

Elevation dependent thickness and ice-volume estimation using satellite derived DEM for mountainous glaciers of Karakorum range

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Abstract: Mountainous glaciers are best climate indicators and contributing to sea level fluctuation in response of any climatic change. The mean thickness and ice volume of these glaciers are the important parameter to justify glacier response to climate and, calculated using Glaptop approach and Area-Volume Scaling law respectively in some of the studies. However, thickness and ice-volume are significantly dependent on elevation and their elevation based distribution is important for the health of any individual glacier. Glaciers of Karakoram range in HKKH region which are famous for stability have significant variance in elevation where, Glaptop approach and Area-Volume Scaling law for calculation of thickness and ice volume over different elevations of an individual glaciers in range is not being properly exploited. This paper is presented with the study of elevation-based thickness and ice-volume through satellite-based DEM for two selected glaciers with GLIMS-ID of G074684E36059N & G074575E36099N of Gilgit river sub-basin. The objective of the study is to estimate thickness and ice-volume over different elevations through spaceborne elevation model and, appraise the stability of glaciers in Karakoram range. GDEM from ASTER and the glacier outline clipped from RGI are the basic input parameters. ArcGIS 10.3 exploited for the extraction of morphometrical parameters of an individual glacier. Mathematical expressions of Glaptop and Area-Volume Scaling law used with morphometrical parameters to provide distributed thickness and ice-volume mapping of individual glaciers over different elevations. The distributed values further analysed to examine the relationship of these parameters with morphometric attributes. Visualization of the derived maps for distributes thickness and ice-volume provided a diversified nature for the selected glaciers of the study area. The thickness of glacier (G074684E36059N) ranged from 0.24-87.31 m has higher magnitude in lower elevation near the glacier snout in contrast of the glacier (G074684E36059N) which has maximized value of thickness along mid elevation zone in the ranged of 03.19-42.08 m. The ice-volumetric range of glacier (G074684E36059N) recorded greater than glacier (G074684E36059N) in lower elevation zone which is eventually the effect of the area in said zone. In linear regression analysis, positive correlation of thickness and ice-volume with area logged for both glacier. The diverse distributed values of thickness and ice-volume concluded the variance in intensity of vulnerability of selected glaciers in the basin toward the climate



change where, the positive correlation established the dependency on area under different elevation intervals. Furthermore, the statistical values extracted with correlation presented for proper protective management of the glacier component in Karakoram range and a supportive knowledge in the context of Karakoram anomalies.

Keywords: Global Digital Elevation Model, Randolph Glacier Inventory, Glaptop, Area-Volume Scaling law, Karakoram Range, Distributed thickness and ice-volume, Morphometric Parameters.

1. Introduction

Mountainous glaciers are known as one of the most influential climate variables and the magnitude changes may contribute to the dynamics of the sea level. According to the World Glacier Monitoring Service (2018), the global glacier is facing hurdle on the effect of global temperature rising. The Hindu Kush Karakoram Himalaya (HKKH) region known as the water tower of Asia is connected by ten major river basins located around the central and southern Asia and it governs the world largest mountainous glaciers of 60000 km² and directly responding to world climate for the last 15000 years [1,2]. The HKKH responses to complex and heterogeneous climate and this has made the HKKH time variant glacier statistics become inconsistent across its southern, western and central aspects (Kääb, 2012) while the global glaciers of Karakoram range is experiencing stability throughout the year. Glacier responses toward climate in Karakoram ranges have been studied at various approach and method though its accuracy in regard to the response and significant climate variability was under discussion [4,5]. The thickness and volume of ice are the important parameters in determining the climate change response for mountainous glacier ranges [6]. There are many analytical models were applied to quantify the abovementioned parameters, however, the space-borne derived products used to extract both parameters are currently under-utilized.

To estimate the thickness of glacier, Glaptop approach is widely applied to derive the mean thickness in regard to its glacier outline, elevation, area and central follow line as the rudimentary parameters. The Glaptop is determined by the following expressions [7].

$$h = \tau \frac{1}{f \cdot \rho \cdot g \cdot \sin \theta} \quad (1)$$

$$\tau = 0.005 + 1.598 \Delta H \quad (2)$$

where, h is the ice thickness (meters), τ is the basal shear stress (Kpa), f is the shape factor (unitless), ρ is the ice density (i.e. typical ice density 900 kg³), g is the acceleration due to gravity (i.e. 9.81 m sec⁻²), θ is the slope (Degree), and ΔH is the range of elevation (km). Literature also has shown that the thickness is depending on the area of the glacier thus derives following expression

$$h = 11.3 - 53.21 A^2 \quad (3)$$

where A is the area of glacier being mapped in km² [8].

The ice volume of glacier is dependent upon the average thickness and the area of glacier (Bahr, Meier, & Peckham, 1997) and it is defined by the area-volume scaling law in which the relation between area and volumetric glacier, V , are expressed as below

$$V = kA^r \quad (4)$$

$$\log(V) = \log(k) + r \log(A) \quad (5)$$

where the coefficients of k and r are derived through statistical and theoretical methods [10]. Grinsted (2013) has briefly presented the area-volume scaling law which has different model with respect to the type of glacier. This also has been explained by Bahr (1997) in which the trivial exponent (r) are 1.375 and 1.25 for mountain glacier and ice sheet estimation respectively.

Elevation has significant role in thickness and ice-volume estimation [11] and for mountainous areas, the diversified elevation gives even more complex contribution in the expression [12]. Previous studies were based on the global mean of elevation but elevation dependent thickness and ice volume is never been addressed because of the limitation on the absolute elevation taken on site particularly in the mountainous glaciers of Karakoram ranges.

This paper focuses on the application of the Glaptop and the area-volume scaling law method to estimate the ice thickness and volume respectively. By using the remotely sensed data of Digital Elevation Model (DEM), different thickness and volume are extracted in each respective elevation for determining the changes more explicitly. For that case, two glacier areas (GLIMS ID of G074684E36059N and G074575E36099N, hereafter named as 74684 and 74575 respectively) of Gilgit river basin in Central Karakoram National Park (CKNP) of Karakoram range are selected as samples. The objective of this study is to estimate the elevation dependent thickness and ice volume at different elevation profile by using the satellite derived digital elevation model in order to assess the glacier health at different elevation towards the climate change. This study contributes in improving the understanding of glacier behavior and response in CKNP and Karakoram range to the climatic change and eventually help to answer most of the questions in debate of Karakoram anomalies [13].

2. Study Area

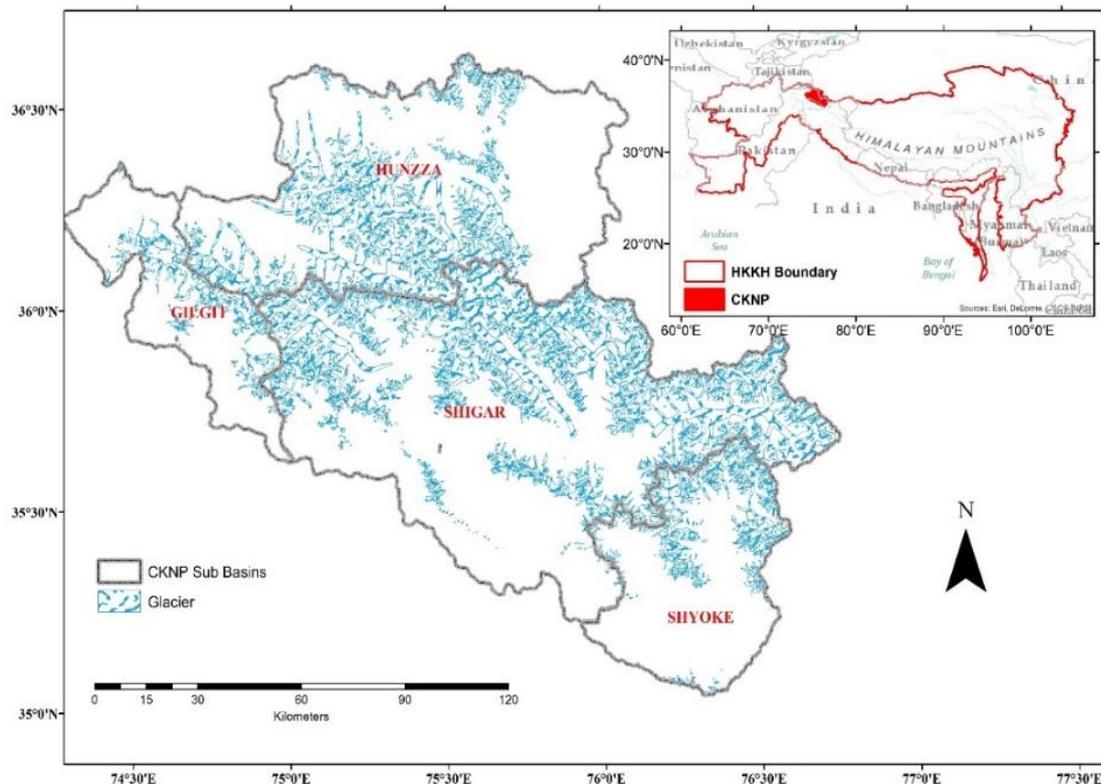


Figure 1. Map of glacier in Central Karakoram National Park (CKNP) within the Hunzza, Gilgit, Shigar and Shayok basins. The inset map shows the area of HKKH and CKNP at regional scale

Karakoram is the main mountain range for HKKH and CKNP that covers an area within 35°N to 36.5°N and 74°E to 77°E. This area has been gazette by the Government of Pakistan and holds for

mountains, glaciers, forest, villages and network of rivers and surrounded with population around 0.2 million [14]. It is the largest source of fresh water used in Pakistan with largest glaciers in the world, includes Siachen-75 km, Baltoro-57 km and Hispur-Biafo-122 km (World Wild Life, Dec 2009). The glaciated area of the park with large number of glaciers summed for 30% of the area of the Karakoram range [15]. Thus, for this study, CKNP seems to be a representative sample specifically for the HKKH and for the world climate in general. The map of glacier distribution in CKNP and respective basins is shown in Figure 1.

3. Data and Methodology

The methodology of this study lies on the purpose to estimate the distributed ice thickness and volume of local glacier in Karakoram ranges at different elevation profiles. To that extent two selected glaciers located in Gilgit basin of CKNP were chosen. Digital elevation model (DEM) derived by space-borne Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was taken in October 2011 and used for extracting altitude profiles of glacier. This data has an overall accuracy of Global DEM (GDEM) of 17 meters at 95% confidence and corresponding uncertainty around $\pm 10-20$ [16,17]. The glacier outlines is acquired from Randolph Glacier Inventory (RGI) compiled by the International Centre for Integrated Mountain Development [18].

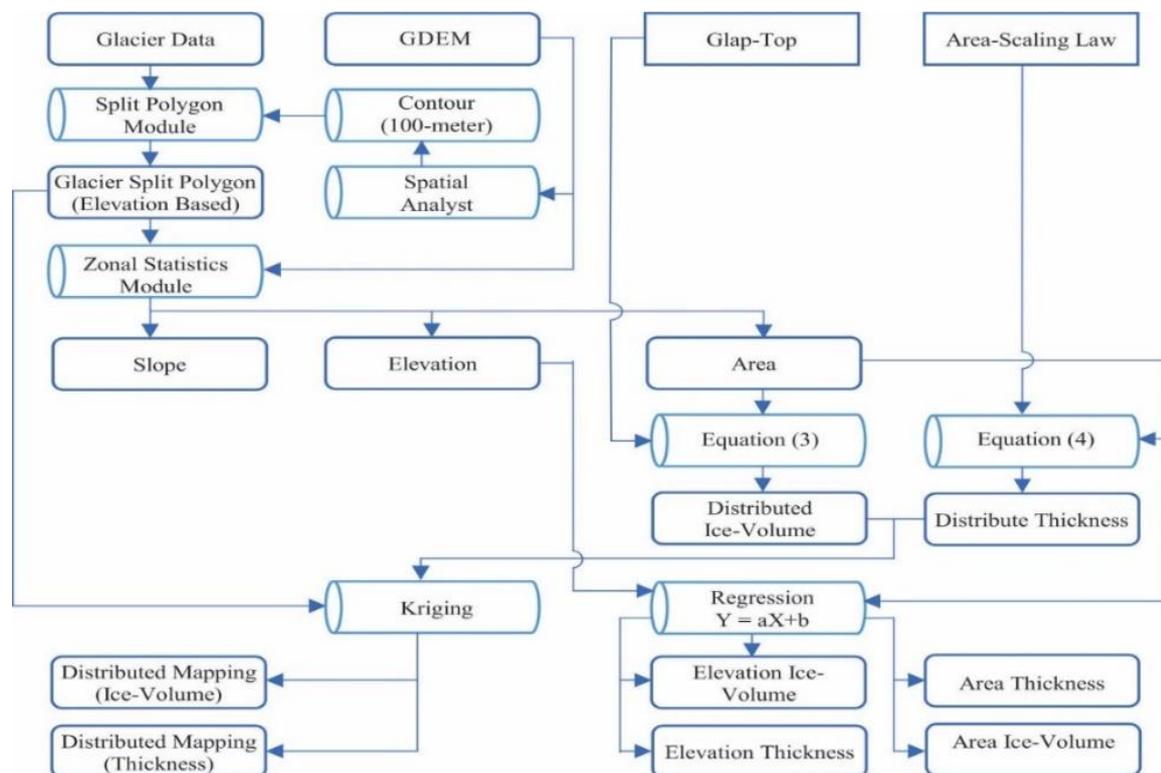


Figure 2. Flowchart of data processing

The research framework is shown in Figure 2 with three main phases. The first phase is the generation of GDEM at 100-m contours and spatial analyst module of ArcGIS 10.3 was used. These elevation contours are selected and split at different glaciers of RGI using split-polygon module. Split polygon of the two glaciers are clipped to DEM to provide area, slope and elevation classes which are used to complete the quantification of ice-thickness and volume using the GlapTop (Equation 3) and area-scaling law (Equation 4) techniques. Here, the exponent coefficient of 1.375 was used. Geo-analytical kriging was used to extract the unbiased interpolation glacier map of thickness and volume

[6]. Linear regression analysis was applied to determine the spatial relationship and dependent variables of thickness and volume with the independent variable of area, elevation and slope [19].

4. Results and Discussion:

Glaciers of CKNP are distributed within the major sub basins - Gilgit, Hunnza, Shigar and Shyoke. The mean elevation derived by GDEM of all glaciers and each sub-basin were computed and compared. Table 1 shows the number of glacier, total glaciated area, the mean slope, the mean thickness and total volume of glacier for each sub-basin. Figure 3 illustrates the mean elevation of every glacier in each sub-basin. The number of glaciers in those basins of CKNP varies therefore the basins have diverse elevation range, glaciated area, mean thickness and ice-volume.

Table 1: Glacier Morphology of sub basins in CKNP.

Sub Basin	No of Glaciers	Total Area (km ²)	Mean Slope (Degree)	Mean Thickness (meters)	Total Volume (Km ³)
Gilgit	21	65.51	32.09	40.16	7.89
Hunnza	451	1324.28	27.59	32.95	253.93
Shigar	561	2560.93	47.30	35.16	621.29
Shayoke	321	402.37	29.79	29.45	100.82

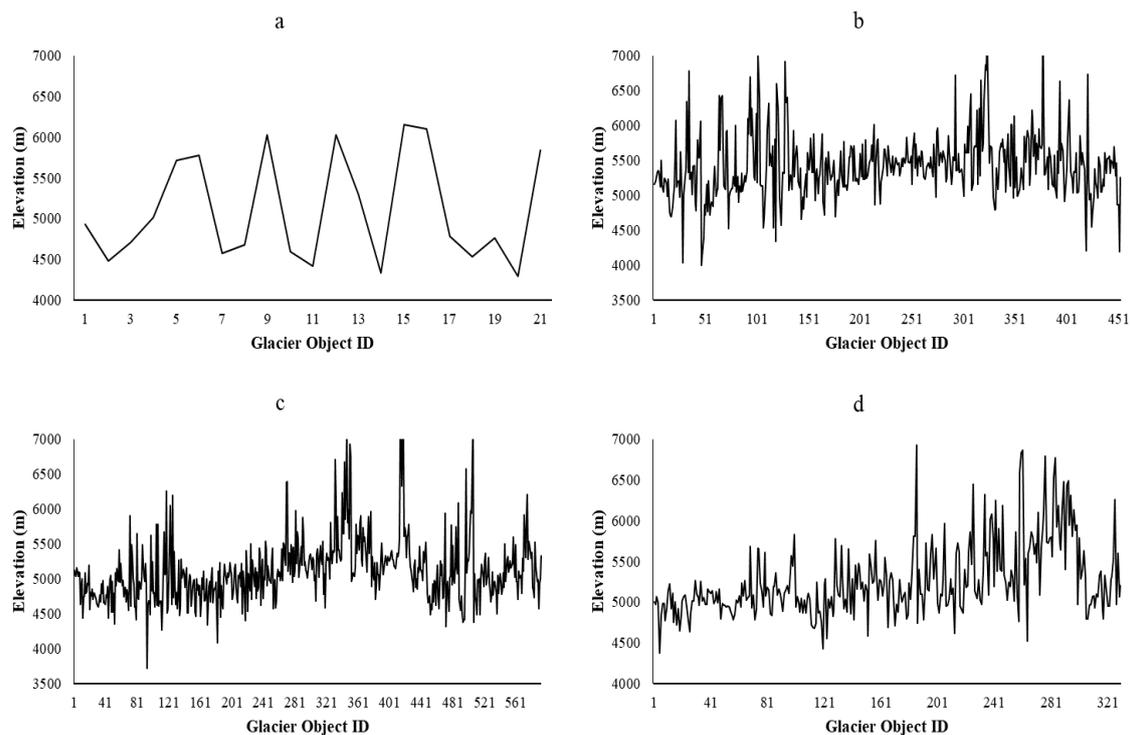


Figure 3. Elevation Distribution of CKNP Basins (a) Gilgit, (b) Hunnza, (c) Shigar and (c) Shyoke

The above Table 1 provides statistics of CKNP glacier and in order to provide greater insight, two selected glaciers in the Gilgit basin namely 74684 and 74575 are considered. The distributed ice thickness in 74684 glacier is about 0.63 to 27.32 m while 74575 is 0.610 to 37.11 m as presented in Figure 4 (left) and (right) respectively. Despite of the fact that these two glaciers have almost similar range distribution, the ice thickness at 74684 is higher and near the glacier snout at lower elevation than of the 74575. For this reason, it shows the evidence of better glacier health. Figure 5 presents the ice volume distribution in the selected glacier areas. In 74684, the distribution is in the range of 5×10^{-4} to 97×10^{-4} km³ while in 74575 the range is 16

$\times 10^{-4}$ to $76 \times 10^{-4} \text{ km}^3$. Contrast to the thickness near to snout and lower elevation, the magnitude of ice-volume for glacier 74684 is higher as compare to 74575 which eventually is the effect of areas under the lower elevation for this specific glacier.

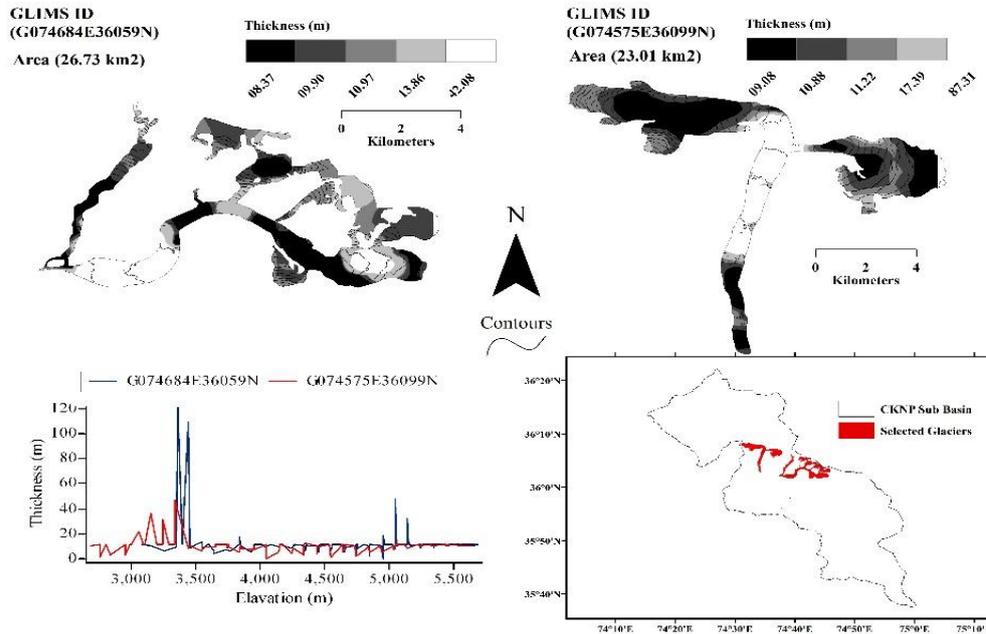


Figure 4. Spatial distribution of ice-thickness of selected glaciers

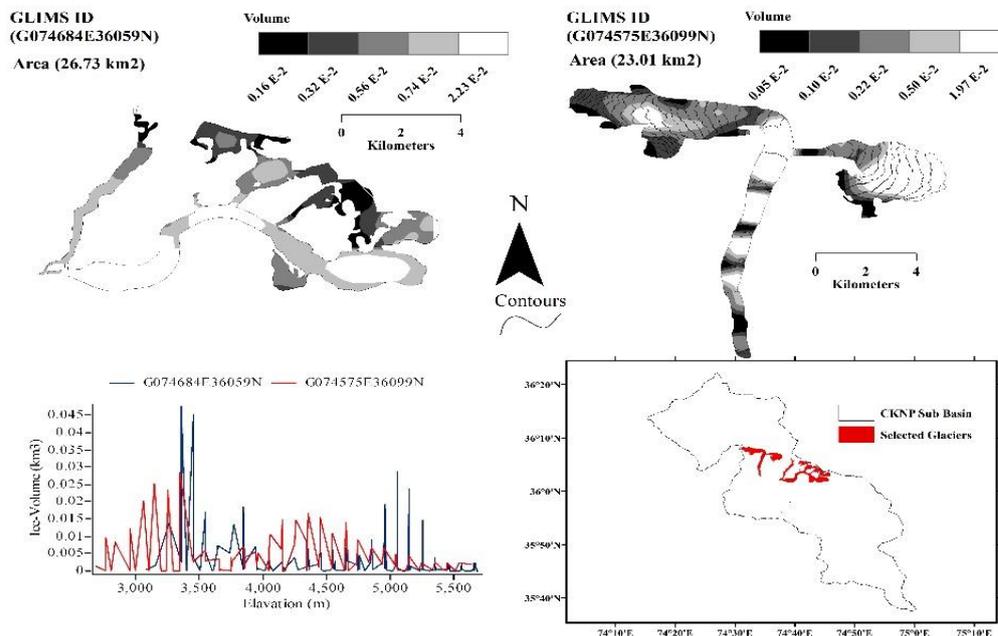


Figure 5. Spatial distribution of ice-volume of selected glaciers

The relationship of elevation and area with thickness and volume was also drawn using double-y graph where, the correlation calculated using leaner regression for the two glaciers. Figure 6 provides the statistics of the two glaciers for the relationship of elevation, area, thickness and ice-volume.

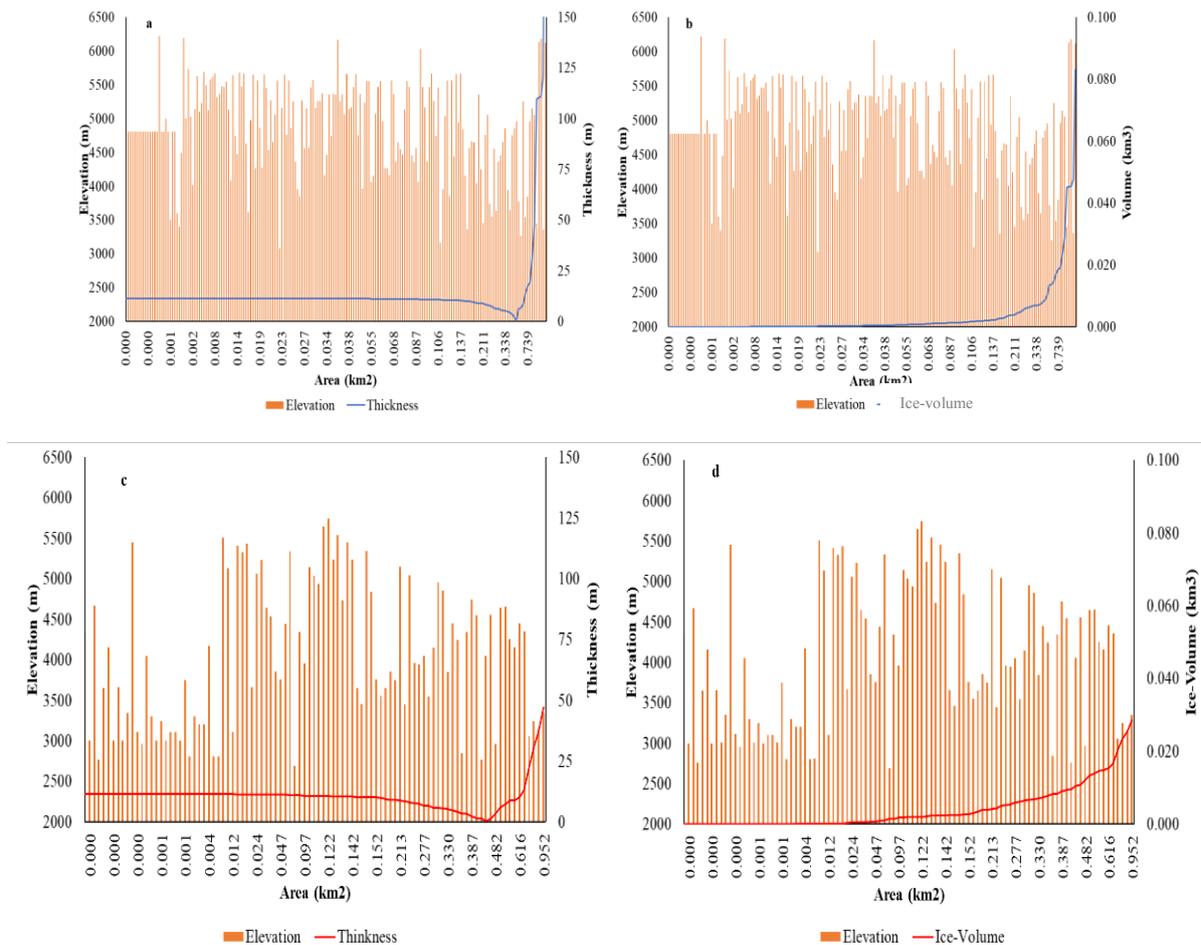


Figure 6. Relation of area with elevation & thickness Glacier (a) G074684E36059N & (c) G074684E36099N and area with elevation and ice-volume (b) G074684E36059N & (d) G074684E36099N.

5. Conclusion

This study provides statistics of the ice-thickness and volume for mountainous glaciers in Karakoram range that give better insight of the glacier health towards climate change in mountainous region. Two selected glaciers in the Karakoram range of CKNP were used and successfully demonstrated the Glaptop and volume scaling law methods using the satellite derived DEM and kriging interpolation routines for ice-thickness and volume estimates. This study suggested that the distribution of ice thickness and volume estimates vary with the elevation in each glacier set. Due to the topographic variations in both selected glaciers, the thickness and ice-volume differs at near snout, in middle of the glaciated area and at higher elevation. With higher thickness of 121m around snout at mean lower elevation of 3300 m, the glacier G074684E36059N (74684) has greater potential to sustain for climate response. This is not a case for glacier G074684E36099N (74684) with thickness of 11m around its snout at lower elevation of 2700 meter which is comparatively vulnerable to the climate change. The positive correlation of area with thickness ($R^2=0.68$ for G074684E36059N & $R^2=0.08$ for G074684E36099N) concluded that the higher elevation glaciated areas reserved more ice thickness. Thickness and ice-volume has better correlation with area ($R^2=0.96$ for G074684E36059N and $R^2=0.97$ for G074684E36099N) but the snout of the glacier G074684E36099N in lower elevation of 2700 m and the ice-volume measured is 0.001-km³ also with lower magnitude in middle and higher elevation zones as compare to the G074684E36069N. This variation of thickness and ice-volume over

different elevation intervals for both glaciers concludes that, the glaciated areas of higher elevations reserved with more ice thickness are more resistant to any climate variability.

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