12).Figure 9 (a,c) shows the snow-glacier hypsometric curve of the UIB** and Gilgit watershed, while (b,d) the monthly 0^{o}C isotherms of these watersheds. Maximum snow- ice covered area in the UIB** lies between 3,500-5,500m, while the average 0^{o}C isotherm during July reaches to 5,500m (see Figure 9 a,b). Gilgit watershed also has nearly the same elevation band of maximum snow- ice-covered area (4,000-5,500m) with a mean 0^{o}C isotherm peak (5,800

m) in July (see Figure 9 c,d). Figure 10 (a,b) shows the snow-glacier hypsometry and $0^{o}C$ isotherms of Hunza watershed, respectively. Most of the snow- ice cover lies between 4,500-6,000m, while most of the ice-cover lies between 4,500-5,200m, and peak $0^{o}C$ isotherm occur during July and August (5,500m). Shigar watershed also has nearly same elevation ranges for both snow- ice-cover area and $0^{o}C$ isotherm (see Figure 10 c,d), however, the snow- ice covered area hypsometric curves are steeper than in the Hunza watershed. Hunza and Shigar watersheds have large valley based glaciers, and therefore their lower-limits, mostly debris-covered areas are below 3,000 m, as reflected in Figure 10 (The Batura Glacier Investigation Group, 1979; Hewitt, 2005,2011,2013). As shown in Figure 11a, glaciers in the Shyok River basin are located at higher elevations with much steeper hypsometric curves for snow and exposed ice areas and a steep curve for debris areas descending only to 3,500 m elevation. The peak $0^{o}C$ isotherm occurs in July (~6,300m) at a higher elevation than in the other sub-watersheds (Figure 11b). In contrast, the hypsometric curves in the Kharmong River basin are flatter for all glacier zones (see Figure 11c). Debris-covered glacier areas descend to 3,500 m elevation, with a peak $0^{o}C$ isotherm in July (~5,800m) (see Figure 11d). Most of the snow and glaciers in the Astore watershed lie between 4,500-5,500m (see Figure 12a), while peak $0^{o}C$ isotherms (~5,500 m) occur during July and August (see Figure 12b).

5.3. ELA and AAR estimates:

The ELAs estimated based on SLEs for various watersheds in the UIB are provided in Table 6. It should be noted that in temperate glaciers, SLEs and ELAs lie below the maximum $0^{o}C$ isotherms (Cuffey and Paterson, 2010). Minimum and maximum SLE limits are shown on all watershed's snow- ice-cover hypsometric curves (see e.g Figure 9 a,c), while the maximum monthly $0^{o}C$ isotherms are also provided for each individual watershed (see e.g Figure 9 b,d). It should be noted that the maximum $0^{o}C$ isotherm values in Table 6 are based on average temperature for July/August, while minimum and maximum SLEs and ELAs (estimated in this study) lie well below the maximum 0^{o}C isotherm.

The average ELAs of Astore, Gilgit, Hunza, Shigar, and UIB** watersheds show nearly the same altitudinal zones (~4,700-5,100m), while Kharmong and Shyok watershed's ELAs range between 5,300-5,500m (see Table 6). These ELA estimates (see Table 6) are consistent with earlier studies (e.g. Hewitt, 2011,2013; Kaab et al., 2012 ;Gardelle et al., 2013;Owen and Benn, 2005;Scherler et al., 2011), and are a baseline estimate around 2000. Our estimate of ELA for Shyok watershed is consistent with ELA values provided in Hewitt (2011, 2013) and Kaab et al. (2012), while ELA values in Gardelle et al. (2013) are on the lower side and could be due to both differences in dates and methodology. Table 6 also provides SLE estimates based on the Hasson et al. (2013) study, where MODIS snow-cover data has been utilized for computation of SLEs. Though no detailed methodology is explained in their study for computation of SLEs, these altitudes are much lower than all other studies and suggest that these are based on snow-cover data only, and no separation of ice and snow has been carried out. It should be noted that the ELA estimates in the current study are for individual watersheds (at regional scale), and may not be a representative of individual glaciers. Therefore, slight differences between various other studies and the current study ELAs can be expected due to difference in time and locations of various ELA data, the number of glaciers under study and methodology. However, it is noteworthy that our study provides the first regional ELA estimates for the entire UIB watersheds.

AARs for various watersheds are based on SLE estimates and show large variation across the entire UIB. In Kharmong watershed the AAR range has maximum variation (7-80%), and could be due to large heterogeneity of glaciers' types and elevation variation in the watershed (Watershed Area > 70,000 km^2).These AAR values are consistent with estimates provided in Hewitt (2011, 2013) and Kaab et al. (2012), while the AAR values of Gardelle et al. (2013) are on the higher side, and could be due to their Landsat image time, methodology of snow-ice classification and AAR estimation.

5.4. Significance of current study's outputs

Outputs from this study can be used in a large variety of scientific studies, such as: hydrological modeling, climate impact analysis of glaciers, glacier mass balance studies, and correction of snow-cover data (e.g. MODIS). Brief details of previous studies and significance of current study's outputs are discussed below:

(i) Application in Hydrological Modeling:

Previous hydrological modeling studies have not considered snow, ice and debris covered ice separately (such as Tahir et al., 2011;Immerzeel et al., 2009) or only considered a reduced melt rate for debris covered ice (such as Immerzeel et al., 2012a, 2013; Lutz et al., 2014). Snow and clean ice have different melt rates (as discussed above), while thin/thick debris cover accelerates/decelerates melting (Hewitt, 2005, 2011, 2013; Kaab et al., 2012; Gardelle et al., 2012; Nuimura et al., 2011). Therefore, the position and extents of separate snow, ice and debris covered-ice zones as provided here can be used as an important input in future hydrological modeling studies. Furthermore, current debris cover estimates can also be used as base line for thick and thin cover separation. Although the current study does not estimate the thickness of debris cover, but provides regional estimates of total debris-covered ice, which could be used in future research of thin/thick debris cover separation.

(ii) Climate change impact studies:

Due to the absence of any regional ELA studies in the UIB, previous studies have used mean ELA values from other regions in Himalaya for the Karakoram glaciers in future climate impact studies(e.g. Chaturvedi et al., 2014).The current study, however, has shown that these regions have different ELA values (see Table 6 for comparison of western Himalayan and western

Karakoram ELAs), which could be useful for estimating uncertainty in future climate impact studies due to regional variability in ELA influenced by different climatic patterns.

(iii) Glacier mass balance studies:

Previous glacier mass balance studies (such as Gardelle et al., 2012,2013; Gardener et al., 2013;Kaab et al. 2012) adopted both uniform and separate snow and ice densities for the entire snow-glacier areas. Perennial and or seasonal snow on steep slopes with a depth up to 10m, could range a density between 100 - 350 kg/m^3 (Cuffey and Paterson, 2010), far less than snow-ice densities (600-900 kg/m^3) used in the above mentioned studies. Therefore, previous glacier mass balance studies may have overestimated melt water contribution. With the detailed mapping provided in the current study, different densities could be assigned to each snow/ice class, which would improve the accuracy of mass balance estimates in the UIB. Additionally, Chaturvedi et al. (2014) adopted western Himalayan ELA and AAR values for the western Karakoram glaciers for glacier mass balance analysis but the current study has shown that the ELA and AAR values in the Karakoram region (see Table 6: the western Karakoram; Hunza and Shigar watershed) are far different from western Himalayan glaciers (see Table 6: Kharmong watershed, and other studies). Using separate classifications for snow, ice and steep slope snow areas and ELAs and AARs values in the current study will provide more improved and precise results in future glacier mass balance studies and predictions.

(iv) Correction of MODIS snow-cover data:

MODIS snow-cover data is available at 500m resolution, and may underestimate the area of small glaciers (<0.01 km^2) typical of the western Himalayas (Astore and Kharmong watersheds), as well as debris covered ice. Such under-estimation can be seen upon comparison of current study with RGI v 3.0 and MODIS monthly data (2000-2010) in Table 5, where Astore and Kharmong glaciers are significantly under-estimated by the MODIS products. Most of the valley based large glacier's tongues are covered by debris, and may not be captured by MODIS data, and could be a reason of such underestimation. The current study's output can provide useful base line data for further detailed study to develop corrections.

6. Conclusions and Recommendations:

The hydro-climatic conditions in glacierized basins of the UIB vary significantly spatially and with respect to altitude . In such a complex system, it is therefore important to assess glacier changes separately for distinct glacier zones such as perennial and or seasonal snow, snow-covered ice, clean and debris-covered ice areas, rather than changes in the total area covered by snow and glaciers. Quantifying glacier mass balance using traditional field-based techniques is labor intensive, time-consuming and expensive for poorly surveyed, large drainage basins. Additionally, manual digitization of glaciers from remotely sensed data may provide more accurate estimates of glacier extent but its application is time-consuming for quantifying glacier changes at larger scale. On the other hand, semi-automated methods of delineating glacierized areas may require post-classification processing and manual editing in some cases, but are more effective for fast mapping of glaciers over large regions. Hence, a semi-automated methodology was adopted to not only delineate regional glacier cover into four zones: perennial and or seasonal snow, snow covered ice, clean and debris covered ice, but also to obtain ELAs, AARs and 0^{o}C isotherms at watershed level in the entire UIB. Current regional separated snow and ice estimates can be used in the future for improved hydrological modeling, degree day factors estimation, snow- and ice-melt contributions in river flows estimation, and glacier response assessment to climate change.

This study has led to the following conclusions:

1. The estimated area of perennial and or seasonal snow cover (on> 25^{o} slopes), snow-covered ice, clean ice and debris covered ice in the UIB is 7,238 ± 724, 5,226 ± 522, 4,695 ± 469 and 2,126 ± 212 km^2, respectively. Thus total perennial snow and glacier cover is 19,285 ± 1,928 km^2, out of which 12,075 ± 1,207 km^2 is glacier cover. Details

are provided in Table 5. Perennial snow cover on steep slopes may provide more in depth knowledge of snowfall variation in UIB, and any increase/decrease in snow on steep slopes can be easily separated for an accurate and precise mass balance analysis (using separate densities for various snow- and ice covers) .

2. Average ELA estimates based on the average snow line elevations for Astore, Gilgit, Hunza, Shigar and UIB** watersheds range between 4,800-5,100m, while ELA values in Kharmong and Shyok watersheds are between 5,300-5,500m.
3. The accumulation area ratios of various watersheds in Hindukush and Karakoram watersheds range between 20 - 50% (in Shigar and Hunza watersheds) and 21-65% in the Gilgit and Shyok watersheds. Kharmong watershed shows the greatest variation in AAR values (7-80%) and could be due to its large size and various glacier types in this region. The Astore watershed also has a significant AAR range (20-75%), while the remaining part of UIB (UIB**) has a similar range as in Shigar watershed (Table 6).

The methodology adopted and explained in the current study is universal and robust and can be used in other parts of the world, particularly in the adjacent western Himalayan watersheds.

Acknowledgements:

The authors would like to thank USGS for providing LANDSAT images and National Snow and Ice Data Center for MODIS data used in this study. The second author is also very thankful to Jonghun Kam, Civil and Environmental Engineering, Princeton University, NJ, USA for providing help with image processing methods of Landsat images used in this study. The first author is thankful to Dr. Jun Hak Lee, Department of Earth and Environmental Science, University of Texas at Arlington, USA, for help in image processing and classification. The authors are immensely grateful to the Water and Power Development Authority of Pakistan for making the climatic data available for research. The authors also express indebtedness to the Pakistan Meteorological Department for providing long-term climatic data. The first author is highly indebted to Mr. Raza Mehmood Farrukh, Senior Project Officer, Asian Development Bank, Philippines, Manila, Mr. Zahoor Ahmed, General Manager, Associate Consulting Engineers (ACE), Lahore, Pakistan, Dr. Ghulam Rasul, Chief Meteorologist, Pakistan Meteorological Department, Islamabad, Pakistan, Mr. Muhammad Riaz, Chief Meteorologist, Pakistan Meteorological Department, Lahore, Mr. Danial Hashmi , Senior Officer, Water and Power Development Authority, Lahore, Pakistan, Dr. Adnan Ahmed Tahir, Assistant Professor, Enivronmental Sciences, COMSATS Institute of Information Technology, Abbottabad, Pakistan, and Mrs. Shan Aman Rana, PhD candidate, Department of Economics, London School of Economics and Political Sciences, UK, Chunqiao Song, PhD candidate, the Chinese University, Hong Kong, David R. Archer, JBA Consulting Engineers and Scientists, South Barn, Broughton Hall, Skipton, North Yorks., BD23 3AE, UK, for their help, provision and support in climatic data collection. The authors would also like to thank anonymous reviewers for their critical but constructive review, which enhanced presentation and insights of current study.

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Figure captions:

Figure 1: The study area showing countries boundaries, the study area location, the Hindukush-Karakoram-Himalayas (HKH) mountain ranges, watersheds, well known mountain peaks and climatic stations. A) The study location along with countries boundaries, westerlies and monsoon trajectories to the study area, (B) The study location, the HKH mountain ranges, main streams/rivers, topographic variation and well known mountain peaks, (C) watersheds in the Upper Indus Basin, location of climatic stations used in the current study .

Figure 2: a) Monthly average flow at Besham Qila during 1969-2010 and climatic stations' (provided in Table 1) average monthly precipitation, (b) MODIS monthly Snow Cover Area (SCA) variation in the Upper Indus Basin during 2000-2010.

Figure 3: The study area showing the location, path and row of the 18 Landsat scenes (mosaic of all scenes with false color composite 543), and watersheds in the Upper Indus Basin. The number indicates the path and row of each scene. Highlighted scene 149/35 has been used for selection of classification bands and training samples, the area within the red-circle is shown in Figure 4, while the area within the purple circle is shown in Figure 6. Area within the red polygon have been utilized for comparison with GLIMS data (shown in Figure 7).

Figure 4: Example of different areas of the glaciers where training data were collected based on visual observation of the image. The image is the RGB composite of Landsat with band combination of 543. The letters indicate (a) perennial snow-covered ice, (b) exposed ice, (c) debris covered ice, (d) water bodies, (e) shadowed regions, and (f) other terrain. Label "a" and

"c" are located on the well known Batura glacier. The location of the selected area can be seen in the red circle in Figure 3.

Figure 5:Percentage accuracies of individual classes and overall accuracy of thematic maps classified using different input datasets of layer combinations in Maximum Likelihood (ML) classifier. The percentage accuracies were estimated using independent set of testing samples and training areas in confusion matrix. SLP refers to surface slope layer combined with the Landsat bands.

Figure 6: Classification processing steps to illustrate the methods used in the study using the Biafo glacier in the Shigar watershed, as an example. The location of the selected area can be seen in the purple circle in Figure 3. (a) RGB image composite of Band5, Band2 and surface slope information, (b) perennial snow-covered area extent, (c) Landsat image excluding snow-covered ice area showed in gray color, (d) resulting map of glacier zones using Maximum Likelihood (ML) classification of Landsat layers (Band1, 2 and 5) and surface slope, (e) map of glacier zones showing snow under shadowed areas estimated using Band 3/ Band 5 ratio method which were added into perennial snow-covered ice class, and (d) resulting map after applying 3 x 3 median filter and manual editing to remove noise. Note: The legend of shadowed regions is only for Figure 6 (e), while only selected classes are labeled in the legend.

Figure 7:Comparison of estimated glacier cover in the central Karakoram region with manually digitized outlines from two ASTER scenes available through the GLIMS database. The location of selected area can be seen in the red-polygon in Figure 3.

Figure 8: Resulting glacier zones map showing extents of perennial snow-covered ice, clean and debris-covered ice areas within the Upper Indus Basin (UIB) above Tarbela Reservoir. The locations of a few large glaciers in the UIB are also shown.

Figure 9 (a-d): Glacier hypsometric plots of perennial snow-cover areas, exposed/clean ice, debris-covered areas, and 0^oC isotherms in the UIB** (area between Tarbela Dam and Kharmong gauging station, excluding all other watersheds) and Giglit watersheds.0^oC isotherms for Gilgit are based on Shendure and Gilgit climatic stations, while for UIB** average values are derived from Archer (2004). Lower and upper limits of Snow Line Elevations (SLEs) are demarcated by vertical dotted lines.

Figure 10 (a-d): Glacier hypsometric plots of perennial snow-cover areas, exposed/clean ice, debris-covered areas, and 0^oC isotherms in Hunza and Shigar watersheds.0^oC isotherms are based on Gilgit and Khunjerab climatic stations for Hunza watershed, and Shigar and Khunjerab climatic stations for Shigar watershed. Lower and upper limits of Snow Line Elevations (SLEs) are shown by vertical dotted lines.

Figure 11 (a-d): Glacier hypsometric plots of perennial snow-cover areas, exposed/clean ice, debris-covered areas, and 0^oC isotherms in Shyok and Kharmong watersheds.0^oC isotherms are based on Skardu and Hushey climatic stations for Shyok watershed, and Leh and Demchock climatic stations for Kharmong watershed. Note: Leh and Demchock common period has been used for lapse rate estimation, and then same lapse rates have been used for 0^oC isotherms calculations, using 1999-2002 average temperature data of Demchock station. Demarcation of lower and upper limits of Snow Line Elevations (SLEs) are shown by vertical dotted lines.

Figure 12 (a,b): Glacier hypsometric plots of perennial snow-cover areas, exposed/clean ice, debris-covered areas, and 0^oC isotherms in Astore watershed.0^oC isotherms are based on Astore and Burzil climatic stations. Demarcation of lower and upper limits of Snow Line Elevations (SLEs) are shown by vertical dotted lines.

Table 1. Information on Landsat images utilized in the current study

No	Sensor	Path/row	Date acquired	% cloud cover
1	TM	150/36	9/19/2009	0
2	ETM+	150/35	9/16/1999	1
3	ETM+	150/34	9/05/2001	8
4	ETM+	149/36	9/30/2001	0
5	TM	149/35	8/13/1998	10
6	ETM+	149/34	9/30/2001	1
7	ETM+	148/37	10/28/2002	1
8	TM	148/36	8/27/2000	10
9	ETM+	148/35	7/21/2002	3
10	ETM+	147/37	8/2/2002	1
11	ETM+	147/36	8/2/2002	1
12	ETM+	147/35	8/28/2000	4
13	ETM+	146/37	8/21/2000	3
14	ETM+	146/36	7/7/2001	2
15	ETM+	146/38	10/30/2002	2
16	ETM+	145/36	7/03/2002	1
17	ETM+	145/38	10/20/2001	1
18	ETM+	144/38	9/24/2000	2

* Cloud cover in all utilized images is below 10%. However, the selected images in the high glacierized areas have less than 3% of cloud cover.

Table 2: Details of climatic stations, their coordinates, data period, and sources of data

S.No	Station	Altitude (m)	Coordinates		Period of Record	No of years	Source*
			Latitude	Longitude			
1	Dir	1375	35.200	71.850	1980-2010	31	1
2	Ushkore	3051	36.027	73.415	1999-2010	12	2
3	Shendure	3712	36.088	72.547	1994-2010	17	2
4	Zani Pass	3839	36.352	72.169	1994-2010	17	2
5	Khotkas	3624	36.583	72.583	1994-2010	17	2
6	Yasin	3280	36.451	73.294	1999-2010	12	2
7	Naltar	2898	36.168	74.175	1999-2012	12	2
8	Ziarat	3020	36.829	74.418	1999-2014	12	2
9	Khunjerab	4730	36.812	75.332	1999-2013	12	2
10	Hunza	2374	36.322	74.646	2007-2010	4	1
11	Gilgit	1460	35.921	74.327	1951-2010	60	1
12	Shigar	2367	35.698	75.481	1996-2010	15	2
13	Hushey	3075	35.342	76.139	1994-2010	17	2
14	Skardu	2317	35.286	75.563	1952-2010	59	1
15	Deosai	4149	35.004	75.592	1995-2010	16	2
16	Leh	3505	34.164	77.587	1978-1990	13	3
17	Demchock	4279	32.500	80.080	1979-2010	32	4
18	Burzil	4239	34.899	75.079	1999-2010	12	2
19	Astore	2168	35.366	74.865	1954-2010	57	1
20	Srinagar	1587	34.1	74.8	1954-2000	47	3
21	Rattu	2718	35.161	74.785	1999-2010	12	2
22	Rama	3179	35.455	74.776	1999-2010	12	2
23	Bunji	1372	35.646	74.629	1953-2010	58	1
24	Chilas	1250	35.472	74.004	1953-2010	58	1
25	Gupis	2156	36.179	73.439	1955-2010	56	1

*Sources: 1 = Pakistan Meteorological Department (PMD); 2 = Water and Power Development Authority (WAPDA), Pakistan; 3= Indian Meteorological Department, India; 4= China Meteorological Department, China. Note: All station's daily data have been obtained, and monthly average has been estimated from these datasets. Leh, Srinagar and Demchock monthly data has been obtained. Few months data of Leh and Srinagar is missing. Altitudes of relevant stations have been obtained from relevant source departments except Leh and Srinagar, which is extracted from SRTM DEM, and verified with other published sources.

Table 3: Summary statistics of Landsat layers (reflectance) and SRTM-derived slope (degree) layers.

Band	**Wavelength (µm)**	**Resolution (m)**	**Min**	**Max**	**Mean**	**Standard Deviation**
Band 1	Red (0.45-0.52)	30	0	0.9	0.16	0.13
Band 2	Green (0.52-0.60)	30	0	1.04	0.19	0.14
Band 3	Blue (0.63-0.69)	30	0	0.98	0.22	0.14
Band 4	NIR (0.76-0.90)	30	0	1.51	0.27	0.16
Band 5	SWIR1 (1.55-1.75)	30	0	1.19	0.25	0.14
Band 7	SWIR2 (10.40-12.50)	30	0	1	0.21	0.12
SLP*		90	0	77	24.4	12.8

*Surface slope layer

Table 4: Accuracy statistics for the two glacier maps with and without adding snow-under shadowed areas in perennial snow cover by comparing with manually digitized glacier outlines in the central Karakoram region.

Description	**With shadowed areas I.**		**Without Shadowed areas II.**	
	Producer's accuracy (%)	User's accuracy (%)	Producer's accuracy (%)	User's accuracy (%)
non-glacier	93.41	96.6	97.16	93.25
glacier	82.75	70.51	63.06	80.87
Overall accuracy (%)	91.7		91.7	
Kappa Coefficient	0.71		0.61	

Table 5: Total snow-glacier, perennial and/or seasonal snow, snow-covered ice, clean and debris-covered ice areas in various watersheds of UIB. DCW 1980, GLC 1992, GLC 2000, MODIS 2000-2010, RGI v 3.0 and Kaab et al. (2012) snow and glacier inventory data.

Watershed	Perennial snow and glacier cover area (km^2)											
							Current study (1998-2002)					
	DCW 1980	**GLC 1992**	**GLC 2000**	**MODIS (2000-2010)***	**RGI v 3.0 (2013)**	**Kaab et al. (2012)**	**Snow-glacier Total**	**Glacier^1**	**Debris-covered Ice**	**clean Ice**	**Snow-covered Ice**	**Perennial and Seasonal snow*** **
Gilgit	1119 ± 112	1414 ± 468	1970 ± 618	830 ± 309	836 ± 83	1360 ± 136	1091 ± 109	686 ± 69	147 ± 14	302 ± 30	237 ± 23	405 ± 23
Hunza	4559 ± 456	5340 ± 1767	3577 ± 1123	3326 ± 300	3843 ± 384	3774 ± 377	4151 ± 415	2194 ± 219	479 ± 48	811 ± 81	904 ± 90.4	1957 ± 196
Shigar	2220 ± 222	2936 ± 972	2464 ± 773	2303 ± 225	2121 ± 212	2671 ± 267	2738 ± 273	1735 ± 173	415 ± 41	656 ± 65	664 ± 66	1003 ± 100
Shyok	8676 ± 867	6847 ± 2266	6206 ± 1948	5857 ± 331	7696 ± 769	7871 ± 787	7372 ± 737	4991 ± 499	704 ± 70	1825 ± 182	2462 ± 246	2381 ± 238
Kharmong	5037 ± 503	2953 ± 977	2506 ± 787	1315 ± 462	2522 ± 252	2315 ± 231	2254 ± 225	1592 ± 159	224 ± 22	786 ± 78	553 ± 55	691 ± 69
Astore	190 ± 19	209 ± 69	468 ± 147	166 ± 85	541 ± 54	299 ± 29	479 ± 48	247 ± 25	45 ± 4	52 ± 5	150 ± 15	232 ± 23
UIB**	605 ± 60	730 ± 241	775 ± 243	605 ± 166	775 ± 77	974 ± 97	1199 ± 119	630 ± 63	112 ± 11	263 ± 26	256 ± 26	569 ± 57
Total	**22406 ± 2241**	**20429 ± 6761**	**17966 ±5641**	**14402 ± 1878**	**18334 ± 1833**	**19264 ± 1926**	**19285 ± 1928**	**12075 ± 1207**	**2126 ± 212**	**4695 ± 469**	**5226 ± 522**	**7238 ± 724**

UIB** The area is between Tarbela dam to Kharmong gauging station (all watersheds are excluded), * Monthly MODIS values are tabulated as 2000-2010 average ± std.dev (Accuracy limits ± 10% have to be added on top of these values), [1] is glacier area obtained from subtraction of perennial and seasonal snow*** from snow-glacier total. *** Perennial snow is snow at slope > 25 degree. Note: Parts of Kharmong and UIB* areas (though very small) are not covered by Kaab et al. (2012) inventory. Accuracy limits of ± 10% have been assumed for Kaab et al. (2012) inventory.

Table 6: Estimates of ELA, AAR, maximum 0°C isotherms, and other studies' ELA and AAR values

Watershed	**SLE/ELA (m)**	**AAR (%)**	**Maximum 0° C Isotherm(m)**	**Hewitt (2011,2013)**	**Hasson et al. (2013) (m)**
Gilgit	4250-5500 (4850)	21-65% (43%)	5970		3900-4000
Hunza	4300-5520 (5000)	25-43% (34%)	5515	4800-5200m (22-40 %)	3400-3500
Shigar	4500-5550 (5050)	21-51% (36%)	5398	4800-5600m (4-37%)	3800-3900
Shyok	5020-6030 (5500)	22-65% (44%)	6263	5200-6000m (29-60%)	4200-4300
Kharmong	4300-6000 (5250)	7-80% (44%)	5793		3200-3300
Astore	4100-5500 (4700)	20-75% (48%)	5500		4100-4200
UIB**	3550-5550 (4700)	17-51% (34%)	5500		

Watershed	**Gardelle et al. (2013)**	**Kaab et al. (2012)**	**Scherler et al. (2011) (m)**	**Other Studies(m)**
Gilgit	4890-5210m (30%)	30%	5140	5050
Hunza				4700-5300
Shigar	4750-5310m (66-76%)	5540m (47%)	4884	4800-5200
Shyok				
Kharmong				5200-5800[1]
Astore		32%		3750-5200[2]
UIB**				
Western Himalayas	5407-5806m (34%)		5102	4800-5700

SLE/ELAs are based on Snow Line Elevation (SLE) method, values are minimum and maximum SLE , while in brackets ELAs are based on average of total snow-glacier area between maximum and minimum SLEs. AAR values are based on minimum and maximum SLEs, while in brackets AAR values are average of minimum and maximum AAR. UIB** is area between Tarbela dam and Kharmong gauge station, excluding all other watershed areas. Hewitt (2011, 2013) ELA and AAR are from Von Wissmann and Hermann (1959) in Hewitt (2011,2013 page 153), and are based on 15 glaciers in Hunza, 4 in Shigar and 15 in Shyok watershed. Gardelle et al. (2013) ELA values are based on 30 glaciers, using Landsat TM and ETM+ data around 2000, however, exact numbers in each watershed are unknown. ELA value of Kaab et al. (2012) is also from Gardelle et al. (2013), while values in front listed for Shigar in both these studies are for Hunza, Shigar and Shyok watersheds. Scherler et al. (2011) provided SLEs using Landsat TM and ETM+ data during 1990-2001, the Hindukush estimates are based on 19 glaciers, while the Karakoram estimates are based on 41 glaciers. For the western Himalayas values are average SLE of 64 glaciers provided in the paper. Other studies are: Kadoka (2000), Kadoka et al. (2002), Owen and Benn (2005), The Batura Glacier Investigation Group (1979), Young and Hewitt (1989, 1993), Osmaston (1994), Kulkani (1992), Pandey et al. (2012). [1] Zanskar and Ladakh region ELA values, while [2] is for Nanga Parbat glaciers. All % values are AAR, and altitudes are in m.