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Evaluation of the global glacier inventories and assessment of glacier elevation changes over north-western Himalaya

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Running Headline: A database of glacier inventory and recent mass changes over North-western Himalaya

Abstract

The study evaluates the global glacier inventories available for the study area viz., RGI, GAMDAM and ICIMOD, with the newly generated Kashmir University Glacier Inventory (KUGI) for three Himalaya basins; Jhelum, Suru and Chenab in the north-western Himalaya, comprising of 2096 glaciers spread over an area of 3300 km^2. The KUGI was prepared from the Landsat data supplemented by Digital Elevation Model, Google Earth images and limited field surveys. The KUGI comprises of 154 glaciers in the Jhelum, 328 in the Suru and 1614 in the Chenab basin, corresponding to the glacier area of 85.9±11.4 km^2, 487±16.2 km^2 and 2727±90.2 km^2 respectively. The investigation revealed that most of the glaciers in the study area are <1 km^2 in size, however, the glaciers in 1-5 km^2 size class cover most (55.8%) of the glacier area. Majority of the glaciers, both in terms of number and area, are at 4500-5500 m asl except in the Jhelum where the glaciers are mostly situated between 4000-5000 m asl altitude. The glaciers in the three basins mainly harbor slopes ranging from 10-30°. It was also observed that the southern aspects host more number of large-sized glaciers than the northern aspects. Comparative analyses of the inventories revealed that the GAMDAM (R_A^B=0.75) and RGI (R_A^B=0.73) inventories are consistent with the KUGI. However, discrepancies were observed in the debris-covered and shadowed glaciers particularly in the ICIMOD inventory. The glacier elevation changes were also estimated for glaciers in the three basins using the Tandem-X and SRTM-C DEMs from 2000 to 2012. The investigation revealed a strong control of glacial morphology, topography, and debris cover on glacier thinning. Glacier elevation change of -1.33±0.8 m a^{-1} was observed in the Jhelum basin but a similar glacier elevation changes of -1.08±0.7 m a^{-1} and -1.09±0.8 m a^{-1} was observed in the Suru and Chenab basins respectively. Evaluation of the glacier inventories and assessment of glacier elevation change in the data-scarce Himalaya, reported in this article, would constitute a reliable database for research particularly in hydrology, glaciology, and climate change. The dataset is freely available at http://doi.org/10.5281/zenodo.4461799 (Romshoo et al., 2021).

Keywords: Glacier inventory; Himalaya; Glacier elevation change; Database

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1. Introduction

Depleting state and health of the Himalayan glaciers have significant implications for the regional hydrological regimes (Immerzeel et al., 2010; Kaser et al., 2010), imperiling the lives and livelihood of millions of people living downstream (Bolch et al., 2012). The far-reaching consequences of the enhanced melting of the Himalayan glaciers on water, food, energy security (Rasul, 2014; Romshoo et al., 2015) and the projected rise in the sea level (Radić and Hock, 2011; Gardner et al., 2013) have attracted the attention of scientific community to investigate the health and behavior of these glaciers (Scherler et al., 2011a; Racoviteanu et al., 2015; Guo et al., 2014; Murtaza and Romshoo, 2017; Cogley, 2016). Assessment of the glacier changes based on *in situ* measurements (Bolch et al., 2012; Yao et al., 2012; Azam et al., 212), remote sensing (Kääb et al., 2012; Gardelle et al., 2013; Gardner et al., 2013; Brun et al., 2019) and modelling approaches (Lutz et al., 2016; Fujita and Nuimura, 2011) indicated that there is no uniform glacier behavior and dynamics observed across the Himalayan region. Inaccessible and rugged terrain together with the logistic and security impediments (Bolch et al., 2012), however, have restricted the *in situ* glacier measurements to a small number of glaciers often small in size and located at lower altitudes (Bolch et al., 2012; Cogley, 2012). Accelerated glacier mass wastages have been reported over the Himalaya (Kääb et al., 2012, Gardelle et al., 2013; Murtaza and Romshoo, 2017, Rashid et al., 2017), except for the Karakoram region where the glaciers are stable or even advancing (Abdullah et al., 2020; Brun et al., 2017; Bahuguna et al., 2014; Ganjoo and Koul., 2013; Raina, 2009; Kääb et al., 2012; Gardelle et al., 2013). The situation is expected to exacerbate under the projected climate change scenarios (Kraaijenbrink et al., 2017; Rashid et al., 2017; Romshoo et al., 2020) which would likely enhance the loss of glacier resources with serious implications on water availability (Immerzeel et al., 2010; Romshoo et al., 2015) inter alia increasing the risk of Glacier Lake Outburst Floods (GLOFs, Richardson and Reynolds, 2000). It is therefore, imperative to have precise, frequent and long-term measurements of glacier change in the Himalaya that will help us to reduce the uncertainty in the projections of future water availability (Kaser et al., 2010; Immerzeel et al., 2010) and for risk reduction of the glacier hazards (Richardson and Reynolds, 2000) in the region. For assessment of glacier behavior and health parameters like area and length change, mass balance and velocity, a well-defined glacier boundary is a perquisite (Nuimura et al., 2015). In view of the fact that manual glacier delineation in the Himalayan region is a cumbersome and time consuming process (Nuimura et al., 2015) particularly for the vast areas of topographically challenging Himalayan region, most of the studies have therefore relied on the global/regional glacier inventories for impact assessment studies (Vaughan et al., 2013)

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and for future projections of glacier mass and streamflows (Raper and Braithwaite, 2005) in the remote and vast Himalayan terrain. These inventories have been utilized in several studies for assessing the recent glacier changes (Bajracharya et al., 2014a, b), modeling the evolution of glacier lakes (Gardelle et al., 2011), modelling the past and future global sea level rise (Gardner et al., 2013; Radić et al., 2014; Marzeion et al., 2012) and ice thickness distribution (Huss and Farinotti, 2012).

However, using the publicly available glacier datasets for glacier change assessment and for future projections of water and glaciers resources is not recommended without proper and adequate quality control measures (Nuimura et al., 2015) as the glacier inventories have inconsistencies in terms of different glacier variables (Nagai et al., 2016). Despite the usefulness of the global and regional glacier inventories for various applications at local, regional and global scales, the reproducibility of the results for various applications in different regions is not assured (Nagai et al., 2016). In addition to the global glacier inventory databases compared and discussed in this paper, a few more glacier inventories (Shukla et al., 2020) and mass balance (Vijay and Braun, 2018) databases from the Himalaya have been recently published online. However, the glacier inventory database by Shukla et al., (2020), restricted to the Suru basin, is primarily based on the automatic approach (normalized-difference snow index) unlike the present study where the glaciers are mapped manually using on-screen digitization. The uncertainties in glacier mapping using the automatic method are considerably minimized by manually delineating the glacier extents (Paul et al., 2013; Rashid and Abdullah, 2016). The glacier mass change database by Vijay and Braun, (2018) is restricted to a small portion of the study region.

In this backdrop, it was considered important to develop a precise and robust glacier inventory of the three glaciered basins of the Himalaya with the glacier boundaries extracted manually using onscreen digitization of glaciers from Landsat data of the year 2000±3 and to compare it with the available global inventories in terms of various glacier parameters so that the most appropriate glacier inventory is identified for precise glacier resource assessment and other applications. Further, geodetic mass changes of the glaciers in the three basins were determined using DEMs during 2000-2012 to get a better idea about the glacier behavior and health in the region. It is hoped that the KU glacier inventory and elevation change databases presented in this paper shall further help in promotion research in fields like climate change, hydrology and other allied fields.

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2. Study area

The study area comprises of the three glacier basins in the UIB including the Jhelum, Suru and Chenab basins (Fig. 1), situated in Jammu, Kashmir and Ladakh region in the north-western part of the Himalayan arc. Extending from 32.17° to 36.58°N 73.26° to 80.30°E, Jammu, Kashmir and Ladakh region covers an area of ~222,236 km^2 (Romshoo et al., 2020a). The region has unique and varied climatology and topography offering suitable niches for the sustenance of glaciers (Romshoo et al., 2020b). The area above 3600 m asl in general remains covered with perennial snow and glaciers. There are 15064 glaciers covering an area 24,022 km^2 (RGI Consortium, 2017; Abdullah et al., 2020) equivalent to ~11% of the geographical area of the region, thus making the study area the most glaciated terrain in the Indian Himalayas. Most of the glaciers in the area are valley glaciers except the glaciers in the Ladakh range where cirque glaciers are more common (Kamp et al., 2011). Most of the major tributaries of the Indus River like Jhelum, Chenab and Indus, originate from the meltwaters of these glaciers distributed across different mountain ranges with varied topographic and climatic settings (Romshoo, 2012).

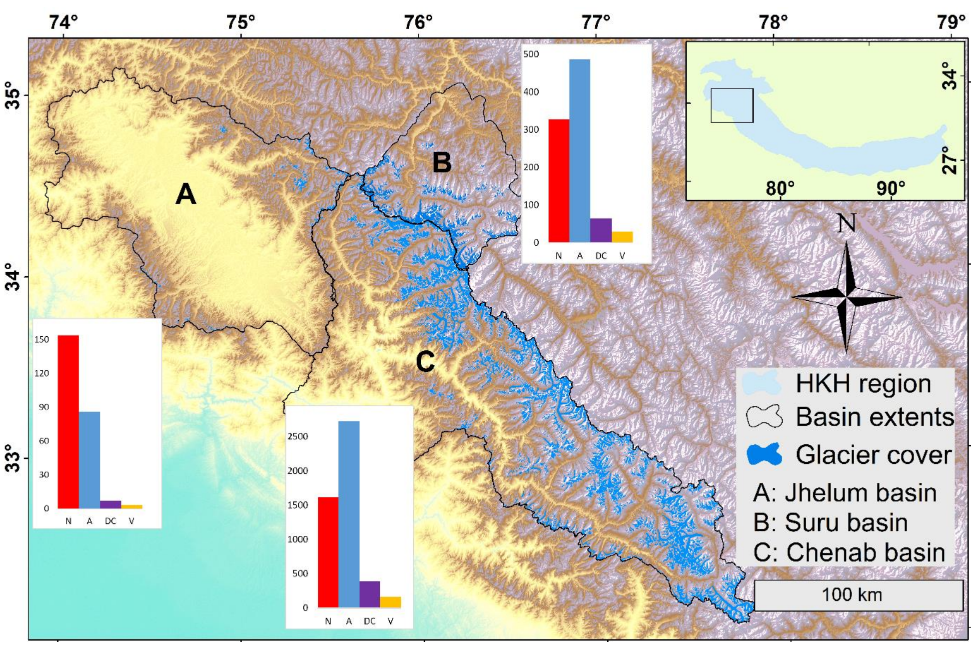

Fig. 1: Location of the study area: A) Jhelum basin; B) Suru basin; C) Chenab basin. The bar graphs overlaid on the figure indicate; N: number of glaciers, A: glacier area (km^2), DC: debris cover (km^2) and V: glacier volume (km^3) in each of the three basins under KUGI.

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2.1 The Jhelum basin

The Jhelum basin in the UIB, is spread over an area of about 13625 km^2, comprises of 24 watersheds (Romshoo et al., 2018) and drains into the Jhelum river (Fig. 1) which is one of the major tributaries of the Indus. The Jhelum basin is surrounded by the Pir Panjal mountain range in the southwest and the Greater Himalaya range in the northeast. About 0.7% area of the basin is covered with glaciers largely located at altitudes between 4500-5000 m asl, and mainly in the Lidder and Sind watersheds of the basin. Kolahoi Glacier in the Lidder watershed, with an area of ~11 km^2, is the largest glacier in the basin. The climatic regime in the basin is dominated by the western disturbances (Dimri and Mohanty, 2009; Slingo et al., 2005; Scott et al., 2012). The precipitation occurs mostly in the form of snow and is largely received during winters. The basin on an average receives annual precipitation of 1200 mm while as the mean annual maximum and minimum temperatures range from 19.3°C and 7.3°C (Hussain 1987; Mushtaq and Pandey, 2014).

2.2 The Suru basin

The Suru basin is located in the Ladakh region, east of the study area. The basin covers an area of ~4472 km^2 (Fig. 1). The basin has ~328 glaciers covering an area of about 487 km^2 with 11% of the basin area under glaciers. The glaciers are distributed at altitudes ranging from 4000-6000m asl with majority of them clustered between 5000-5500 m asl. The glacier- and snow-melt waters in the basin are drained into the Suru river in the UIB, originating near the PensiLa. The annual mean temperatures in the cold desert Ladakh region settles at around 7.8°C. The region receives annual precipitation of ~102 mm, least in the entire region (Chevuturi et al., 2018) and temperatures vary from 34.8 °C in summer to -27.9 °C during winters (Schmidt and Nüsser, 2012; Chevuturi et al., 2018).

2.3 The Chenab basin

The Chenab basin has an area of ~18824 km^2 of which ~14.5% is occupied by glaciers (Fig. 1). Like the Suru basin, the glaciers in the Chenab basin are clustered between 5000 and 5500m asl elevation range. The basin is significantly influenced by the Indian summer monsoon during summer and the westerlies during winter (Bookhagen and Burbank, 2006). At the Chotta Shigri Glacier in the Lahaul and Spiti valley, the daily temperature ranging from -22°C to +7.3°C were observed during 2009-2013 (Azam et al., 2014) with the mean temperature of -5.8 °C. The monthly precipitation varies from 183-238 mm during January-February, and 14-18 mm during October-November (Azam et al., 2014)

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3. Data sets

3.1 Satellite images

A number of terrain-corrected Landsat satellite images of the period between 1999 and 2002, available from the United States Geological Survey (USGS) Earth Explorer website (http://earthexplorer.usgs.gov/) were used for delineation of glacier boundaries. The details of the datasets used in the study are given in Table 1. Satellite data with minimal cloud and snow cover, which is normally possible during the autumn season (August, September and October), were chosen for easy and accurate delineation of glacier extents as well as for clear differentiation between glacier accumulation and ablation zones (Paul et al., 2011; Rashid and Abdullah, 2016). The of moderate resolution Landsat satellite images for assessment of various glaciological parameters is well established and widely reported in the literature (Paul et al., 2004; Bhambri et al. 2011; Kamp et al., 2011; Hanshaw and Bookhagen, 2014; Murtaza and Romshoo, 2017; Racoviteanu et al., 2015; McFadden et al., 2011; Berthier et al. 2007; Kääb et al., 2012).

Table 1: Description of the datasets used in the present study.

Dataset/Resolution	Acquisition date	Source
1. SRTM-C (90 m)	2000	http://srtm.csi.cgiar.org
2. TanDEM-X (90 m)	2011-2015	https://download.geoservice.dlr.de/TDM90/
3. Randolph Glacier Inventory (RGI) 6.0	2000±3	https://www.glims.org/RGI/rgi60_dl.html
4. ICIMOD Glacier Inventory	2000±3	Bajracharya and Shresta, 2011
5. GAMDAM Glacier Inventory	2000±3	Nuimura et al., 2015
6. ETM+ (30 m)	27-09-2000	USGS
7. ETM+ (30 m)	02-08-2000	USGS
8. ETM+ (30 m)	04-09-2000	USGS
9. ETM+ (30 m)	12-10-2002	USGS
10. ETM+ (30 m)	28-10-2002	USGS
11. Google Earth (0.5-8m)		Google Earth

3.2 Digital Elevation Model

Glacier topographic parameters were derived from the ASTER GDEM V2 available from the Earth Remote Sensing Data Analysis Center, Japan Space Systems, with horizontal resolution of 1 arcsec (~30m) (Tachikawa et al., 2011). The DEM-derived parameters like slope, aspect and elevation were used to aid in the glacier delineation. The ASTER GDEM has been widely used for various glaciological studies at different spatial scales the world over (Wu et al., 2014; Bhambri et al., 2011; Kamp et al., 2005). Further, Shuttle Radar Topography Mission (SRTM)

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DEM and TanDEM-X DEM were used to estimate the geodetic mass balance glaciers in the three basins from 2000 to 2012. The SRTM DEM was acquired between 11 and 22, February, 2000 in two frequencies (X-band and C-band). We used the non-void filled version of the SRTM DEM with 90 m spatial resolution. The TanDEM-X mission, a TerraSAR-X-Add-on for Digital Elevation Measurements was acquired during 2010 and 2015. The TanDEM-X 90m DEM, released in September 2018, is a product variant of the global Digital Elevation Model (DEM) with the vertical accuracy up to 2 m (Shean et al., 2020).

3.3 Glacier inventories

The manually delineated glacier outlines of the three basins, hereafter named Kashmir University Glacial Inventory (KUGI), were compared with the existing global glacier inventories, viz., ICIMOD, GAMDAM and RGI6.0. The International Centre for Integrated Mountain Development (ICIMOD; Mool et al., 2001) glacier inventory covers the entire Hindu-Khush Karakoram Himalaya (HKH) region (Bajracharya and Shrestha, 2011). The glacier outlines in the ICIMOD inventory have been extracted semi-automatically from the Landsat ETM+ satellite imagery acquired during 2002 to 2008 and is available at http://apps.geoportal.icimod. The topographic characteristics for each individual polygon have been derived from the Shuttle Radar Topographic Mission (SRTM) 90 m DEM.

The Randolf Glacier Inventory (RGI, RGI Consortium, 2017) is the only glacier inventory with the entire global coverage except for the Greenland and Antarctica (Arendt et al., 2014). For comparative evaluation, we used the version 6.0 of the RGI inventory (RGI Consortium, 2017) available at https://www.glims.org/RGI/rgi60_dl.html. The RGI glacier outlines have been extracted semi-automatically from the Landsat satellite images between 1998 and 2009. However, most of the glaciers (~98%) in the inventory over the study area have been extracted from the images acquired during 1998-2002 (RGI Consortium, 2017). The inventory, besides providing information about glacier area and length, comprises of a set of topographical parameters viz., glacier slope and aspect derived from the ASTER GDEM V2.

The Glacier Area Mapping for Discharge from the Asian Mountains (GAMDAM) glacier inventory, on the other hand, is a collection of manually extracted glacier outlines for the entire High Mountain Asia (HMA, Nuimura et al., 2015). The glaciers in the database have been extracted from the Landsat ETM+ satellite images acquired during 1999 and 2003. In addition to the basic glaciological attributes like glacier area and length, the inventory comprises of a set of topographic parameters like slope, aspect and minimum, maximum and median elevation, slope associated with each glacier polygon and derived from the ASTER GDEM V2 (Nuimura et al., 2015).

4. Methodology

4.1 Delineation of glacier outlines

The glacier extents were delineated manually from the Landsat images using on-screen digitization technique (Berthier et al., 2007; Sarikaya et al., 2012) supplemented by the use of DEM-derived parameters like slope and aspect, thermal data, high resolution Google Earth™ images and limited field surveys. The Global Land Ice Measurements from Space (GLIMS) protocol defines all perennial snow excluding the exposed rock as a glacier, as such any ice body above the bergschurnd connecting to the glacier must also be considered a part of the glacier (Raup and Khalsa, 2007; Racoviteanu et al., 2009). However, the development of permanent snow cover on the steep headwalls above the bergschurnd is often prevented by the recurrent sliding and avalanching of snow and that is why the headwalls even covered with snow are excluded while delineating glacier boundaries (Nuimura et al., 2015). Nagai et al., (2016) excluded all the snow-covered slopes, where snow/ice flow is not expected, from glaciers extents. Furthermore, the differentiation of glacier ice and snow on headwalls is not easy to discern from a single date satellite imagery (Bolch et al., 2011; Nuimura et al., 2015). This limitation often results in variable glacier boundary delineations towards the glacier headwalls (Salerno et al., 2008; Thakuri et al., 2014). In this study, the surface conditions on headwalls with slopes exceeding 40˚ (McClung and Schaerer, 2006) were verified from the Google Earth™ (Nuimura et al., 2015) for accurate delineation of glacier extents. False Color Composites with various band combinations of SWIR-NIR-Green, NIR-SWIR-RED, and NIR-Red-Green were found efficient in delineation of the largely debris-free glaciers (Shukla and Qadir, 2016). The thermokarst-like features like small ponds, ice cliffs and relatively rough surfaces with numerous small crinkles (Nagai et al., 2016) are distinguished from the high-resolution Google Earth™ images. The thin debris layer on the glacier surface, often bearing lower surface temperature discerned from the thermal infrared band, was found useful in the demarcation of thinly debris-covered glaciers (Alifu et al., 2015; ISRO, 2010). Thick debris-covered glacier tongues in the Himalayan terrain poses a significant challenge in the accurate delineation of glacier extents (Bhambri and Bolch, 2009; Paul et al., 2013; Racoviteanu et al., 2008). On such glaciers, diagnostic evidence available in the form of a water stream and other proglacial geomorphological features are better identified from the Google Earth™ supported by the field evidences collected on a few selected glaciers in the three basins during glacier expeditions. In case of the shadowed or cloud-covered glaciers, either Google Earth™ images or the Landsat images acquired on some other cloud-free date were used to map the glaciers. In case of the shadowed glaciers, slope transition zones were also found useful in the glacier

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demarcation (Paul et al., 2004). Once the glacier outline was delineated from the satellite data, the exposed bedrocks and nunataks in each glacier polygon were removed (Nagai et al., 2016). To designate a glacier as debris-covered or a clean glacier, a debris cover fraction threshold of 19% proposed by Brun et al., (2019) was used. Each spatially disconnected polygon was regarded as an individual glacier as per the GLIMS protocol and each polygon was given a unique identification number (ID). Glacier area for each polygon was calculated in the ArcGIS environment. Topographic parameters, viz., minimum, maximum and median elevation, derived from the ASTER GDEM V2, were added for each glacier polygon and stored as attribute in the GIS database. Mean slope gradient and aspect for each glacier were extracted from the ASTER GDEM and added to the KUGI database. The glacier outlines delineated in the KUGI were compared in terms of glacier number and area with the ICIMOD, RGI and GAMDAM glacier inventories

4.2 Overlap ratio

The overlap ratio (r_{ov}) is an index to evaluate the geometric consistency of multiple inventories (Nagai et al., 2016), and was computed for all the four glacier inventories used in this study as follows:

$$r_{ov} = \sqrt{\frac{C}{S_A}\frac{C}{S_B}} \tag{1}$$

Where, *c* indicates the overlapping area of two glacier polygons in the participating inventories, S_A and S_B are areas of glacier polygons in inventory *A* and *B* respectively. The higher r_{ov} indicates that a larger proportion of the glacier area is shared between the two inventories and the lower values of r_{ov} indicate the opposite. No similarity or overlap between the glacier outlines in two inventories is indicated by r_{ov} equal to zero. The consistency between two glacier inventories is represented by the mean values of overlapping ratio(R_A^B) of all the glaciers in the inventory and is represented as follows:

$$R_A^B = \frac{1}{N_A}\sum r_{ov} \tag{2}$$

A and *B* are the two glacier inventories called Base and Target inventories respectively and N_A is the number of glaciers in the Base inventory *A*.

4.3 Glacier elevation change estimation

The participating DEMs in the present study were corrected for the vertical and horizontal off-sets using the universal co-registration algorithm (Nuth and Kääb, 2011). The algorithm employs a slope normalized cosine relationship between aspect and elevation change to minimize the offsets as follows:

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$$\frac{dH}{\tan(\alpha)} = a.\cos(b - \Psi) + C \quad (3)$$

$$C = \frac{\overline{dH}}{\overline{\alpha}} \quad (4)$$

where α is slope; Ψ is glacier aspect; and the variables a, b, and c are the magnitude, direction, and mean bias respectively. dH and $\overline{dH}$ is elevation difference and overall elevation bias respectively. The minimization process was repeated till either the magnitude of shift was <0.5m or the normalized median absolute difference (NMAD) on off-glacier terrain was <5% than the previous pass (Nuth and Kääb, 2011). The voids in the DEMs were filled using the Natural Neighbour (NN) algorithm (Abdullah et al., 2020).

The DEMs were corrected for radar penetration bias before generating the DEM difference map at pixel level. The relative penetration bias was calculated as a function of altitude (Vijay and Braun, 2016; Abdullah et al., 2020). KUGI was used to calculate the mean glacier elevation changes between 2000 and 2012 and the volume changes thereof. Using the density conversion factor of 850 kg m^{-3}, the volume changes were then converted into glacier mass changes (Huss, 2013).

4.4 Uncertainty assessment

a) Glacier mapping

Complex topography, debris-cover and shadowed ice areas are some of the potential sources of discrepancies for automatic and semi-automatic glacier mapping approaches (Paul et al., 2013). The uncertainties in glacier mapping from satellite images are minimized to a large extent using manual glacier delineation approach (Rashid and Abdullah, 2016), however, there may still be some uncertainties associated with the demarcation of glacier extents related to the perception and skill of the image interpreter (Paul et al., 2011). Braun et al., (2019) recently proposed a new approach based on glacier perimeter-area ratio to estimate the uncertainty in the glacier area (δA). The method is described by the following equation:

$$\delta A = \frac{R_P/_A}{R_P/_{A_P}} \times 0.3 \quad (5)$$

Where $R_P/_A$ is the glacier perimeter-area ratio and $R_P/_{Ap}$ is a constant equal to 5.03 km^{-1} (Paul et al., 2013).

b) Geodetic mass balance

The uncertainties in the estimation of geodetic mass balance due the uncertainty in DEM differencing, radar signal penetration, uncertainty due to void fill, glacier outlines and mass conversion were considered. For the uncertainty assessment, we followed the methodology

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after Huber et al, (2020) with an additional term to account for the radar penetration error ($^{\sigma}$penetration^2) (Abdullah et al., 2020) assuming that all the errors are uncorrelated and random. The uncertainty of glacier-wide specific elevation change (Δ_h) is computed as:

$$\delta_{\Delta h} = \sqrt{{\sigma_z}^2 + {\sigma_{voidfill}}^2 + {\sigma_{TDXdate}}^2 + {\sigma_{penatration}}^2} \qquad (6)$$

The σ_z, $\sigma_{TDXdate}$ and $\sigma_{penatration}$ are uncertainty of elevation change rates, temporal uncertainty of TanDEM-X and uncertainty of radar signal penetration respectively.

Uncertainty in the elevation change rate was estimated by evaluating the off-glacier elevation changes (Seehaus et al, 2019). The elevation changes were corrected for outliers by widely used Normalized Median Absolute Deviation (NMAD) approach (Höhle and Höhle, 2009) as:

$$NMAD = 1.4826.median.[|\Delta hj - m\Delta h|] \qquad (7)$$

Where, Δ_{hj} and $m\Delta_h$ denotes the individual elevation changes and median of all the Δ_{hj} respectively. The influence of the outliers is significantly minimized in the NMAD approach and is a preferred statistical uncertainty estimator (Höhle and Höhle, 2009).

Considering the spatial autocorrelation, the final uncertainty in elevation change rate (σ_z) was calculated using the widely accepted approach (Seehaus et al., 2019) as:

$$\sigma_z = \begin{cases} \sigma\Delta h\sqrt{\frac{A_{Cor}}{5A}} & , A \geq A_{Cor} \\ \sigma\Delta h, A < A_{Cor} \end{cases} \qquad (8)$$

where $\sigma\Delta h$ is the off-glacier NMAD, A is the glacier area analysed in the study area and Acor = πd^2, with d being the decorrelation length. We assumed a mean value d=950 for glaciers in the study area (Abdullah et al., 2020). The uncertainty due to the TanDEM-X date ($\sigma_{TDXdate}$) was assumed to be equal to be ±2 times the annual elevation change rate from 2000 to 2012 (Huber et al., 2020). The uncertainty in radar penetration was assumed as high as the correction factor itself (Huber et al., 2020). A constant value of ±60 kg m^{-3} was used to account for the uncertainty associated with the volume to mass conversion (Huss, 2013).

5. Results

5.1 Glacier characteristics and distribution

Glacier distribution based on the manually delineated KUGI outlines in the three basins are described in the following sub sections:

a) The Jhelum basin

154 glaciers, covering an area of 86±11.4 km^2, were delineated from the satellite data in 2000±3 in the Jhelum basin which is equivalent to the glacier reserve of 3.3 km^3 (Table 2). The glacier-

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cover constitutes about 0.7% of the geographical area of the basin. Majority of the glaciers (~80%) are concentrated in the Lidder and Sind watersheds, two of the 24 watersheds of the Jehlum basin. The glaciers range in size from 0.01 km^2 to 12.5 km^2 with an average glacier size of 0.6 km^2. Majority of the glaciers (n=136; 88.3%) are small in size (<1 km^2) and constitute ~39.4% of the glacier area. The glaciers in the size range between 1-2 km^2 (n=6) constitute 10.4% of the glaciers area in the basin. There are 10 glaciers in the basin with area ranging between 2-5 km^2 covering 28.9% of the glacier area of the basin. The glacier size category of 5-10 km^2 and 10-20 km^2 host only one glacier each with the area of 5.8 km^2 and 12.5 km^2 respectively covering 6.7% and 14.5% of the glacier area of the basin respectively (Table 3).

Table 2: Glacier number, area and glacier volume in the three glacier basins derived from the four different glacier inventories.

	Jhelum			Suru			Chenab		
	N	**km^2**	**km^3**	**N**	**km^2**	**km^3**	**N**	**km^2**	**km^3**
KUGI	154	85.9 ±11.39	3.30	328	488.04 ±16.15	29.28	1614	2727 ±90.21	162
RGI	234	85.93 ±32.97	2.56	468	465.9 ±38.78	26.45	2273	2658 ±218.39	175
ICIMOD	340	96.2 ±38.72	2.70	486	434.49 ±33.97	24.49	2187	3102 ±21.10	220
GAMDAM	255	84.66 ±15.98	2.63	492	494.78 ±42.17	29.77	2452	2860 ±244.93	189

The glaciers in the Jhelum basin are distributed at elevations ranging between 3566 and 4931 m asl, with the majority of the glaciers (n=97), comprising ~66.9% of the glacier area, falling between 4000 and 4500 m asl, followed by 29.2% of glacier (n=42) in the basin falling in the elevation range of 4500-4950 m asl. Only 15 glaciers, covering ~4.1% of the glacier cover of the basin, are situated at mean altitudes <4000 (Table 4). Analysis of the topographic characteristics further revealed that the mean glacier slope in the basin varies between 9° and 50°, however, most of the glaciers (n=105) comprising 82.2% of the glacier area, have mean slope ranging between 20° and 30°. 23 glaciers, constituting 11.5% of the glacier area in the basin, have the mean slope varying between 30° and 40°. 6 glaciers, occupying 0.9% of the glacier area, have the mean slope ranging between 40° and 50°. The glaciers under the slope categories 10°-20° and <10° harbor 19 and 1 glaciers comprising 5% and 0.3% of the total glacier area (TGA) of the basin respectively (Table 5). 98 glaciers in the basin, covering an area of 56.9 km^2, have southern aspect, while as 30 glaciers (17.2 km^2) and 26 glaciers (11.7 km^2) are situated on north and east facing slopes respectively (Table 6).

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Table 3: Distribution of glaciers in different area classes in a) Jhelum; b) Suru and c) Chenab basin based on different glacier inventories.

	GAMDAM		ICIMOD		RGI		KUGI	
	N	A	N	A	N	A	N	A
				JHELUM				
<1	208	46.55	320	54.01	216	48.34	136	33.84
1-2	9	13.91	11	18.75	11	15.93	6	8.94
2-5	7	17.19	9	23.43	6	14.98	10	24.86
5-10	1	7.01	-	-	1	7	1	5.77
10-20	-	-	-	-	-	-	1	12.49
20-30	-	-	-	-	-	-	-	-
30-40	-	-	-	-	-	-	-	-
40-50	-	-	-	-	-	-	-	-
>50	-	-	-	-	-	-	-	-
Total	**225**	**85**	**340**	**96**	**234**	**86**	**154**	**86**
				SURU				
<1	392	102.20	398	93.18	374	99.31	229	79.46
1-2	47	63.48	45	63.27	47	64.92	48	69.49
2-5	35	110.88	28	89.47	31	100.12	31	99.42
5-10	11	68.25	9	50.51	10	58.79	14	90.14
10-20	3	37.50	3	40.86	3	37.32	3	35.40
20-30	1	29.66	2	50.91	1	27.40	1	28.19
30-40	1	32.68	-	-	1	31.81	1	31.78
40-50	1	50.06	1	46.30	1	46.30	-	-
>50	-	-	-	-	-	-	1	53.43
Total	**491**	**495**	**486**	**434**	**468**	**466**	**328**	**487**
				CHENAB				
<1	1955	514.58	1718	453.20	1824	488.20	1161	371.81
1-2	234	324.52	186	258.18	196	272.40	187	266.34
2-5	165	526.79	169	532.24	159	505.11	158	505.38
5-10	57	401.57	57	401.27	56	384.43	64	441.05
10-20	22	312.60	29	416.65	20	287.36	25	343.33
20-30	8	188.74	17	425.14	10	247.43	8	187.88
30-40	4	133.25	4	150.83	1	36.64	4	133.92
40-50	4	185.44	2	86.89	4	172.19	4	176.40
>50	3	272.77	5	377.68	3	264.94	3	300.82
Total	**2452**	**2860**	**2187**	**3102**	**2273**	**2659**	**1614**	**2727**

The supra-glacial debris-cover was mapped for all the glaciers in the basin. The analysis revealed that only 8.4% of the TGA in the basin (7.2 km^2) is covered with debris. A debris fraction threshold of 19% was used to designate whether a glacier is debris-free or debris-covered (Brun et al., 2019). As per the criterion, most of the glaciers in the basin (n=136; 79.5 km^2) are classified as clean glaciers with the average size 0.4 km^2 in the range of 0.02-12.5

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km^2. The debris-covered glaciers (n=18; 6.9 km^2) with average size of 1.5 km^2 in the range of 0.01-1.5 km^2 (Table 7). It was further observed that the debris-covered glaciers have relatively lower mean altitudes (~4322 m asl) and shallower mean slope (~18°) compared to the clean glaciers with the mean altitude and slope of ~4392 m asl and ~21° respectively.

b) The Suru basin

The Suru basin has 328 glaciers, covering an area of 487.3±16.15 km^2 with mean glacier area of 1.5 km^2 varying between 0.03 and 53.4 km^2 (Table 2). The glaciers in the Suru basin cover ~11% of the geographic area of the basin. Most of the glaciers (n=229) in the basin are <1 km^2 in size.

Table 4: Distribution of glaciers in different elevation categories in a) Jhelum; b) Suru and c) Chenab basin based on different glacier inventories.

	GAMDAM		ICIMOD		RGI		KUGI	
	N	A	N	A	N	A	N	A
				JHELUM				
<4000	18	4.73	32	4.37	11	1.94	15	3.50
4000-4500	146	58.47	232	52.83	150	48.37	97	57.29
4500-5000	60	21.34	76	38.98	72	35.48	42	25.12
5000-5500	1	0.13	-	-	1	0.14	-	-
5500-6000	-	-	-	-	-	-	-	-
6000-6500	-	-	-	-	-	-	-	-
6500-7000	-	-	-	-	-	-	-	-
Total	**225**	**85**	**340**	**96**	**234**	**86**	**154**	**86**
				SURU				
<4000	5	0.34	-	-	-	-	-	-
4000-4500	10	6.16	4	2.01	9	7.74	7	5.48
4500-5000	97	111.53	114	110.13	119	120.06	83	131.27
5000-5500	331	366.45	326	269.14	304	331.00	227	348.33
5500-6000	44	9.59	40	53.12	34	6.97	11	2.23
6000-6500	3	0.41	2	0.08	2	0.19	-	-
6500-7000	1	0.24	-	-	-	-	-	-
Total	**491**	**495**	**486**	**434**	**468**	**466**	**328**	**487**
				CHENAB				
<4000	20	4.94	26	9.93	46	34.20	9	12.22
4000-4500	191	186.46	220	227.27	235	235.79	101	167.69
4500-5000	889	1097.62	778	1065.13	875	1028.01	623	1039.16
5000-5500	1028	1438.39	955	1649.52	896	1255.83	805	1424.92
5500-6000	313	126.75	201	148.77	215	103.62	76	82.98
6000-6500	11	6.11	6	0.71	6	1.25	-	-
6500-7000			1	0.76	-	-	-	-
Total	**2452**	**2860**	**2187**	**3102**	**2273**	**2659**	**1614**	**2727**

The glaciers with area <1 km^2 and 1-2 km^2 comprise 16.3% (n=229) and 14.3% (n=48) of the TGA in the basin respectively (Table 3). Glaciers having size <5 km^2 (n=308) harbor half of

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the glacier area in the basin. The glaciers in the 2-5 km^2 size category (n=31), having average area of 3.2 km^2, cover 99.4 km^2 which is 20.4% of the glacier area in the basin. The glaciers between 5 and 10 km^2 (n=14), having average size of 6.4 km^2, which is 18.5% of the glacier area in the basin. The glaciers having size >10 km^2 (n=6) constitute only 1.5% of the glacier count but cover ~30% (~148.8 km^2) of the glacier area in the basin.

Table 5: Distribution of glaciers in different slope categories in a) Jhelum; b) Suru and c) Chenab basin based on different glacier inventories.

	GAMDAM		ICIMOD		RGI		KUGI	
	N	A	N	A	N	A	N	A
				JHELUM				
<10	2	1.77	3	0.26	18	2.41	1	0.29
10-20	30	21.84	93	42.25	75	23.45	19	4.29
20-30	152	55.74	187	47.65	125	43.25	105	70.65
30-40	38	4.64	54	5.94	15	16.74	23	9.87
40-50	3	0.67	3	0.08	1	0.08	6	0.80
50-60	-	-	-	-	-	-	-	-
60-70	-	-	-	-	-	-	-	-
>70	-	-	-	-	-	-	-	-
Total	**225**	**85**	**340**	**96**	**234**	**86**	**154**	**86**
				SURU				
<10	151	322.03	3	11.96	1	0.05	-	-
10-20	248	146.89	200	351.17	215	371.52	124	275.91
20-30	64	21.99	209	60.72	185	85.31	167	204.22
30-40	18	3.23	63	8.92	67	9.08	32	6.45
40-50	4	0.24	10	1.66	-	-	5	0.73
50-60	6	0.34	1	0.05	-	-	-	-
60-70	-	-	-	-	-	-	-	-
>70	-	-	-	-	-	-	-	-
Total	**491**	**495**	**486**	**434**	**468**	**466**	**328**	**487**
				CHENAB				
<10	40	71.23	21	117.53	7	17.96	6	38.13
10-20	593	736.65	778	2314.11	766	1800.70	418	1579.00
20-30	1182	1216.37	734	487.70	900	655.43	870	940.33
30-40	549	694.04	396	135.10	384	135.71	287	160.78
40-50	91	188.67	178	36.88	210	48.38	33	8.70
50-60	10	8.59	67	9.70	6	0.52	-	-
60-70	2	1.68	11	0.89	-	-	-	-
>70	-	-	2	0.17	-	-	-	-
Total	**2467**	**2917**	**2187**	**3102**	**2273**	**2659**	**1614**	**2727**

Altitude-wise, the glaciers in the Suru basin are distributed at altitudes between 4000 and 6000 m asl. Majority of the glaciers (n=227), covering an area of ~348.4 km^2, which is ~71.5% of the TGA, is situated between 5000-5500 m asl. The glaciers (n=83) situated between 4500-5000 m asl cover 131.3 km^2, which is ~27% of the basin glacier area. The elevation zones of 4000-4500 and 5500-6000 m asl harbor an area of 5.5 km^2 (n=7) and 2.2 km^2 (n=11)

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respectively (Table 4). The mean slope of the glaciers varies between 10° and 45° with the average slope of 23°. More than half of the TGA (~56.6%) is under glaciers with the mean slope between 10° and 20°. The glaciers having mean slope between 20°-30° (n=167) and 30-40° (n=32) cover ~41.9% and ~1.3% of the glacier area in the basin respectively. The glaciers having slopes between 40°-50° (n=5) cover only 0.2% of the glaciated area (Table 5). Aspect analysis of the glaciers in the basin revealed that ~69.8% of the glaciers (n=229) are oriented in the south, 19.8% of the glaciers (n=65) are oriented in the east and 37 glaciers are oriented in the north direction (Table 6).

Table 6: Distribution of glaciers in different aspects in a) Jhelum; b) Suru and c) Chenab based on different glacier inventories.

	GAMDAM		ICIMOD		RGI		KUGI	
	N	A	N	A	N	A	N	A
				JHELUM				
N	67	22.74	107	11.00	180	70.38	30	17.20
S	131	42.05	186	70.70	44	14.37	98	56.94
E	27	19.87	47	14.48	10	1.19	26	11.74
W	-	-	-	-	-	-	-	-
Total	**225**	**85**	**340**	**96**	**234**	**86**	**154**	**86**
				SURU				
N	71	12.15	94	15.49	300	367.90	34	10.71
S	326	433.31	292	371.45	80	53.32	229	435.48
E	94	49.25	100	47.54	63	37.44	65	41.13
W	-	-	-	-	25	7.29	-	-
Total	**491**	**495**	**486**	**434**	**468**	**466**	**328**	**487**
				CHENAB				
N	383	335.16	287	69.85	992	1397.13	181	94.87
S	1691	2168.33	1585	2803.79	1000	1089.38	1170	2282.72
E	378	356.78	315	228.43	281	172.20	259	311.32
W	-	-	-	-	-	-	4	38.04
Total	**2452**	**2860**	**2187**	**3102**	**2273**	**2659**	**1614**	**2727**

In Suru basin, it was observed that ~13.2% of the glacier area (64.2 km^2) is covered with debris. Using 19% debris cover threshold, 10 glaciers (13.7 km^2) were categorized as debris-covered. Contrarily, 318 glaciers (473.6 km^2) are characterized as clean glaciers in the basin. From the analysis of the data provided in the Table. 7, it was observed that the clean glaciers are situated at relatively higher mean altitudes (~5170 m asl) compared to the debris-covered glaciers having mean altitude of ~4917 m asl. The clean glaciers were also found to have steeper mean slopes (22.3°) compared to the debris-covered glaciers which have lower mean slope of 21°.

c) The Chenab basin

The Chenab basin has a glacier coverage of 2727±90.2 km^2 which is 14.5% of the basin area (Table 2). The glaciers in the basin range in size from 0.02 km^2 to 132.6 km^2 with the average

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glacier size of 1.7 km^2. ~97% of the glaciers (n=1517), with size <10 km^2, cover ~58% of the basin. The glaciers in the 10-20 km^2 size category (n=25) cover 12.6% of the TGA of the basin. There are 8 glaciers having 20-30 km^2 size which cover 5.8% of TGA of the basin. 4 glaciers each lie in the class of 30-40 km^2 and 40-50 km^2 cover 133.9 km^2 and 176.4 km^2 of the TGA in the basin respectively. The basin has also three large glaciers with size >50 km^2, covering 300.8 km^2, which is 11% of the glaciated area in the basin (Table 3).

Table 7: Debris-cover characterization of the glaciers in the three basins.

	Jhelum Total DC =7.2 km^2 (8.37%)		**Suru** Total DC =64.2 km2 (13.17%)		**Chenab** Total DC =394.43 km^2 (14.46%)	
	Clean	**DC**	**Clean**	**DC**	**Clean**	**DC**
Number	136	18	318	10	1234	380
Area (km^2)	79.46	6.94	473.6	13.7	1279	1448
Mean elevation (m asl)	4392	4322	5170	4917	4832	4658
Mean slope (°)	21	17.97	22.32	21	26.37	27
(Area %)	92.50	8.07	97.18	2.81	46.90	53.09

Altitude-wise, it was observed that 9 glaciers (12.2 km^2), are situated between 3800 m and 4000 m asl. Majority of the glaciers (n=805) are situated between 5000 m and 5500 m asl covering ~1425 km^2 of the area which is ~52% of the entire glaciated area of the basin. 632 glaciers comprising of~38% of the glacier cover in the basin are situated between 4500 m and 5000 m asl. 110 glaciers covering 6.6% and 76 glaciers covering 3% of the glacier cover are situated at mean altitudes <4500 m asl and >5500 m asl respectively (Table 4).

1575 glaciers which constitute ~97% of the glaciers by count have mean slope between 10°-40°. 870 glaciers in the 20-30° slope category comprise 34.5% of the TGA, 418 glaciers in the 10°-20° slope category constitute 57.9% of the TGA. 287 glaciers in the 30° and 40° slope category constitute 5.9% of the basin TGA. There are 6 glaciers in the basin having mean slope <10° covering 38.1 km^2 which is 1.4% of the TGA. Further, there are 33 glaciers with the mean slope >40° spread over 8.7 km^2 and constituting 0.3% of the TGA (Table 5). Like the Suru and Jhelum basins, the glaciers in the Chenab basin are also predominantly south facing. 1170 glaciers have the mean south aspect, 181 glaciers have the mean north aspect, 259 are oriented east and 4 glaciers are oriented in the west direction in the basin (Table 6).

In the Chenab basin, 394.4 km^2 glacier area, which is 14.5% of the TGA of the basin, is covered with debris. Clean glaciers with average size of 1.1 km^2 (n=1234) cover 1279 km^2 of the glacier area. 380 glaciers in the basin are classified as debris-covered as per the criterion and cover an area of 1148 km^2 (average glacier size =3.9 km^2, Table 7). Similar to the Jhelum and Suru basins, the debris-covered glaciers in the Chenab basin also tend to have lower mean elevation

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(~4658 m asl) compared to the clean glaciers (4832 m asl). However, the mean slope does not vary much between the clean (26.3°) and debris-covered glaciers (27°) in the basin.

5.2 Comparison of KUGI with global glacier inventories

KUGI developed for the three basins was compared with the existing regional and global glacier inventories, viz., GAMDAM, ICIMOD and RGI 6.0 check for any discrepancy and the reasons thereof. The glacier number, glacier area and glacier volume of glaciers under each inventory is presented in Table 2. The glacier elevation, slope, aspect and debris-cover was also compared among the four inventories. It was observed that the Chenab basin has the most extensive glacier cover followed by the Suru and Jhelum basins. For all the basins in KUGI, the number of manually delineated glaciers is lower than the other glacier inventories (Table 2). In the Jhelum basin, the glacier number among the four inventories varies between 154 glaciers in KUGI to 340 in the ICIMODGI, however, significant variation was not observed in the glacier area among the four inventories; ±4.0 km^2 for Jhelum, ± 20.60 km^2 for Suru and ±144 km^2 for the Chenab basin (Table 8).

Table 8: Differences in glacier number and area of the three different glacier inventories w.r.t the KUGI in Jhelum, Suru and Chenab basins.

	Jhelum		Suru		Chenab	
	N	km^2	N	km^2	N	km^2
Absolute difference						
RGI	80	0.03	140	-22.14	659	-69
ICIMOD	186	10.3	158	-53.55	573	375
GAMDAM	101	-1.24	164	6.74	838	133
% Difference						
RGI	51.95	0.03	42.68	-4.54	40.83	-2.53
ICIMOD	120.78	11.99	48.17	-10.97	35.50	13.75
GAMDAM	65.58	-1.44	50.00	1.38	51.92	4.88

Compared to the KUGI, the RGI overestimates the glacier number by n=80 (52%) in the Jhelum basin, however the glacier area estimates are in good agreement between the two inventories showing a mean difference of 0.03% only. Compared to the KUGI, the ICIMODGI for the Jhelum basin overestimates the glacier number and area by 186 and 10.3 km^2 respectively. Like the RGI and ICIMODGI, the glacier number in the GAMDAMGI is 101 more than the KUGI, however, the inventory slightly underestimates glacier area by 1.4%. For the Suru basin, compared to the KUGI (n=328), the glacier number is more in all the glacier inventories; RGI, n=468; ICIMODGI, n=486; and GAMDAMGI, n=492. The glacier area under the RGI (465.9 km^2) and GAMDAMGI (494.78 km^2) agree reasonably with that of the

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KUGI (488 km^2). The glacier area under the ICIMODGI is, however, considerably lower (434.5 km^2) compared to the KUGI. For the Chenab basin, all the three glacier inventories show higher number compared to the KUGI (Table 8). The ICIMODGI provides the glacier number and area of 2187and 3102 km^2 respectively. The RGI has 2273 glaciers with an area of 2658 km^2, and the GAMDAMGI has 2452 glaciers with an area of 2860 km^2, compared to the glacier number (n=1614) and area (2727 km^2) in the KUGI (Table 8).

The distribution of glaciers in different size classes among the inventories was also evaluated and it was observed that for all the inventories in all the basins, most of the glacier area is under smaller glaciers. On an average, ~60% of the glacier area is concentrated in glaciers with area <5 km^2 (Table 3). The glacier area class <1 km^2 constitutes ~30% of the glacier cover in the three basins. Similarly, 1-2 km^2 and 2-5 km^2 size classes host 20.7% and 12.4% of the TGA respectively. Rest of the glacier area classes together comprise <=10% of the TGA in the three basins (Table 3).

From the comparative analysis of the global inventories with KUGI over the Jhelum basin, it was observed that the glaciers with area <1 km^2 (n=136) constitute 39.4% (33.8 km^2) of the TGA. In the RGI, ICIMODGI and GAMDAMGI, there are 216, 320 and 208 glaciers covering 48.3 km^2, 54 km^2 and 46.6 km^2 of the TGA respectively under the said category. The glaciated area under 1-2 km^2 category varies between 8.9 km^2 (n=6) and 18.8 km^2 (n=11) amongst the four inventories (Table 3). The KUGI outlines for the Jhelum show 28.9% of the glacier area concentrated under 2-5 km^2 category compared to 17%, 24.4% and 20.3% in RGI, ICIMODGI and GAMDAMGI respectively (Table3). The glacier category 5-10 km^2 comprises of 6.7% (KUGI), 7.8% (RGI) and 8.3% (GAMDAMGI) of the glacier area. It is pertinent to mention that the ICIMODGI does not show any glacier in this category. In the KUGI, the single glacier in 10-20 km^2 category covers 14.5% of the glacier area, however, no glacier is shown under this class in any of the other inventories.

In the KUGI, the glaciers with size <1 km^2 (n=229) occupy 16.3% glacier area of the Suru basin (Table 3). Under GAMDAMGI, ICIMODGI and RGI, <1 km^2 glacier category occupies 2.7% (n=392), 21.5% (n=398) and 21.3% (n=374) respectively. The comparative analysis of the glacier size class 1-2 km^2 indicated a small variation of 0.5% on average with respect to the KUGI (14.3%, n=48), RGI (13.9%, n=47), ICIMODGI (14.6%, n=45) and GAMDAMGI (12.3%, n=47). The size class 2-5 km^2 occupies the largest area in all the glacier inventories (KUGI: area=69.5 km^2, n=31; RGI: area=64.9 km^2, n=31; ICIMODGI: area=63.3 km^2, n=28 and GAMDAMGI: area=63.5 km^2, n=35) (Table 3). The size class 10-20 km^2 shows three glaciers in each of the four inventories, however, the glacier area varies among the inventories

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with the glacier coverage of 35.4 km^2, 37.3 km^2, 40.9 km^2 and 37.5 km^2 under KUGI, RGI, ICIMODGI and GAMDAMGI respectively. Overall, compared to the KUGI, all other inventories show higher glacier coverage in this category. In the glacier size class 20-30 km^2, the glacier area estimates of RGI (27.4 km^2) and GAMAADMGI (29.7 km^2) are in reasonable agreement with KUGI (28.2 km^2), however, again the ICIMODGI with area 50.9 km^2) shows considerably higher area under this size category. Again, the area estimates for 30-40 km^2 size glacier category under KUGI, RGI and GAMDAMGI are similar. However, no glacier is shown under this category in the ICIMODGI. KUGI does not show any glacier in the size class 40-50 km^2, however, the RGI, ICIMODGI and GAMDAMGI show 1 glacier each in this category covering 50.6, 46.3, and 46.3 km^2 respectively. The KUGI shows one glacier in the size class >50 km^2, however, no glacier is show under this class in any other inventory (Table 3).

In the Chenab basin, glaciers under 2-5 km^2 size class occupy the largest area of 505.4 km^2 (~18%) among all the inventories, while as the glaciers in 30-40 km^2 size category occupy the lowest glacier area (4.5 km^2). Under the KUGI, majority of the glaciers numbering 1161 (371.8 km^2) fall under the glacier size class of <1 km^2. For other inventories also, the majority of the glaciers are concentrated under this category (Table 3); RGI (n=1824, area=488.2 km^2), ICIMODGI (n=1718, area=453.2 km^2) and GAMDAMGI (n=1955, area=514.6 km^2). The glacier size category of 1-2 km^2 occupies 272.4 km^2, 324.5 km^2 and 258.2 km^2 area under RGI, GAMADMGI and ICIMODGI respectively compared to 266.3 km^2 under KUGI. The glaciers under 2-5 km^2 size category number 158 (505.4 km^2) under the KUGI, 159 (505.1 km^2) under RGI, 169 (532.1 km^2) under ICIMODGI and 165 (526.8 km^2) under GAMDAMGI. Under the size class of 5-10 km^2, glacier count is 57 each under GAMDAMGI and ICIMODGI covering 401.6 km^2 and 401.3 km^2 respectively. The category occupies 384.4 km^2 under the RGI (n=56) and 441 km^2 (n=64) in the KUGI. The size class of 10-20 km^2 covers an area of 35.4 km^2, 37.3 km^2, 40.9 km^{2}and 37.5 km^2 with n=3 each in KUGI, RGI, GAMDAMGI and ICIMODGI respectively. The glacier size category of 20-30 km^2 have same number of glaciers (n=8) and similar area under KUGI (187.9 km^2) and GAMDAMGI (188.7 km^2). ICIMODGI and RGI on the other hand show 17 and 8 glaciers covering 425.1 km^2 and 247.4 km^2 of the glacier area under the category. The rest of the glacier size categories comprise <1% of the glacier number but constituting ~20% of the TGA. The inventories do not vary much in terms of both the number and area under these categories. The comparative analysis revealed that in the Chenab basin, ICIMODGI, and GAMDAMGI overestimated the area by 13.8% and 4.8% respectively contrary to the RGI which underestimated the area by 1.2% (Table 3).

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In the Jhelum basin, a majority (>90%) of the glaciers KUGI (n=139), RGI (n=222), ICIMODGI (n=308) and GAMDAMGI (n=206) are situated at 4000-5000 m asl covering ~96% (82.4 km^2) of the glacier area (Table 4). KUGI for the Suru basin indicates that 98.4% of the glacier cover is hosted by the glaciers (n=310) situated between 4500-5500 m asl altitude. With n=423 (RGI) and n=428 (GAMDAMGI) about ~96% of the glacier area in distributed this elevation range as indicated by the analysis of the in each of RGI and GAMDAMGI. In ICIMODGI, 4500-5500 m asl elevation range hold 440 of the glaciers accounting for 87.3% of glacier coverage (Table 4). In the Chenab basin, KUGI indicates that majority of the glaciers numbering (n=1428) equivalent to 90.3% of the TGA is at 4500-5500 m asl elevation. RGI (n=177, harboring 85% of the glacier area is found in this elevation range. The ICIMOD and GAMDAM inventories have 87.5% (n=1733) and 88.6% (n=1917) of the TGA in the elevation range (Table 4).

Majority of the glaciers in the three basins in all the four inventories have slope gradient ranging from 10-30°. Under the KUGI for the Jhelum, n=105 glaciers covering 82.2% of TGA have mean slope between 20-30°, while as, in case of the RGI, ICIMODGI and GAMDAMGI, 50.3% (n=125), 49.5% (n=187) and 65.8% (n=152) of the TGA respectively fall under this slope category. Under GAMDAMGI and KUGI, there are 30 (21.8 km^2) and 19 (4.3 km^2) glaciers respectively having slope between 10-20°. However, the number of glaciers falling in the slope category is higher in case of RGI (n=75) and ICIMODGI (95) (Table 5). The slope analysis of the glaciers in the KUGI for the Suru basin revealed that 88.7% of the glaciers (n=323) covering more than half of the TGA have the mean slope between 10-30°. RGI shows that 98 % of the glacier area (n=467.) is covered in this slope category. The ICIMODGI and GAMDAMGI show that 94.8% (n=472) and 94.7% (n=330) of the TGA respectively is under this slope category (Table 5). In the KUGI for the Chenab basin, ~80% (n=1288) of the glaciers have the mean slope between 10-30° covering 92.3% of the TGA. The RGI, ICIMODGI and GAMDAMGI shows that 92.4% (n=1666), 92.3% (n=1512) and 66.9% (n=1775) of the TGA respectively falls in the slope category (Table 5).

Aspect analysis of the KUGI revealed that 63.64 % of the glaciers (n=93) in the Jhelum basin have the mean south aspect. In the ICIMODGI, GAMDAMGI and RGI, 54.7% (n=44), 58.2% (n=186) and 18.8 (n=44) of the glaciers respectively have the mean south aspect. Compared to 30 glaciers covering 20% of the TGA in the KUGI, the RGI shows a high number of glaciers (n=180) covering 81.9% of the TGA having the mean north aspect. However, the ICIMODGI and GAMDAMGI show only 11.4% (n=107) and 26.9% (n=67) of the TGA oriented in the north direction. The glaciers with the mean eastern aspect are again lower (n= 10) in the RGI

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compared to the KUGI (n=26). Under the ICIMODGI and GAMDAMGI, there are 47 and 27 glaciers comprising 15% and 12% of the TGA respectively having eastern aspect (Table 6). Like in the Jhelum, a majority of the glaciers in the Suru have the mean south aspects under all the inventories, except for the RGI where majority of the glaciers (n=300) have mean north aspect. It was also observed that 25 glaciers under RGI covering 1.6% of the TGA have the mean western aspect. However, in other inventories no glacier has west aspect (Table 6).

In the Chenab basin, it was found that majority of the glaciers under KUGI (n=1170), ICIMODGI (n=1585) and GAMDAMGI (n=1691) covering 83.7%, 90.4%, and 76% of the TGA respectively have the mean south aspect. However, the RGI shows only 40% of the TGA (n=1000) under this aspect. The RGI has 922 glaciers with the mean north aspect, compared to 181, 287, 383 glaciers under the KUGI, ICIMODGI and GAMDAMGI respectively (Table 6). The glaciers having the mean eastern aspect do not vary much among the inventories. The analysis indicated that there are 4 glaciers with the mean western aspect under the KUGI, but no glacier has the mean western aspect in other three inventories.

Table 9: Mean glacier elevation changes and glacier morphological characteristic of the study region.

Basin	Elevation change (m a^{-1})	Mean elevation (m asl)	Mean slope (°)	Area (%) south aspect	Average glacier size (km^2)	Debris cover (%)
Jhelum	-1.33 ±0.75	4349	26.12	66.3	0.55	8.37
Suru	-1.08 ±0.73	5136	22.76	89.36	1.48	13.17
Chenab	-1.09 ±0.75	5004	24.6	83.71	1.68	14.46

5.3 Glacier elevation changes

In this study, glacier elevation changes were estimated using SRTM-C and TanDEM-X DEMs acquired between 2000 and 2012.

Table 10: Glacier elevation changes in different elevation ranges in the Jhelum, Chenab and Suru basins.

Elevation category	Elevation change (m a^{-1})		
	Jhelum	**Chenab**	**Suru**
<4000	-1.7 ±0.59	-0.15 ±0.26	-
4000-4500	-1.33 ±0.34	-0.86 ±0.34	-1.07 ±0.41
4500-5000	-1.28 ±0.53	-1.09 ±0.58	-1.15 ±0.44
5000-5500	-1.55 ±0.61	-1.4 ±0.53	-1.04 ±0.41
5500-6000	-	-0.76 ±0.25	-1.03 ±0.43
6000-6500	-	0.2 ±0.30	0.1 ±0.23

The analysis revealed that almost same elevation changes were observed for glaciers in the Suru and Chenab basins, i.e., -1.08±0.7 m a^{-1} and -1.09±0.8 m a^{-1} respectively. On the other

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hand, higher elevation loss of -1.30±0.8 m a^{-1} was observed in the Jhelum basin (Table 9). The glacier elevation changes vary from -3.6 to -2.2 m a^{-1}, -3.4 m a^{-1} to 2.5 m a^{-1} and -4.5 m a^{-1} to -7.1 m a^{-1} in the Jhelum, Suru and Chenab basins respectively.

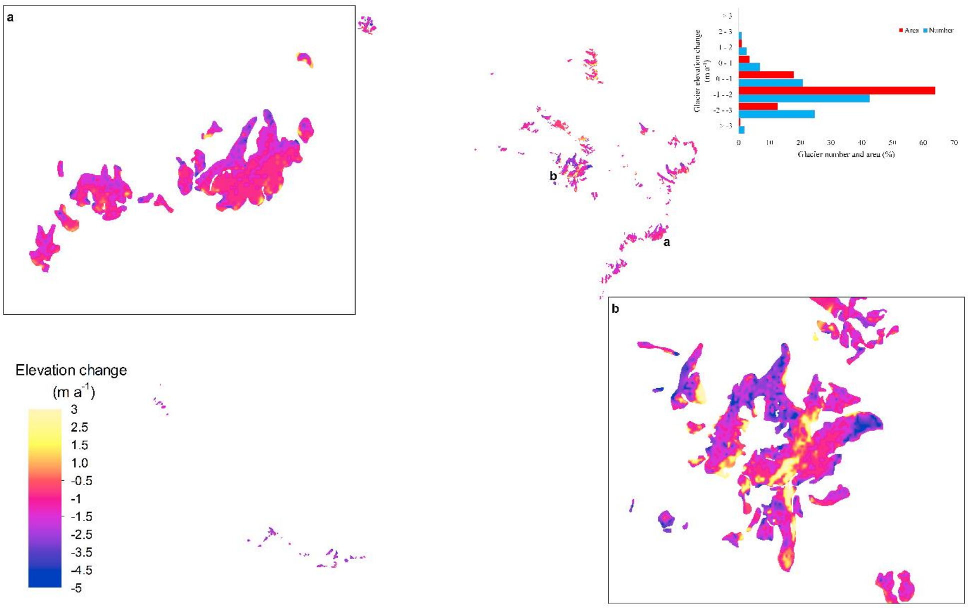

Fig. 2: Glacier elevation changes in the Jhelum basin: the zoomed in insets highlights; a) Shishram and Wakhalbal group of glaciers in the west Lidder sub-basin; b) Kolahoi group of glaciers in the east Lidder sub-basin. The distribution of glaciers (number and area) in different elevation change categories is also depicted in the bar chart.

However, in the three basins a majority of the glaciers showed elevation changes between -1 and -2 m a^{-1}. The elevation changes of >-3 and >3 m a^{-1} are exhibited relatively by a few number of glaciers (Fig. 2, 3, 4). The study indicated that the glaciers at lower mean altitudes have usually experienced relatively higher elevation losses.

Table 11: Influence of mean glacier slope on glacier thinning.

Slope category (°)	Elevation change (m a^{-1}) Jhelum	Chenab	Suru
<10	-2.5 ±0.67	-1.72 ±0.52	-
10-20	-1.79 ±0.52	-1.37 ±0.40	-1.54 ±0.52
20-30	-1.16 ±0.47	-1.09 ±0.38	-0.95 ±0.35
>30	-0.52 ±0.26	-0.83 ±0.27	-0.72 ±0.24

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For example, the elevation changes of -1.5 ±0.46 m a^{-1} are witnessed for glaciers situated at mean altitudes <4500 m asl in the Jhelum compared to the glaciers situated at mean altitudes >4500 m asl which showed the average thinning of -1.4 ±0.57 m a^{-1} (Table 10).

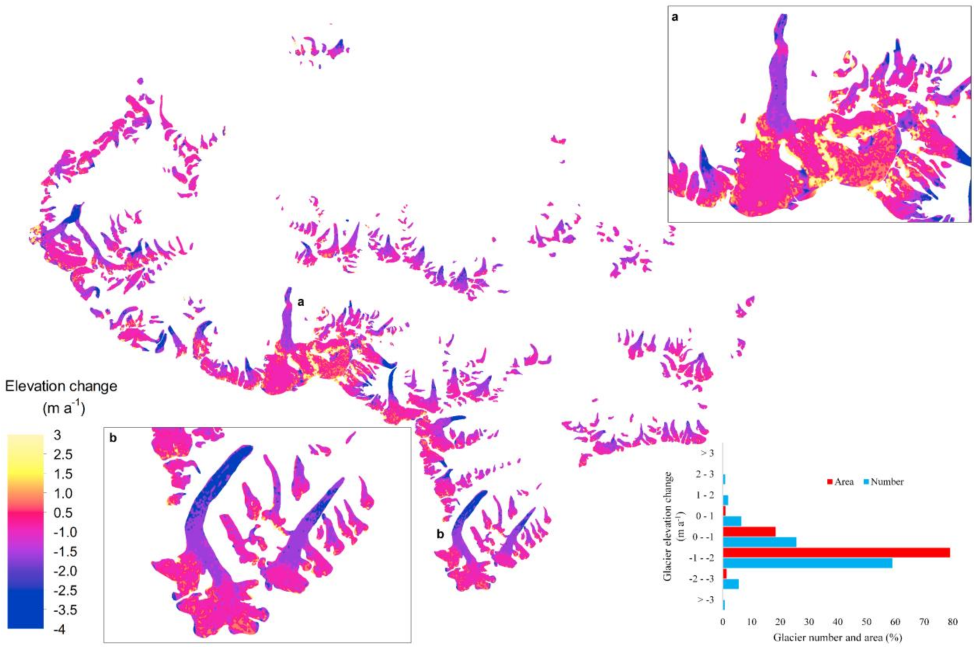

Fig. 3: Glacier elevation changes in the Suru basin: a) zoomed in view of the Kangraz group of glaciers; b) the zoomed in inset highlights then elevation changes for the Lalung, PensiLa and other small glaciers near PensiLa (pass). The bar chart depicts the glacier distribution both number and area in different elevation change categories.

Similarly, the glaciers in the Suru and Chenab, situated at mean altitudes <5000 m asl have thinned at the rate of -1.1 ±0.42 m a^{-1} and -0.7 ±0.39 m a^{-1} respectively compared to the glaciers at mean altitudes >5000 m asl which have thinned ~-0.6 ±0.35 m a^{-1} (Table 10). The study also demonstrated a strong control of glacier slope on elevation change with the glaciers having mean slopes <20° showing the highest elevation loss compared to the glacier having mean slope >30° (Table 11).

The influence the aspect on elevation changes as the south-oriented glaciers have experienced higher thinning showing the elevation change of -1.8 ±0.59 m a^{-1}, -1.5 ±0.51 m a^{-1} and -1.7 ±0.60 m a^{-1} in the Jhelum, Chenab and Suru basins respectively (Table 12). The study also revealed the role of glacio-morphological parameters like glaciers size and extent of debris cover on the observed elevation changes.

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Table 12: Observed glacier elevation changes in different aspects.

	Elevation change (m a^{-1})					
	Jhelum		**Chenab**		**Suru**	
N	-1.11 ±0.43		-0.58 ±0.28		-0.77 ±0.34	
NE	-1.17 ±0.63	-1.27 ±0.54	-0.55 ±0.25	-0.63 ±0.27	-0.98 ±0.33	-1.09 ±0.36
NW	-1.54 ±0.58		-0.75 ±0.30		-0.95 ±0.42	
SE	-2.08 ±0.70		-1.26 ±0.46		-1.65 ±0.65	
S	-1.52 ±0.52	-1.85 ±0.59	-1.6 ±0.43	-1.51 ±0.51	-1.69 ±0.60	-1.70 ±0.60
SW	-1.94 ±0.56		-1.67 ±0.64		-1.75 ±0.55	
W	-1.61 ±0.54		-1.27 ±0.47		-1.22 ±0.45	
E	-1.08 ±0.34		-1.11 ±0.52		-1.22 ±0.43	

It was observed that in general the smaller glaciers in all the three basins have experienced more thinning compared to the larger glaciers. The glaciers with the area <5 km^2 witnessed higher thinning rates of -1.1 ±0.44 m a^{-1}, -1.2 ±0.57 m a^{-1} and -1.1 ±0.40 m a^{-1} compared to the elevation change of -1.0 ±0.48 m a^{-1}, -0.8 ±0.38 m a^{-1} and -1 ±0.35 m a^{-1} observed for the glaciers having area >5 km^2 in the Jhelum, Chenab and Suru basins respectively (Table 13).

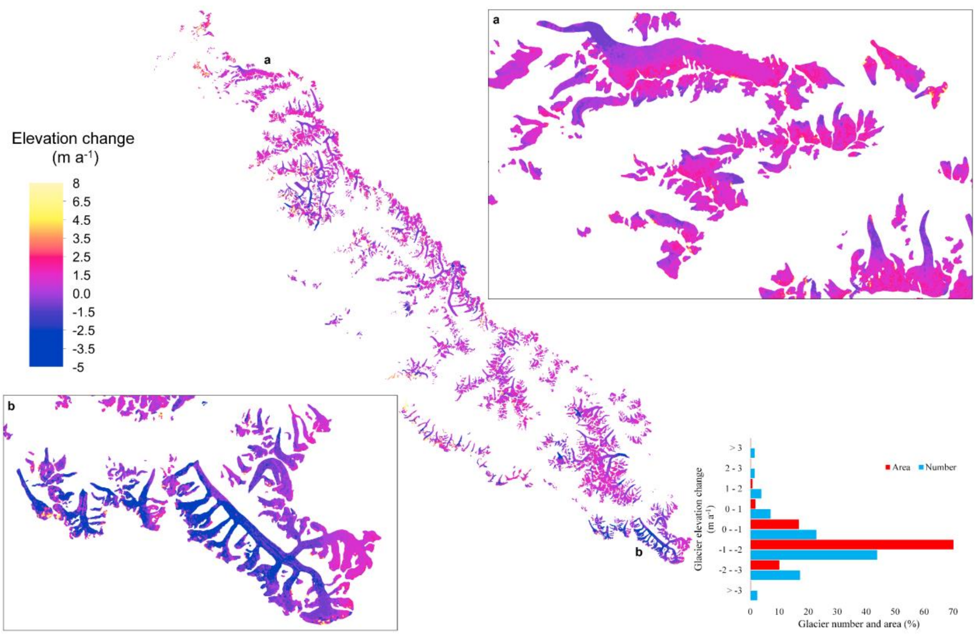

Fig. 4: Glacier elevation changes in the Chenab basin: a) Brankton group of glaciers in highlighted in the zoomed in inset; b) Bara Shigri, Chotta Shigri and some of the adjacent glaciers are zoomed in in the inset. The distribution of glaciers (number and area) in different elevation change categories is also depicted in the bar chart.

Compared to the clean glaciers, the debris-covered glacier showed the higher elevation changes of -1.5 ±0.54 m a^{-1}, -1.2 ±0.45 m a^{-1} and -1.2 ±0.51 m a^{-1} in the Jhelum, Chenab and Suru basins respectively (Table 14).

Table 13: Glacier elevation changes in different area classes.

Area class	Elevation change (m a^{-1}) Jhelum	Chenab	Suru
<1	-1.27 ±0.56	-1.51 ±0.67	-1.03 ±0.37
1-2	-1.17 ±0.43	-0.94 ±0.59	-1.12 ±0.34
2-5	-0.90 ±0.34	-1.16 ±0.46	-1.16 ±0.51
5-10	-1.03 ±0.50	-0.79 ±0.32	-1.15 ±0.32
10-20	-1.10 ±0.46	-0.61 ±0.30	-1.17 ±0.34
20-30	-	-0.87 ±0.30	-1.11 ±0.43
30-40	-	-1.73 ±0.64	-
40-50	-	-1.50 ±0.52	-0.71 ±0.32
>50	-	0.51 ±0.23	-

6. Discussion

6.1 Glacier distribution

Analyses of the three inventories indicated that the glacier-size class of 1-5 km^2 occupies the largest area, and the glaciers <1 km^2 in area constitute the majority of glaciers in terms of numbers (Table 3). The observed glacier distribution in terms of number and area is typical of the low-latitude regions (RGI Consortium, 2015). Similar glacier distribution was observed in the Bhutan Himalaya by Nagai et al., (2016). The relationship between elevation and temperature (Salerno et al., 2008; Salerno et al., 2014; Racoviteanu et al., 2015) justifies the presence of large glaciers at relatively higher altitudes observed in this study. Relatively lower glacier-cover at higher altitudes (>5500 m asl) is most probably due to the fact that the headwalls above this altitude tend to be steeper facilitating snow/ice avalanches, thereby precluding the glacier formation (McClung and Schaerer, 2006).

Table 14: Elevation change variability in debris-covered and clean glaciers.

Basin	Elevation change (m a^{-1}) DC	Clean
Jhelum	-1.45 ±0.54	-1.33 ±0.60
Chenab	-1.19 ±0.45	-1.08 ±0.36
Suru	-1.21 ±0.51	-1.07 ±0.39

The study also indicated that the glaciers are largely distributed on north and south aspects with the majority, both in terms of number and area, oriented in south direction. Taking aspect as a proxy for solar insolation, the observation seems counterintuitive in view of the fact that southern aspects receive more solar insolation (Oliphant et al., 2003), however, topographic parameters particularly slope gradient seems to support the glacier formation and growth observed on the southern slopes. Surface gradient is considered as one of the main factors controlling glacier surface development. The shallower surface gradients of south-facing glaciers (10-30°) observed in this study justifies the presence of relatively large glaciers on south aspects (Salerno et al., 2017). It is pertinent to mention that the north facing glaciers in all the three basins have steeper slopes than the south-facing glaciers (Table 15). The relatively higher mean altitude (Table 15) of the south-facing glaciers is due to their faster snout melting and the consequent retreat in response to higher solar insolation (Fujita and Ageta, 2000; Azam et al., 2012). The occurrence of the debris-covered glaciers at relatively lower altitudes and on shallower slopes as observed in this study is in tune with the findings of Scherler et al., (2011a).

Table 15: Topographic and morphological characteristics of north and south facing glaciers.

	Jhelum		Suru		Chenab	
Topographic characteristics	**N**	**S**	**N**	**S**	**N**	**S**
Mean min. Elevation (m asl)	4163	4206	4910	4838	4779	4703
Mean max. Elevation (m asl)	4550	5013	5351	5441	5221	5332
Mean slope (°)	27.9	25.4	29.3	21.6	29.42	23
Average glacier size (km^2)	0.57	0.58	0.31	1.9	0.52	1.94

6.2 Inconsistencies among the global glacier inventories

The analyses revealed discrepancies among the glacier inventories in terms of the glacier number in the Jhelum basin as indicated by the highest number of non-overlapping outlines (n=164) occurring between ICIMODGI and KUGI. Contrarily, the non-overlapping glaciers outlines in the GAMDAMGI and RGI with respect to the KUGI are 71 and 87 respectively. Similarly, in the Suru basin, the largest number of non-overlapping outlines (n=117) with respect to the KUGI were found in the ICIMODGI compared to 80 non-overlapping polygons found for RGI and 82 for the GAMDAMGI. In the Chenab basin, the highest number of non-overlapping glacier outlines (n=113) also occurred between ICIMODGI and KUGI, and 76 and 90 non-overlapping polygons found in GAMDAMGI and RGI respectively w.r.t the KUGI.

The number of non-overlapping polygons observed in this study are in line with the observations of Nagai et al., (2016) who compared different glacier inventories over the Bhutan Himalaya. This study revealed that glacier polygons, often smaller in size, were erroneously delineated in the existing global inventories where no glacier exists *(*Fig. 5*)*, resulting in non-overlapping outlines. In view of the fact that the data sets used in these inventories were

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acquired almost during same time period, the inclusion of temporary snow cover in the global inventories is primarily responsible for the variability in glacier number (Nagai et al., 2016).

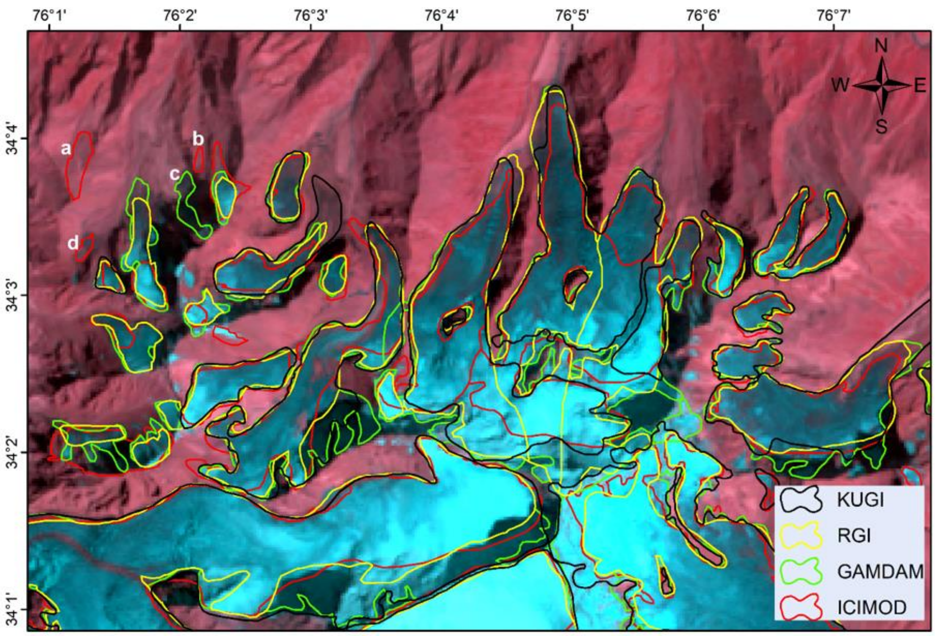

Fig. 5: The figure highlights the significant distortion in glacier outlines from different glaciers inventories under consideration. Labelled as a, b, c, d, the figure also highlights some non-existent glaciers that have been delineated in some of the global glacier inventories.

The difference (overestimation) of glacier number observed among different inventories is also attributed to the misidentification of multiple glaciers from a single connecting glacier (Fig. 6). Fragmentation of the debris-covered glaciers particularly shown in the ICIMODGI (Fig. 7) has added to the discrepancy in glacier number (Table 2) evidenced by difference of 186 glaciers between KUGI and ICIMODGI in the three basins. The mean overlap ratio of GAMDAMGI $R_A^B = 0.75$ and RGI $R_A^B = 0.73$, indicated consistency with the KUGI than the ICIMODGI which showed the mean overlap ratio of $R_A^B = 0.70$ averaged over the three basins. The ICIMODGI glacier area, on an average (over three basins) varies by ~12%, w.r.t. KUGI, the largest variation among the three inventories. RGI and GAMDAM showed significantly lower variation of 2.36 % and 2.56 % respectively (Table 2). Significant distortion was observed in the ICIMOD outlines (Fig. 7) largely due to the variable identification/treatment of debris-covered and shadowed glaciers in the delineation approach (Fig. 7), leading to a large

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discrepancy in number and area. A few inconsistencies, though not of the extent observed in ICIMODGI, were also encountered in RGI (Fig. 7).

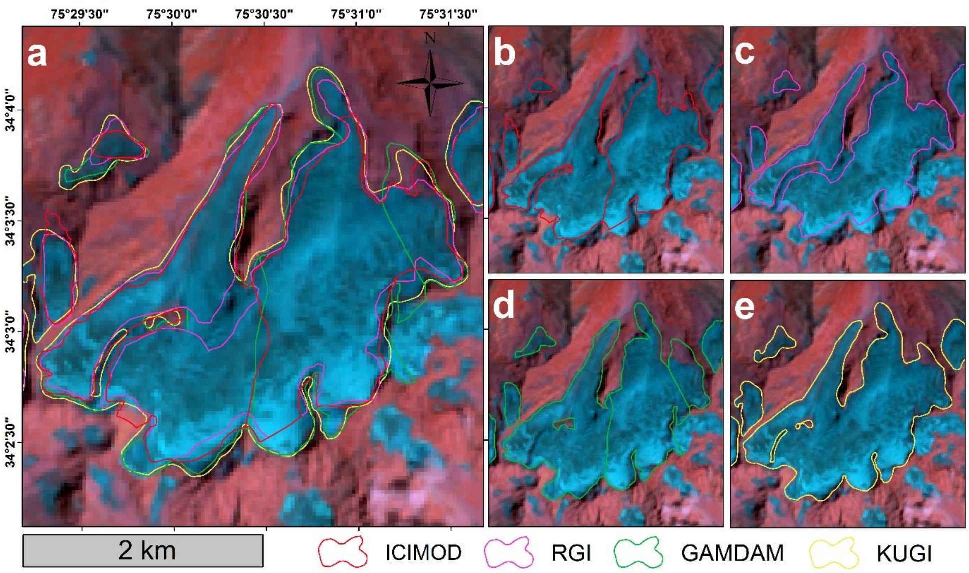

Fig. 6: Example of the delineation of multiple glaciers from a single connecting glacier: (a) the Shishram glacier in the Jhelum basin is a single connected glacier even on the satellite images of 2018, however, the glacier has been delineated as a group of glaciers in all the existing global glacier inventories; b, c, d) indicate the glacier outlines in different glacier inventories.

Exclusions of the shadowed glaciers in GAMDAMGI and inclusion of the seasonal snow-cover in the RGI explains the disparity observed in the glacier variables amongst the four glacier inventories (Nuimura et al., 2015). The relatively smaller average size of glaciers (0.6 km^2) in the Jhelum basin is also responsible for the observed higher disparity because the smaller glaciers, being cumbersome to delineate, usually show higher inconsistency than the larger glaciers (Nagai et al., 2016). The advantage of the manual delineation of glaciers over the automatic approach particularly for the debris-covered and shadowed glaciers (Paul et al., 2013) is evident from the relatively higher mean values of r_{ov} observed for GAMDAMGI (Table 16). Furthermore, the definition of glacier extent, inclusion and exclusion of the steep snow-covered headwalls (Nuimura et al., 2015), variable delineation methods employed and the differences in interpretation skills amongst the investigators (Paul et al., 2013) are the other possible reasons for the observed disparity among the four glacier inventories. The rectification of the inconsistencies observed among the three glacier inventories w.r.t. the KUGI requires

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extra effort and focus on mapping the debris-covered and shadowed glaciers and the use of complementary data sets like thermal data, high resolution satellite images (like Google Earth^{TM}), and DEMs together with the local knowledge of the area (Bhambri et al., 2011). Despite the general disparity observed among the glacier inventories, the inventories show a good correspondence among them in terms of glacier number and area with similar topographic and morphological characteristics.

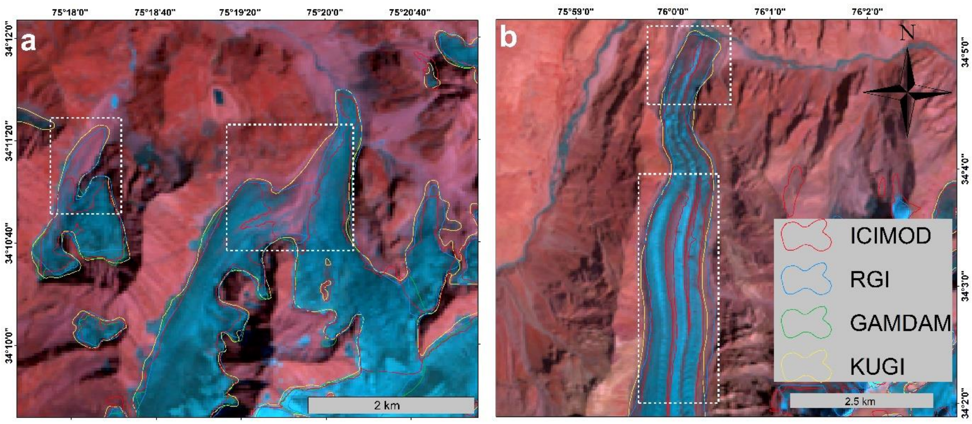

Fig. 7: An example of the treatment of supra-glacial debris cover in the different glacial inventories: a) the debris-covered part of the Hoksar Glacier (the white dotted polygon) on the left and the Kolahoi Glacier on the right (of the panel a) have been excluded in the ICIMODGI, misconstrued as the fragmentation of the glacier; Exclusion of some of the debris-covered parts is also observed for the Kolahoi Glacier in the RGI; b) The highlighted area marks the exclusion of debris-covered part of the Kangraz glacier in the Suru basin from the ICIMOD inventory.

The error in the delineation of the debris-covered glaciers particularly the termini have significant implications as the misidentification of glacier terminus affects the estimation of the retreat rates of such glaciers (Scherler et al., 2011b). Similarly, the inclusion or exclusion of the steep headwalls adjacent to glacier surfaces in high relief regions, an important source of glacier mass, has the potential to add discrepancy in mass balance, runoff and glacier elevation change estimates (Hewitt, 2011; Nuimura et al., 2015).

Though the specific values of glacier area, altitude, slope and aspect for individual glaciers vary among the four inventories, but similarities were found in the frequency and distribution of the most common glacier size classes. For example, the largest number of glaciers having size <1 km^2 and the largest area covered under glaciers in 1-5 km^2 size category are similar across the inventories. Similarly, there is good correspondence in hypsometry (highest glacier

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cover between 4500-5500 m asl) and mean slope (most of the glaciers having slope between 10-30°) observed among all the four inventories.

Table 16: Glacier surface area under different glacier inventories and the overlap ratio between the glacier outlines of the KUGI and other inventories. Uncertainty in area in given in brackets.

		RGI	ICIMOD	GAMDAM
Jhelum	85.9 (±11.39)	85.93 (±32.97)	96.2 (±38.72)	84.66 (±15.98)
	Overlap ratio	0.65	0.64	0.66
Suru	487.31 (±16.15)	465.9 (±38.78)	434.49 (±33.97)	494.78 (±42.17)
	Overlap ratio	0.80	0.78	0.83
Chenab	2727 (±90.21)	2658 (±218.39)	3102 (±212.10)	2860 (±244.93)
	Overlap ratio	0.73	0.67	0.77
	Mean r_{ov}	**0.73**	**0.70**	**0.75**

6.3 Glacier elevation changes

The variable glacio-morphological and topographical regimes prevalent over the three basins, to a large extent, explain the variation of the observed glacier elevation changes. The relatively higher elevation changes observed for the glaciers at lower mean altitude is explained by the fact that the glaciers are more sensitive to the rising temperatures (Oerlemans and Reichert, 2000). The findings are in agreement with the previous studies in the Himalayan region (Scherler et al., 2011a; Brun et al., 2019).

Similarly, the glaciers on shallower slopes have relatively longer response time, resulting in slow glacier dynamics and do not usually respond immediately to the changes in climate and therefore, remain out of balance for a longer time (Cuffey and Paterson, 2010), justifying the higher recession observed for the glaciers situated on shallower slopes.

Glacier aspect has a profound effect on the glacier thinning (Furbish and Andrews, 1984; DeBeer and Sharp, 2009; Wang et al., 2009; Pandey and Venkataraman, 2013). The north-facing glaciers receive less solar radiations compared to the south-facing glaciers (Bhambri et al., 2011), explaining their higher observed elevation loss.

The lower observed thinning of the large glaciers in this study is justified by the slow reaction of the glaciers to climate perturbations (Oerlemans and Hoogendoorn, 1989; Bolch, 2007).

Despite debris being one of the important factors affecting glacier dynamics (Scherler et al., 2011a; Benn et al., 2012; Salerno et al., 2017), its influence is still debatable (Ali et al., 2017). Various studies reported enhanced melting of debris-covered glaciers (Shukla and Qadir, 2016). However, others have reported slowdown in melting for debris-covered glaciers (Benn et al., 2012; Dobhal et al., 2013). Similar melting rates for both debris-covered and debris-free

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glaciers are also widely reported in the literature (Gardelle et al., 2012, 2013 and Kääb et al., 2012). The results reported in this study are more or less in sync with the studies suggesting relatively higher thinning for the debris-covered glaciers (Shukla and Qadir, 2016).

7. Data availability

The glacier inventory (KUGI) for the three basins discussed in the present study is freely available at http://doi.org/10.5281/zenodo.4461799 (Romshoo et al., 2021).

8. Conclusions

In this study, the three existing regional and global glacier inventories, viz., RGI, ICIMOD and GAMDAM, available for the three basins in the north-western Himalaya, were compared and evaluated with the newly created KUGI. The KUGI outlines were delineated manually from Landsat data supplemented by DEM, Google Earth imagery and limited field surveys. It was observed that the glaciers in the three basins have size <1 km^{-2}, however most of the glacier area is concentrated in glaciers of 1-5 km^2 size. Majority of the glaciers are situated in 4500-5500 m asl elevation range except in the Jhelum basin where the glaciers are mainly found between 4000-5000 m asl. Most of the glaciers in the three basins have the mean slope ranging from 10-30°. It was also observed that a large number of glaciers with sizeable coverage are south-oriented. The comparative analysis of the inventories with the KUGI revealed that the GAMDAMGI and RGI are consistent and comparable with the KUGI showing the overlapping ratio of R_A^B=0.75 and R_A^B=0.73 respectively. The inconsistency observed in the delineation of glaciers is obvious in the ICIMODGI particularly for the debris-covered glaciers. Though, the specific values for glacier area, altitude, slope and aspect vary among different inventories, but there is overall similarity in the TGA, common area classes and hypsometry. The significant glacier area in all the four inventories is concentrated in 4500-5500 m asl elevation range with the mean slope of 10-30°. The differences observed among the inventories often arise from differential definition of glaciers, the methodological approaches adopted, difficulties posed by the presence of snow and/or cloud cover in the satellite images used, treatment of debris-covered glaciers and expertise of the analysts. The investigation also indicated the highest glacier thinning of -1.3±0.8 m a^{-1} in the Jhelum but similar elevation changes of -1.08±0.7 m a^{-1} and -1.09±0.8 m a^{-1} were observed in the Suru and Chenab basins respectively. Significant topographic, morphological and debris-cover influences were observed on glacier elevation changes across the three basins in the study area. The critical assessment of the global inventories is imperative for assessing the uncertainties associated with the use of the readily

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available glacier databases for various applications related to hydrology, climate change and allied fields.

Author contributions

SAR conceptualized the research, conducted the comparative analyses of the global glacier inventories in the three basins w.r.t KUGI and prepared the manuscript with inputs from TA. TA did the processing of the satellite data, generated glacier outlines of KUGI for Suru and Jhelum basins and estimated the geodetic mass balance of the glaciers in the 3 basins. MB did the satellite data analysis of the glaciers in the Chenab basin.

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Conflict of Interest

The author(s) declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

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