

Status of Major Glaciers of Hunza River Basin, Under Changing Climatic Conditions of Pakistan Over the Period of (1990-2018)

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Abstract

Ice masses and snow of Hunza River Basin (HRB) are an important primary source of fresh water and lifeline for downstream inhabitants. Changing climatic conditions seriously put an impact on these available ice and snow masses. These glaciers may affect downstream population by glacial lake outburst floods (GLOF) and surge events due to climatic variation. So, monitoring of these glaciers and available ice masses are important. This research delivers an approach for selected glaciers of the Hunza river basin. An attempt is made in this study using Landsat (OLI, ETM, ETM+, TM), digital elevation model (DEM), Geographic Information System and Remote Sensing techniques (RS&GIS) techniques. We delineated 27 glaciers within HRB from the period of 1990-2018. These glaciers' total area is about $2589.75 \pm 86 \text{ km}^2$ in 1990 and about $2565.12 \pm 68 \text{ km}^2$ in 2018. Our results revealed that from 2009 to 2015, glacier coverage of HRB advanced with a mean annual advance rate of $2.22 \pm 0.1 \text{ km}^2 \text{ a}^{-1}$. Conversely, from 1994 to 1999, the strongest reduction in glacier area with a mean rate of $-3.126 \pm 0.3 \text{ km}^2 \text{ a}^{-1}$ is recorded. The glaciers of HRB are relatively stable compared to Hindukush, Himalayan and Tibetan Plateau (TP) region of the world. The steep slope glacier's retreat rate is more than that of gentle slope glaciers, and the glaciers below elevation of 5000 m above sea level change significantly. Based on climate data from 1995-2018, HRB shows a decreasing trend in temperature and increasing precipitation. The glacier area's overall retreat is due to an increase in summer temperature while the glacier advancement is induced possibly by winter and autumn precipitation.

Introduction

Snow and ice masses in the high mountains of Hindukush, Karakorum and Himalaya (HKH) are the primary source of water for the mountainous population's living. These snow and ice masses are likely to be affected by changing climatic conditions of the region, but to what extent is yet unclear (Immerzeel et al., 2010). Changes in temperature and precipitation are expected to affect the melting characteristics of the cryosphere seriously. Hassan et al. (2017) have shown that the snow and ice melt contribution in river discharge is significant. In recent ten years, the ice caps and glaciers are retreating worldwide (Oerlemans et al., 2007). Himalayan Glaciers are important natural resources and feed the major rivers of South Asia. In the past 20 years, there is a decrease in the mass of Himalayan glaciers (Yutaka et al., 2001). Glaciers' ablation in the Himalayan region is due to decreased annual precipitation and an increase in average annual temperature (Ren et al., 2006). Glaciers are the good indicators of climate change in mountainous areas; however, mountainous region of HKH is poorly gauged. Most glaciers of the Himalayan region are shrinking (Kadota et al., 2000). IPCC (The Intergovernmental Panel on Climate Change) states that the declining of Himalayan glaciers is faster than any other region of the globe. If the earth's temperature is increased by the current rate, then these glaciers will be diminished by 2035 (IPCC, 2007). This may be due to the presence of Himalayan region near the equator, and a small increase in temperature cause huge impact and loss of fresh ice and glacier mass. Apart from Polar Regions, the Himalayan and Tibetan plateau has the world's most glaciated area (Racoviteanu et al., 2008). There is a significant climate trend that influences glacier behavior (Bocchiola & Diolaiuti, 2013). The Himalayas is considered the third pole of the world (Kehrwald et al., 2008). It comprises ice bodies and glaciers over more than $60,000 \text{ km}^2$ and the largest ice mass source apart from the polar region (Gardelle et al., 2013). The major part of Pakistan's glaciated region is nested within Upper Indus Basin (UIB), which provides a significant amount of water for the downstream population and their livelihood. More than 20,000 glaciers in the HKH region, out of which 5000 glaciers are located in the Upper Indus basin (Inman, 2010).

The major sub-Basins of UIB are Hunza, Gilgit, Shigar, Shyok, Shingo and Astore rivers with a number of smaller and larger tributaries. Glaciers in UIB are majorly nourished by winter precipitation; avalanches winds can further add mass to the glacier ice which contributes to the positive mass balance of glacier (Akhtar, 2008). Avalanches may also transport debris load to glacier surface, later on debris cover lead to change the glacier response to the changes in climatic conditions by altering melting rate. Snow and ice melt contribute significantly in river discharge of UIB. More than 50% of the water in UIB is contributed by snow and ice melt. More than 7000 glaciers in the Karakorum region but only 15 largest glaciers of the region (Karakorum) cover the 50% of glaciers area (Kehrwald et al., 2008). Since the 20th century there is a negative mass balance of Karakorum glaciers and mass loss of 5%, however, this mass loss is slowed down in 1970s (Mayewski & Jeschke, 1979). Some glaciers in this region are displayed positive mass balance (Kotlyakov, 1999). According to (Hewitt, 2005), from the 1920s to early 1990s, most of the Karakorum, Himalayan glaciers were also observed that these are retreating except in the 1970s. However, most of the Karakorum glaciers began advancing in the late 1990s (Hewitt, 2005). The glaciers present in Upper Indus Basin are retreating due to the increase in mean air temperature. Karakorum glaciers have unique behavior than rest of world glaciers.

Glaciers around the world are showing negative mass balance except for the glaciers of Central Karakorum region which is termed as "Karakorum Anomaly" these glaciers are either stable or advancing (Dehecq et al., 2019; Hewitt, 2005). Stability and advancement of Karakorum glaciers are also suggesting from snout monitoring in Central Karakorum about 50 % glacier's snout is either stable or advancing (Scherler et al., 2011). Karakorum glaciers' anomalous behavior is might be due to decreasing summer temperature and increasing precipitation trend in the region (Hassan et al., 2017). The Karakorum glaciers' changes are different from the neighboring mountain ranges like Himalayas and Tangshan, where glacier are in negative mass balance. Climatic condition is one of the major factors which control the glacier fluctuation in the Karakorum region (L Iturrizaga, 2011).

The aim and objectives of current study are to use Landsat satellite imagery between 1990 and 2018 to measure temporal and spatial variations of selected glaciers in Hunza river basin, western Karakorum (Fig. 1).

Study Area

Geographically Hunza river basin (HRB) is located in the Karakorum region (western Karakorum) and is a major sub-basin of Upper Indus Basin (UIB) Pakistan (Fig.1). The study area comprises of three districts of Gilgit-Baltistan (Hunza, Nagar and Gilgit). Hunza river basin is present between latitude $35^{\circ}55'$ to $37^{\circ}06'N$ and longitude $74^{\circ}03'$ to $75^{\circ}49'E$. According to (Garee et al., 2017), the drainage area of Hunza river Basin is $13,567 \text{ km}^2$, and the total

glacier-covered area is 30% to 38% (Hakeem *et al.*, 2014). There are 1384 glaciers, and about 1/3 glaciated area is covered by three major glaciers, namely, Hisper, Batura and Khurdopin (Immerzeel *et al.*, 2010). Elevation of HRB ranges between 1394m to 27885 meters above sea level (m.a.s.l). Glaciated area of Hunza river basin lies between 2280m to 7850m, and the non-glaciated area lies between 1460m and 7570m. 1/3 glaciated area is covered by three major glaciers, namely, Hisper, Batura and Khurdopin (Immerzeel *et al.*, 2010). Common surging glaciers are present in the Karakorum region, and debris-covered glaciers are 32% of the total basin area (Hewitt, 2007). Climatically, the area is alternatively influenced by mid-latitude winter Westerlies and Asian summer monsoon. The total annual precipitation is 840.8mm, 60 per cent of which is fallen in winters, indicating the main precipitation is brought into the Westerlies and Asian summer monsoon area. The study area is located in the subtropical climate zone and the valleys between elevation range of 2810 m and 3669 m a.s.l. has an average annual temperature of 2.8 to 6.5°C (Qureshi *et al.*, 2017).

Data And Methods

Datasets

Glacier Data

We analyzed the glacier changes within seven periods: 1990–1994, 1994–1999, 1999–2004, 2000–2004, and 2004–2009, 2009-2015 and 2015-2018. The main sources of data were Landsat Thematic mapper (TM), Enhanced thematic mapper (ETM), Enhanced thematic mapper Plus (ETM+), and Operational land imager (OLI), which are available from the U.S. Geological Survey (<http://earthexplorer.usgs.gov/>). Alaska Satellite Facility (ASF) Digital elevation model (DEM) having a spatial resolution of 12.5m is downloaded from <https://earthdata.nasa.gov/eosdis/daacs/asf>. All remote sensing tiles of ablation season (July to August) having minimum cloud cover (<10%) were acquired from 1990-2019 (Table 1). All remote sensing images were preprocessed (image enhancement, co-registration and image stacking, image mosaicking) and were projected into World Geodetic System 1984 (WGS84), Universal Transverse Mercator (UTM) zone 43 projection, using Environment for Visualizing Images (ENVI), Erdas Imagine and ArcMap.

Table 1 list of Landsat images used in the study

Sensor	Path/Row	Date acquired	Cloud cover	RMSE
Landsat 8 OLI	149/35	4/8/2018	2.57%	3.9m
	150/35	14/08/2018	2.57%	
Landsat 7 ETM+	149/35	3/7/2015	2.00%	4.1m
	150/35	23/07/2014	2.00%	
	149/35	26/07/2009	5.00%	
	150/35	25/07/2009	5.00%	
	150/35	28/06/2005	1.00%	
	149/35	5/8/2004	1.00%	
Landsat 5 TM	149/35	16/08/1999	8.00%	4.5m
	150/35	20/08/1998	10.00%	
	150/35	8/7/1994	4.00%	
	149/35	17/07/1994	5.00%	
	149/35	7/8/1990	1.00%	
TM	149/35	26/07/1989	Less than 10%	6.3m

Note: Root mean square error (RMSE) is obtained during the image registration process

Meteorological data

In the upper Indus basin, around 20 meteorological stations are operated by different data collection organizations such as the Pakistan meteorological department (PMD). As PMD operated their stations from 1960s, after that in 2005 EvK2-CNR operated three stations in high altitude. The third automatic meteorological stations known as Data Collection Platforms (DCPs) are operated by Water and Power Development Authority (WAPDA) these stations are providing Data since 1995. There are around three high altitudes meteorological stations in Hunza river basin with one valley-based station namely Karimabad installed Pakistan met department in 2006. These stations provide daily climate data (temperature maximum and minimum, precipitation, solar radiation etc.). For this study, we have collected daily data of Minimum temperature, maximum temperature and precipitation from three stations (Khunjerab, Ziarat and Naltar) which WAPDA operates between 1995 and 2018 (Table 2).

Table 2. Overview of meteorological data of Hunza river basin (HRB) from 1995-2018

Station	Longitude °E	Latitude °N	Elevation m.a.s.l	T _{max} °C	T _{min} °C	T _s °C	T _w °C	P mm/yr
Khunjerab	74.397	36.838	4730	-0.88	-10.97	6.43	-13.44	202.21
Ziarat	74.459	36.817	3669	6.56	-2.65	9.46	-4.06	228.59
Naltar	74.177	38.157	2810	10.01	1.403	13.78	-1.01	648.89

Note: T_{max}-mean maximum temperature, T_{min}-mean minimum temperature, T_s-mean summer temperature, T_w-mean winter temperature and P- total annual precipitation

Method

Variations in glacier coverage

The automated mapping of glaciers from satellite/remote sensing imagery is hindered by debris cover of the glacier (Racoviteanu et al., 2008). Though automated methods are intended to these debris-covered glaciers, the results are less reliable, requiring post manual corrections (Paul et al., 2004 and Bhabri et al., 2011). Therefore, manual digitization was performed to ensure the interpretation of glacier boundaries as accurate as possible and control the error of <2% (Bolch et al., 2008). We performed visual and manual interpretation of remote sensing data for the identification and delineation of glacier masses. For the delineation of glacier outlines, we used the Normalized Difference Snow Index (NDSI).

$$NDSI = \frac{Green - SWIR}{Green + SWIR} \dots \dots \dots 1$$

NDSI measures the relative magnitude of the reflectance difference between visible (green) and shortwave infrared (SWIR). Firstly, we created our glacier inventory then we compared this with Randolph glacier inventory (RGI) version 6.0. After extraction of glaciers, we calculated the slope and Aspect of each glacier using ASF DEM. Finally, area and length of each glacier are calculated using geometry toolbox of ArcMap. All of the work is conducted in a system research institute (ESRI) ArcGIS 10.8 software. Additionally, it is for preprocessing remote sensing data like co-registration, image enhancement, and image mosaicking ENVI software is used. We have also used Google Earth is also used for identification of delineation of glacier boundaries.

Aspect and slope of glaciers

Using the approaches used in Manley (2008) and Paul et al. (2009), each glacier aspect is calculated. Using statistical tool of ArcMap tool, the mean gradient is estimated for each glacier, and then used dominant aspect is used to name an aspect of each glacier. Firstly, for slope calculation, using median filtering removed potential outlier altitudes then extracted ASF DEM for each glacier, and the elevation range is calculated based on their outlines.

Climate Trend

Daily climate data taken from three stations of HRB (Khunjerab, Ziarat and Nalter) were processed. For this study 3 climate indices (T_{max}, T_{min}, precipitation) were selected to explore changes in the climate of HRB from 1995-2018 using the 'Rclimdex' package (Zhang and Yang 2004). The RclimDex program uses linear regression for trend calculations (Powell and Keim, 2015). Using the package as mentioned above of RStudio mean monthly and mean annual Temperature and Precipitation is calculated.

2.3 Errors and Accuracy Assessment

The error in glacier delineation comes mainly from the operator's experience who identifies and demarcates the glacier boundaries Xiang et al., (2014). For the current study, the uncertainty is estimated based RS uncertainty approach proposed by Ye *et al.* (2006) and Li *et al.* (2015).

the area uncertainty is calculated byes

$$U_A = \sum \tau^2 \times \frac{2(U_{st})}{\sqrt{\sum \tau^2}} \times \sqrt{\sum \sigma^2} \dots \dots \dots (2)$$

Where, U_A is Area uncertainty of glacier area, and U_{st} is linear uncertainty which is given in eq.3. Area uncertainty ranges between 0.004 and 0.01 km².

While the linear uncertainty is described as

$$U_l = \sqrt{\sum \tau^2} + \sqrt{\sum \sigma^2} \dots \dots \dots (3)$$

Where U_l is linear uncertainty of glacier terminus, is the original pixel resolution of the satellite image, and is a co-registration error. Linear uncertainty was 6.3m for TM (1990) is, 4.5m for ETM (1994), 4.1m for ETM+ and 3.9m for OLI.

Results

Variations in glacier area

Results from current research on glacier coverage indicate significant loss of Hunza river basin (HRB) glaciers. The 27 major glaciers of HRB experienced a significant loss of glacier coverage of $-37.63 \pm 2 \text{ km}^2$ (from 2589.75 ± 36 to 2552.12 ± 28) in recent 28 years (1990-2018). The variations in glacier coverage varied for each glacier and each period (Table 3 and 5). Overall, there is -1.45% loss of glacier coverage detected. The highest reduction in glacier area of $-15.63 \pm 1 \text{ km}^2$ was recorded from 1994 to 1999. Conversely, about $19.16 \pm 1.6 \text{ km}^2$ increment was detected from 2004-2015. The total annual area loss was $-1.34 \pm 0.2 \text{ km}^2 \text{ a}^{-1}$ from 1990-2018 and this appears to be accelerated $-3.126 \pm 0.3 \text{ km}^2 \text{ a}^{-1}$ during 1994-1999. However, from 2004-2015 the overall glacier coverage of HRB increased about 18.92 ± 34 at annual rate $1.893.126 \pm 0.3 \text{ km}^2 \text{ a}^{-1}$.

Table 3. Variations in glacier coverage of HRB from 1990-2018

Year	Area (Km^2)	Glacier area change			
		Period	Area change	Area change	Mean change rate $\text{Km}^2 \text{ a}^{-1}$
			(km^2)	(%)	
1990	2589.75 ± 86				
1994	2577.72 ± 74	1990-1994	-12.03 ± 1	-0.46	-3.01 ± 0.3
1999	2561.13 ± 71	1994-1999	-15.63 ± 1	-0.61	-3.126 ± 0.3
2004	2560.0 ± 71	1999-2004	-1.06 ± 0.4	-0.04	-0.212 ± 0.01
2009	2565.6 ± 72	2004-2009	5.53 ± 0.6	0.21	1.106 ± 0.1
2015	2578.94 ± 77	2009-2015	13.34 ± 1	0.51	2.22 ± 0.1
2018	2565.12 ± 68	2015-2018	-26.82 ± 2	-1.05	-3.45 ± 0.4
Total		1990-2018	-37.63 ± 2	-1.45	-1.34 ± 0.2

Note: $\text{km}^2 \text{ a}^{-1}$ is square kilometers per year

Variations in glacier length

The analysis of glacier length from 1990-2018 reveals interesting details (Table 4). Overall, for 27 studied glaciers, there is a decrease of 1.95% of the area. The glaciers show two phases. Firstly, most glaciers retreat until 2004 and then exhibit advancement up to 2015. However, an accelerated retreat in 1994-1995 is observed with peak retreat of about -3.92 km variation in the terminus position of glaciers for different periods is depicted in Figure 7. It is also observed that the major changes occurred in low altitude ($<5000 \text{ m}$) glaciers of HRB. The glacier behavior is shown in figure 6.

Table 4. Variations in glacier length of HRB from 1990-2018.

Year	Length change Km^2	Glacier length change			
		Period	Length change	Length change	Mean change rate kma^{-1}
			(km)	(%)	
1990	594.58 ± 31				
1994	593.66 ± 31	1990-1994	-0.92	-0.15	-0.037
1999	593.24 ± 27	1994-1999	-0.42	-0.07	-0.014
2004	589.32 ± 25	1999-2004	-3.92	-0.66	-0.13
2009	586.28 ± 25	2004-2009	-3.04	-0.51	-0.11
2015	587.31 ± 21	2009-2015	2.03	0.34	0.05
2018	583.42 ± 22	2015-2018	-4.11	-0.32	-0.10
Total		1990-2018	-11.6	-1.95	-0.06

Note: $\text{km}^2 \text{ a}^{-1}$ is square kilometers per year

Aspect and Slope of Glaciers

For most of the glaciers in HRB, the dominant glacier aspect is north facing (12 glaciers out of 27). In the study period (1990-2018) the glaciers with different aspects behave differently. The second most dominant aspect is northeast (6), followed by south (3), east (2), southeast (2) and southwest (2) respectively. North facing glaciers occupies about 36.53% of total area and 44.25% of the total length of studied 27 glaciers (Figure 2).

Each glacier slope is calculated separately and classified into four classes with a slope of $0-25^\circ$, $25^\circ-30^\circ$, $30^\circ-35^\circ$, and $>35^\circ$. For steep and very steep gradients the glacier length and coverage both reduced significantly (Fig 3). In 1990 17 glaciers were having a slope greater than 25° and cover an area of $2041.8 \pm 39\text{km}^2$ and length of $297.55 \pm 17\text{km}$ while in 2018 there is $2027.31 \pm 36\text{km}^2$ area and length of $289.17 \pm 17\text{km}$ respectively. Ten glaciers have a gradient of less than 25° , but they show less reduction in both coverage and length than steep glaciers as general rule steeper glaciers have high glacier area and terminus loss than gentle slope glaciers.

Table 5. Summary of major glaciers of HRB studied in current research and their characteristics, snow and ice coverage (1990-2018).

Glacier ID	Long (°E)	Lat (°N)	Elevation range (m.a.s.l)	Slope (°)	Aspect	Linkages	Surge history	Area(km ²)						
								1990	1994	1999	2004	2009	2015	2018
SA1	74.82	36.07	2800-7289	22.30	North	9	3	105.78	115.9	103.6	102.6	104.8	103.8	105.9
SA2	74.28	36.70	3268-6860	23.00	North	9	2	17.11	16.99	17.31	17.07	16.95	17.06	17.16
SA3	74.40	36.68	3657-6866	24.30	North	9	1	41.59	41.98	42.21	42.05	42.21	42.34	42.32
SA4	74.58	36.50	2612-7778	25.00	Northeast	0	0	318.36	318.4	318.3	318.3	317.6	318.9	314.7
SA5	74.46	36.46	3015-7735	31.20	Southwest	9	1	100.8	100.9	100.8	100.9	99.98	101	101.2
SA6	74.24	36.49	2820-6902	25.30	Southeast	9	1	155.54	140.6	140.8	140.9	139	141.1	140.2
SA7	74.51	36.44	2901-7732	32.20	South	0	0	92.64	92.71	92.79	92.71	92.64	92.58	92.51
SA8	74.21	36.41	3411-5669	29.30	Northeast	9	0	8.23	7.41	7.44	7.44	7.39	7.36	7.36
SA9	74.71	36.47	2568-7569	24.40	East	0	0	62.89	62.76	63.1	63.09	62.88	59.65	62.51
SA10	74.78	36.43	2505-7294	29.10	East	0	0	32.94	33.07	33.07	33.02	33.09	33.08	33.1
SA11	75.31	36.24	3203-7782	24.40	Northeast	0	0	145.44	145.1	145.3	144.8	145.1	153.8	143.9
SA12	74.82	36.41	2955-6645	31.70	Northeast	0	0	14.92	14.96	14.92	14.89	14.91	15.93	14.95
SA13	75.14	36.32	2929-7611	29.30	North	0	0	86.68	86.77	86.68	86.54	86.54	86.55	86.53
SA14	74.96	36.11	3301-6168	28.3	Northeast	9	3	10.23	10.51	10.43	10.34	11.27	9.51	9.71
SA15	75.00	36.36	3318-7186	25.90	North	0	0	19.19	19.17	19.16	19.23	19.3	19.35	19.34
SA16	75.21	36.34	2923-7841	26.90	North	0	0	124.95	121	120.9	120.9	121	122	118.9
SA17	74.99	36.25	3414-7606	28.70	Southwest	9	1	77.76	77.76	75.16	74.79	75.86	76.57	77.54
SA18	74.51	36.17	2433-7395	35.20	North	9	3	14.96	14.99	14.97	14.95	14.95	14.9	14.87
SA19	75.65	36.15	3595-6522	23.10	North	9	2	176.71	175	175.4	175.2	175.4	175.6	172.8
SA20	74.68	36.17	3285-5678	22.20	North	0	0	25.23	25.35	25.54	25.11	25.05	25.03	24.77
SA21	75.44	36.19	3301-7733	23.60	North	9	3	207.78	206.8	208.7	208.7	209.2	208	205.6
SA22	74.59	36.16	2583-7239	26.70	North	9	3	57.45	57.38	57.32	57.25	56.19	59.16	57.12
SA23	74.70	36.10	2234-7245	27.60	North	9	3	68.6	68.74	68.77	68.8	68.83	68.85	66.91
SA24	75.28	36.06	3100-7850	23.30	Southeast	9	3	523	516.4	517.5	520.8	525.7	523.9	519.7
SA25	74.49	36.10	3201-7339	34.00	South	0	0	16.42	16.41	16.48	16.54	16.59	16.62	16.79
SA26	75.00	36.04	3863-6608	25.70	Northeast	9	3	18.47	23.71	18.63	18.55	18.55	18.6	18.7
SA27	74.62	36.44	2454-7557	35.10	South	9	3	66.05	66	65.91	65.8	64.79	67.8	67.12

Note: the information about surge history and linkages are taken from the Randolph Glacier Inventory (RGI) 6.0.

Climate Trend

Mean monthly climate

In Hunza river basin there are three meteorological stations (Khunjerab, Ziarat and Naltar) operated by WAPDA, the mean monthly climate indices (Tmin, Tmax and precipitation) indicates that temperature and precipitation increase from extreme north Khunjerab towards Nalter which is on the southern side. The monthly mean maximum temperature (Tmax) trend of Khunjerab stations remains below freezing point 7 months a year while the minimum temperature (Tmin) remains below 0°C ranges from 0°C throughout the year. Precipitation of region ranges from 7mm/month to 36mm/month, peak precipitation is observed in August. Data from Ziarat station shows that Tmin ranges from -13°C in January and February to 7°C in July and August. Precipitation of region ranges between 16mm/month in May to 28mm/month in December. Maximum Temperature (Tmax) and minimum temperature (Tmin) at Nalter ranges between -2°C and -9°C in January to 21°C and ten °C in August. Precipitation at Nalter is observed above 30mm/month each month while peak precipitation is recorded in April (97mm) and 31mm month of November respectively. Figure 4 shows the monthly climate of three station of HRB.

Mean annual climate trend

This research indicates in recent 25 years there is an increasing trend of total precipitation and decreasing trend of the mean temperature of three meteorological stations of Hunza river basin. Highest Temperature is recorded in the year 1998, 2001 and 2011 (4.08 °C, 3.84 °C and 4.15 °C). The lowest mean temperature is 2.45 °C, 2.37 °C and 2.43 °C recorded in 1996, 2005 and 2009 respectively, and about a 0.4 °C decrease in temperature. Total precipitation is also asymmetric in Hunza river basin. Peak precipitation occurred in 2011, and 2012 (1770.31mm and 1701.3mm) and the lowest precipitation of 867.6mm is recorded in 2001 (Figure 5).

From 1995 mean temperature of HRB shows many episodes and climate extremes with abrupt variations. In 1995 the mean temperature of HRB was 3.28 °C, but in 1996, about 0.8 °C decreased in mean temperature. After 1996 it increased, and in the next two years, i.e., 1998 mean temperature was 4.08 °C. From 1998 to 2011 there were little variations in mean temperature, but after 2011 it shows declining trend up to 2018. Overall, there are 0.5 °C decreases in mean temperature of HRB. According to Chaudhary et al (2009), there is a 0.40 °C increase in Pakistan's temperature in the last 40 years. The mountainous regions face more increase in temperature of 1.5°C (Yasmeen & Javed, 2018).

Discussion

To evaluate the total glacier area, change in response to climate change and behavior of glaciers of HRB is observed in this study. A complete analysis of glacier area change in response to climate change is difficult. There required time lag for glacier variation in climate change response (Pan et al., 2012). This time lag depends on thickness, size and type of glacier (Mao et al. 2010 and Yao et al., 2004) and there is a direct relation of glacier response time to glacier thickness (Jóhannesson et al., 1989). Snow and ice masses in the high mountains of Hindu-Kush Karakorum and Himalaya (HKH) are the primary source of water for the mountainous population. The mountainous population of HKH depends on the upstream snow and ice reserves for seasonal water availability in rivers and streams. These snow and ice masses are likely to be affected by changing climatic conditions of the region, but to what extent is yet unclear (Immerzeel et al., 2010). Temperature is also one of the important factors of the glacier area change. Ablation of glaciers occurs due to an increase in temperature and decreased stability and accumulation of glaciers. Changes in temperature and precipitation are expected to seriously affect the cryosphere's melting characteristics (Milly et al., 2002). According to (Milly et al., 2002), there is a 0.40 °C increase in Pakistan's temperature in the last 40 years. The temperature of HKH has been reported to raise by 1.5°C, which is almost twice/double than the other parts of Pakistan, where the temperature has risen approximately 0.76°C (Rasul et al., 2012). Glaciers of HKH are losing mass since last thirty-three decades (Mastny, 2000). The mountainous regions face more increase in temperature of 1.5°C (Yasmeen & Javed,

2018) and mean annual precipitation of the Hunza river basin also shows an increasing trend. According to (K. Hewitt et al., 1989), Karakorum glaciers face three types of weather and two-third of snow accumulation occurs on major Karakorum glaciers in winter. Remaining one third accumulates in winter, which also suggests that monsoon advance over the area in many years (Mayewski & Jeschke, 1979). Negative net mass balance has been reported for the high mountain Asian glaciers between 2000 and 2016; however, some regional anomalies exist (Bocchiola & Diolaiuti, 2012). This anomalous behaviour of Karakorum glaciers might be because of geomorphological and climatic settings (Bocchiola & Diolaiuti, 2012).

There is a balanced mass budget in the Hunza-Nagar valley from 1973 to 1999 and an insignificant mass loss from 1999 to 2009 (Bolch et al., 2017). According to (Baig et al., 2017) Hunza river basin shows loss of glacier area since 1989-2002. Other researchers also suggest that in recent studies it is confirmed that Hisper glacier present in the Hunza river basin is thickened about 100m. It is also thickened in the earlier period (Bolch et al., 2017). Khurdopin and neighboring glaciers thickened and thinned at their tongue and show surge behavior during period 1999-2009 and October 2016 to August 2018. Glaciers worldwide are receding except Karakorum glaciers that show positive mass balance or stable (Hewitt, 2005). Western and Central Karakorum's glaciers show irregular behavior with possible mass gain in the last decade (Copland et al., 2011). Even though that the Karakorum glaciers are showing signs of retreat, most of the glaciers having length >45 km such as the Batura and Baltoro.

While some of the glaciers which have debris-free, such as Yazghil and Barpu glaciers did not lose their mass significantly (L Iturrizaga, 2011). There has been a considerable increase in the Karakorum region's glacier surging (Copland et al., 2011). It is recorded that the Karakorum glaciers are frequently

surging since the end of the 19th century (Clarke, 2015). Karakorum glaciers are getting more attention because of anomalous behavior (Kääb et al., 2015). Surges on Khurddopin glacier have been documented since the late 1800s, and the most recent surges occur in 1979 and 1999 (Copland et al., 2011). The velocity measurements of Karakorum glaciers have been shown that they are moving rapidly, with rates in the ablation zones ranging from 240m – 460m per year (Pillewizer, 1957). Generally, Karakorum surging streams are steeper than others which are most reported. Hassanabad and Minapin glacier in Hunza-Nagar valley having the greatest elevation range for mountain surging glaciers, 5.5 km and 5.4 km, respectively, to the lower limit of their last surges (Hewitt, 1998). Our results indicate that overall, there is 0.12% decrease in the total glacier area of 27 glaciers. From 1990-1998 there is 0.30°C decrease in temperature and 0.5° C increase from 1998-2018. Precipitation also shows an increasing trend since 1990.

Conclusions

This research demonstrated that it is very good to use multi-temporal satellite images to study glacier area change where observational data records are insufficient. This study analyzed 27 glaciers of the Hunza river basin from 1990-2018 in five intermediate periods (1994, 1999, 2004, 2009, 2015) using available Landsat imagery. Generally, both glacier coverage and glacier length are decreased from 1990 to 2018, and an overall loss in glacier coverage of $-37.63 \pm 2 \text{ km}^2$ is observed. For different glacier periods, the change in the glacier area and length vary differently. Between 1994-1999 and 2015-2018, the glacier coverage and length loss are accelerated with mean annual loss in glacier coverage of $-3.126 \pm 0.3 \text{ km}^2$ and $-3.45 \pm 0.4 \text{ km}^2$. Conversely, the glacier length and glacier coverage are extensively increased from 2009 to 2015 with the annual change rate of $2.22 \pm 0.1 \text{ km}^2$. Climate data region from 1995-2018 revealed an increasing trend of precipitation and decreasing trend of temperature but the highest glacier loss rate during the period of 1994-1999 is due to increase in summer temperature in that period. While the extensive advancement of glaciers during 2009-2015 is induced possibly by winter and autumn precipitation. Steep and low elevation glaciers are sensitive climate change, and more glacier fluctuations occur in these glaciers during 1990-2018.

Declarations

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Author declaration: Please refer to the article submitted to the [Environmental Science and Pollution Research](#) (ESPR) entitled “*Status of Major Glaciers of Hunza River Basin, Under Changing Climatic Conditions of Pakistan over the period of (1990-2018)*” for publication. As the corresponding author, I undertake on behalf of myself and my co-authors that:

Ethical Approval: Not applicable

Consent to Participate: Not applicable

Consent to Publish: Not applicable

Authors' contributions: All authors equally contributed from introduction to conclusion under supervision of our principal investigator (PI) and this task completed with the collaboration of all the authors. **Garee Khan**, developed main concept of research, and supervised the study. **Sajid Ali and Wajid Hassan**, involved in write manuscript and conducted study. **Javed Akhter Qureshi**, assisted in establishing graphs, maps and manuscript writing. collected field data and help in modification and editing of writing. **Iram Bano**, did provision of relevant literature, and did review before submission and proof read of the manuscript.

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Availability of data and materials: The datasets used or analyzed during current study are available from the Crossponding authors on reasonable request, and all data generated or analyzed during this study are included in this published article.

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Figures

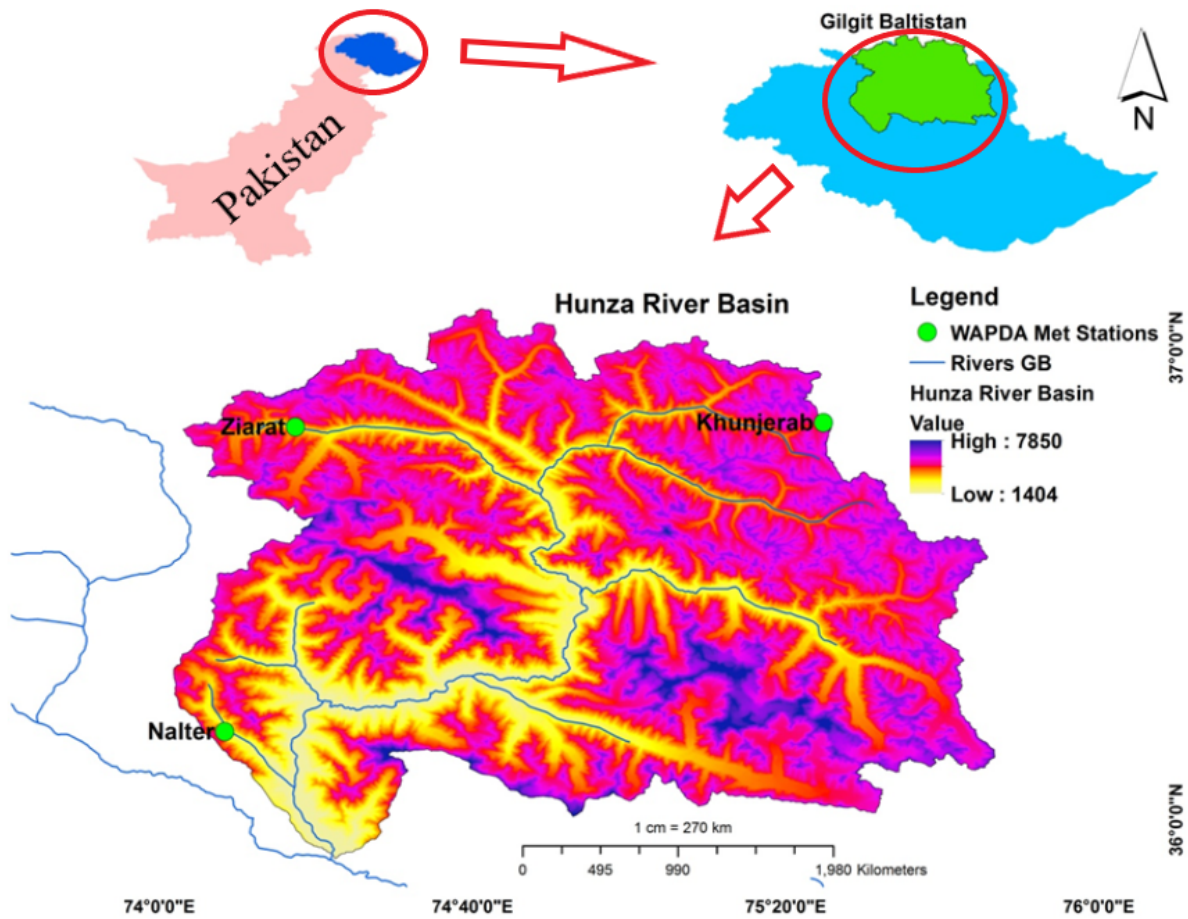


Figure 1

Map of Study area with meteorological station locations (HRB) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

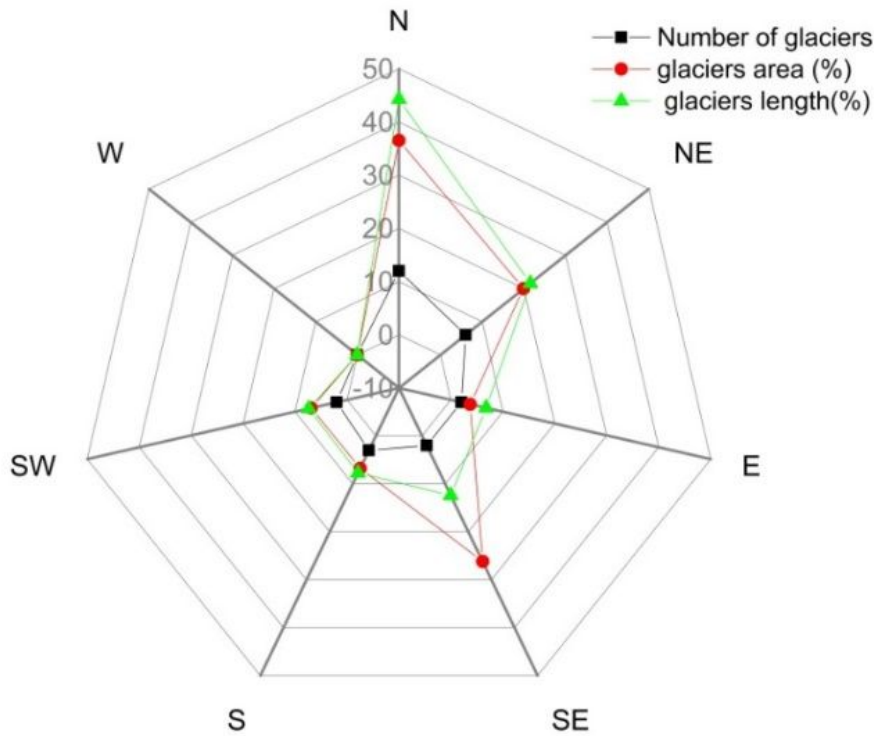


Figure 2

Distribution of a number of glaciers, glacier area (%) and length (%) concerning aspect.

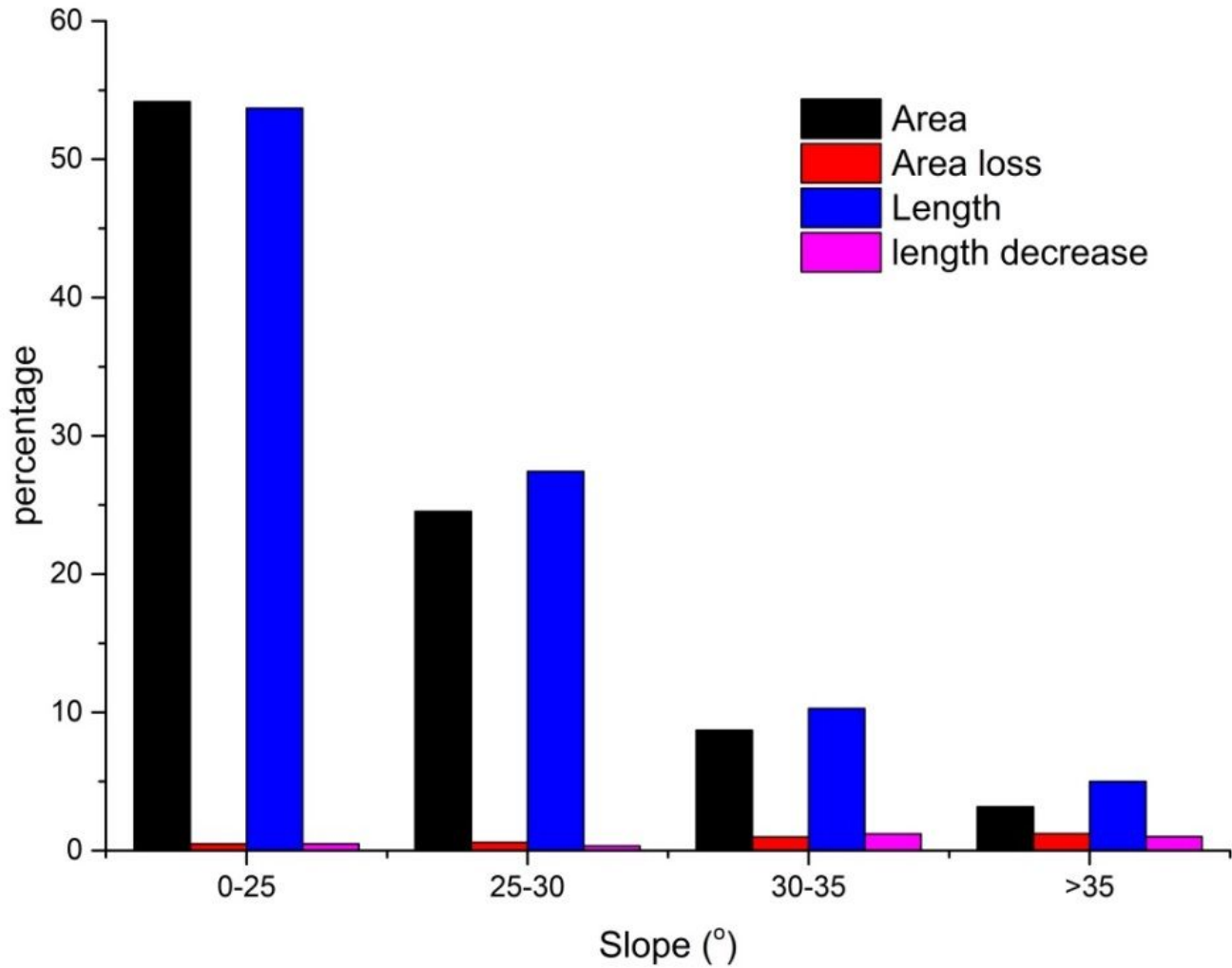


Figure 3

Distribution of area (%), length (%), variations in area and length concerning the slope.

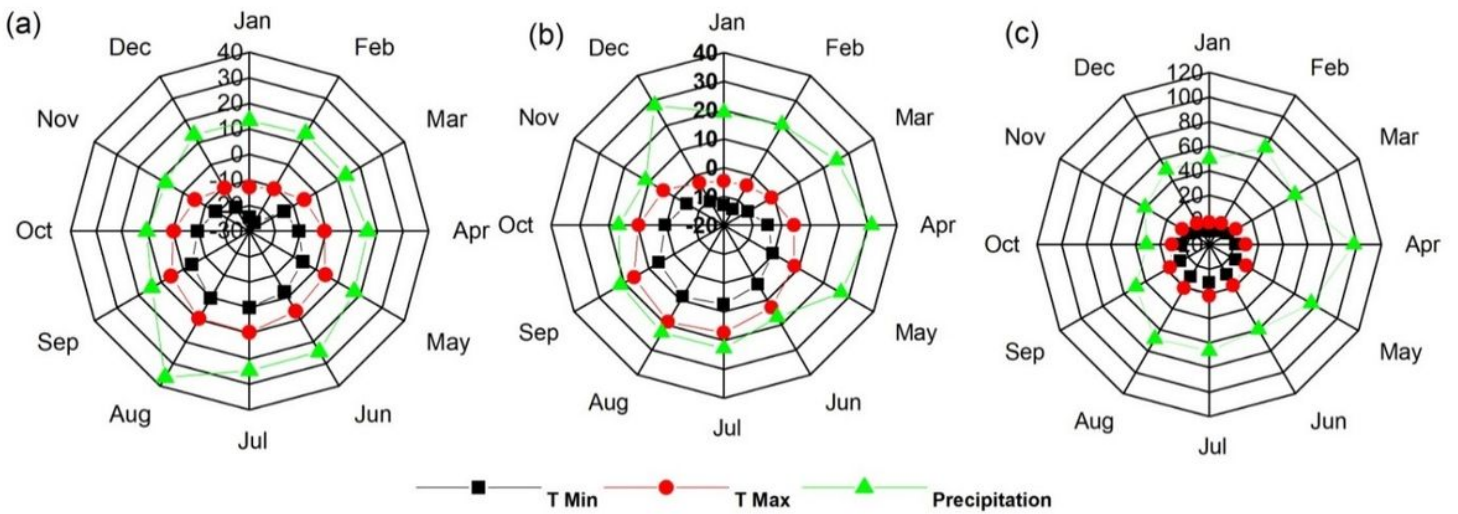


Figure 4

Mean Monthly Climate Trend of 3 meteorological Stations (a) Khunjerab station (b) Ziarat station and (c) Naltar station

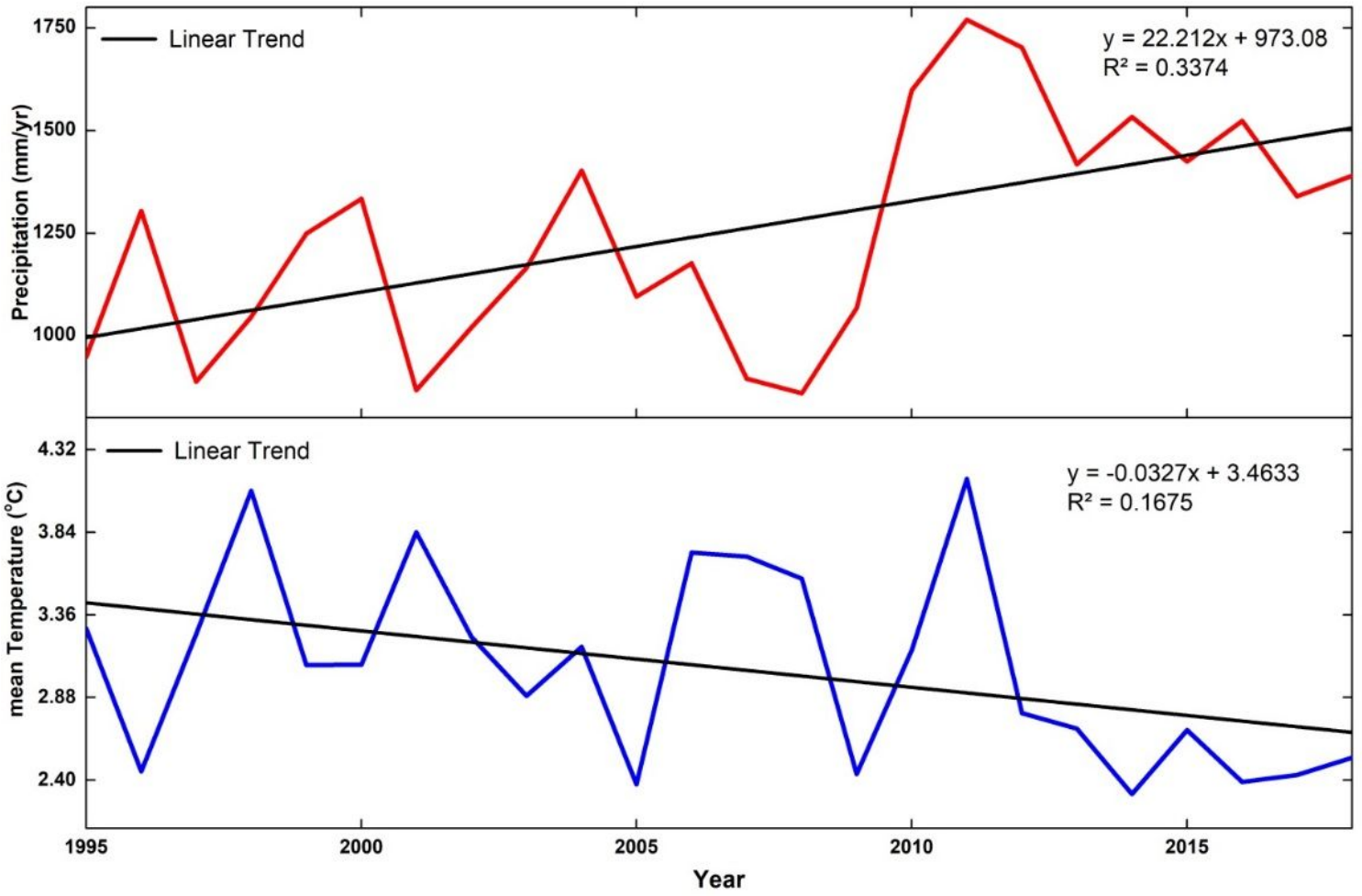


Figure 5

Graph of Annual Climate Trend of Hunza River Basin (1995-2018)

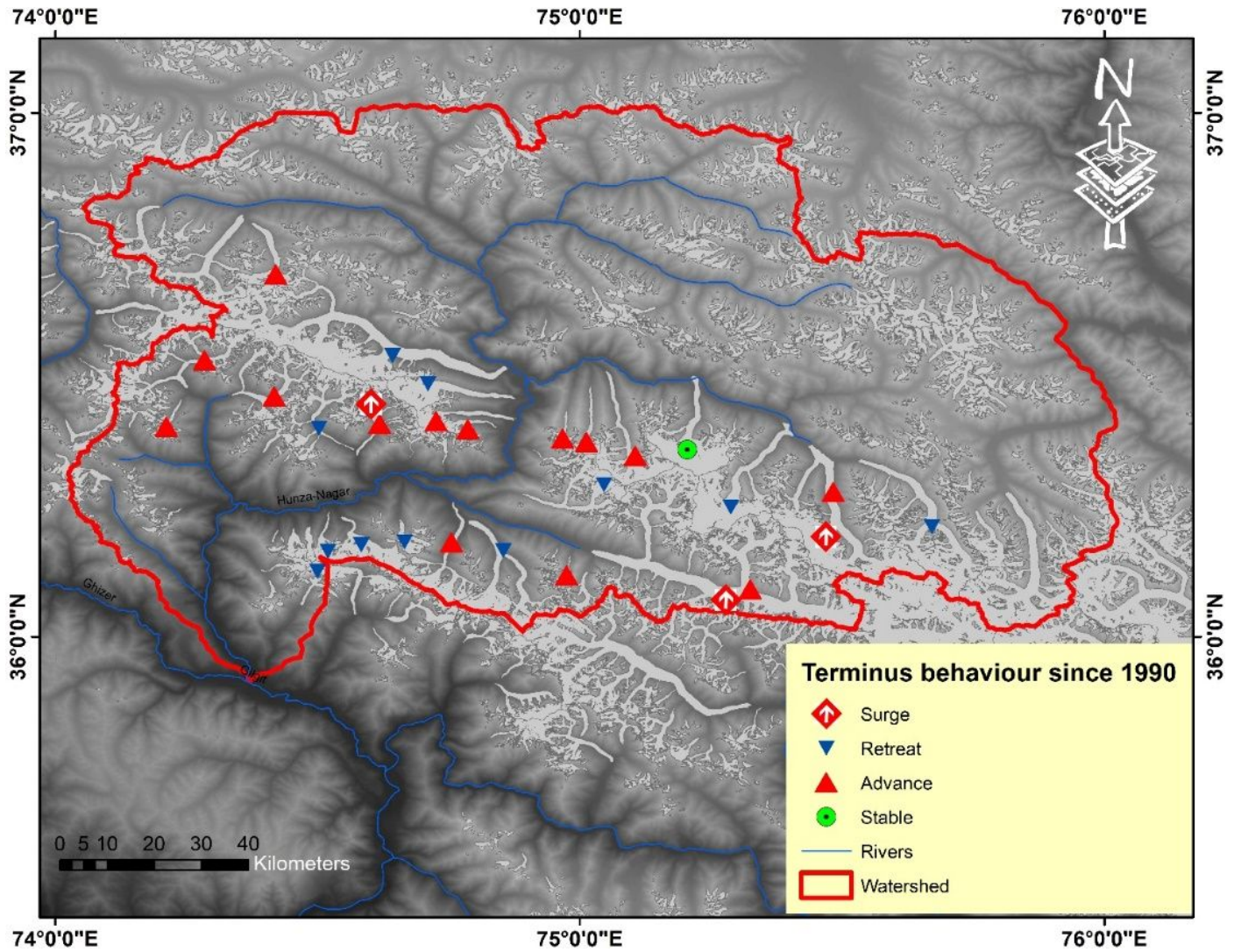


Figure 6

Spatio-temporal variations and behaviour of HRB glaciers Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

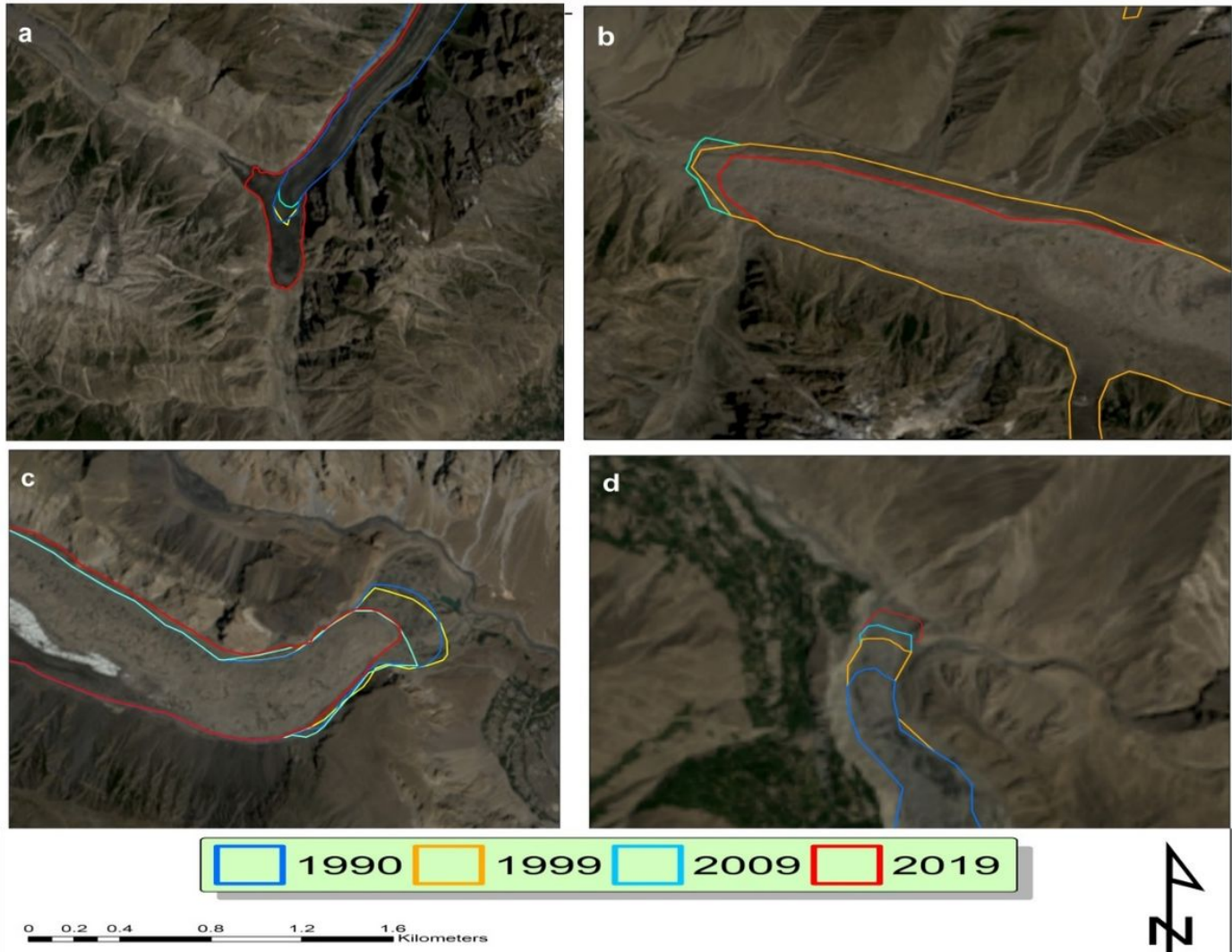


Figure 7

terminus position of four major glaciers of HRB. (a)=Shishper, (b)= Hisper, (c)= Batura and (d)= Bualtar glaciers have been in equilibrium in the last century. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.