Chapter 4

Remote Sensing of the Glacial Environment Influenced by Climate Change

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Additional information is available at the end of the chapter

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Abstract

Remote sensing-based observations prove to be critical for the monitoring and assessment of cryosphere in the Himalayan region, where routine data collection in mountainous regions is often hampered by highly inaccessible terrain and harsh climatic conditions. The glacierized region of High Asia is also facing the effects of climate change in the form of rapid melting of glacial ice, creation of new lakes, and expansion of the existing ones, which eventually result in hazardous glacial floods downstream. Multisensor remote sensing (RS) data, e.g., MODIS, Landsat-7 & 8, and SPOT-5 XS, coupled with Google Earth and digital elevation model (DEM) data were used to investigate the snow/glacier resources and their dynamics in the Karakoram–Himalaya basins adopting variable image interpretation and modeling techniques. Minimum numbers of large-sized glaciers were identified in the Himalaya range, which points toward higher rates of glacial ice melting in this range. On the contrary, the presence of relatively higher numbers of medium- to large-sized glaciers in the Karakoram range provides an evidence of favorable climate conditions for the glaciers' existence at higher altitudes. A significant gain in snow cover was observed in Hunza basin during the 2001–2011 period, which may feed high-altitude zone resulting in net expansion of the snow cover and ice mass gain in the Karakoram. The integrated use of RS and geographical information systems (GIS) techniques with sparse in situ data is found to be helpful in analyzing the glacial environment in the context of changing climate in the high-altitude Himalayan region.

Keywords: Snow cover, Glacial environment, Climate change, Karakoram range

1. Introduction

The glacierized region of Hindu Kush–Karakoram–Himalaya (HKH) often referred to as the 'water tower of Asia' stores large volumes of water in the form of ice and snow after the polar ice releases freshwater to the Indus, Ganga, and Brahmaputra rivers. Climate change is being predicted by glacial lakes due to their property of acting as sensitive indicators [1], and unstable lakes can pose potential threats to downstream communities and infrastructure [2]. Monitoring of glaciers, glacial lakes, and assessment of glacial lake outburst flood (GLOF) impact downstream can be done quickly and rather reliably through remote sensing data interpretation and analysis. RS technology and GIS have often been used by decision makers as an effective and powerful tool to solve environmental issues [3]. In combination with GIS, RS methods provide useful means to detect potentially hazardous situations and to perform a preliminary assessment of the related hazard potential [4]. Remote sensing data from satellites are very helpful for mapping and monitoring glaciers and their changes over large areas, repeatedly, and by covering large regions with sufficient spatial detail at the same time [5, 6]. In combination with digital elevation models, RS data and methods offer the possibility to generate standardized glacier and glacial lake inventories.

When electromagnetic (EM) energy encounters matter, such as solid, liquid, or gas, a number of interactions are possible that may take place at the surface or beneath the surface of a substance. These interactions produce numerous changes in the incident EM radiation primarily in the form of change in magnitude, direction, wavelength, polarization, and phase. The science of RS detects and records these changes, which can be interpreted to identify the characteristics of the matter or land use/land cover, such as various types of vegetation cover, water bodies, soils, farming fields, and exposed rocks. The reflectance characteristics of the features like snow and ice vary according to their surficial/physical characteristics: the reflectance of snow is generally very high in the visible portions of the spectrum, whereas the reflectance of old snow and ice is always lower, i.e., due to compaction and presence of impurities, than that of fresh snow and clean/fresh glacier [7]. Similarly, the reflectance of fine-grain snow is comparatively higher than that of coarse-grain snow and glacial ice in the visible portion of the spectrum [8] (Figure 1). Comprehensive reviews of remote sensing systems, data types, techniques, and application to glacier-related hazards have been provided in Refs. [9–11]. RS technique provides additional opportunities for more complete surveys of glaciers to provide early warning of the potential formation of ice-dammed lakes [12]. The widely used earth observation (EO) sensors in the context of glacier inventory production include the Landsat MSS (Multispectral Scanner), TM (Thematic Mapper), ETM+ (Enhanced Thematic Mapper Plus), OLI (Operational Land Imager), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) onboard the Terra platform, and the SPOT (Satellite Pour l'Observation de la Terre) satellites. In combination with freely available DEM datasets, remote sensing data offer integrative approaches for observing and assessing the current situation of glaciers, glacier lakes, and associated hazard potential, as well as the means to develop scenarios of potential future evolutions [13]. The snow and ice-melt model like SRM (snowmelt runoff model), which is used to simulate and forecast daily streamflow in snowy and glacierized basins [14], requires accurate data on snow-cover area (SCA), which are provided by Landsat, Terra-MODIS (Moderate Resolution Imaging Spectroradiometer), ERS-SAR (European Remote Sensing-Synthetic Aperture Radar), and NOAA-AVHRR (National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer) satellite sensors

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[15]. For the first time, NOAA began to use remote sensing in 1966 for the detection of SCA to provide weekly estimates of snow cover in the Northern Hemisphere [16].

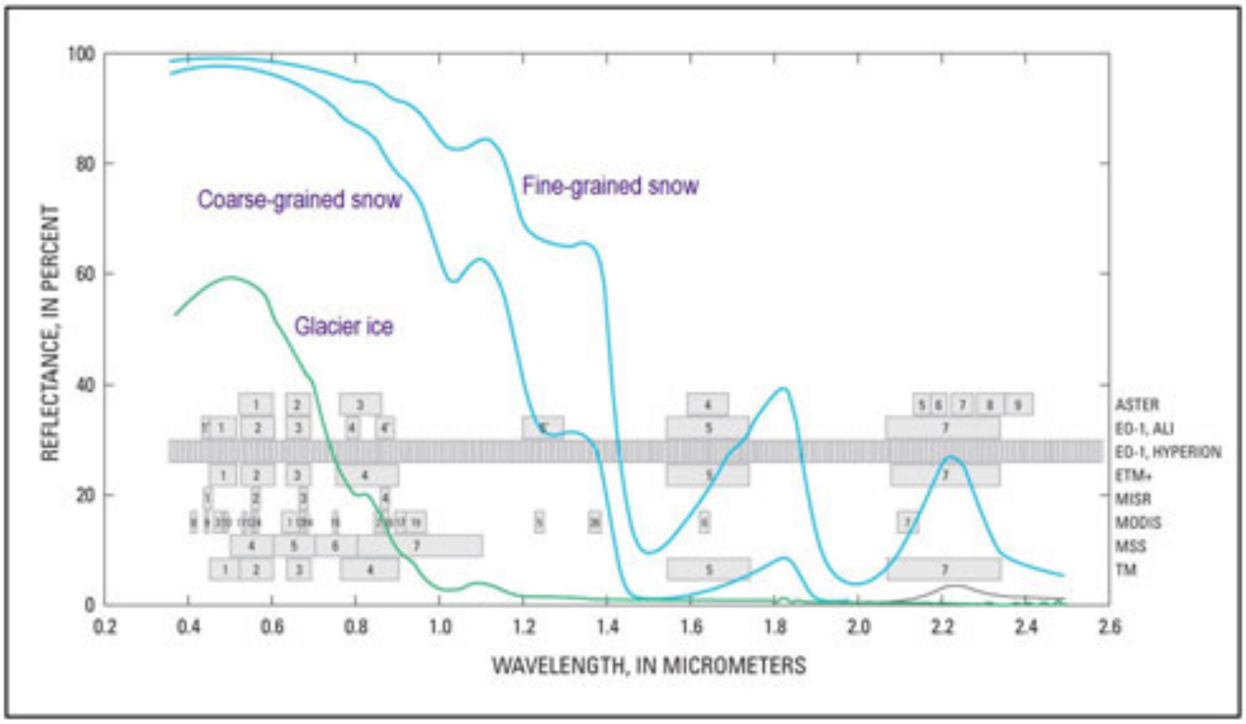

Figure 1. Reflectance response of snow and glacial ice in multisensor remote sensing data [8].

2. Climate change impacts on glacial environment

Glaciers are considered as very reliable and easily understandable natural indicators of climate change [17] due to their sensitive response to changes in temperature and precipitation [18]. They have been selected for this reason as an essential climate variable (ECV) by the global climate observing system (GCOS) [19]. According to IPCC [20], the global temperature has risen by 0.85°C since 1880 and the surface warming amounting to 3.7°C will be likely between 2081 and 2100 if greenhouse gas emissions stay roughly on their current path. The observed and projected changes in global average temperature relative to the 1986–2005 average under four emissions pathways are shown in Figure 2. The increase in air temperature influences the glacier mass balance [21], which is the balance between accumulation and ablation of glaciers [22]. The changes in mass balance cause variations in the volume and thickness of glaciers, which ultimately affect the flow of ice [21], and as a large fraction of the Indus flow is originated from meltwater, both magnitude and timing of the flow are vulnerable to climate change [23]. Furthermore, due to the temperature increase in the region, more precipitation in winter will fall as rainfall than as snowfall compared with the current situation. This rainfall will be added directly to the river system, instead of storing in the form of ice or snow in glaciers [24].

The IPCC Report of 2007 estimates a further warming of 3.7°C at the end of the 21st century; climate change has been observed through significant warming in the Hindu Kush Himalayas [25]. The climatic change in recent decades has made considerable impact on the glacier life cycle in the Himalayan region. With few exceptions, there has been a global trend toward glacier retreat since the beginning of the 20th century, with this retreat becoming more rapid and more uniform since the 1980s [26]. There will be a decrease of the glacier coverage in the coming decades as a result of global warming. This will lead to a short-term increase in water availability, in the coming decades, due to an increase in meltwater. However, the water availability will decrease in the long term during the second half of the 21st century. This decrease in water availability combined with a projected increase in water demand will cause water shortage for irrigation and thus food insecurity [27].

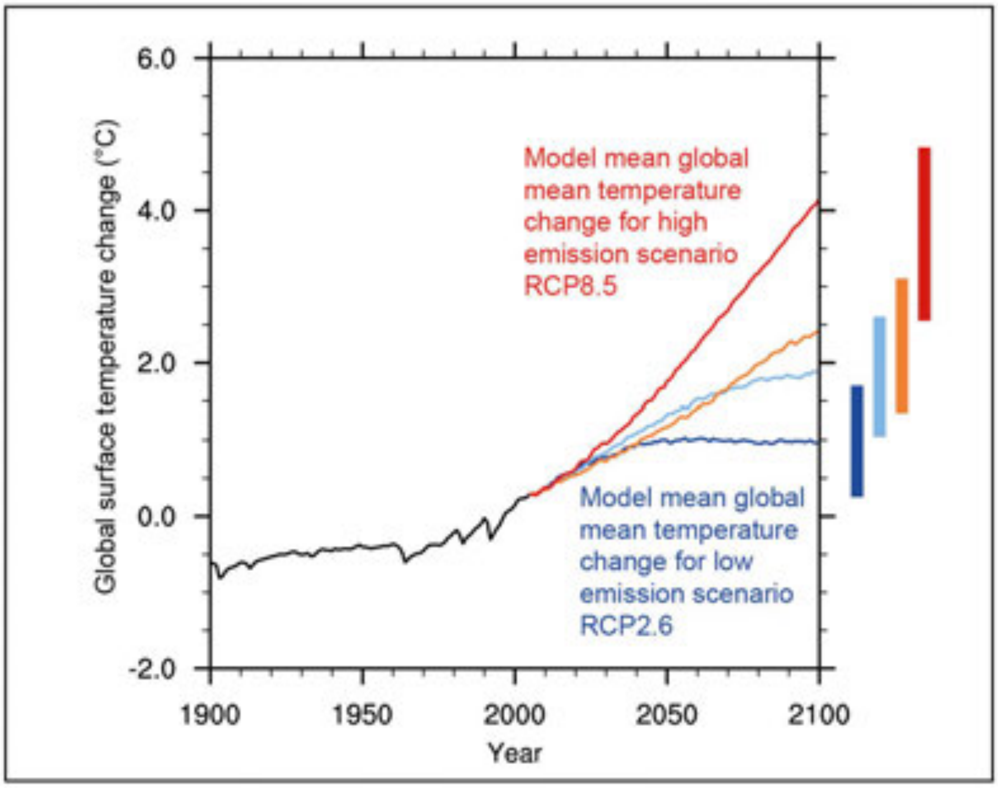

Figure 2. The changes in observed and projected global average temperature relative to the 1986–2005 average. The projections are averaged across a range of climate models. The vertical bars shown at right are likely ranges in temperature by the end of the century [20].

Some of the serious consequences of global warming in the Himalayan region include rapid melting of glaciers, creation of new lakes, and expansion of the existing ones posing high risk of glacial lake outburst flood hazard for downstream communities. The sudden increase in the frequency of floods in recent years, e.g., during 2007, 2008, 2010, 2012, and 2013 [28], demands a better understanding and investigation of the prevailing situation of the glaciers and glacial lakes in this region. The chapter describes a remote sensing-based approach to investigate environmental challenges posed by global warming in the Himalayan region.

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2.1. Case study

According to Chaudhry *et al*. [29], Pakistan experienced 0.76°C rise in temperature during the last four decades and the increase was 1.5°C in the mountain environment hosting thousands of glaciers. The average annual temperature and annual rainfall at Gilgit meteorological station in the Central Karakoram indicated overall rising trends during the 1960–2013 period (Figure 3). Under varying climate conditions, glaciers in various regions of the Hindu Kush–Karakoram–Himalayan belt behave differently under changeable climate conditions. A general shrinkage of glaciers has been observed in the Himalaya [30, 31]; however, this does not imply a synchronous behavior of all glaciers, because there can be local differences and even advancing of existing glaciers [32, 33]. In the present study, snow-cover mapping of Hunza River basin situated in the Karakoram range of Pakistan was carried out using MODIS snow product for assessment of snow-cover dynamics under the changing climate. Multisensor RS data, i.e., MODIS product, LANDSAT-7 ETM+ (Enhanced Thematic Mapper plus), LANDSAT-8, and SPOT-5 XS (Multispectral) coupled with Google Earth and digital elevation model data (ASTER/SRTM) were used to investigate the snow/glacier resources and their dynamics in the selected Karakoram and Himalayan basins adopting variable image interpretation and modeling techniques. The snowmelt runoff model was employed to simulate the daily discharges at Gilgit stream gauging station in Gilgit River basin. World Meteorological Organization (WMO) tested SRM successfully for runoff simulations [34]. The model has been applied widely all over the world to compute snowmelt runoff. With the development of satellite remote sensing (SRS) and GIS, it is possible to apply SRM to a large-sized basin. It uses remote sensing snow-cover data for the estimation of snowmelt runoff. The study would provide base for future monitoring of glaciers and glacial lakes in response to changing climate in this high-altitudinal mountainous region.

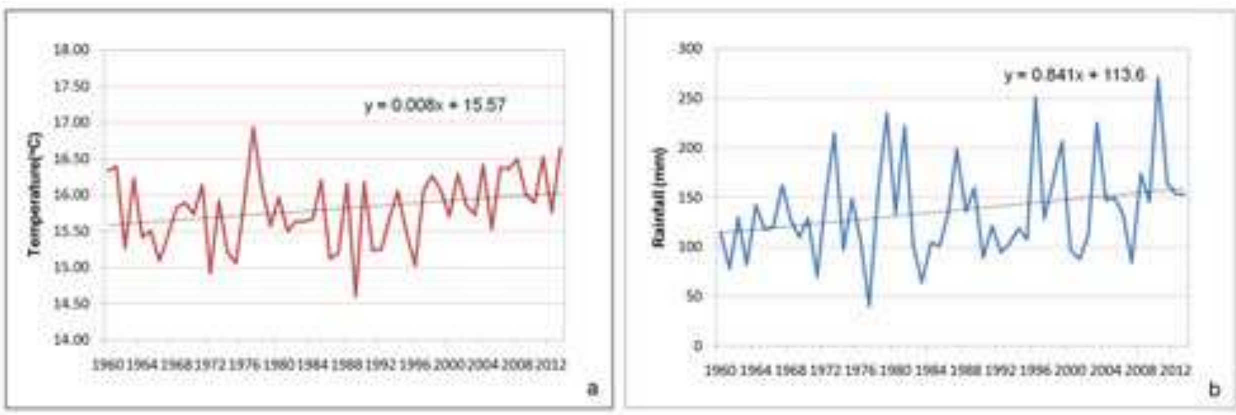

Figure 3. Trends of average annual temperature (a) and annual rainfall at Gilgit (b) during 1960–2013.

2.2. Description of the study area

The glacierized region of Pakistan lies within longitudes 70° 57′–77° 52′ E and latitudes 33° 52 ′–37° 09′ N (Figure 4). The elevation ranges from 366 m in the south to more than 8,500 m in the northeast. The snow and glacial ice reserves of freshwater nourish the main Indus River system (IRS) of the country. Approximately 11.57% of the overall area (i.e., 22,000 km^2) of Upper Indus basin (UIB) is covered by seasonal glacial ice occupied by majority of the largest valley glaciers, the biggest and prevailing snow/ice-covered area outside the polar regions [35]. The high mountain region, i.e., between 35° and 37° N, is mostly dominated by winter rains, whereas the submountainous region, i.e., between 33.5° and 35°N, is dominated by summer rains. The bulk of the snowfall received from westerlies during the winter half of the year and more local conditions prevail in winter under the existing influence of the Tibetan anticyclone [36]. In addition to the influence of global weather systems, the mountain climates are also influenced on the medium and local scale by elevation, valley orientation, aspect, and slope [37]. The Himalayas have four subregions. The sub-Himalayas or Siwaliks are a range of low hills up to 1,000 m altitude above the mean sea level. The outer Himalayas go up to about 5,000 m altitude. The central Himalayas have an average height of about 6,000 m. The trans-Himalayas including the Karakoram Range are also very high, which include the second highest peak (8,611 m) in the world. The Hindu Kush and the Western Mountains form the boundary between Pakistan, Afghanistan, and China. The main rivers in these ranges are Swat and Kabul, which eventually run into the river Indus.

Gilgit basin is bounded in the west by Chitral River basin, a small portion in the north by Afghanistan, in the east by Hunza River basin, and in the south by Indus and Swat River basins. The basin occupies an area of about 14,082.4 km^2 out of which about 6.9% is glacierized. The elevation ranges from 1,500 masl to more than 6,500 masl. Hunza basin is located in the upstream part of Upper Indus basin covering an area of about 14,235 km^2 in which about 27.6% area is glacierized. The Hunza River has formed the main subbasin of the Gilgit basin. The tributaries joining the Hunza River are Chapursan, Khunjerab, Ghujerab, Shimshal, and Hispar rivers. Generally, most parts of the ablation areas are debris covered in this region. The Hunza River gauged at Dainyor bridge has a mean annual flow of 323 $m^3 s^{-1}$ based on 1966–2008 flow record of the Surface Water Hydrology Project of the Water and Power Development Authority (SWHP-WAPDA). The Astor basin lies in the eastern side of the Nanga Parbat mountain. Astor River drains the snow- and glacier-covered mountains of Ladakh – Deosai and High Himalayas in the northern territory of Pakistan. Shingo basin (4,680 km^2) lies in the southeast of Astore basin within the elevation range of 3,800–6,000 m. Generally, the glaciers are few in number and small in size in this basin. The Jhelum basin is bounded in the west by southwestern part of Indus River basin, in the north by Astore basin, and in the east by Shingo basin (Figure 4). The elevation in this basin ranges from 1,200 m to more than 4,700 m.

3. Material and methods

3.1. Data used

A dataset of MODIS processed images of MOD10A2 (h23V05, h24V05) and MYD10A2 (h23V05, h24V05) available since 2000–2011 was downloaded from the web link http://nsidc.org/cgi-bin/snowi/ with a minimum cloud cover of 15%. MODIS is an optical sensor that

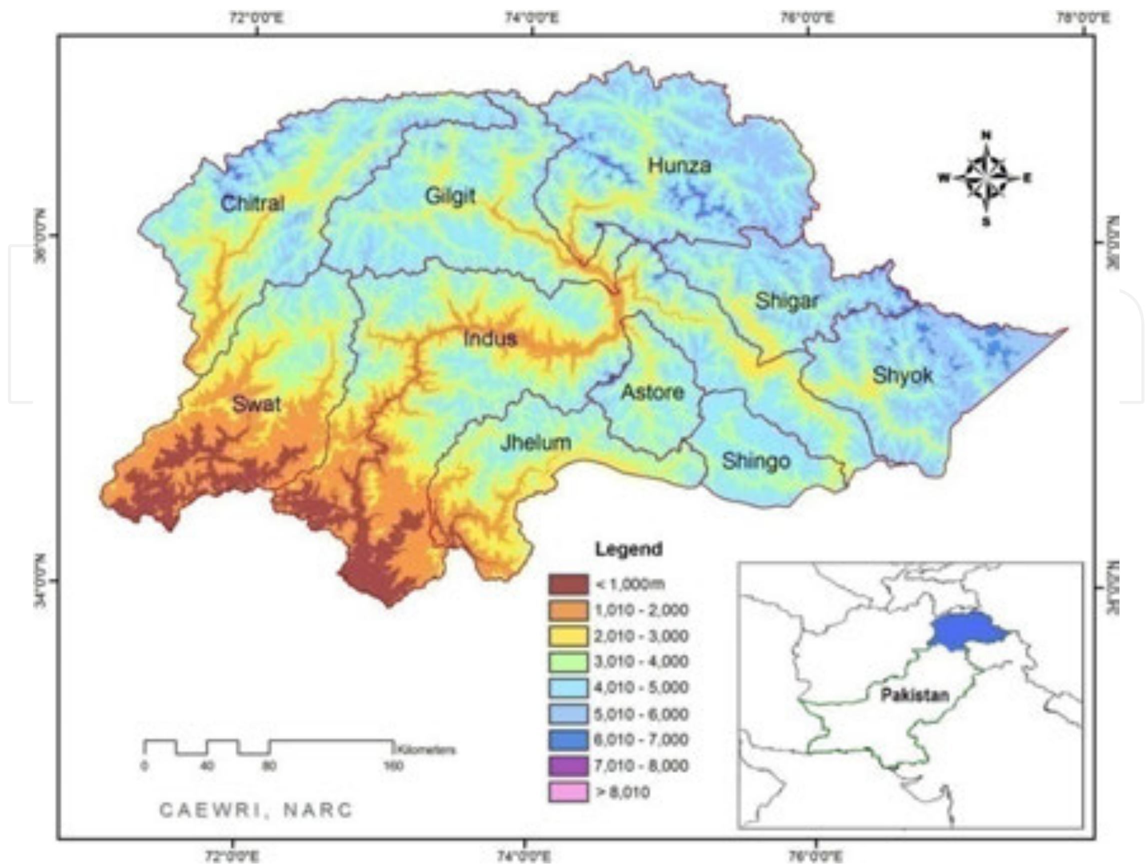

Figure 4. Location map of the glacierized region of Pakistan indicating various river basins and altitudinal ranges.

provides imagery of the earth's surface and clouds in 36 discrete, narrow spectral bands ranging from 0.4 to 14.4 μm of the electromagnetic spectrum. MODIS snow-cover images are available globally at a variety of different resolutions and projections. MODIS, aboard terra spacecraft of earth observing systems (EOS), is being very handy for the estimation of normalized differential snow index (NDSI). The MODIS snow-cover product used in this study (MOD10A2 and MYD10A2) contains data fields for maximum snow extent over an 8-day repeated period and has a spatial resolution of 500 m covering the Hunza River basin completely in two scenes (h23V05 and h24V05).

The glaciers and glacial lakes mapping was based on the Landsat 7 ETM plus and Landsat 8 satellite data of 2001 and 2013, respectively. The later data were downloaded from the web link http://glovis.usgs.gov with minimum cloud and snow cover. The detail of satellite data used in the present study is given in Table 1. The RS analysis for glacial lakes mapping was supplemented by Google Earth imageries and the topographic maps published by Survey of Pakistan. The Landsat 8 satellite images the entire earth every 16 days in an 8-day offset from Landsat 7 ETM plus. The images are terrain-corrected having spatial resolution of 30 m for multispectral bands 1–7, 9, and 15 m for panchromatic band 8 and 100 m for thermal infrared sensor (TIRS) bands 10–11 resampled to 30 m to match the multispectral bands. The Landsat 8 carries two instruments: the OLI sensor includes refined heritage bands, along with three new bands and thermal infrared sensor provides two thermal bands. The satellite remote sensing data of 1993 (Landsat MSS), 2001 (Landsat TM), and 2005 (SPOT XS multispectral) periods acquired from various sources, such as SUPARCO, were used for spatiotemporal analysis of glaciers and lakes in the Astore basin. The location of selected glaciers and lakes in the basin is shown in Figure 5. For historical trend analysis, glacier cover from topographic map of 1:50,000 scale of the year 1964 was acquired from Survey of Pakistan. Digital elevation model data of shuttle radar topography mission (SRTM) 90 m were used to estimate altitudinal characteristics of the glacial lakes. The DEM is provided with a geographic coordinate system (CGS), and the elevation values refer to datum WGS-84 both horizontally and vertically.

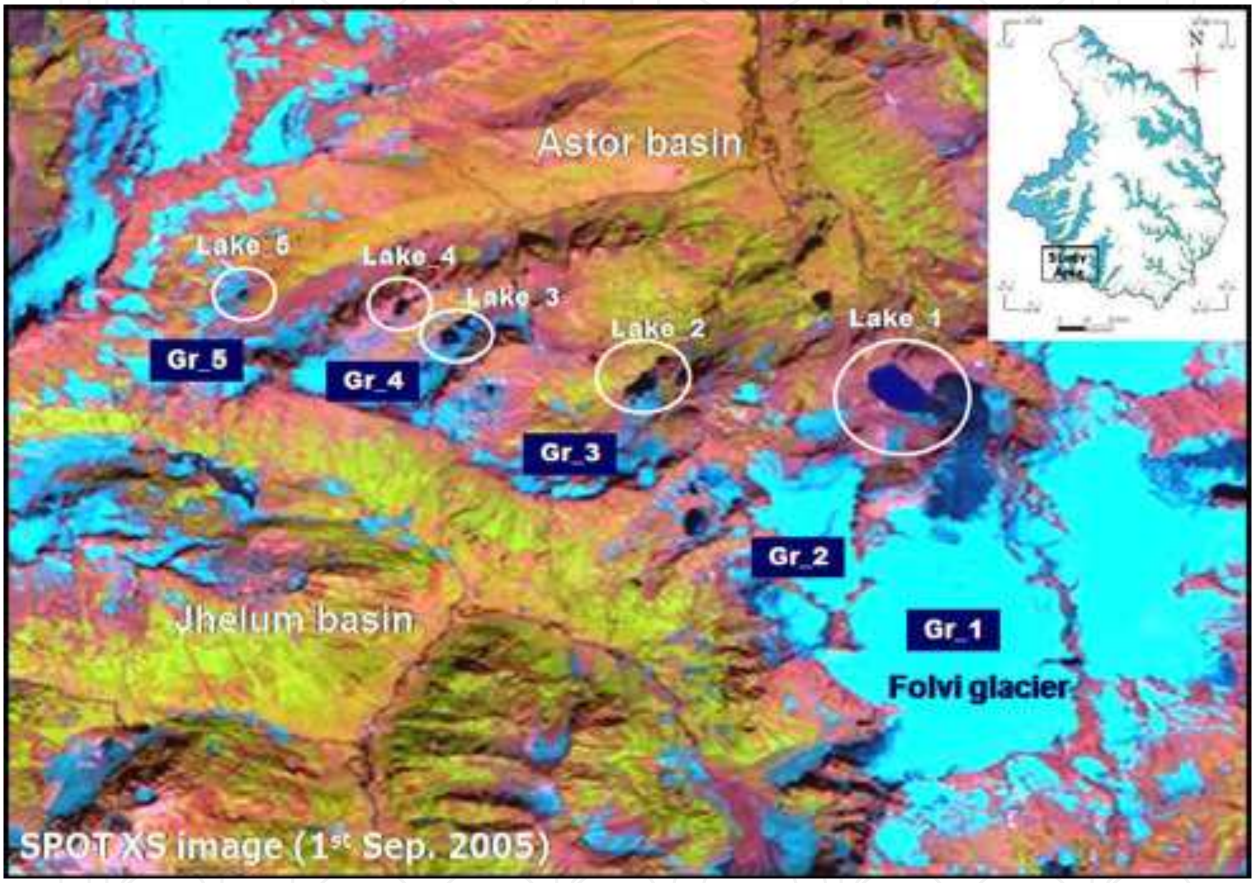

Figure 5. Location of the study site in Astore basin in Himalayas.

The daily flows data of Hunza and Astore rivers were acquired from SWHP-WAPDA for seasonal correlation with climate data and snow-cover dynamics in the catchment since 2000. The Hunza River is gauged at Dainyor Bridge, whereas the Astore River is gauged at Doyean station near Bunji.

3.2. Image processing and geo-spatial analysis

Originally downloaded MODIS product was in sinusoidal projection, which was then re-projected into Universal Transverse Mercator (UTM) Zone 43N projection with datum WGS-1984 using MODIS Re-projection Tool. MODIS images only for the months of January,

SRS data	Resolution	Period
MODIS snow-cover product	500 m	2000–2011
Landsat 8 OLI/TIRS	30 m	2013
Landsat 7 ETM+ (Enhanced Thematic Mapper Plus)	15 m, 30 m	2001
Landsat MSS (Multispectral Scanner)	80 m	1993
SPOT 4 XS (multispectral)	20 m	2005
Google Earth	Variable	Variable

Table 1. Satellite remote sensing data used in the present study.

February, and March were mosaicked and used for mapping the maximum SCA to observe snow-cover dynamics in Hunza basin, Karakoram range. The snow cover in these months usually dominates most of the basin area. The month-wise distribution of SCA in the study area during 2011 is shown in Figure 6. The SCA was minimum during August, followed by July, June, and May. It appears to increase from September to March then starts declining. The maximum snow-cover area change (SCAC) was assessed using the MODIS snow-cover product, e.g., MOD10A2 and MYD10A2, available since 2000. Subset of the study area was masked from the MODIS layer. The snow extracts of maximum snowfall period consist of the five classes of the MODIS attribute data from which the snow class (value = 200) was extracted.

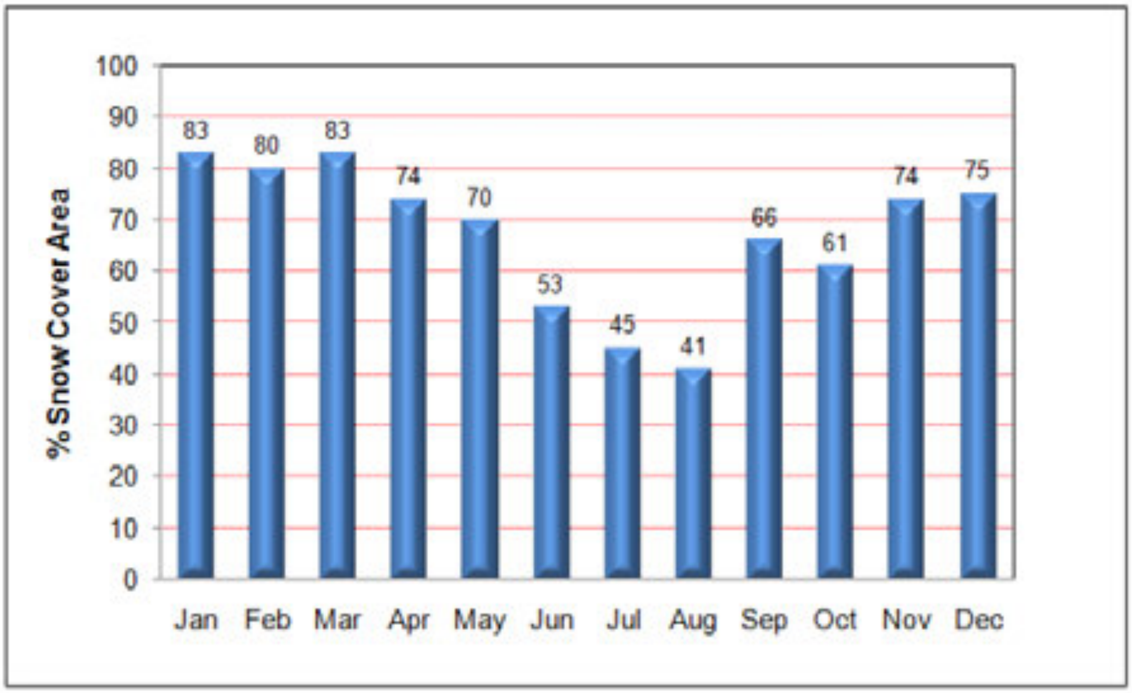

Figure 6. Monthly distribution of maximum SCA during 2011 in Hunza basin.

The spatiotemporal and altitudinal changes in the lakes were studied to observe the influence of climatic changes occurred during recent decades in this part of the HKH region. The spatial database of the lakes such as location coordinates, area, and length was systematically developed and analysis was performed for each river basin for 2001 and 2013. For the glacial lakes mapping, the methodology developed by Lanzhou Institute of Glaciology and Geocryology, the Water and Energy Commission Secretariat, and the Nepal Electricity Authority [38] was adopted. The uncertainty analysis for lakes area was performed following the methods provided by researchers, e.g., Refs. [39, 40]. According to the analysis, the shoreline of the glacial lake passes through the center of pixel giving an uncertainty of 0.5 pixel.

Five glaciers and five associated glacial lakes were selected in Astore basin of the Himalaya range. Spatial data layers of the glaciers and glacial lakes were developed through on-screen digitization in GIS and using different analytical techniques and logical operators. All the polygons representing glaciers and glacial lakes are numbered clockwise sequentially. For geospatial analysis, the attribute data were linked to the spatial data layers of glaciers and glacial lakes in GIS. Time series data of hydrometeorology were used to study the trends in climate data, i.e., summer and winter temperatures (maximum and minimum), precipitation, and river discharge.

3.3. Remote sensing technique in glaciers and lakes mapping

The detection of glacial lakes using multispectral imagery involves discriminating between water and other surface types. Delineating surface water can be achieved using the spectral reflectance differences. Water strongly absorbs in the near- and middle-infrared wavelengths (0.8–2.5 μm). Vegetation and soil, in contrast, have higher reflectance in the near- and middle-infrared wavelengths; hence, water bodies appear dark compared with their surroundings when using these wavelengths [41]. Methods for semiautomated mapping of glaciers and lakes based on remote sensing data have been well established for several years, and model approaches to assess the hazard potential of glacier lakes have been developed and successfully tested as well. The global elevation datasets of the shuttle radar topography mission and the ASTER global DEM (GDEM) offer the possibility to derive such topographic parameters for glaciers in most regions of the world.

The spatial and radiometric resolution of panchromatic band of Landsat ETM plus images was used for delineation of glacier's boundaries in selected basins. The very low reflectance of ice and snow in the middle-infrared has been widely used for glacier classification, for example, with threshold ratio images from raw data of digital number of TM bands 4 and 5 [42, 43]. This technique has proved to be simple, robust, and accurate [44]. It has also been proposed as a method for reducing multiple effects (e.g., the topographic effect of direct light) within multispectral data [45–47]. Visual interpretation is considered to be the most accurate way to delineate snow line in the scale of one outlet glacier, because it is the only method to take topography into account [48]. Because of a pronounced topographic effect, none of the most common band ratios or principal components could offer sufficient contrast to set one threshold value to delineate the ice-cap glaciers. The glaciers were mapped based on methodology developed by the Temporary Technical Secretary (TTS) at the Swiss Federal Institute of Technology, Zurich, for the data compilation of World Glacier Inventory [49]. The flowchart of the methodology adopted is shown in Figure 7. After digitization of glaciers' polygons, the numbering of glaciers was started from mouth of the major stream and proceeded clockwise round the basin. If there is a name assigned to the glacier, it was recorded through literature search and information included in the topographic maps. The geographic location of the glacier was recorded from the grid. The area of the glacier was calculated through database of the delineated glacier.

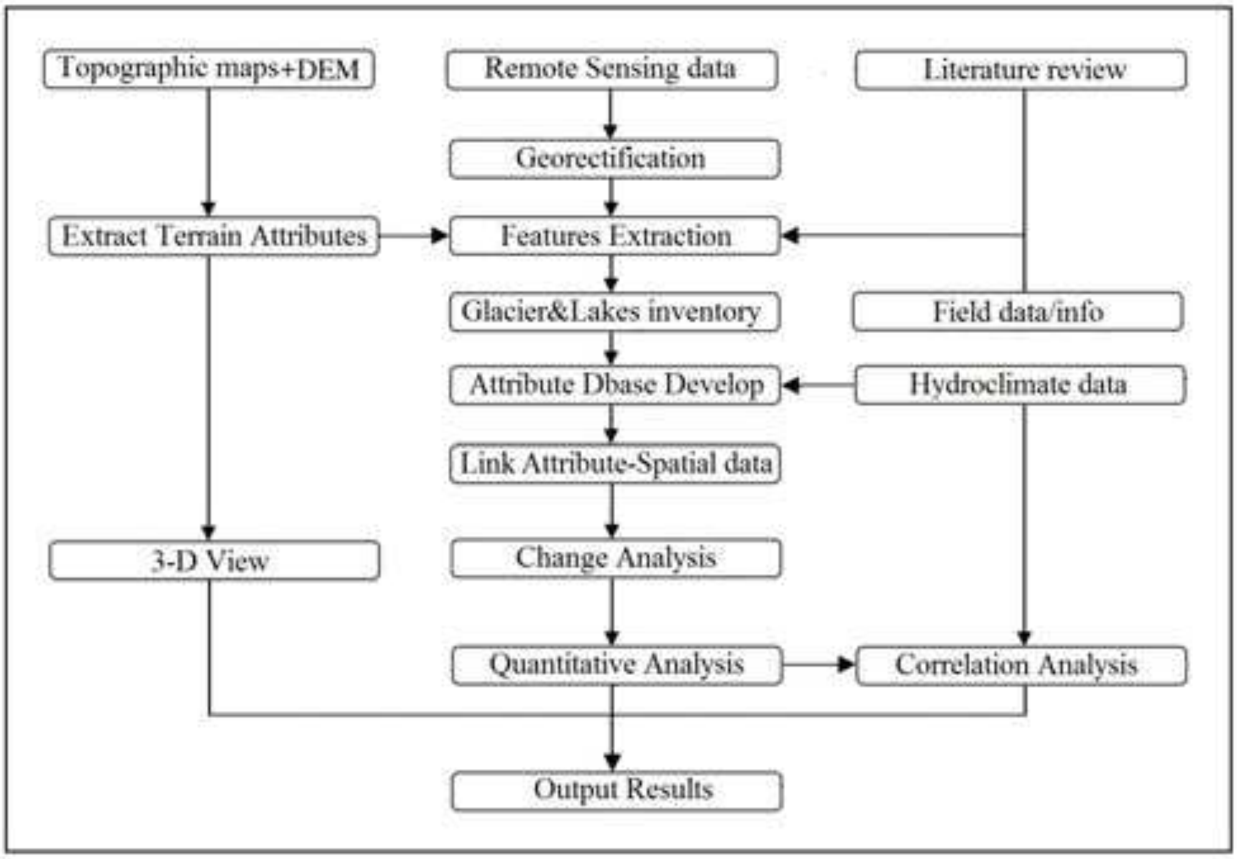

Figure 7. Flowchart of methodology adopted for temporal analysis of glaciers and glacial lakes.

3.4. Snow Runoff modeling

Currently, SRM is being used to analyze the effects of changed climate on seasonal river flows in snow and glacierized basins using MODIS satellite data. The daily input data used in the model are precipitation, air temperature, and snow-covered area. The model also requires some basin characteristics such as latitude–longitude, number of zone, zone areas, and means hypsometric elevation of each zone of basin. In the model phenomena, snowmelt and rain are computed every day and then superimposed on the calculated recession flow and transformed into the daily discharge from the catchment. The main equation used in SRM for snowmelt runoff simulation is:

$$Q_{n+1} = \left[c_{Sn} a_n \left(T_n + \Delta T_n\right) S_n + c_{Rn} P_n\right] \frac{A \times 10{,}000}{86{,}400} \left(1 - k_{n+1}\right) + Q_n k_{n+1} \tag{1}$$

where Q is the average daily discharge (m^3/s), C_{sn} and C_{Rn} are the coefficients of snow and rain, respectively, a_n is the degree-day factor (cm $^{o}C^{-1}d^{-1}$), T_n is the number of degree days in ^{o}C d, S is the ratio of the snow-covered area to the total area, P is the precipitation contributing to runoff (cm), T_{crit} (^{o}C) is the critical temperature that differentiates between snow and rain, A is the area of the basin or zone in km, K is the recession coefficients that indicate the decline of discharge in a period without snowmelt or rainfall, and n is the sequence of days during discharge computation period. The degree-day factor is evaluated with regard to snow density, stage of the snowmelt season, and presence of glaciers. The runoff coefficient is an expression of hydrological losses and is estimated by comparing the annual precipitation and runoff, by taking into account the vegetation and current snow coverage, as well as size of the basin. The critical temperature (T_{crit}) can be estimated using actual meteorological records, stage of snowmelt season, and visual observations.

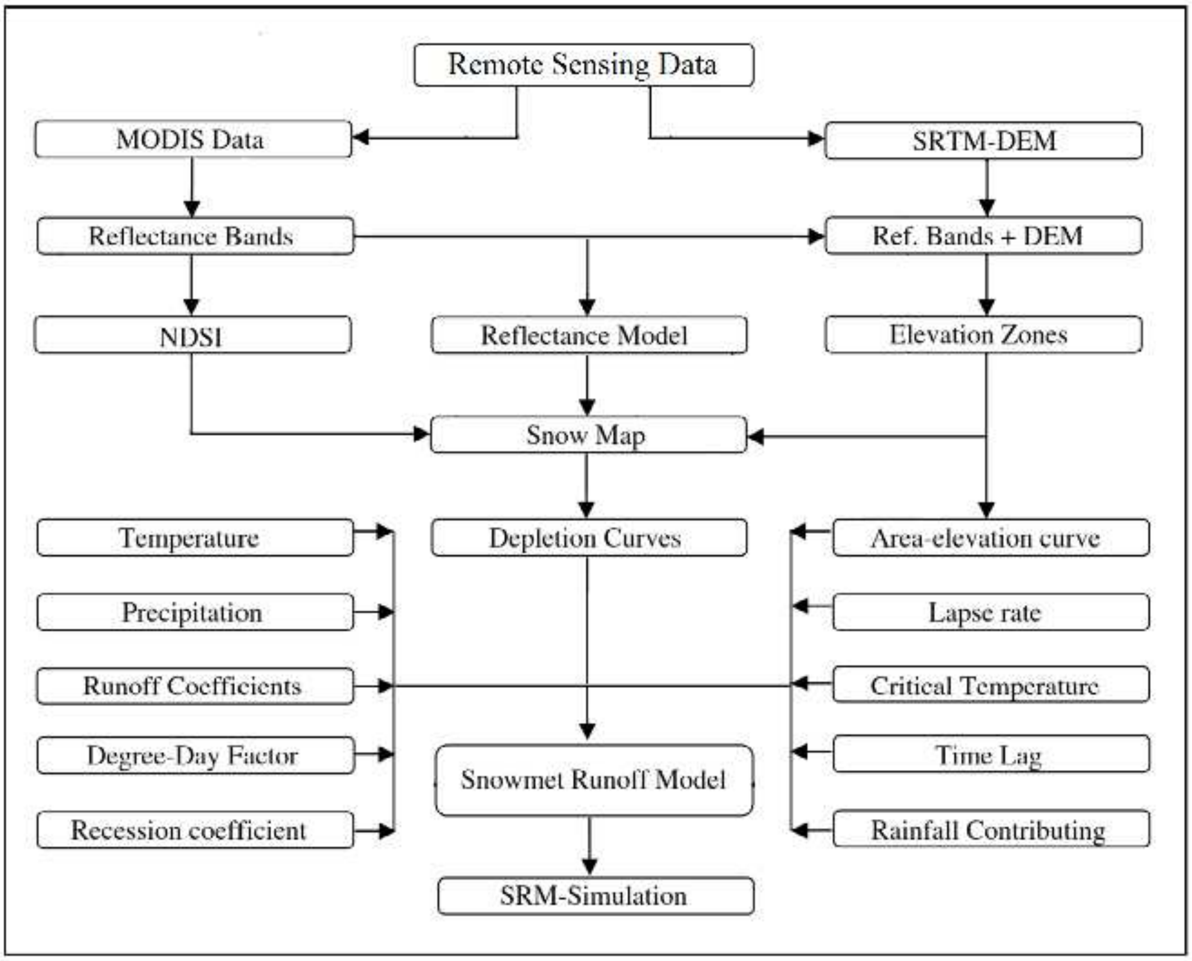

Figure 8. Major steps involved in simulation of snowmelt runoff model (SRM).

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The Gilgit River basin is a snow-covered and glacierized basin, therefore the snowmelt runoff model can be successfully used to simulate and forecast daily stream flows as well as to study the effect of climate change on river flows. The SRM model was calibrated for 4 years from 2001 to 2004 and the model simulations were performed from year 2007 to 2010. The initial values of the parameters used during model calibration such as temperature lapse rate, degree-day factor snow and rain coefficients, and recession coefficients were extracted from past data and from previous studies, e.g., Ref. [50]. The parameters were adjusted during the calibration process until satisfactory results were achieved. The SRM model was calibrated with a coefficient of determination (R^2) value of 0.64 and validated with R^2 value of 0.78, indicating a close agreement between the observed and the simulated discharge data. The stepwise methodology followed in the study is shown in Figure 8. Different scenarios were used in SRM to predict future flows of Gilgit River: i. under rise in annual temperature 'T' and ii. increase in cryosphere area in the basin.

4. Results and discussion

4.1. Analysis of maximum snow-cover area

The maximum SCA in the Hunza basin, Karakoram range, was evaluated for trend and change analysis using MODIS product of the 2001–2011 period. Figure 9 shows the maximum snow-cover area in the Hunza basin during the 2001–2011 period. Except central valleys consisting of drainage network of the basin, most of the land appears to be snow covered during the period from January to March. From the results, it was observed that percentage SCA is predominantly increasing with time in this high-altitude cryospheric region. From the trend analysis of percentage snow-cover area on annual basis, it was observed that more than 80% of the basin area was snow covered particularly during the time periods of 2003, 2004, 2005, 2009, and 2011 (Figure 10). The maximum SCA during these years ranged from 80% to 92% of the study area. The historical data of precipitation (1961–2000) exhibited a rising trend in the Northern areas [51]. This may give rise to an increasing trend of SCA, which likely feeds the high-altitude zones (usually above 5,000 masl), resulting in net expansion of the snow cover and ice mass gain in the basin.

The maximum snow-cover area change observed during 2001–2011 indicated a significant increase of about 719 km^2 in SCA during an 11-year period (Figure 11). From the trend analysis of maximum snow extent on annual basis, it has been observed that the maximum snowfall month has shifted slightly from December to January indicating a spatial shift of winter season, which generally starts from November and continues until the end of March. The possible reasoning for this shift might be attributed to the observed facts that the solid precipitation in winter has been converted into liquid precipitation probably due to increased atmospheric temperatures.

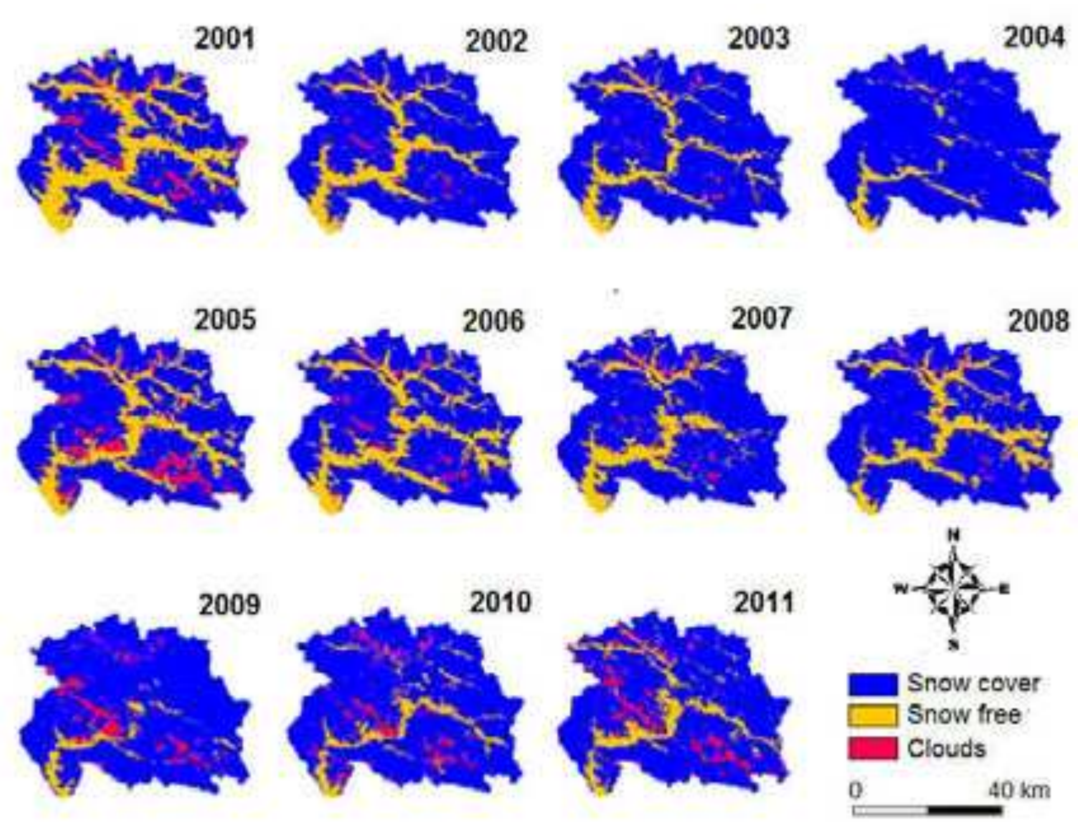

Figure 9. Maximum snow-cover area (SCA) in Hunza basin during the 2001–2011 period.

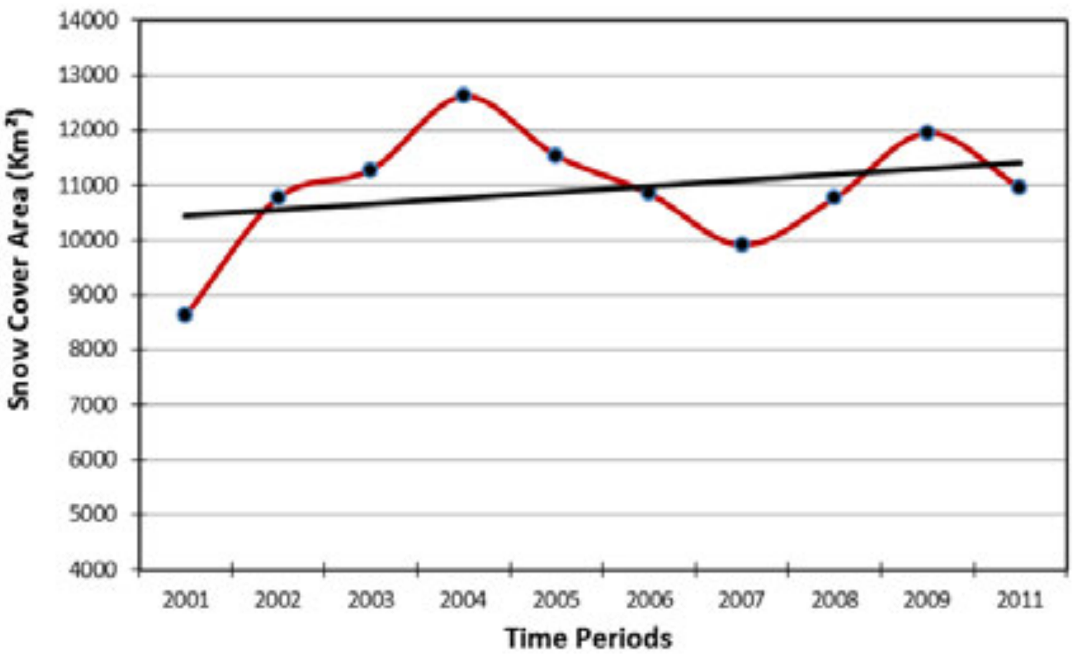

Figure 10. Trend of maximum snow-cover area (SCA) in Hunza basin during the 2001–2011 period.

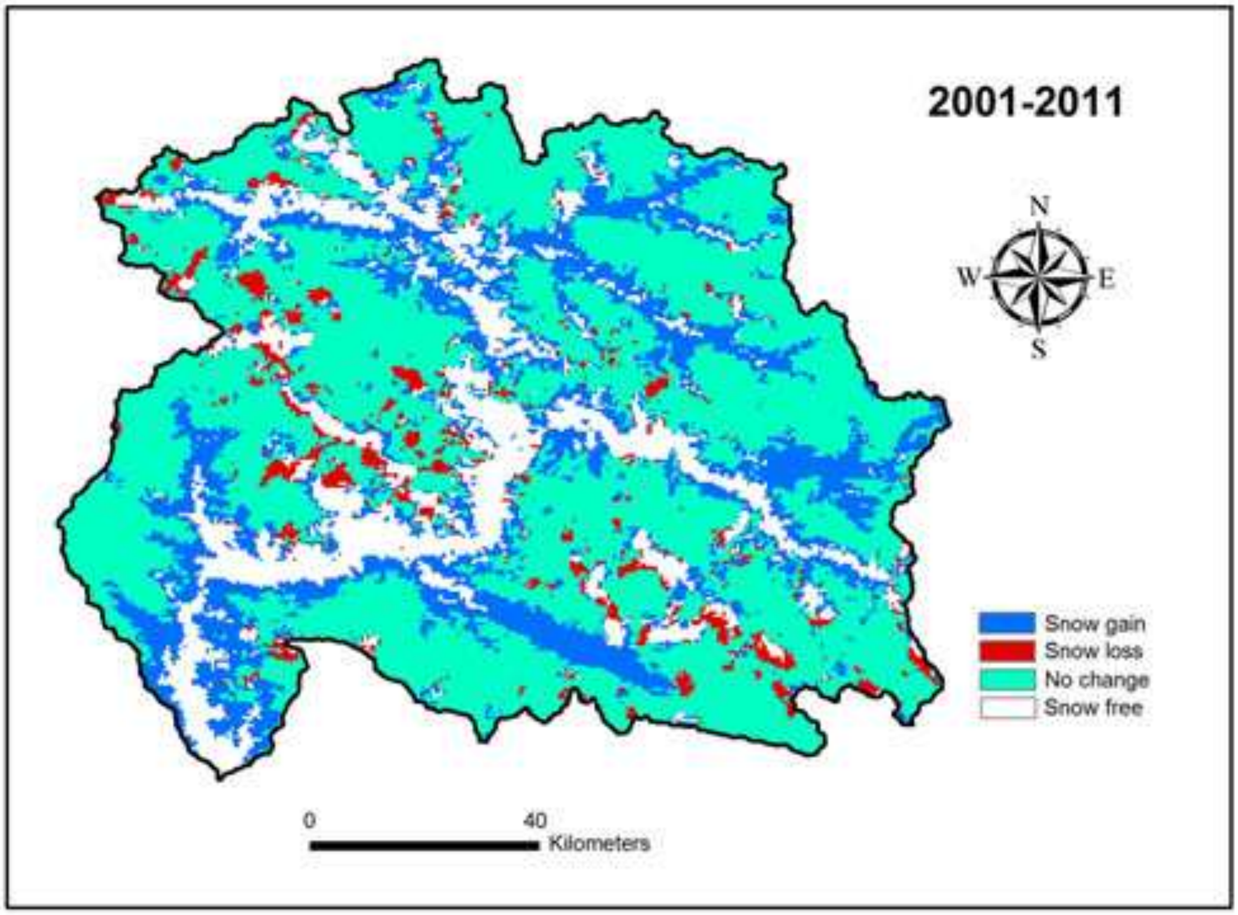

Figure 11. Snow-cover area change (SCAC) during 2001–2011 in Hunza basin.

The snow accumulation has an increasing tendency in the central Karakoram experiencing unique climate signatures, characterized by low temperatures, and enhanced precipitation [52]. The fact also points toward previous observations, e.g., Ref. [53], indicating a regional deviation of the Karakoram glaciers from the usual glacier thinning observed in most glacierized areas of the world and a retreat of some other neighboring Asian glaciers [54]. Since the early 1960s, a rise in winter precipitation in the Karakoram has been observed [55]. From the analysis of interannual variations in the snow-cover area, it has been observed that snow gain is predominantly increasing at the rate of 360 km²/year in this region perhaps because of high elevation and complex orographic features. During the periods of maximum snow gain, snow was found even at the lowest elevation of 1,400 m. Retention of snow at this low-elevation zone indicates heavy snowfall during this period. Snow gain may be characterized by many factors because the high-altitude region is influenced by complex weather systems. From the analysis of snow loss in terms of elevation (extracted from DEM), it was seen that maximum loss occurred at an elevation ranging from 2,000 to 4,000 m during 2002, 2004, 2005, and 2009 probably because of more liquid precipitation than solid within this elevation range. Most of the snow loss was observed within lower elevations of the valley glaciers, such as Batura, Hispar, and Khinyang.

4.2. Analysis of the glacial environment

The identification of glacial features was performed effectively through variable stretching of the pixel values of Landsat ETM+ panchromatic image data (Figure 12). The land features such as ridgelines and drainage network are highlighted in 0–150 stretch in values of panchromatic image. Similarly, the moraine boundaries are distinct in this stretch range providing good approximation of limits of debris-covered glaciers. Low stretch in values (i.e., 0–100) has proved helpful in extracting glacial ice appearance within the high mountainous shadows. Table 2 indicates stretching values of panchromatic image suitable for identification and delineation of various glacial features. The delineation of snow-/ice-covered ridge and catchment boundaries in panchromatic image is possible using greater than 200-value range. The surface variations and flow pattern of glacial ice become highly distinct using this range in the image.

In the Hunza basin, a total of 1,050 glaciers were identified, which contain 10 glaciers of more than 100 km^2 area (Figure 13), Batura, Hispar, and Hasanabad being the renowned ones. These and some other glaciers in this basin penetrate well below 3,000 m, e.g., the 59-km-long Batura glacier, one of the eight largest glaciers of the middle and low latitudes, has its terminus at about 2,400 m. About two-thirds of the middle and lower parts of the glacier is covered with debris (shown in reddish brown color resembling the surrounding rocks in Figure 14) except for a thin strip of white ice (visible in variable shades of cyan color) that extends to within about 4 km of the terminus. There are seven glaciers that have an area ranging within 50–100 km^2, whereas 12 glaciers belong to 20–50 km^2 category. The medium-sized glaciers (10–20 km^2) are 24 in number, whereas the rest belong to small-sized glaciers (less than 10 km^2 in size). According to Hewitt [53], the central Karakoram region is one of the exceptional and exclusive cases throughout the world where the expansion of glaciers has been observed. The Karakoram glaciers are the largest store of moisture in Central Asia and the single-most concentrated source of runoff for the whole Upper Indus basin. The glaciers residing on the steep mountains as well as lying in valleys are highly susceptible to global warming, which may create future hazards for downstream communities (Figure 15a). One of the glaciers of surging type in the Upper Hunza valley, e.g., Ghulkin, has burst several times in the past (recently in early 2015) resulting in a loss of infrastructure, property, and valuable lives (Figure 15b). The glaciers prone to surging or that display irregular flow might be expected to be possible candidates for the generation of outburst floods [13].

In the Astore basin, there were 588 glaciers identified, among which about 99% glaciers belong to 0–10 km^2 size category, while only 0.2% glaciers belong to 50–100 km^2 category (Figure 13). No glacier of greater than 100 km^2 area was found in this basin. The presence of relatively higher numbers of medium- to large-sized glaciers in the Karakoram basin provides an evidence of favorable climate conditions for the glaciers' existence at higher altitudes. The minimum numbers of large-sized glaciers identified in the Himalayan basin point toward higher rates of glacial-ice melting due to increased warming conditions in this range.

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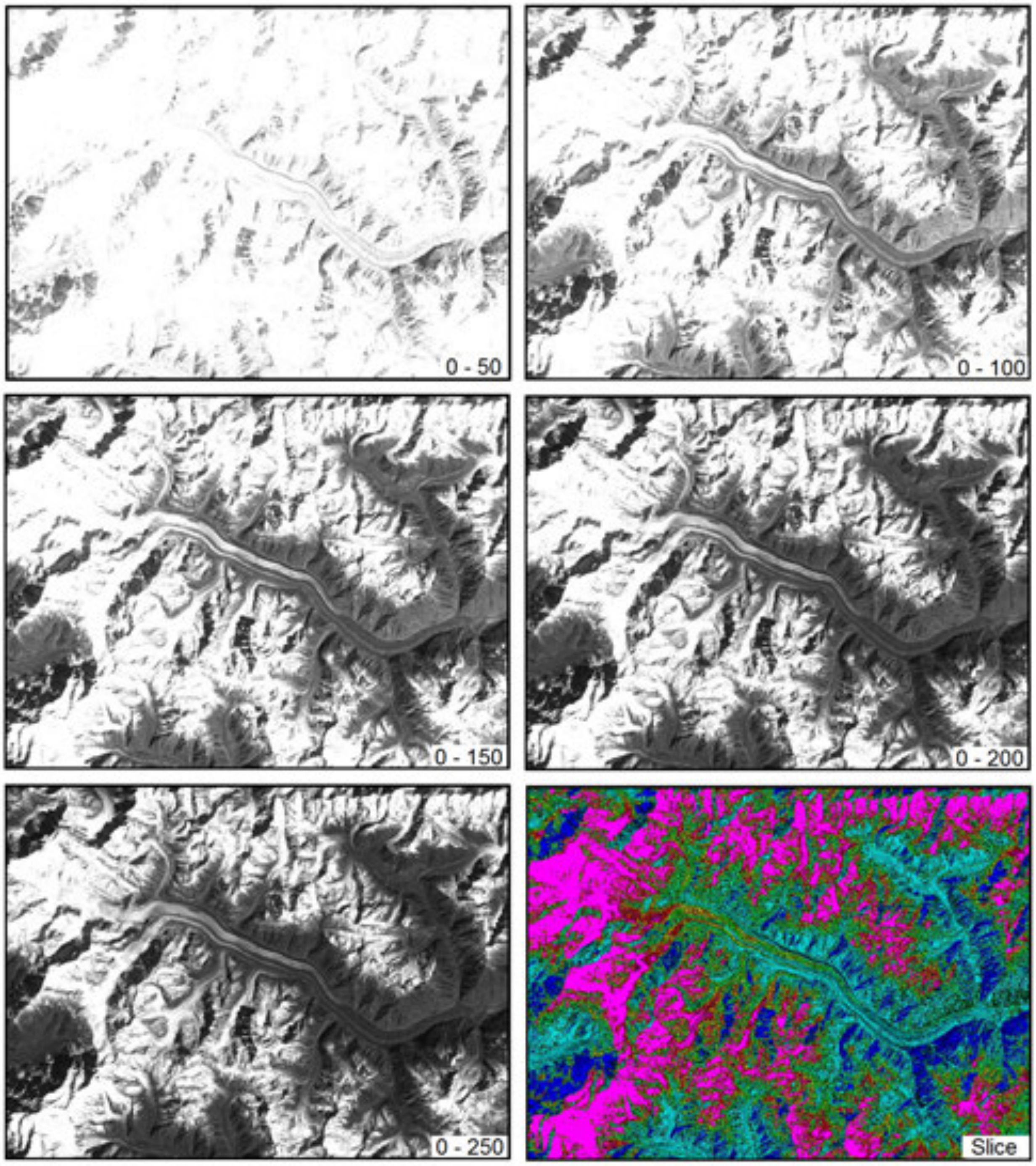

Figure 12. The extraction of glacial features is facilitated by stretching of gray scale values of Landsat ETM+ panchromatic image.

Three basins of the Himalayas, e.g., Shingo, Astore, and Jhelum, were selected to analyze variations in the glacial lakes during 2001 and 2013. Overall, 463 glacial lakes common during the two periods were selected for the analysis. The 204 glacial lakes in Shingo basin indicated an increase in area from 10.35 to 10.84 km^2 (Table 3). The 93 lakes in Astore and 166 lakes in Jhelum basin indicated a minor decrease in coverage during the 12-year period. Overall changes in the lakes area were positive in the three river basins indicating a net expansion in lakes area in the Himalaya range. Variable changes in the lakes area in the basins during the 2001–2013 period are shown graphically in Figure 16 and geographically in Figures 17a–c. The formation of several new glacial lakes is mainly a result of glacier retreat that is observed in most of the Hindu Kush–Karakoram–Himalayan region [19]. The influence of climate on glacial lakes is rather complex and cannot solely account for lake variations [4].

S.No.	Feature	50	100	150	200	250	Slice
1	Exposed ridgeline	L	M	H	M	L	L
2	Ridgeline covered under snow/ice	N	P	L	M	H	N
3	Snow/ice in shadow cover	H	M	L	P	N	P
4	Cascading glacier/ice flow pattern	N	P	L	M	H	P
5	Glacial lake	H	M	L	P	P	L
6	Drainage network	P	M	H	M	L	P
7	Moraine boundary	P	M	H	M	L	P
8	Cloud cover/shadow	M	M	L	L	P	P

H = High; M = Medium; L = Low; P = Poor, N = Nil

Table 2. Suitability of stretching values of panchromatic image for identification of various glacial features.

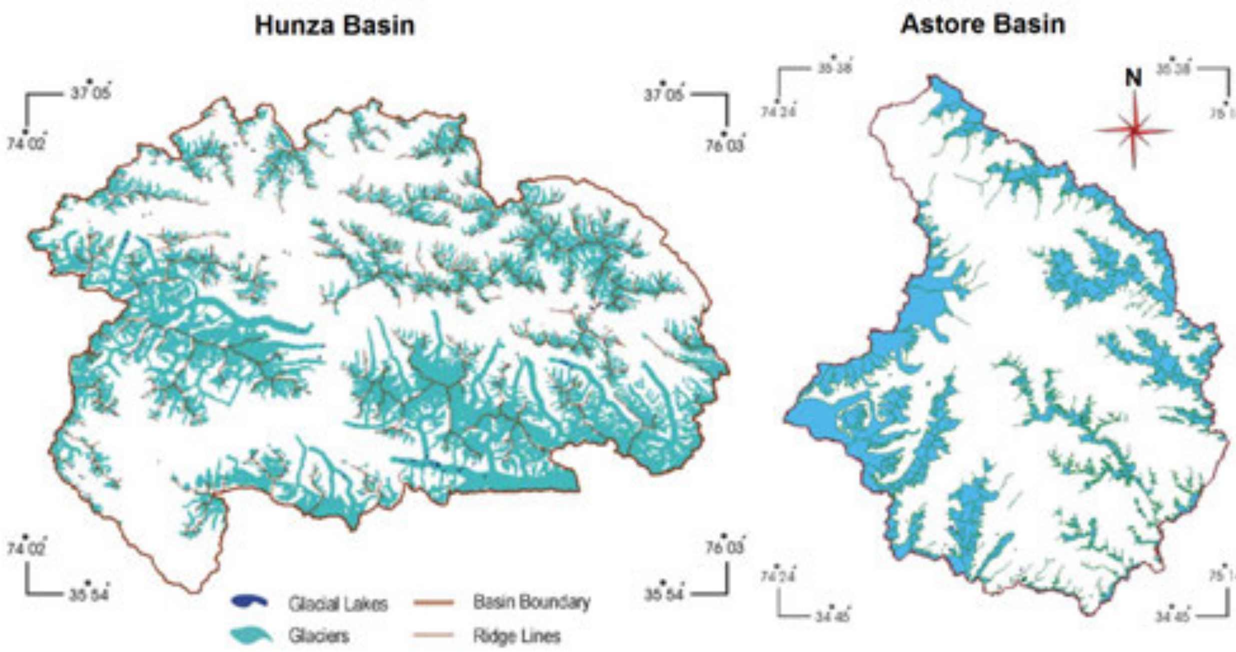

Figure 13. Glaciers and lakes distribution in Hunza and Astore basins.

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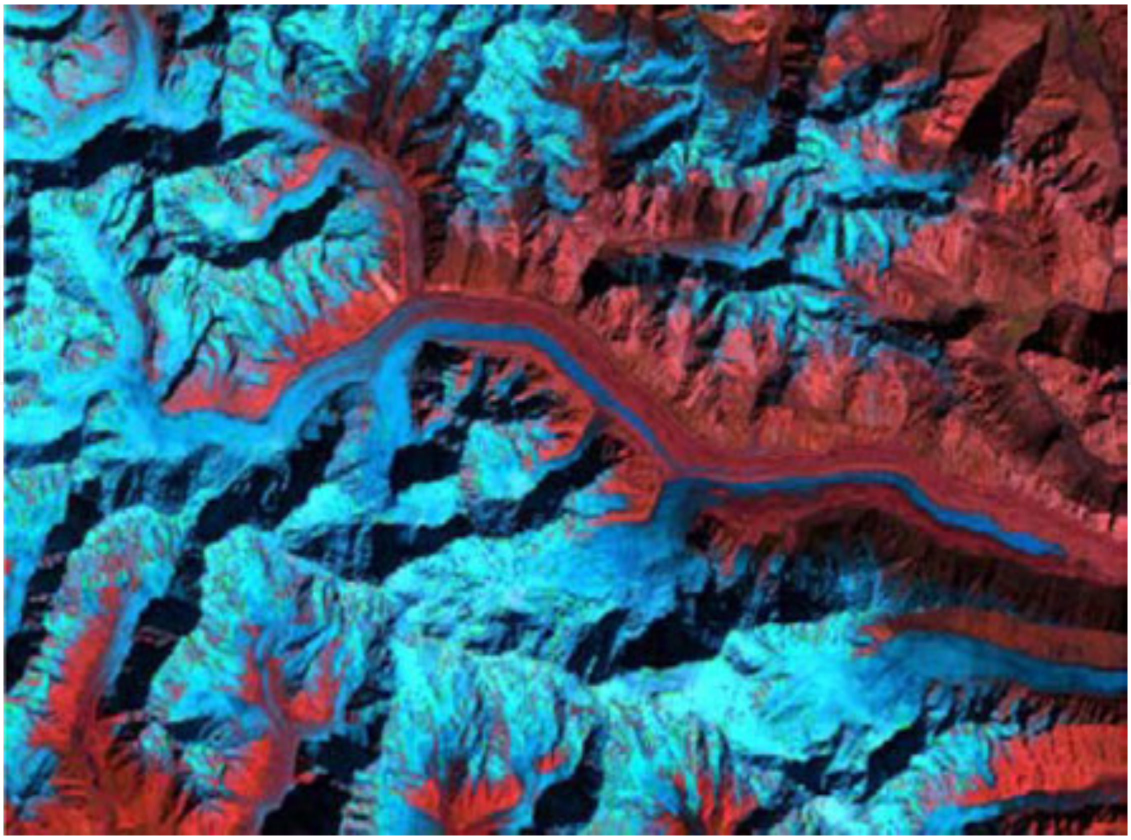


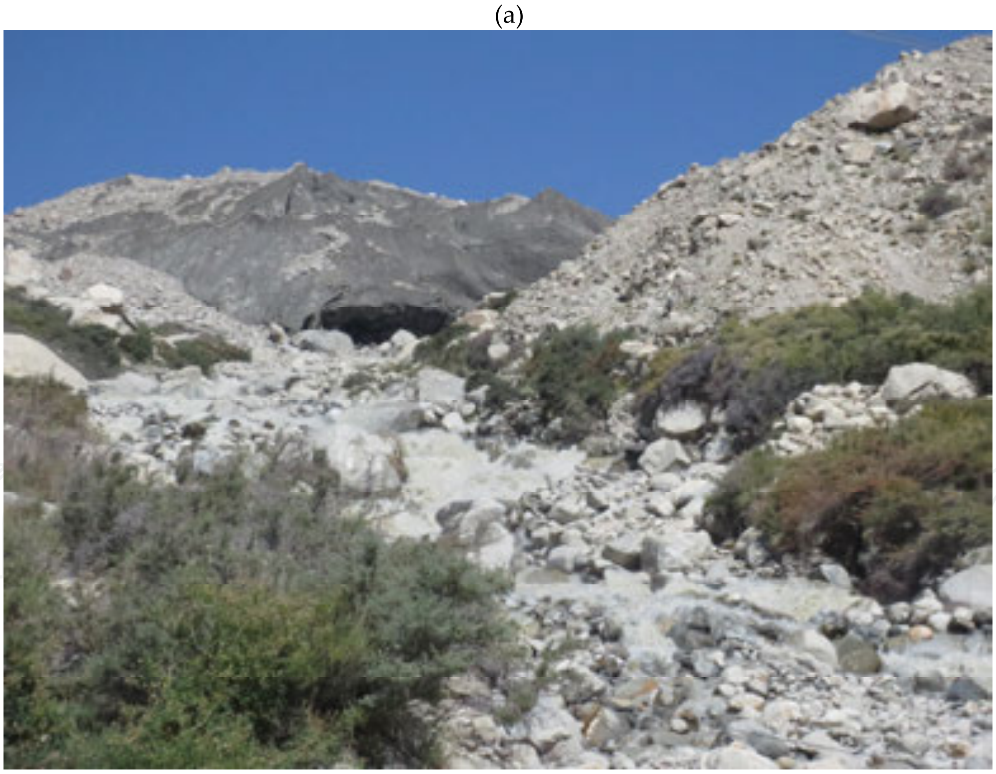
Figure 14. Landsat ETM+ image of a large valley glacier – Batura in upper Hunza valley.

Basin	Number	Area 2001 (km^2)	Area 2013 (km^2)	Change (km^2)
Shingo	204	10.35	10.84	0.49
Astore	93	4.20	3.98	−0.22
Jhelum	166	10.78	10.52	−0.25
Total	463	25.32	25.34	0.02

Table 3. The glacial lakes status in the Himalayas during 2001 and 2013.

In terms of altitude, the expansion in the lakes area of Shingo basin was positive within the 3,500–5,000 elevation range (Table 4). The expansion in the glacial lakes area within 4,500–5,000 m points toward changes in the climatic pattern, e.g., increase in warming condition resulting in melting of snow/ice or liquid precipitation that might contribute to growth of lakes area. In Astore basin, the change in glacial lakes area was positive within 3,000–4,000 and 4,500–5,000 m elevation ranges (Table 4). The maximum number of glacial lakes within 4,000–4,500 m indicated a decline in area due to the effect of glacial hydrodynamics and/or climatic variations at this elevation range. In Jhelum basin, the change in glacial lakes area was positive within 3,000–3,500 m, while it was negative within 3,500–4,500 m elevation range (Table 4). The maximum number of glacial lakes lie within 4,000–4,500 m in this basin (similar to Astore basin), which also indicated a decline in coverage during the 12-year period.

(a)



(b)

(a): The glaciers descending from steep gradients of Karakoram mountains are susceptible to global warming. (b): Frequency of glacial floods has been increased in the HKH region.

Figure 15. (a): The glaciers descending from steep gradients of Karakoram mountains are susceptible to global warming. (b): Frequency of glacial floods has been increased in the HKH region.

Three basins of the Himalayas, e.g., Shingo, Astore, and Jhelum, were selected to analyze variations in the glacial lakes during 2001 and 2013. Overall, 463 glacial lakes common during the two periods were selected for the analysis. The 204 glacial lakes in Shingo basin indicated an increase from 10.35 to 10.84 km^2 (Table 3). The 93 lakes in Astore and 166 lakes in Jhelum basin indicate a minor decrease in coverage during the 12-year period. Overall change in lakes area in the three basins was positive indicating a net expansion of about 0.02 km^2 in the Himalayan range. Variable changes in the lakes area in three river basins during the 2001–2013 period are shown graphically in Figure 16 and geographically in Figures 17a–c. The formation of several new glacial lakes is mainly

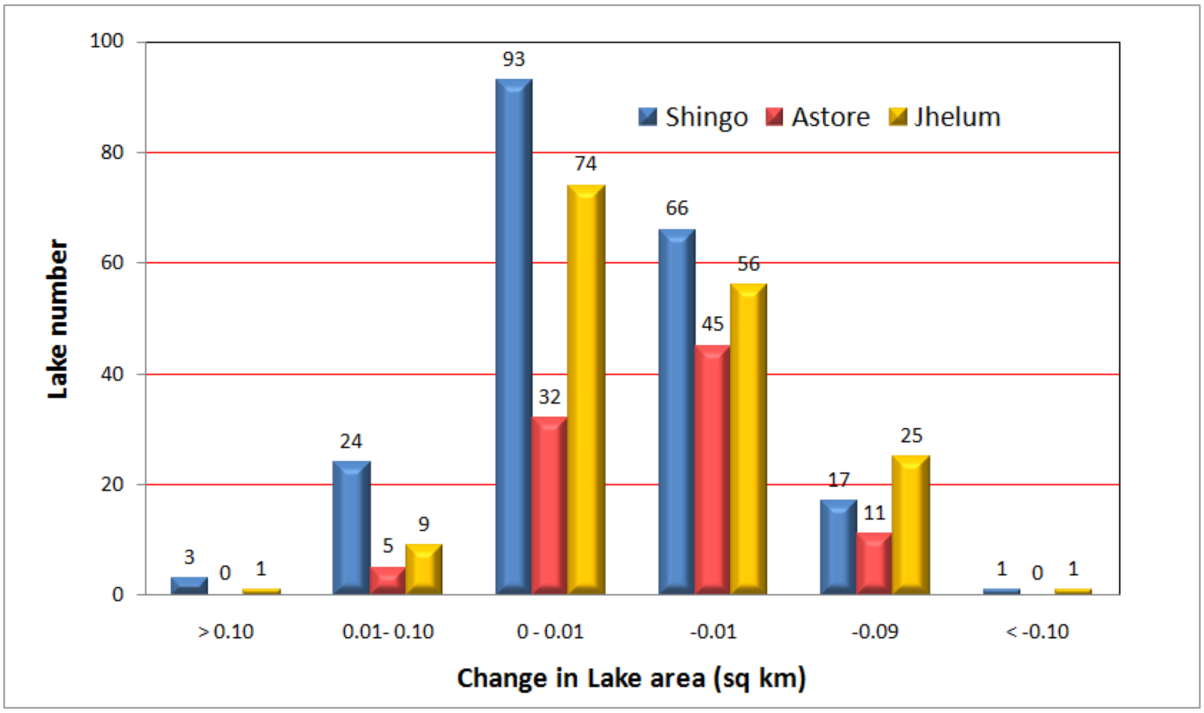
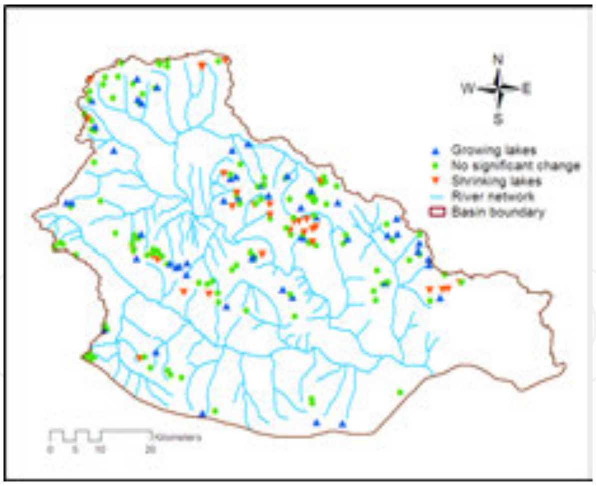


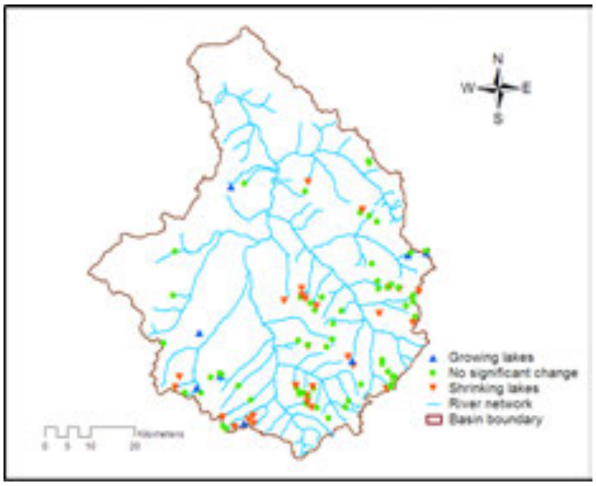
Figure 16. Variable changes in the lakes area in three river basins during the 2001–2013 period.

Elevation (m)	No. of Lakes	Area_2001 (km²)	Area 2013 (km²)	Difference
		Shingo Basin		
3,500–4,000	1	0.01	0.23	0.22
4,000–4,500	75	4.02	4.16	0.14
4,500–5,000	128	6.31	6.45	0.14
Total	**204**			
		Astore Basin		
3,000–3,500	2	0.18	0.21	0.03
3,500–4,000	12	1.37	1.42	0.05
4,000–4,500	62	2.24	1.93	−0.31
4,500–5,000	17	0.41	0.42	0.01
Total	**93**			
		Jhelum Basin		
3,000–3,500	3	1.29	1.46	0.17
3,500–4,000	28	3.27	3.13	−0.14
4,000–4,500	135	6.21	5.93	−0.28
Total	**166**			

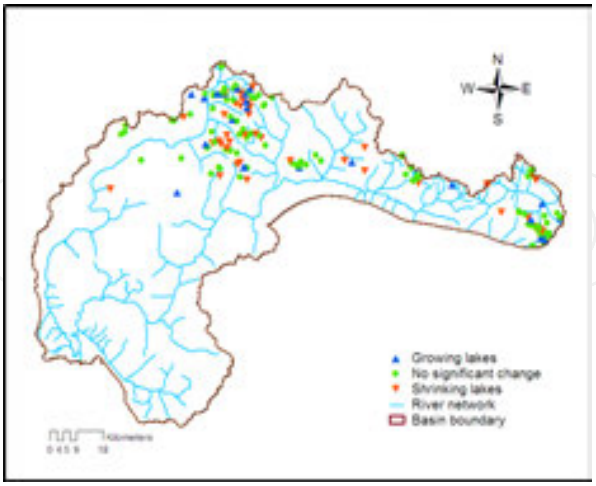
Table 4. Changes in the lakes area by elevation in three river basins during the 2001–2013 period.



(a)



(b)



(c)

Figure 17a: Changes in the lakes area in Shingo basin during the 2001–2013 period. Figure 17b: Changes in the lakes area in Astore basin during the 2001–2013 period. Figure 17c: Changes in the lakes area in Jhelum basin during the 2001–2013 period.

Figure 17. (a) Changes in the lakes area in Shingo basin during the 2001–2013 period. (b) Changes in the lakes area in Astore basin during the 2001–2013 period. (c) Changes in the lakes area in Jhelum basin during the 2001–2013 period.

In terms of altitude, the expansion in the lakes area of Shingo basin was positive within the 3,500–5,000 elevation range (Table 4). The expansion in the glacial lakes area within 4,500–5,000 m points toward change in climatic

The glacier retreat in the Himalayas has resulted in the formation of new glacial lakes and the enlargement of existing ones due to the accumulation of meltwater behind loosely consolidated end-moraine dams [56]. There was a rising trend observed in Astore River flow during the period 1974–2005. The situation may be attributed to the increase in contribution of snow and ice melts in the river flows. The increase in summer temperatures had affected the overall glacial coverage, thickness, and ice reserves during the period 1964–2005. There was a gradual decline in the glacial coverage since 1960s (Figure 18). The melting rates of small glaciers appeared higher than those of the large ones. The trend in depletion of the glacial coverage during 1964–2005 is shown in Figure 19. There are previous studies that highlight the receding of glaciers in most of the Himalaya and a general shrinkage on a global scale [30, 31].

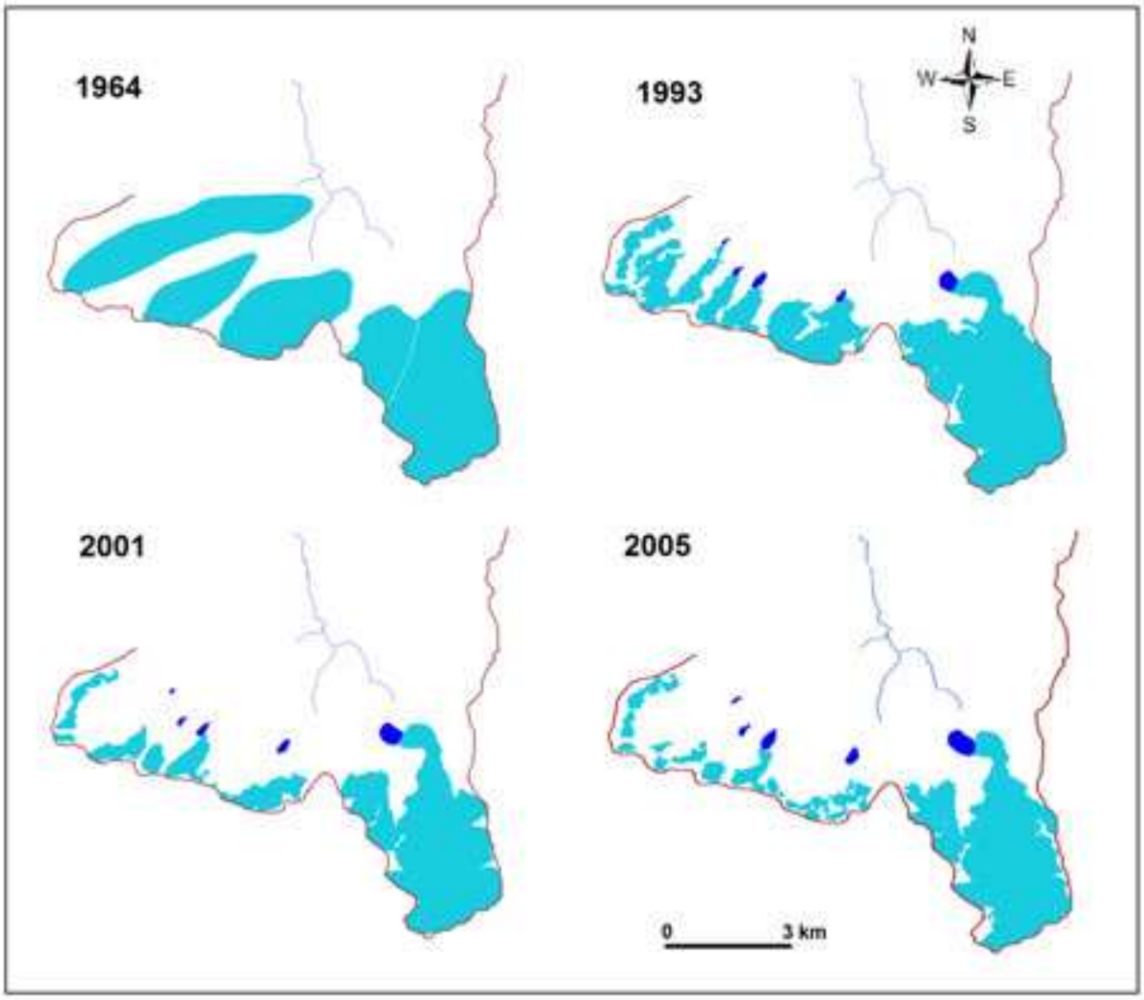


Figure 18. Spatiotemporal analysis of glaciers and glacial lakes in Astore basin.

The melting of glaciers results not only in reduction of surface area and thickness of glaciers but also in expansion of the associated glacial lakes. A large valley glacier *Folvi* (Gr 1) is expanding at a rate of about 0.013 km^2 y^{-1} [57], while the depletion of this glacier resulted in expansion of its associated glacial lake at a rate of about 0.009 km^2 y^{-1} since 1993. Local geomorphic and climatic parameters may influence the retreat of individual glaciers and may not represent the regional changes in climatic condition.

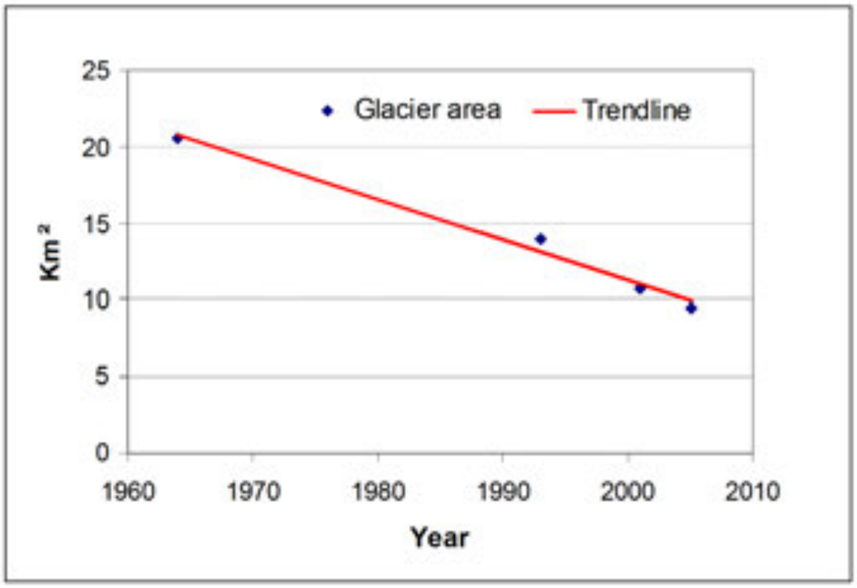


Figure 19. Variation in glacierized area at different time periods in Astore basin.

4.3. Scenarios of impact of climate change

The impact of rise in annual temperature '*T*' on river flows was analyzed. It was observed that there was an increasing trend in winter maximum and minimum temperatures of Gilgit from 2011 to 2099. The average values of winter maximum and minimum temperatures were used in snowmelt runoff model to predict future flows of Gilgit River. By increasing the annual maximum and minimum temperatures to 1.24°C until 2050, the summer flows will increase by 16%, and when this temperature increases to 2.78°C untill 2099, summer flows will increase by 34% (Figures 20a&b). Global warming may intensify the summer monsoon, and thereby enhances precipitation especially downstream of the Indus River [25]. The rise in temperature may accelerate the process of seasonal snow and glacier melting resulting in a gradual increase in the river flows.

The results obtained from regional climate model (PRECIS) show that there is an increasing trend of winter precipitation in Gilgit River basin. On this basis, scenarios were developed such that if cryosphere area in Gilgit increases in future due to increase in winter precipitation then what will be its effect on future flows? In previous studies, it was assumed that cryosphere area would increase due to increase in precipitation in Karakorum region as explained in Refs. [53, 58]. Therefore, on this basis, the scenario of 10% increase in the cryosphere area until 2050 and 20% increase in the cryosphere area until 2075 was used in SRM to predict future flows of Gilgit River. According to the modeling results, if cryosphere area increases to 10% and 20% in the basin, summer flows will increase to 13% and 27%, respectively (Figures 20c&d).

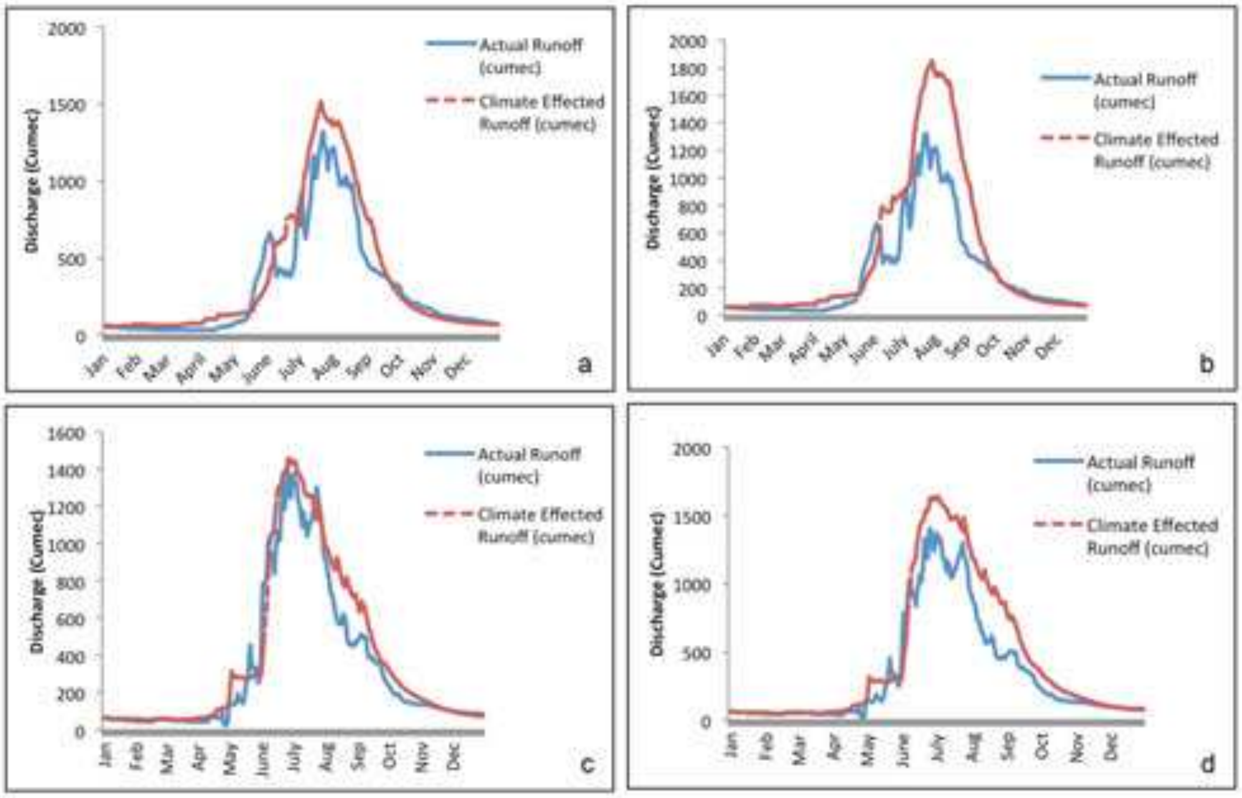


Figure 20. Climate effected runoff due to rise in average annual temperature until 2050 (a); until 2099 (b); increase in cryosphere area by 10% (c); and by 20% (d) in Gilgit basin, Central Karakoram.

4.4. Hazard assessment and early warning using RS technique

The primary functions of remote sensing approach within the climate risk cycle in glacial environment are to develop understanding of the hazards and monitoring the status of glacial lakes and associated glaciers. Predicting whether a glacier will block a valley and, if so, whether a hazardous lake will develop is difficult and requires monitoring of glaciers through physical approach or remote sensing technique. Current hazard assessment efforts depend on detecting margin fluctuations of those glaciers in physiographical settings favorable to lake development observed through field inspection or derived from optical satellite images. Small supraglacial lakes in majority of cases are not hazardous, but they may generate surprisingly large floods that represent hazards at local scales. They can be particularly difficult to identify and assess using remote sensing because of their frequent small size and short life span. Because of the tendency for repeat events from a single glacier, historical reports of GLOFs and local knowledge are important sources of information.

Early warning systems are helpful in reducing the threat of glacial hazards posed to people in downstream. A complete and effective early warning system mainly comprises interrelated elements: risk knowledge, monitoring and warning service, dissemination and communication, and response capability. The human dimensions of early warnings imply that traditional systems are more likely to factor in attachment to the home environment, assets, belief systems, and traditional coping strategies [59]. Although community's involvement in early warning systems is important, remote sensing technology can facilitate in solving the scientific issues related to hazard monitoring, forecasting, and telecommunications.

5. Conclusions

The results of the study reveal that glaciers in this part of Himalayan region are being affected by global warming. Increase in the number of glacial lakes in the recent decade provides clue to the changing glacial environment of the Upper Indus basin. The integrated use of RS and GIS techniques with sparse in situ data is found helpful in analyzing the glaciers' behavior of the Himalayan region. Minimum numbers of large-sized glaciers were identified in the Himalaya basin, which points toward higher rates of glacial ice melting in this range. On the contrary, the presence of relatively higher numbers of medium- to large-sized glaciers in the Karakoram basin provides an evidence of favorable climatic conditions for the glaciers' existence at higher altitudes. Similarly. the increase in snow coverage observed in the Hunza basin of Karakoram during the 2001–2011 may result in ice mass gain in the basin. In order to detect potentially critical glacial lakes in advance, adoption of reliable and robust RS-based approaches is required. The rapidly expanding glacial lakes especially near the headwaters and settlements in the glacierized basins needs to be monitored periodically on a long-term basis to mitigate the risk of any future flood hazards in the HKH region. An in-depth study of the impact of global warming on cryosphere of the Himalayan region using high-resolution remote sensing data (IKONOS, QuickBird, aerial photographs) combined with detailed field investigations is required to cope up with situations such as diminishing water resources and flood hazards in the downstream areas in future.

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