Impact of Climate Change on Equilibrium Line Altitude in the Hunza Basin

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Introduction

The study of the changes in the complex alpine glacier system (e.g. Hindukush, Karakoram,and Himalaya) is crucial. Such studies impart vast information about the response of glaciers towards continuing rapid implications of climate changes. According to previous studies, the rise in global average surface temperature all the way through the world has caused the glaciers to retreat and shift towards lower altitudes. Thus, glaciers are considered as a key and warning symbol of the escalating temperature due to changes in climate (Atif et al., 2016; Dobreva et al., 2017). The Indus River basin (IRB) is one of the significant basins of a giant and complex mountainous range of HKH where approximately 50 % of stream flow is generated by snow-glacier melts (Soncini et al., 2015). Various reports have affirmed IRB, the most vulnerable and threatened region with immense losses due to the retreat status of the HKH glaciers (Hewitt et al., 20…; Soncini et al., 2015). Due to various patterns and sources of precipitation, variations in climatic condition have been observed over different time periods in complex terrain of the HKH region (Qing-Long et al., 2017). Based on different glacier inventories, various existing studies estimated glacier covered area varying from 36,845 km^2 to 50,750 km^2 in HKH region (Azam et al., 2018), The Karakoram range, roughly, contains about half of this glacierized area (Azam et al., 2018). Previous studies reported remarkable decline of glaciers in the high lands of Asia and "Great Himalaya" range. Over the past few years, general retreat and negative glacier mass balance has been observed in the Central and Eastern parts of the HKH region (Bolch et al., 2011). On contrary, different studies concluded that Karakoram glacier system shows diverse behavior and exhibits thickening and growing of glaciers with stable /positive mass balance (Hewitt et al., 20…; Soncini et al., 2015; Lin et a., 2017; Siddique ullah et al., 2018). This state of stable/positive mass balance in the highly glacierized central parts of the Karakoram refers to "Karakoram Anamoly" (Minora et al., 2016).

The study of the glaciers in the Upper part of the IRB is imperative and ideal because it covers some of the highly glaciated basins with different climatic conditions such as Hunza, Gilgit, Astore, Chitral, Swat, Kharmong, Kabul, Jhelum, Chenab, Shigar and Shyok sharing by four countries: Pakistan, India, China and Afghanistan. The temporal trend analysis of Equilibrium Line Altitude (ELA) in such basins can contribute great knowledge towards the changes in snow and glacier extents and their relationship with climate. The variability of historical ELA can also be used to assess the possible future changes in regional hydrological cycle and within glacier system. In current study, Hunza River basin (Karakoram mountainous range) has been taken as a case study.

ELA refers to an average altitude on alpine glaciers that represents a divide between glaciers lying in accumulation and ablation zones. This altitude greatly influences by the local/ regional temperature and precipitation patterns. Thus, this altitude is considered as a fundamental and key measure of a "Glacier-Mass-Balance" in a particular glacier system. The accumulation zone, usually sited on the upper part of the glaciers, signifies "Winter-Glacier-Mass-Balance", where glaciers experience thickening and growing owing to different processes including precipitation fall, avalanches and wind- blown snow. On contrary, the lower part of the glaciers indicated by "Summer- Glacier- Mass- Balance" refers to an ablation zone, where thinning and shrinkage of glaciers can be observed. The quantitative measure of location of this altitude and its long term fluctuations over ablation period is of great importance to considerate the hydrological processes within glacier systems. In highly glacierized areas having features of intricated topography such as the Hunza River basin, it is seldom possible to measure ELA by field observations and measurements. However, previous studies have shown that wide use of remote sensing data-sets can be used successfully in determining this altitude.

Many studies have been carried out to determine the snow and ice covered extents in the UIB, but less consideration is given in evaluating the temporal variation of ELA in highly glacierized sub- basins of the UIB by improving the input datasets. Thus, the main goal of this study is to determine ELA for the Hunza River basin and to analyze its temporal trend by improving the long term available base data used in the study.

Study Area

The Hunza River basin, a highly glacieirzed sub-basin of the HKH, runs through high alps of the Central- Karakoram. The basin lies within altitudinal range of 1415 m to 7809 m with mean altitude of 4570.61 m. The total surface area of the study area is 13733 km^2 stretching between 35˚54'18.29" N to 37˚5'47.86" N (latitude) and 74˚0'37.76" E to 75˚47'34.72" E (longitude) (See Figure 2). According to Randolph Glacier Inventory (RGI v 6.0), the total glacier area covered by a study area is approximately 4290.44 km^2 making 31.27% of the study area. RGI shows that the total number of glaciers in Hunza River basin is about 2329. The statistics shows that 78.08% of glacier area in the Hunza River basin is occupied by large glaciers in sizes greater than 5 km^2, 16.83 % of glaciers are in sizes ranging from 1 km^2 to 5 km^2, 8.73% of glaciers have sizes varying from 0.05 km^2 to 1 km^2 and 0.36% of glaciers less are than 0.05 km^2. About 85% of the Hunza River basin remains covered with seasonal snow in winter season, which reduces to 30% in summer season. It carries an average annual flow of 323 m^3/s recorded over period of 1966 to 2008 at Dainyor Bridge (Tahir et al., 2011). For measuring precipitation, there are three gauge stations installed by WAPDA at different elevations i.e. 4730 m (Khunjerab), 3669 m (Ziarat) and 2858 m (Naltar). According to the record of 1999- 2008, the average precipitation at these stations is 165 mm/year, 292 mm/year and 660 mm/year, respectively (Shrestha et al., 2015??). One rain guage station at elevation 2156 m (Hunza) is installed by PMD.

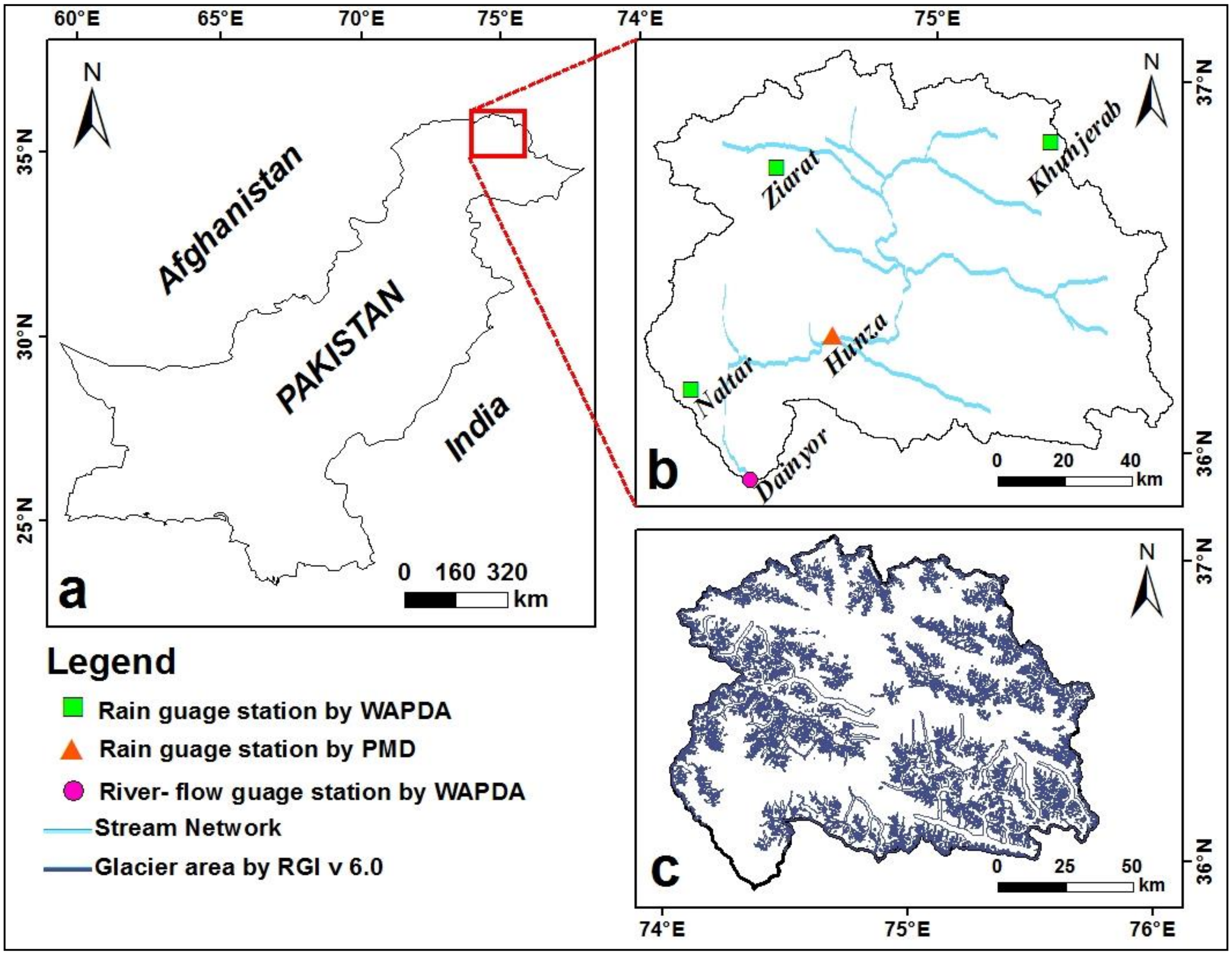

Figure 2 Map of study area showing Hunza River basin in sub-figure b and c, In sub- figure c glacier area derived from RIG is shown.

Methodology

In this study, we have used a variety of satellite data-sets including Moderate Resolution Imaging Spectroradiometer (MODIS) 8-day snow cover product (500 m spatial resolution), Landsat imageries (30 m spatial resolution), RGI v.6.0 (Randolph Glacier Inventory), and MODIS 8-day Surface Reflectance (250 m spatial resolution). For appropriate hydrological-climatic studies there is a dreadful need of accurate evaluation of snow and ice- covered extents. For this purpose, "National Aeronautics and Space Administration's" (NASA) has employed two satellites namely Terra and Aqua launched in 1999 and 2002, respectively, being operated by MODIS instrument. Both Terra and Aqua satellites manage to take the image of same part of the Earth at 10: 30 am and 1: 30 pm, respectively, and hence providing two values of snow- covered area for same site per day. In this study, snow- cover product from MODIS/ Terra (MOD10A2) is utilized as the principle data source on the basis of the study conducted by Wang et al. (2009) for China, in which the MODIS/ Terra has shown better results as compared to MODIS/ Aqua for least cloud coverage. Besides this, many authors have successfully used MODIS/ Terra snow cover product in the UIB or parts of the UIB such as Tahir et al. (2011), Forsythe et al. (2012), Hakeem et al. (2014), Atif et al. (2015), Khan et al. (2015), Cheema et al. (2016); Tahir et al. (2017); Atif et al. (2018) and Hussain et al. (2019). In this study, we have downloaded MODIS 8-day snow cover product for 18 years from 2000 to 2017 followed by mosaicking of two tiles (h23v05 and h24v05 shown in Figure 3) to swathe the entire the Hunza River basin.

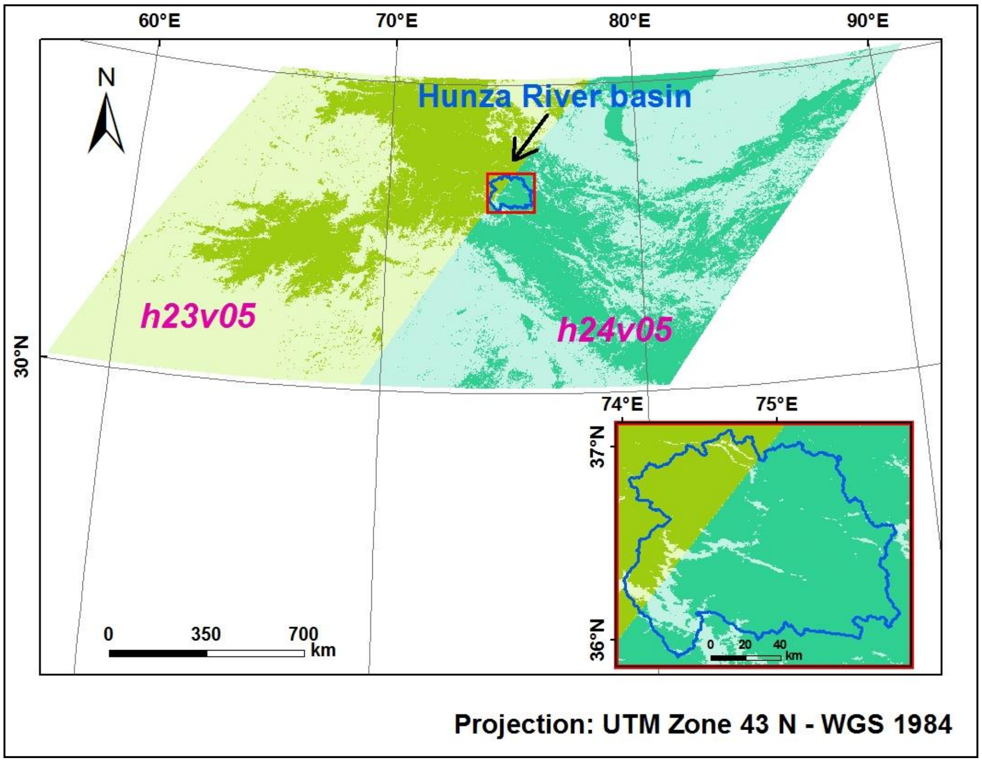

Figure 3 Example of MODIS mosaicked tiles (h23v05 and h24v05), dated: 01-01-2001 to cover the study area (Hunza River basin)

In spite of having coarse spatial resolution of 500 m, MODIS snow- cover product compared to Landsat images is a widely used data- set on account of availability of long term series data- sets. Mis-classification of snow- ice due to the presence of cloud cover in MODIS images is the prime limitation in the use of MODIS snow cover data for estimating snow and ice covered areas. Since, HKH region is persistently roofed with clouds, it is imperative to rectify the MODIS images with cloud-coverage to curtail the effect of cloud-cover and to avoid the under-estimation and/or over-estimation errors.

- In this study, the first step is to determine the “No- data- cells” in MODIS images.

- In second step, the cloud region in MODIS images is identified by masking the cloud pixels over the glacier region by using global glacier inventory RGI v 6.0. The RGI data is downloaded from website “http://www.glims.org/download/”.

- The key issues associated with MODIS product is that it cannot identify small glaciers due to its coarse resolution and the glaciers with size less than 0.01 km^2 may be under-estimated by MODIS data (Khan et al., 2015). Also, MODIS data cannot differentiate between snow and ice extents. For this purpose, in third step, RGI is used to reinstate the small glaciers in MODIS data.

- MODIS /Terra Surface Reflectance 8-day L3 Global 250 m SIN Grid V005 (MOD09Q1 with spatial resolution of 250 m), a very powerful and useful albedo data particularly for separation of snow and ice, shows variation in albedo for snow and ice surfaces which influences the melt rate largely. The albedo data for 2000 to 2017 years are downloaded from………… followed by mosaicking the two tiles (h23v05 and h24v05) to cover the study area. The lower and upper limits of surface reflectance provided in the albedo data for the study area ranges from -100 to 16000, however, no such threshold is available to separate the snow and ice from this data. Khan et al. (2015) separated snow and ice for some of the sub-basins in the UIB using single time series data-set of landsat images. The Albedo images together with the pre-processed MODIS images of the same date as were used for Landsat images by Khan et al. (2015) are selected for determining the threshold. Hence, in forth step, by using trial and error technique, the threshold value is continuously adjusted until the same/approximated snow/ ice covered area is obtained as was estimated by Khan et al. (2015).

- In fifth step, the final product is intersected from SRTM 90 m DEM to get an average ELA for each week.

- In sixth step, which is the main goal of current study i.e. the temporal trend analysis of ELA during ablation period i.e. the months of July, August and September is then carried out because most of the snow over the glaciers melts away during this period (see Figure 4).

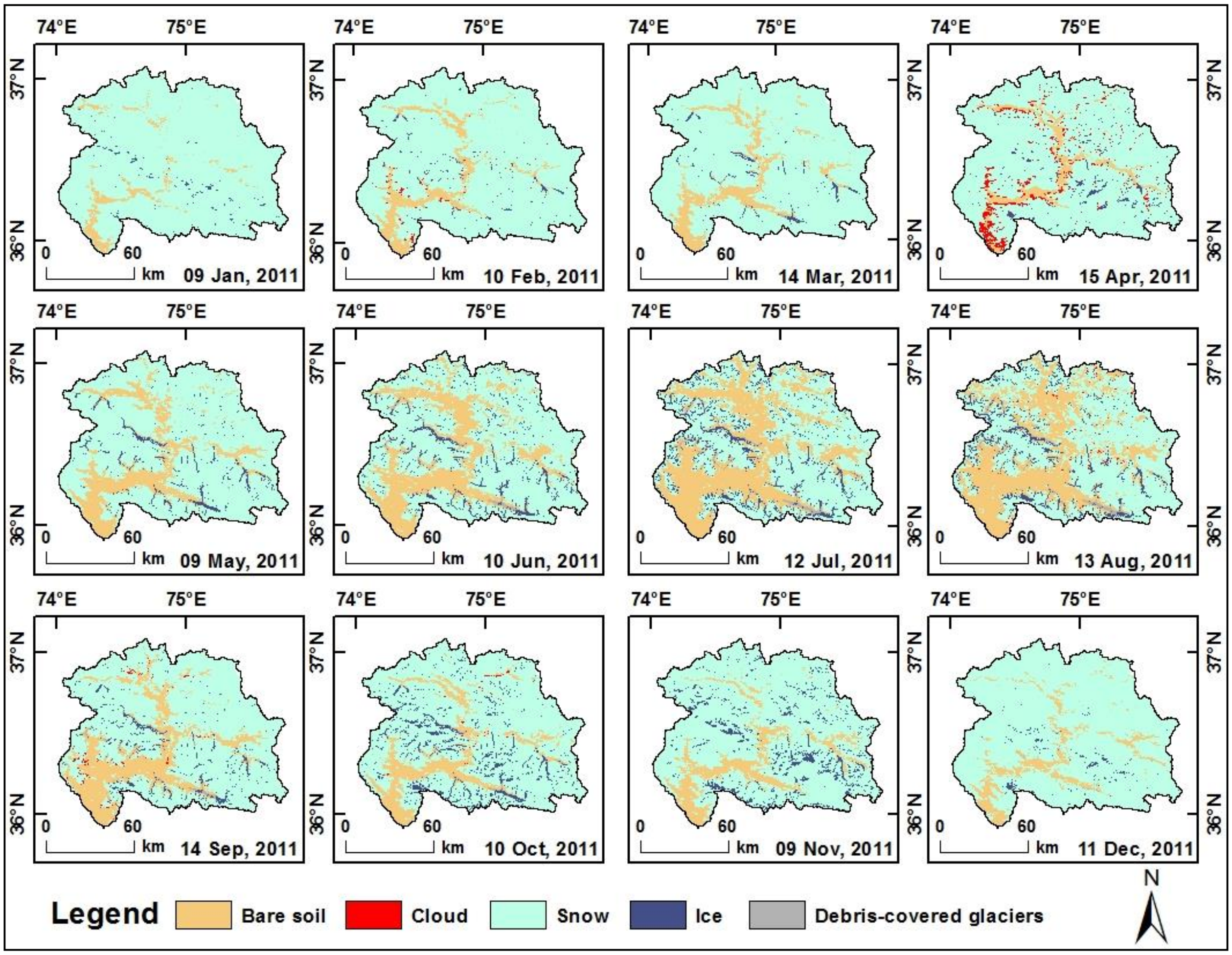

Figure 4 Processed MODIS images for each month from 2011 year is shown. It is clearly visible that major part of the ice is exposed during ablation period (July, August and September) due to the melting of seasonal snow.

Non-Parametric tests

Parametric statistical tests usually require some strict assumptions to be satisfied for correct application (e.g. normality in data distribution, sample/ data independency, linearity in data etc) (Huth and Pokorna., 2004). However, climatic data due to continuing changes in climatic condition may infringe these assumptions. Thus, Distribution- free statistical tests also known as non- parametric tests are often preferred over parametric tests for time- series trend analysis of hydro-climatic variables. They are less sensitive to the outliers/ missing values present in the data and also suitable for small size sample data. The Mann- Kendall’s test (M-Kt) is the simplest and widely used non-parametric test used for identifying the existence/significance of trends in hydro- climatic variables. For detection of climate changes and its relationship with hydro- climatic variables, it is not important merely to determine the significance of trend but also to estimate its magnitude. Thus, the M-Kt complemented with Sen’s slope test (S-St) can be used to estimate trend magnitude.

Existing studies show that several authors around the world have employed M-Kt in the trend analysis of various hydro- meteorological variables and sediment load, e.g. Zelenáková et al (2018) used M-Kt for evaluating temperature and precipitation patterns in Eastern Slovakia. Latif et al. (2018) used M-Kt together with S-St to detect the trends and changes in seasonal and annual precipitation in the UIB. Rehman et al. (2018) applied the M-Kt along with Sen's slope pattern in the UIB. Trends in the monthly, seasonal and annual precipitation for Amhara regional state of Ethiopia were analyzed by Gedefaw et al. (2018). Gumus et al. (2017) carried out trend analysis of various hydro- meteorological variables including temperature, total precipitation, humidity and wind speed in Sanliurfa, Turkey. Salami et al. (2016) examined trends of various hydro- meteorological variables including temperature, rainfall, sea level rise, relative humidity and wind speed in the coastal region of Lagos, a city of West Africa.

Mann- Kendall's test, M-Kt

M-Kt is the commonly used and robust statistical method presented by Mann (1945) and Kendall (1975) to investigate the existence of significant trends in time- series datasets of hydro- climatic variables. This method is not restricted in/by the use of specific type of data distribution as in the case of parametric test and thus can be used for non- normal distributed datasets. The efficiency of the test is validated by Yue and Wang (2004) by comparing with other statistical tests (Folton et al., 2018????mk3). The significance level indicated by "p- value" is used to accept or reject the "Null- hypothesis (H_o)" of the M-Kt. If p- value > SL, the trend is significant and p- value < SL, the trend is insignificant. In this study, trend analysis is carried out using two significance levels i.e. 5% and 10%.

The M-Kt statistic "S_{MK}" is determined as:

$$S_{MK} = \sum_{P=1}^{N-1} \sum_{Q=P+1}^{N} \operatorname{sgn}(X_Q - X_P) \qquad eq(1)$$

Here, "N" represents number of observations in data sample. X_P and X_Q are the consecutive values in data sample. Taking $(X_Q - X_P) = Y$, the value of "sgn Y" can be calculated as:

$$\operatorname{sgn} Y = \begin{cases} 1 & if \quad Y > 1 \\ 0 & if \quad Y = 1 \\ -1 & if \quad Y < 1 \end{cases} \qquad eq(02)$$

The positive value of S_{MK} shows a rising trend while negative value indicates a declining trend.

Sen's slope test, SSt

SSt (non- parametric test) is coupled with MKt to determine the slope of a trend line identified in a hydro-meteorological time series data- sets. This method is based on the assumption of linear trend present in the dataset. The Sen's slope (SS) is calculated by:

$$SS = Median\left[\frac{X_Q - X_P}{Q - P}\right] \qquad eq(06)$$

Where;

time Q > time P

X_P = data value taken at time P

X_Q = data value taken at time Q

The Sen's slope (*SS*) provides the information of change in any hydro- meteorological variable with respect to time, which helps in estimating the total change occurring over the analysis period.

Results and Discussion

In total 215 (one image missing for 12-08-2000) MODIS 8-day Snow cover images for the months of July, August and September over period of 18 years are passed through the three subsequent processing steps i.e. No data cells removal, cloud removal and reinstatement of small glaciers. The results show that "No data cells" are not found in any of the 215 images. The technique used in the current study to reduce cloud coverage from the MODIS data results in removing 100% of cloud cover over the glacier area. One such example has been shown Figure 5a in which original MODIS image (dated: 22 Sep, 2003) is shown with initial cloud coverage and in Figure 5b a processed image after reduction of the cloud- cover is shown. The analysis shows that 191 out of 215 MODIS images still have cloud- cover pixels less than 4% of the total pixels while 24 images have cloud cover ranging from 4.5% to 14% over the snow covered area. Since the main focal area for determining ELA is the glacier area, hence, cloud covers in the surrounding areas or over the snow area are not influencing the results.

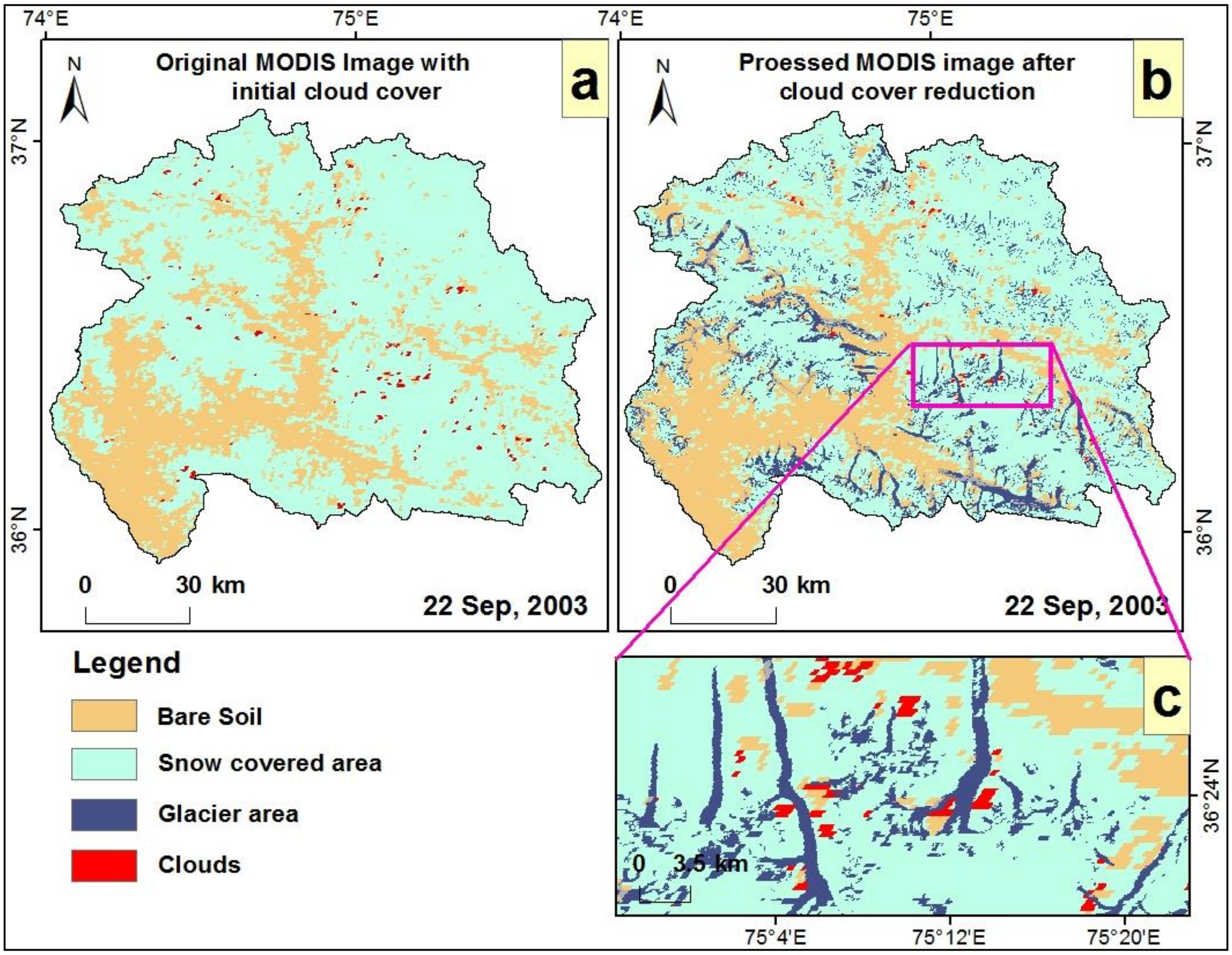

Figure 5 MODIS image of 22nd Sep, 2003. Sub- figure a shows the original cloud- coverage in that particular image. Sub-figure b shows the processed MODIS of same date after reduction of cloud- cover. In sub- figure c it is clearly visible that clouds are removed over the glacier area.

The analysis of re-instatement of small glaciers in the Huzna River basin shows that variation of small glaciers over ablation period ranges from 0.5 % to maximum 7.2 % of the total glaciers in the study area. Least percentage of reinstatement may be attributed to the wet year with maximum snow-fall, whereas, maximum reinstatement may be associated to dry years with minimum snow-fall. The threshold limit of albedo (surface reflectance) for separating snow and ice over the glacier area founds to be 3241 with value less than 3241 indicating ice- covered area and the value above 3241 provides snow-covered area. The results obtained from MODIS Albedo images together with the MODIS Snow- covered product are extracted from SRTM (DEM) with spatial resolution of 90 m to get the average ELA for each month (ablation period) during 18 years. The fundamental statistical parameters based on M-Kt and SSt i.e. Tau, p- value and *SS* are shown in Table 1 to show the temporal trends of ELA tested at two SL (5% and 10%).

Table 1 Statistical parameters of M-Kt and SSt for Average Annual ELA in the Hunza River basin

Basin name	Statistical parameters of M-Kt and SSt	July	August	September
Hunza	**Kendall's tau (τ)**	0.111	-0.294	-0.163
	S_{MK}	17	-45.000	-25.000
	p-value (Two-tailed test)	0.55	0.096	0.369
	Null Hypothesis (H_O) at SL = 5%	Accepted	Accepted	Accepted
	Null Hypothesis (H_O) at SL = 10%	Accepted	Rejected	Accepted
	Sen's slope, *SS*	1.687	-7.106	-2.846

H_o = No trend exists in time series data.

H_1 = Trend exists in time series data.

Results are graphically presented and explained as follows:

The results of this study suggest that average ELA for the Hunza River basin is 5022 m ± 103 m. Different values of ELA for the region are estimated using different techniques and data-sets. Butt et al. (2013) estimated this altitude between 5000 m to 5500 m for the HKH region by using the techniques of supervised and unsupervised classification of Landsat 7 images coupling with ASTER DEM (30 m resolution). Shrestha et al. (2015) suggested mean ELA of 5050 m for Hunza River basin using hypsographic analysis (Siddique ullah et al., 2018). Khan et al. (2015) estimated minimum and maximum values of ELA for the Hunza River basin as 4300 m and 5520 m , respectively, with average value of ELA 5000 m based on average of the snow and glacier extents existing between minimum and maximum ELAs. In another study conducted by Racoviteanu et al. (2016) an ELA of 5260 m is reported for the year 2013 for Hunza River basin by taking average elevation of snow and ice-extents (Siddique ullah et al., 2018).

Though the statistical parameters in Table 1 "**τ**" and "S_{MK}" show that positive trend exists in the time series data set for the month of July; p- value 0.55 greater than 0.05 and 0.1 indicates that no significant trend is identified at both SL. On contrary, August and September show contrasting pattern of ELA with decreasing trend. In September, no significant trend exists with p- value 0.369 greater than 0.05 and 0.1. Unlike July and September, a trend is significant in the month of August at SL 10% only with p-value 0.096 less than 0.1. However, this trend cannot be considered as a strong trend. The decreasing trend in August and September supports the theory of "Karakoram Anamoly" which confirms that glaciers are nourishing and gaining mass in this region. The decreasing trend in ELA in August and September may be attributed to the fact of observing significant positive trend in precipitation and negative trend in mean temperature in summer by Archer and Fowler (2004). Hussain et al. (2005) investigated that in high elevated areas of the Hunza River basin, pre- monsoon and monsoon seasons are complemented with decreasing trend of temperature. Atif et al. (2018) found positive trend in solid precipitation and declining trend in temperature in Hunza River basin.

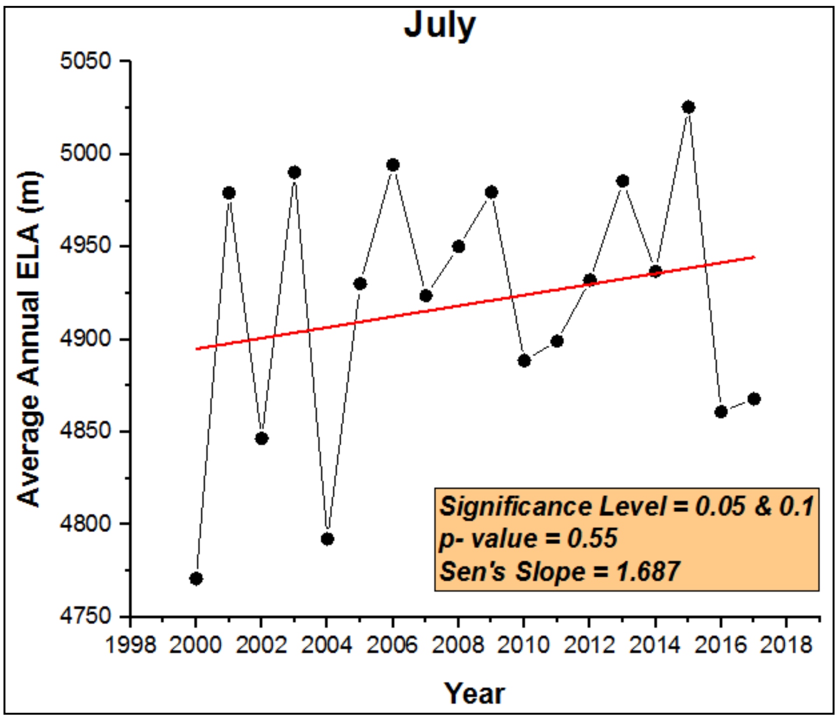

Figure 6 Trend analysis of Average ELA in the month of July at SL =5 % & 10 % over period 2000 to 2017 years for the Hunza River basin; red line shows positive trend

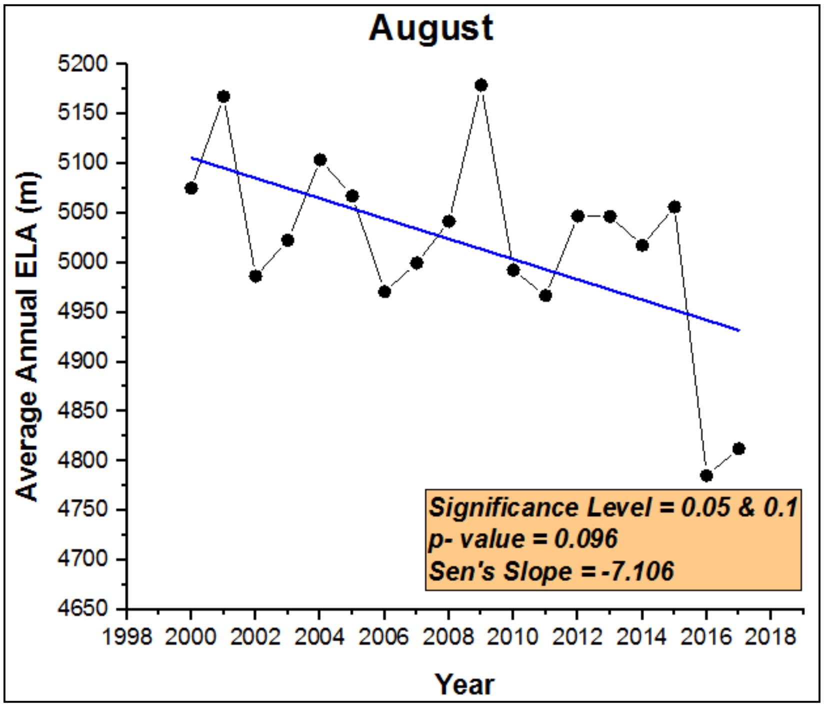

Figure 7 Trend analysis of Average ELA in the month of August at SL =5 % & 10 % over period 2000 to 2017 years for the Hunza River basin; blue line shows negative trend

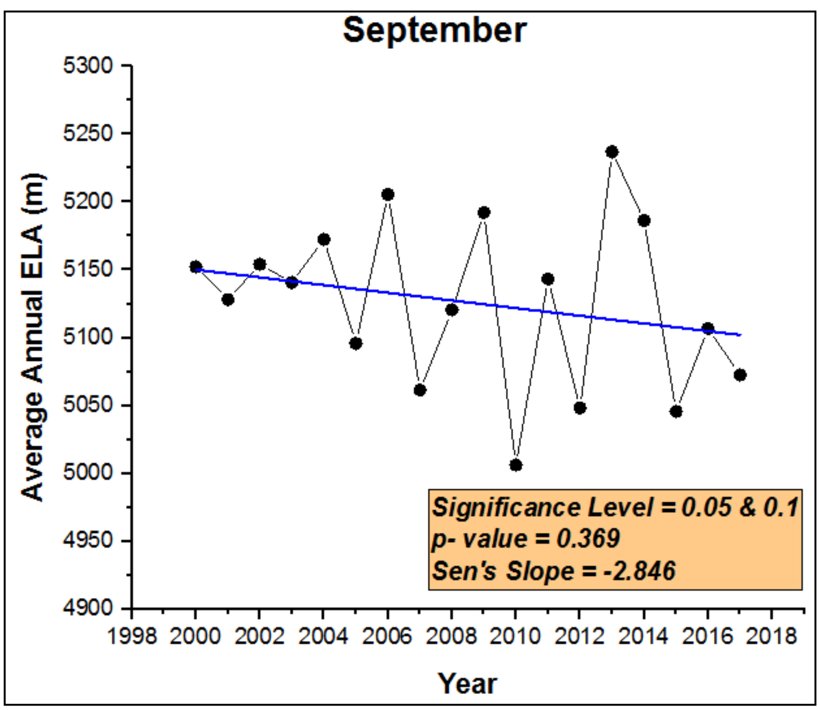

Figure 8 Trend analysis of Average ELA in the month of September at SL =5 % & 10 % over period 2000 to 2017 years for the Hunza River basin; blue line shows negative trend

Conclusion and Recommendations

- The results of M-Kt and SSt revealed that statistically in- significant increasing trends at both pre-selected SL are obtained in the month of July. In contrast, an in-significant decreasing trend in August and September is obtained except for the month of August at SL = 10%, where a significant trend is observed. The results of this study coincide with the theory of "Karakoram Anamoly" referring to a neutral or slightly positive mass balance in highly glacierized basins in the Karakoram region.
- From the results of this study, it is concluded that there is an overall increase in the accumulation zone in ablation period. It means that glaciers are growing and with this continuing positive trend, a reliable source of water can be expected in future in the form of frozen reserves in the Hunza River basin.
- The temporal decreasing trend in ELA in August and September are verified by the existing studies conducted for precipitation and temperature trend analysis in the Hunza River basin. From the results of this study and existing studies, it is concluded that temporal decrease in ELA in the study area is characterized by positive and negative trends in precipitation and temperature in summer. However, the positive trend in the month of July cannot be conclusive. It is, therefore, recommended to use varying technique………...
- To evaluate the sensitivity of the Hunza River basin's ELA towards continuing climate changes, it is recommended for future studies to determine the correlation of Hunza 's ELA with temperature, precipitation, flow and snow- ice extents.

Acknowledgement

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(Note: References will be updated in final report)

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Simulation of snowmelt-runoff under climate change scenarios in a data-scarce mountain environment

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