Climate Change and its Impact on Glaciers in Hindu Kush Region: A Case Study of Yarkhun Valley, Chitral Pakistan

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ABSTRACT: The impact of Climate change on water resources, especially glaciers, is an important issue today. Glaciers located in mountainous ranges namely the Alps, Himalaya, Karakoram and Hindu Kush have thousands of glaciers and glacial lakes. The Hindu Kush (HKH) glaciers, particularly the Chitral valley glaciers, are a visible indicator of climate change through the decrease of glacier cover area, recently formed glacial lakes and the increase of glacial lake outburst flood events. This paper presents a spatiotemporal analysis of precipitation and temperature trends and a GIS&RS base investigation of the related glacier dynamic in Yarkhun valley Chitral district. Temporal glacier coverage was delineated using objected base classification coupled with manual digitization of accurate glacier outline in the debris cover area with high resolution imagery. Finally, the results were validated with field data acquired from field assessment and ICIMOD inventory data. Trend and correlation analysis for the period of 1990 to 2010 at 2 climate stations and 10 weather monitoring posts (WMPs) shows that there is 1.2 degree increase in annual temperature and an increase of 20 mm for precipitation. Temporal dynamic analysis Yarkhun valley glaciers shows that there is a decrease of snow and glacier cover area - from 679.61 to 632.54 sq.km and an increase of debris cover area – from 60.52 to 84.51 sq.km between 2000 and 2015. Overall the glaciers of Yarkhun valley glacier faces are retreating and the need for vigilance in assessing glacier behaviors regarding climate change is apparent.

1. Introduction

The impact of Climate change on glaciers of the Hindu Kush region, especially the Yarkhun valley in the Chitral river basin, is very much apparent through the decline trend of glacier mass, newly formed glacier lakes and glacial lake outburst floods (Bolch et al. 2012; Dar et al. 2014 and PDMA, 2015 Hussain, A and Bano, D. 2019). The decline is mostly controlled by temperature and precipitation trends (Akhtar al. 2008; Bhutiyani 2015; Shrestha and Aryal, 2011; Wang et al. 2015). Precipitation and temperature govern the mass balance of snow and glacial cover in mountainous regions. The snow and glacier melt water play a pivotal role in the water supply for irrigation and power generation in areas downstream. Various studies have already anticipated aggravated glacial melt under future climate change scenarios (Li et al. 2015; Lutz et al. 2014). Water availability, in terms of quantity and time, is directly linked to the glaciers dynamics (Hussain. A 2018, Rabatel et al., 2013 and Immerzeel et al. 2012). Glacier changes in length, mass balance and formation of new glacial lakes can cause hazards like glacial lake outburst flood (GLOF), avalanches and landslides, which directly impact the communities in the low lying areas (Barjracharya et al.2007, Carey 2010). An extensive understanding of glacier temporal changes will help to implement better hydrological planning in downstream areas, inform water resource management decisions and impact sustainable development in the glacier hazard prone areas (Rankl, Kienholz, & Braun, 2014). The glacier response varies because of local terrain i.e. slope and slope aspect and climate zones from colder to drier and wetter (monsoon dominated) to warmer west to east and from colder??? north to south. Glacier growth at accumulation zones, the melting of glaciers at ablation and uphill of elevation line of equilibrium (ELA) have been commonly used in climate change studies to assess the glacier variation with climate parameters. Climate change has impacted the decline and advancement of glaciers in mountainous regions (Fujita & Nuimura, 2011; Kargel, Cogley, Leonard, Haritashya, & Byers, 2011; Kaser, Cogley, Dyurgerov, Meier, & Ohmura, 2006; Scherler, Bookhagen, & Strecker, 2011; Zemp, Hoelzle, & Haeberli, 2009). Some studies demonstrated that the Karakorum glacier of Pakistan shows different behavior (Hewitt, 2005, 2011; Scherler et al., 2011), through there is an increase in precipitation in winter and limited warming in summer season (Archer & Fowler, 2004; Tahir, Chevallier, Arnaud, & Ahmad, 2011).

Climate change also increases the number of newly formed glacier lakes, which could lead to an increase in glacier lake outburst flood and a shifting of precipitation (snowfall) trends from November toward February and March. This results in more snow avalanches and causes death in the HKH regions, especially the Chitral river basin. Some major events have been described in Bajracharya & Mool, 2010; Bajracharya, Mool, & Shrestha, 2007; Richardson & Reynolds, 2000, FOCUS, 2015, and NDMA, 2016. Heavy thunder and rain in the rainfall season (June-August) causes more flash flood events which destroys houses, washes out agriculture land, as well as increases the melting of glaciers due to the slight increase of rainfall temperature as compared to snow and ice of glaciers. Devastating flash floods in the Chitral district have been documented by Handicap International (HI), Help Age International (HAI), Islamic Relief Pakistan (IRP) & Malteser International (MI), 2015 and Dawn news, 2015.

Despite the significance of the HKH region, there is limited reliable data available about the glaciers and their dynamics with respect to climate change. Many glacier inventories exist such as World Glacier Monitoring Service (Haeberli, Bo¨sch, Sherler, Østrem, & Walle`n, 1989), Global Land and Ice Measurements from Space (GLIMS) (Raup et al., 2007), the Glob Glacier project (Paul et al., 2010), the Randolph Glacier Inventory (Pfeffer et al., 2014), ICIMOD (Bajracharya, SR; Shrestha, B (eds) 2011) and CKNP (2008). However, none of these glacier initiatives have highly accurate and reliable data especially concerning debris cover glacier and glacier lakes potential risk. Therefore, there is a need for a detailed standardized geodatabase which covers all aspects of the glaciers and their geographical and socio-economic impact on the polulation residing below the glaciers. This present study of climate change impact on Yarkhun glacier includes the delineation of debris cover glaciers on high resolution satellite imagery in coordination with topographic data like watershed boundaries generated from Shuttle Radar Topography Mission digital elevation model (SRTM 30 meter) and validated with field observation data as well (Bajracharya & Shrestha, 2011; Bolch et al., 2012)). A chronology of targeted glacier dynamics and its impact on the downstream community was also acquired through filed surveys and field group discussion (FGDs) with the community, while glacier temporal changes were mapped using Landsat images (data compiled since 2000).

2. Methods and materials

2.1 Study Area

The Yarkhun valley is located in the mountains of Hindu Kush in Chitral district, Pakistan. It extends approximately 88 km from 36.74º to 36.79º N latitude and 72.88º to 73.79º E longitude, encompassing an area of about 1868 square kilometers (AKAH, 2016) and it borders Wakhan Corridor Afghanistan in the north, Ghizar District to the east and Shimshal valley to the northeast (NDMA, 2015).It currently includes 63 sub watersheds, 190 glaciers, 15 glacial lakes and 24 natural lakes.

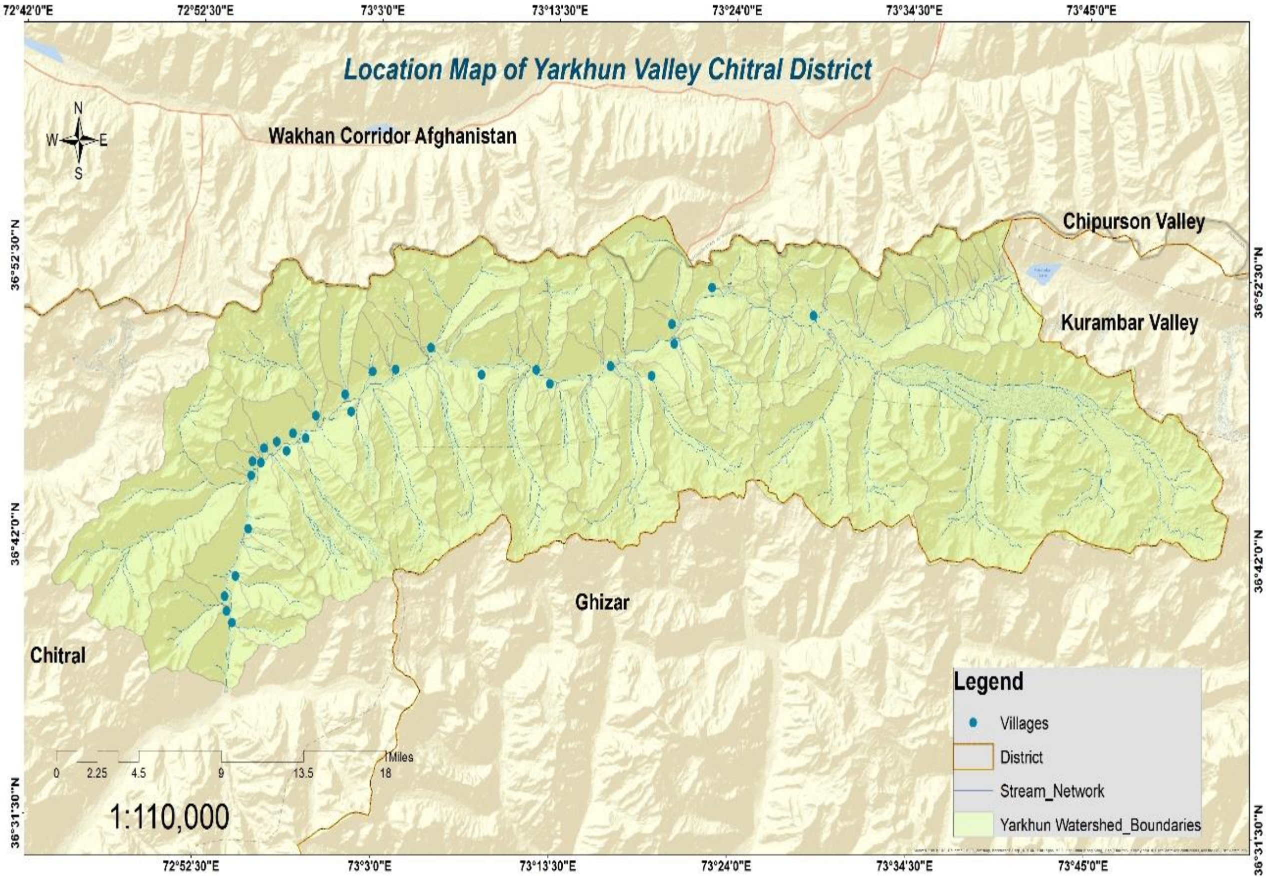


Figure: 1. Location map of Yarkhun Valley, Chitral District, Pakistan

2.2 Data

Satellite imagery of Landsat 4,5TM and Landsat-8 were acquired (from USGS website) for the years 2000 and 2015 in order to map the glaciated area of Yarkhun valley. A 30 Meter SRTM digital elevation model (DEM) was used to derive watershed boundaries and derive the attribute data of each glacier. The 2000 and 2015 Landsat images were used to analyze the changes in glaciers of Yarkhun valley. Climate data such as precipitation and temperature was acquired from the Pakistan Metrological Department (PMD) and weather monitoring post (WMP) data of Yarkhun valley for 2015 were used to analyze the changes in climate parameters. Field visits were carried out to acquire the chronological data and track the snout line of target glaciers. As well, FGDs were held to identify climate change impacts on the community's social life as well as glacier and snow cover temporal changes.

2.3 Methodology

Glacier mapping was carried out through object base image classification in Erdas image environment and manual delineation of glacier outline on high resolution images in google earth environment coupled with a digital elevation model (DEM). This is a well-established procedure that has been adopted by many scientists (Frey and Paul, 2012; Bhambri and Bolch, 2009; Bolch et al., 2010; Paul and Kaab, 2005; Paul and Andreassen, 2009; Racoviteanu et al., 2009). The climate change analysis was carried out on climate data acquired from PMD through statistical interpolation techniques in Arc GIS platform. Finally, the targeted glacier outline data was verified through field observations and validated with ICIMOD glacier inventory data of 2014. Furthermore, a Geodatabase was developed which includes all the parameters related to glacier and climate change. This is fruitful for future climate change impact analysis research studies on glacier modelling in the Chitral river basin.

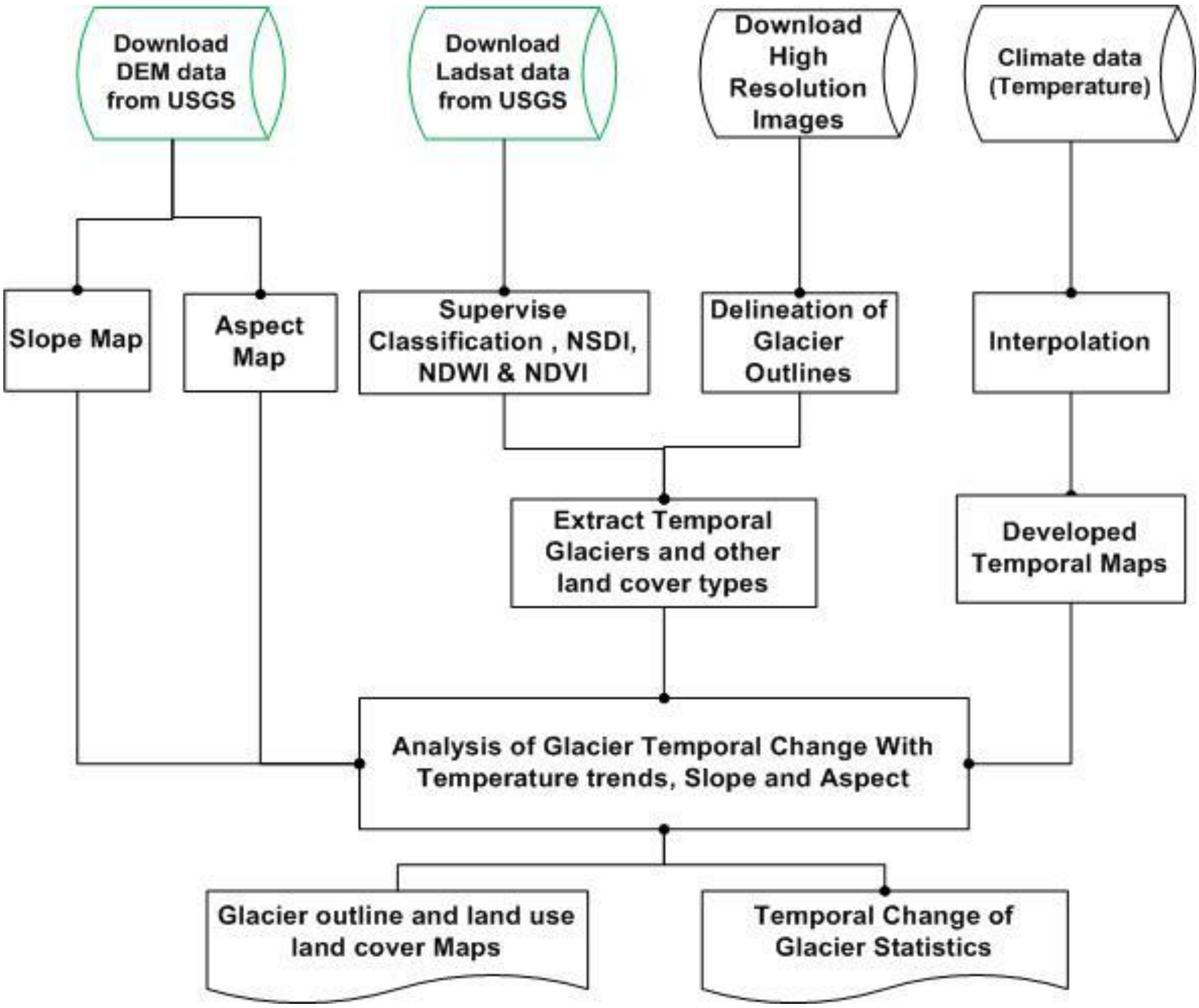


Figure: 2 Work flow diagram

3. Results and Discussion

3.1 Temporal Change of Glacier in Yarkhun Valley

A glacier area includes snow cover, debris cover and glacier and natural Lakes. Glacial and natural lakes are identified separately through a water index method such as the normalized difference water index (NDWI) (Ageta Y, et al. 2000, Campbell JG, 2005 and Bolch T et al. 2011). The glacier cover map and statistics from 2000 for the area, showed 190 glaciers, 9 glacial and 50 natural lakes with a total area of 532.4 sq. km2. There were estimated ice reserves of 815.25 Km3 and only 36 % of the Yarkhun Valley is glaciated (see Figure 3 and Table 1). However, in 2015 the 190 Yarkhun Valley glaciers were mapped with a total area of 528.3 sq. km2, the estimated ice reserves were 806.74 Km3 and only 33.67 % of Yarkhun valley was glaciated (Figure 2 and Table 1).The total ice reserves were roughly equal to three times the annual precipitation (Bookhagen & Burbank, 2006; Immerzeel et al.2010). The temporal change from 2000 to 2015 of the glaciated area and lakes using satellite imagery and GIS techniques depicted an impact of climate change on the glacial area. In 2000, the snow cover area was 27.25%, and it decreased by 1.83% within fifteen years. The debris cover area was 3.49% of the watershed increased up to 5.08%. Glacial lake area also increased by 0.001% between 2000 to 2015. Other land cover types including vegetation also increased by 0.1 %, barren land by 0.03%, river cover area by 0.1% and the urban area (settlement) by 0.2% (Table 1 and Figure 3).

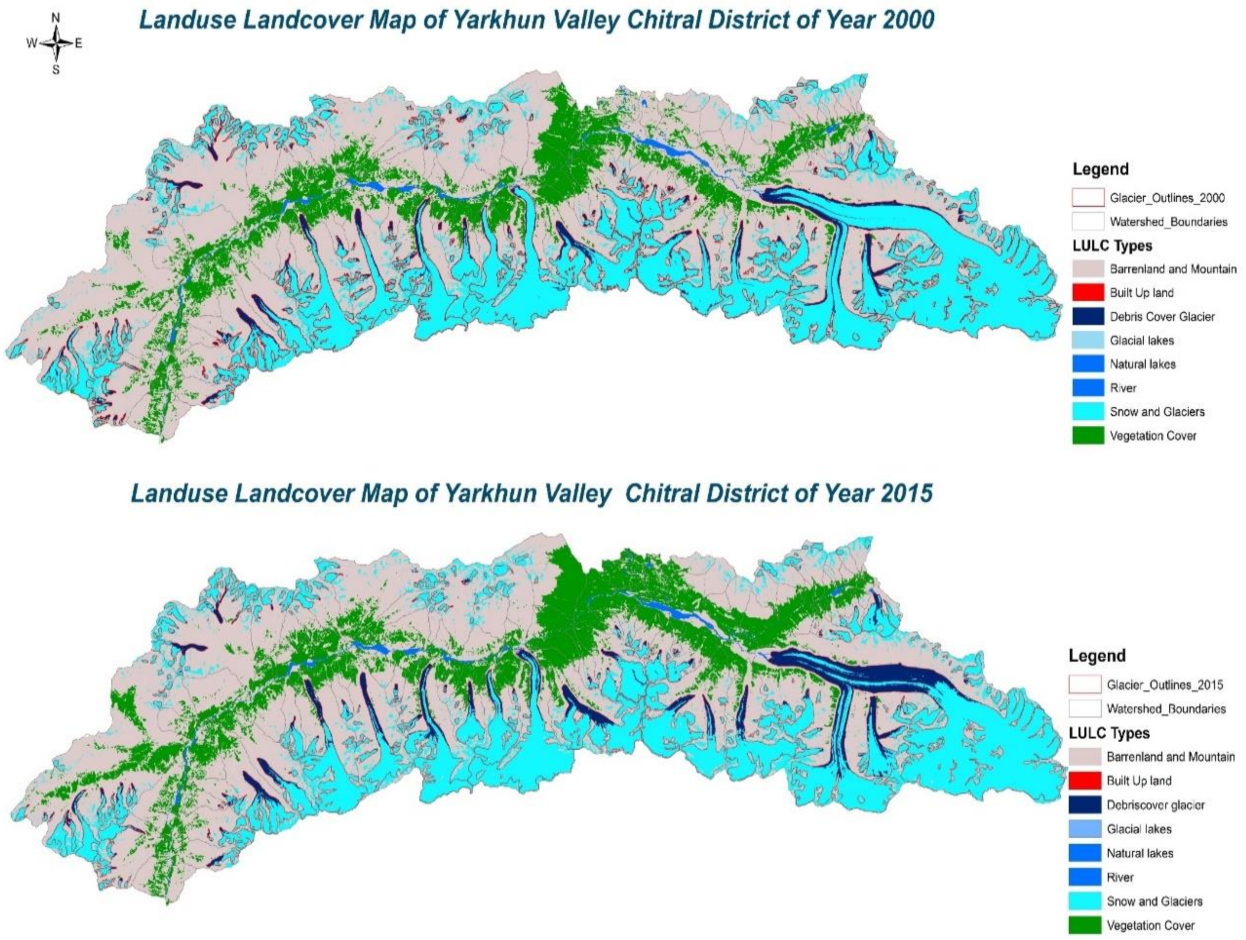
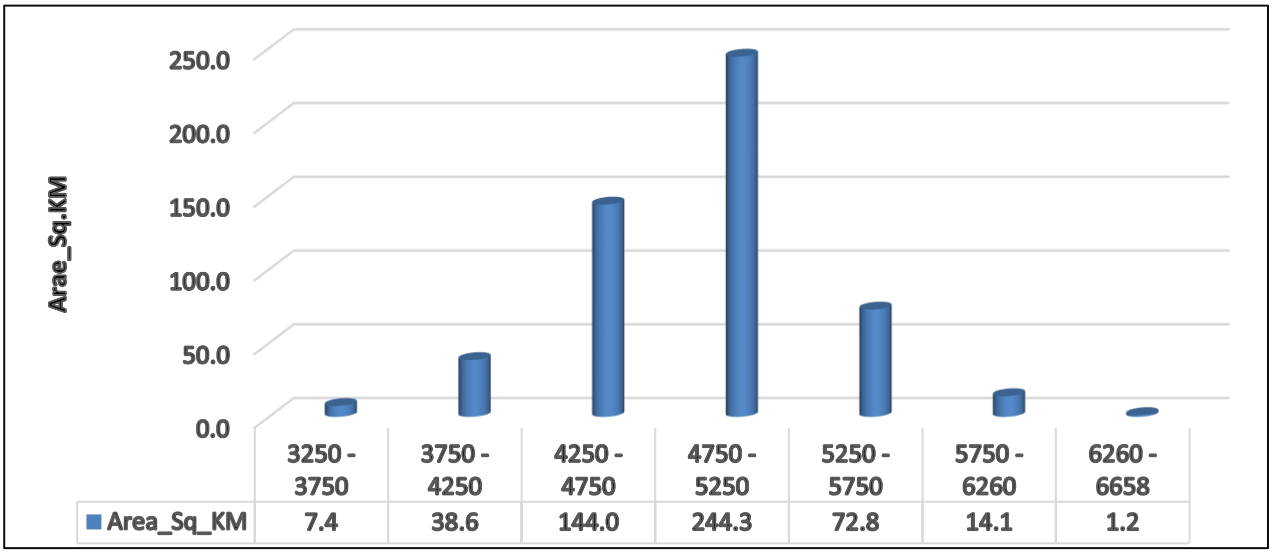


Figure 3 Temporal variation of land use land cover map of Yarkhun valley

Table: 1 Land use Land Cover Statistic of Yarkhun valley

LULC Types	Area_Sq.km_2000	Area_Sq.km_2015	Difference 2001-2015
Barren land and Mountain	928.5	929.1	0.6
Built Up land	0.3	0.5	0.2
Debris cover glacier	60.5	88.1	27.6
Glacial lakes	0.0	0.0	0.001
Natural lakes	1.0	1.1	0.1
River	8.3	10.5	2.2
Snow and Glaciers	471.9	440.2	-31.7
Vegetation Cover	261.5	262.5	1.0
Grand Total	1732.0	1732.0	0.0

The glacier area of Yarkhun valley is located in the elevation ranges of 3248 – 5812 meters from mean sea level (Graph 1). The glaciers below the 5000 mean sea level are particularly sensitive to climate change unless they are covered by thick debris cover (Bajracharya et al., 2014). The debris cover area increased by 3.2% from 2000 to 2015 with respect to the elevation. As well, there was an increase of existing glacier lake sizes and the formation of newly glacial lakes in the high altitude regions.



Graph: 1 Glacier area distribution in 500m elevation bands

The major part of the glacier slope cover is between 0-25 degrees (around 79 %) which is more feasible for the development of lakes as well as more growth of snow in the accumulation zone (Graph 2 and Figure 3). Slope aspect is one of main topographic factors which determines the amount of solar insolation and causes warming of the glacier. Slope aspect maps have 8 directions and each direction has its own capacity of solar insolation. In north region of earth from equator especially our study area southeast and south aspect receive more solar radiation compared to other slopes. The formation of glacier lakes and retreat of the glacier occurred on the south east and south slopes (Gruber et al. 2004, Pepin et al 2017 and Gruber et al 2003). The southeast and south aspect of the Yarkhun glacier covers about 16.57% of the area (Graph 3 and Figure 4).

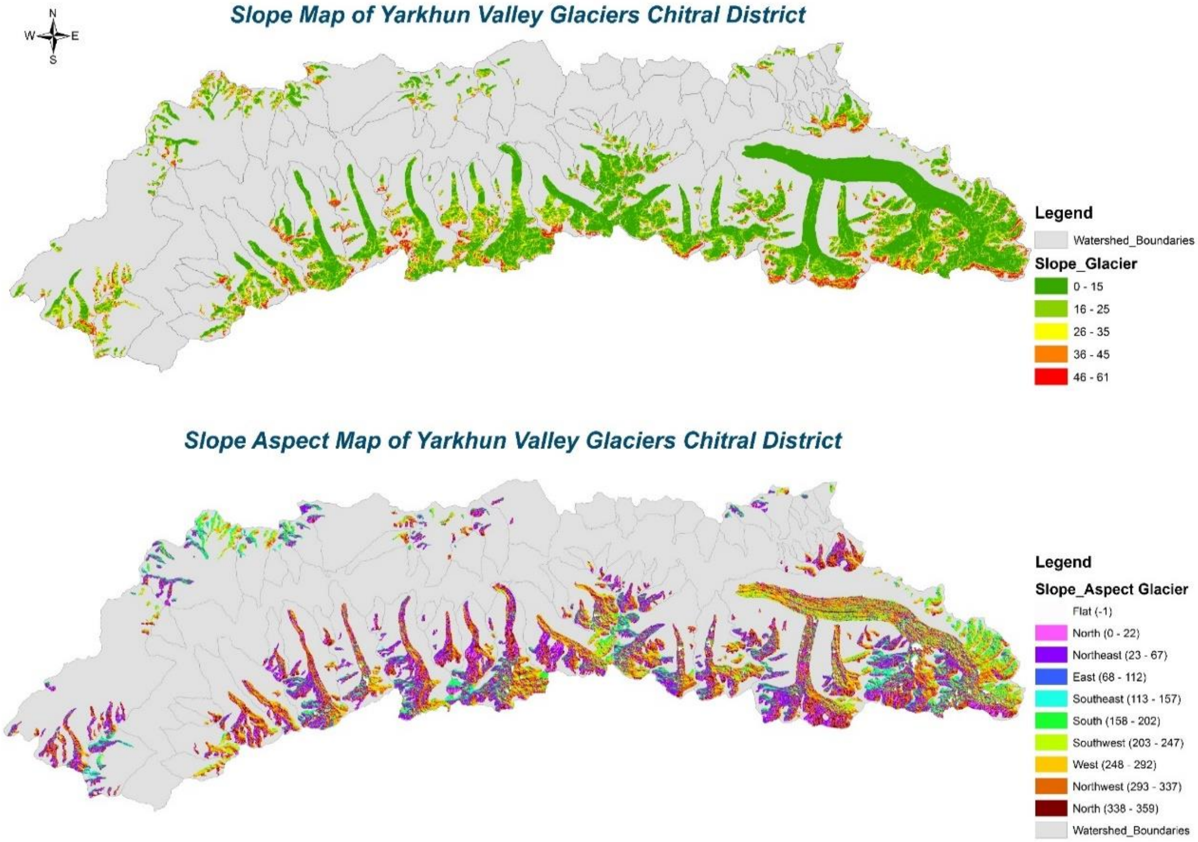
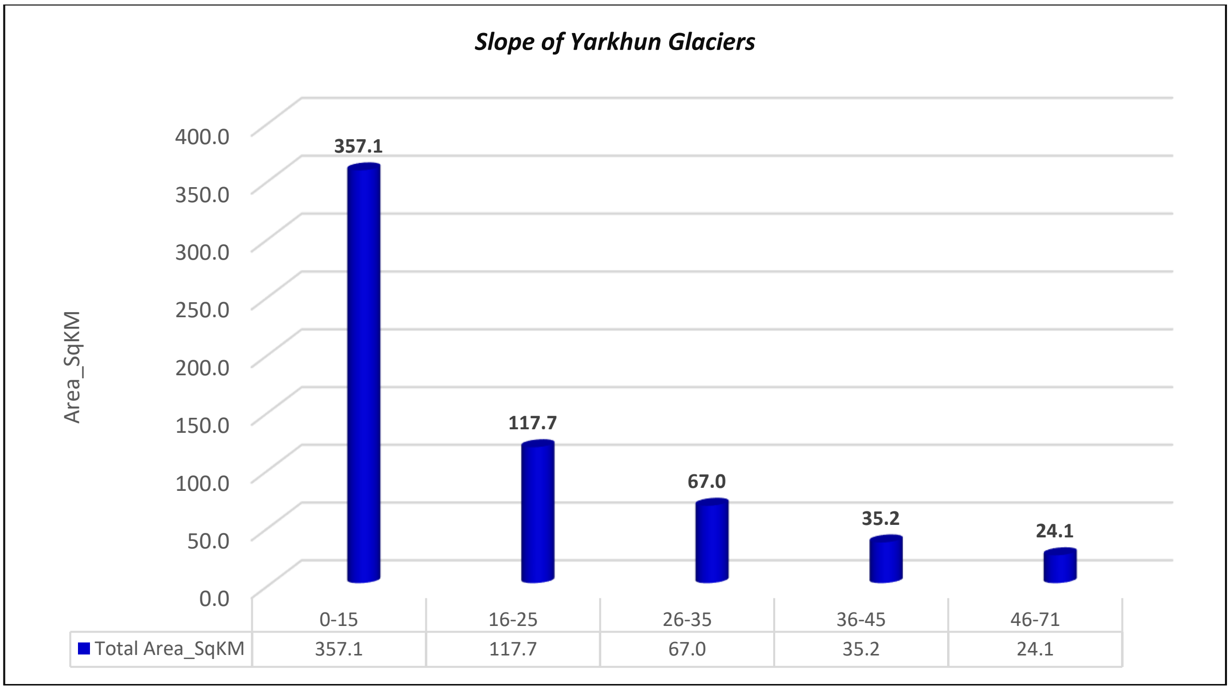
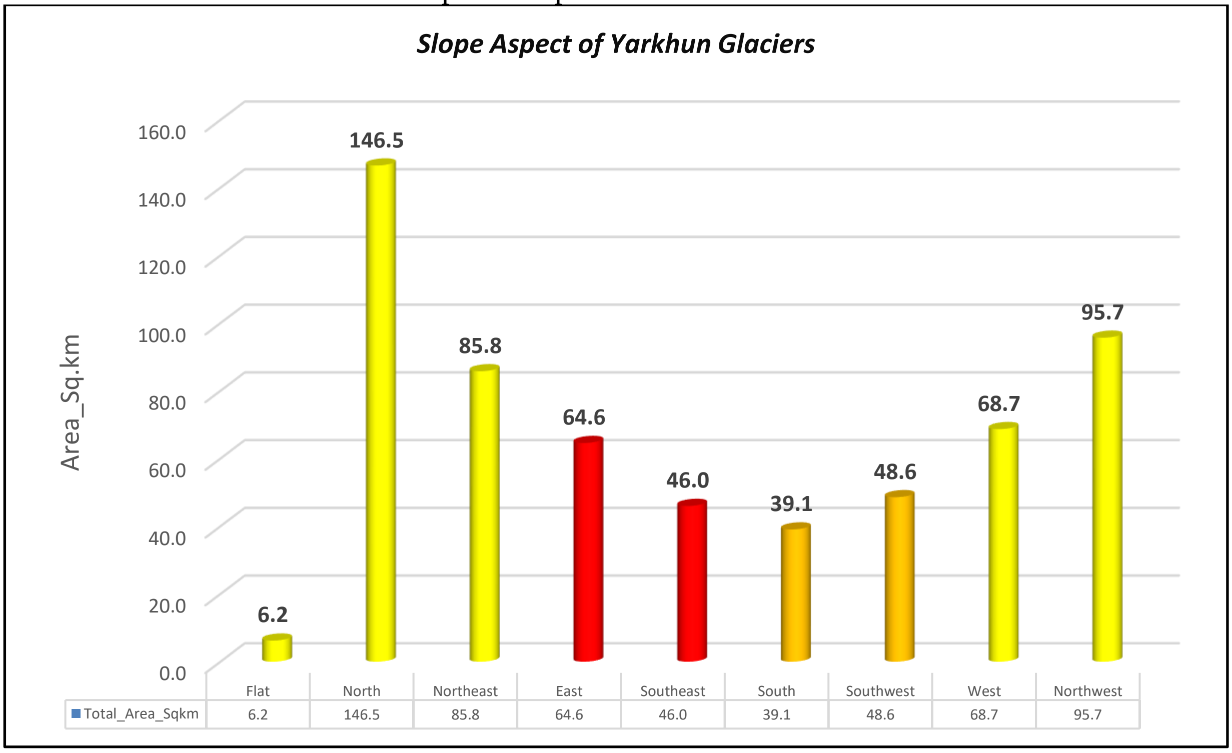


Figure: 4 Slope and Aspect Map of Yarkhun glacier valley



Graph: 2 Slope of Yarkhun Glaciers



Graph: 3 Slope Aspect of Yarkhun Glaciers

Most glacier are clearly visible as a Snow Covered glacier (SC) surface, but part of the debris cover glacier is not visible at the snout of the glacier. We used high resolution imagery to delineate the glacier outline and extract the overall glacier reserve in the Yarkhun valley. The total area of glacier outline cover in 2000 was 532.2 Sq. Km while by 2015 it decreased to 528.4 Sq. Km according to the AKAH glacier inventory, while the glacier area was estimated to be 518.0 Sq. Km area covered in 2011 by ICIMOD. This large variation is due to an inaccurate delineation of debris cover of the glaciers which is show in the map below (Figure 5 and Graph 4).

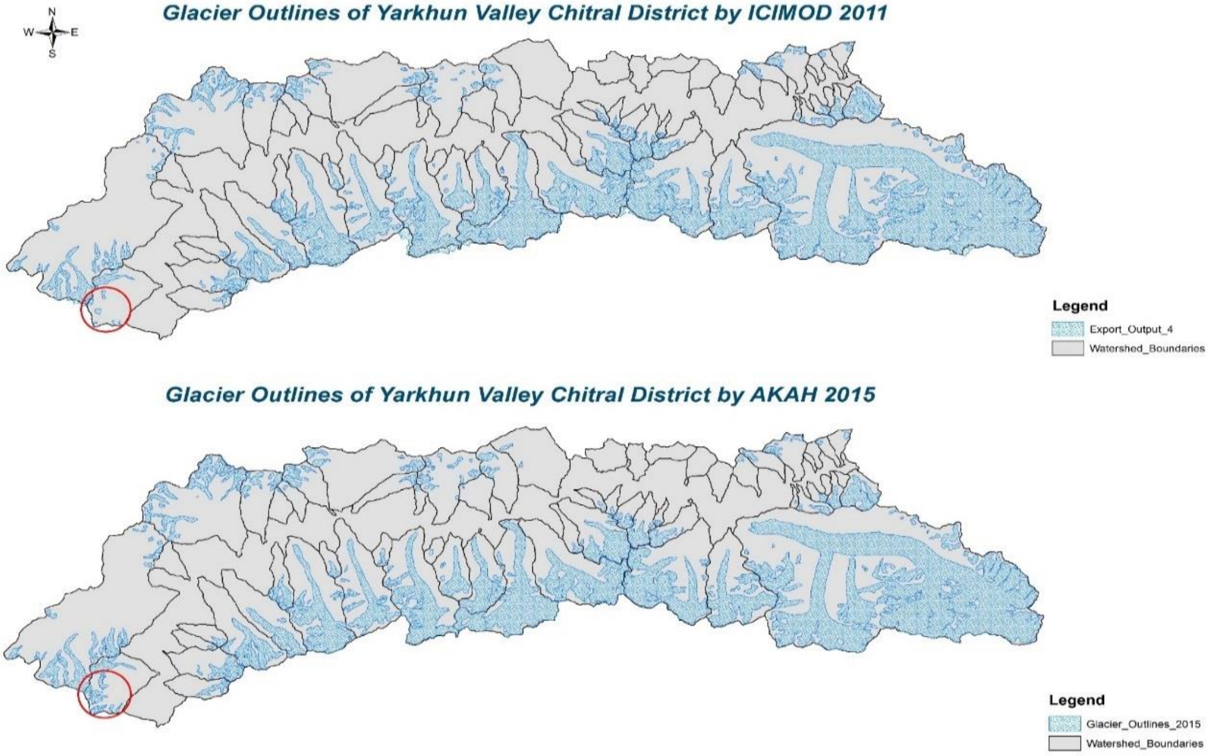
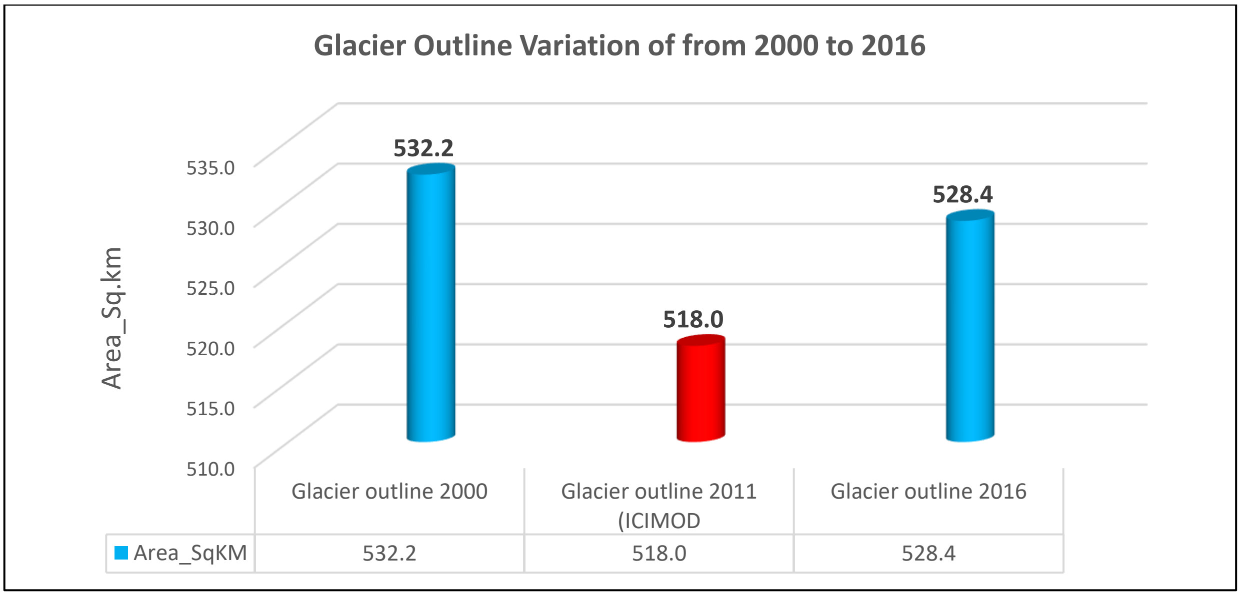
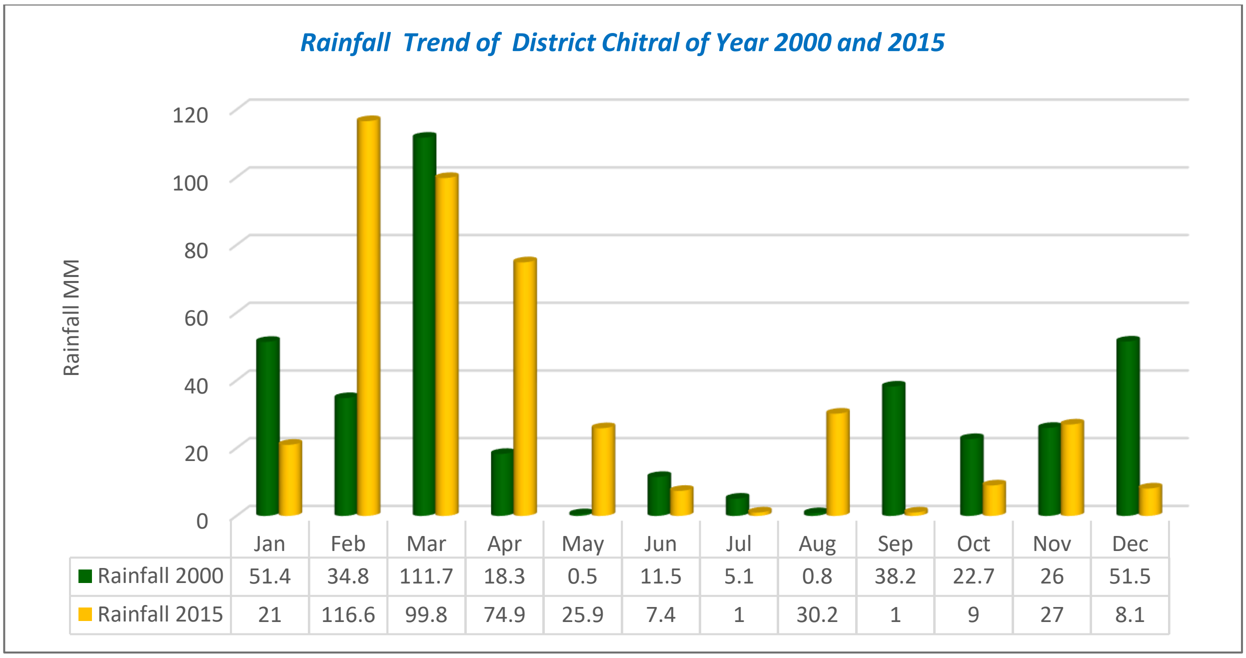


Figure: 5 Comparison of Glaciers outlines of ICIMOD 2011 and AKAH 2015



Graph: 4 Glacier Outline Variation of from 2000 to 2015

The climate of Yarkhun valley, similar to the rest of the Chitral district, is distinctly continental and dry temperate. It is hot in summer, ranging from very hot in the lowlands to warm in the uplands and cool in the higher elevations. Spring weather is unpredictable with frequent rain and snowfall. Long term temperature and precipitation records are available only for Chitral. Precipitation in the valley is mainly received from snow and low intense rains during the months of December to April. The summer spell is generally hot and dry in the valley while in winters the weather is chillingly cold. According to Pakistan Meteorology Department (PDM) data, the precipitation of Chitral in 2000 was 51.4 mm in January, 34.8 mm in February, 111.7 mm in March and 51.5 mm in December. However, in 2015 there was a significant increase in February (116.6mm), March (99.8 mm), and Apr (74.9) and a decrease in Dec (8.1). (Graph 5).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall 2000	51.4	34.8	111.7	18.3	0.5	11.5	5.1	0.8	38.2	22.7	26	51.5
Rainfall 2015	21	116.6	99.8	74.9	25.9	7.4	1	30.2	1	9	27	8.1

Graph: 5 Precipitation trend of Chitral district in 2000 and 2015

According to weather monitoring posts (WMP(s) which were installed by the Aga Khan Agency for Habitat (AKAH), the precipitation trends increased from December toward March (Figure 5).

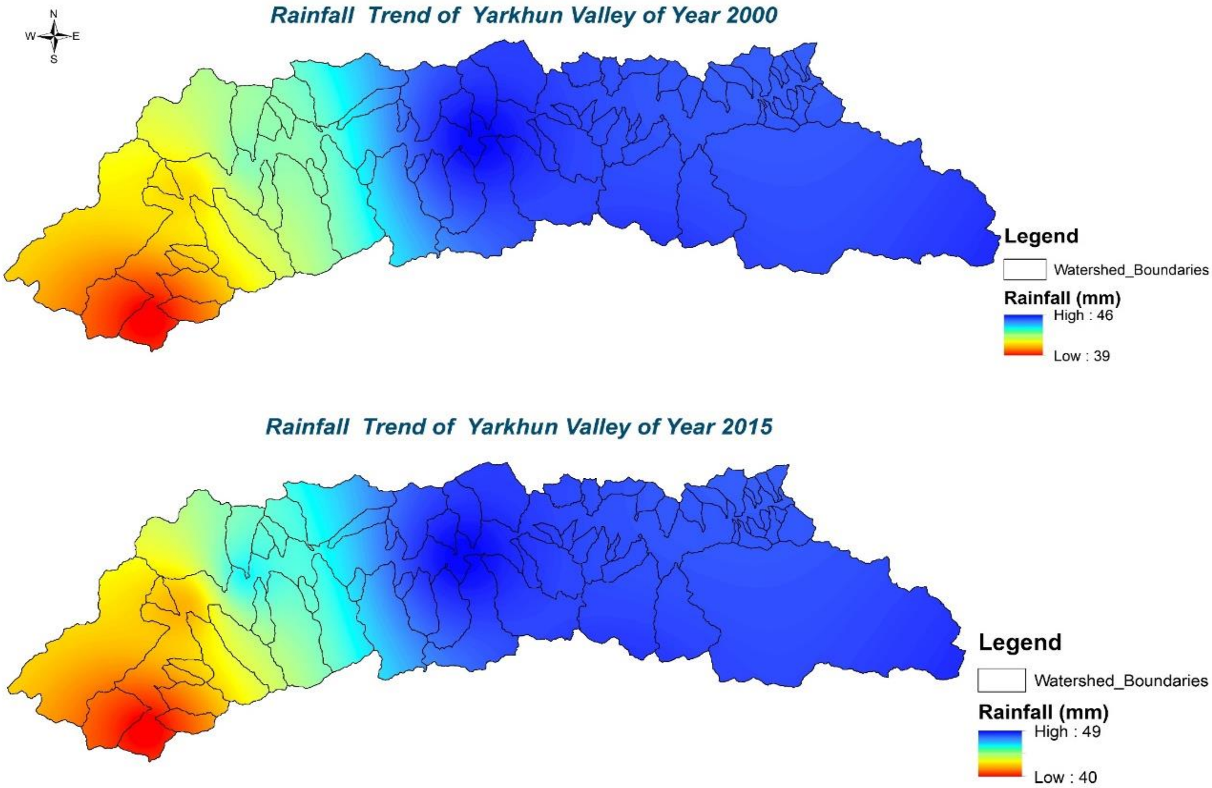
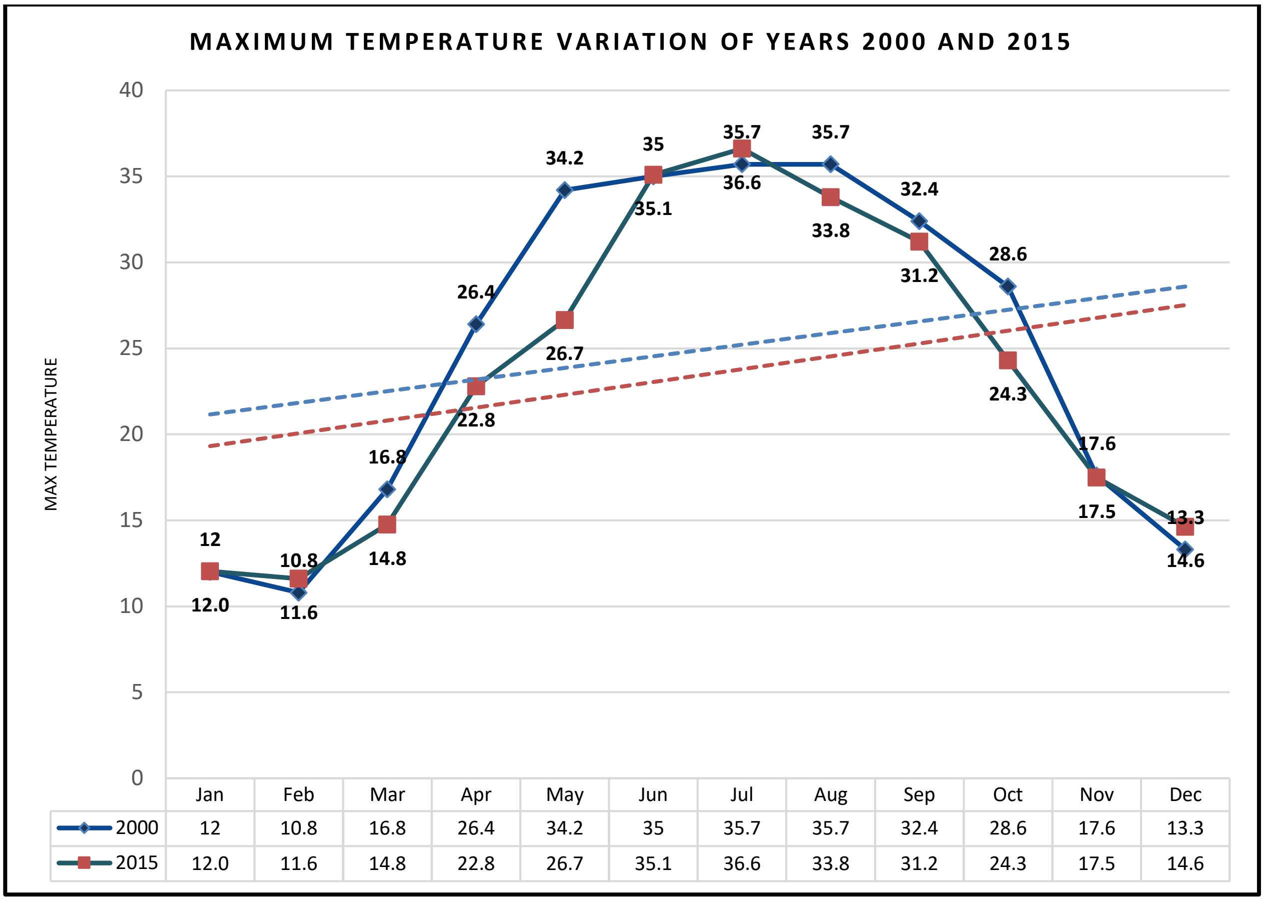


Figure: 6 Precipitation trends of Yarkhun in 2000 and 2015

According to PMD data, there was an increase of 1.2-degrees in the average temperature from 2000 to 2015. The following graph shows the temperature increase in each month (Graph 6).



Graph: 6 Maximum temperature variation of Chitral district from 2000 and 2015

4. Discussion

The melting of glaciers, formation of glacial lakes at higher altitudes of the Chitral region coupled with glacial lake outburst flood (GLOF) events are signs of climate change. The increase in temperature trends and changes in winter and summer season duration are examples of global warming. High mountain glaciers and lake formation are sensitive to these changes. This spatiotemporal assessment of Yarkhun valley glaciers and lakes which used remote sensing and field validation reveals a decrease in snow cover glacier through melting, uplifting of snow line (equilibrium line of altitude ELA) and the formation of newly glacier lakes. As well, there was an increase in the size of existing glacial lakes, and an increase in rangelands and vegetation cover which all indicate global warming and its impact. The shifting of snow fall season from December to April also changed the climate system in Chitral region and caused more snow avalanches. Thus, monitoring the climate change impact on water resources, especially glacier and glacial lakes, is very important currently. Temporal inventories of glaciers can be used to monitor glacier and lake dynamics in mountainous regions in the Chitral district and in particular the Yarkhun valley because of its sensitivity towards changes in climate parameters an (increase in temperature trend and shifting of snow fall season). In 2015, a number of GLOF events occurred which damaged the agriculture land and washed out houses, bridges and power houses. The increase of temperature caused more glacier melting and the formation of new glacier lakes at surface and subsurface levels which generated floods. The precipitation, especially during snow fall season of the valley, has dramatically changed its intensity from December toward April. A large number of snow avalanches and their damage especially in 2015 and 2016 in Lotkhow Tehsil of Chitral also resulted in the shifting of the snow fall season and its caused less accumulation of snow and a slight increase of temperature from in February according of AKAH WMP weather data. The increased temperature and shifting of the snowfall season is beneficial for an increase of vegetation cover, especially for the rangeland area of Yarkhun valley; however, this phenomenon also causes floods and flash floods through more melting and outburst of glacial lakes.

5. Conclusion

To assess the glacier dynamics of Yarkhun valley, AKAH Pakistan invested in the development of a glacier geodatabase, which includes remote sensing base mapping of glaciers and cross check capability with ICIMOD inventory spatial data. The monitoring and validation from the field was also carried out for reliability, which can in turn be used for the calculation of future water availability and to develop risk reduction strategies with respect to glacier hazards like GLOF. The Glaciated region (or cryosphere) in the Yarkhun valley varies; however, the downstream impact remains undeterred. We recognize four main limitations that need to be addressed before we can arrive at more detailed spatially clear forecasts of water availability: (1) Rainfall and snowfall increase the growth of glaciers, but Spatio temporal quantification of the present climate is uncertain and it is difficult to make future projections due to the unavailability of automatic weather stations. (2) Unavailability of hydro metrological models for future climate in the study area (3) rate of melting is unknown due to the complex reality of glacier cover especially glacier debris cover and sub glacier lake formation. (4) There is vigilant need for a high topographic study to extract the exact coverage area of the glacier by using high resolution images and digital elevation models and there is a need for a robust algorithm for future projection of glacier dynamics.

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