

Remote Sensing Data Application to Monitor Snow Cover Variation and Hydrological Regime in a Poorly Gauged River Catchment—Northern Pakistan*

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ABSTRACT

Snow- and glacier-nourished river basins located in the Himalaya-Karakoram-Hindukush (HKH) ranges supply a significant amount of discharge in River Indus upstream Tarbela Dam. It is, hence, important to comprehend the cryosphere variation and its relationship to the stream flow in these high-altitude river catchments. The MODIS remotely sensed database of snow products was chosen to examine the average annual snow and glacier cover (cryosphere) variations in the Shigar River basin (poorly gauged mountainous sub-catchment of the Indus River). Hydrological regime in the area was investigated through monthly database of observed stream fluxes and climate variables (precipitation and mean temperature) for the Shigar River catchment. Analysis indicated the usefulness of remote sensing techniques for estimation of the snow cover variation in the poorly or un-gauged high-elevation catchments of the HKH zone. Results also showed that Shigar River discharge was influenced mainly by the seasonal and annual snow cover area (SCA) variation and the temperature seasonality. Moreover, it is important to uncover such inter-relationship of stream flow, climate variables and snow cover in the poorly gauged high-altitude catchments of Karakoram region for better water resource management and accurate flood hazards predictions at Tarbela.

KEYWORDS

Shigar River Basin; Satellite Remote Sensing; MODIS Snow Products; Water Resources Management; ASTER-GDEM

1. Introduction and Background

Pakistan, the world's sixth largest populated country, is an agro-based economy where the lives of ~60% people (mostly rural inhabitants) are either directly or indirectly affiliated to agriculture. Pakistan is an arid to semi-arid country with rainfall contributing only ~10% to agriculture [1]. Agriculture of Pakistan thus depends on irrigation system constituted by a gigantic chain of hydraulic structures. The Indus River and its two eastern tributaries—Jhelum and Chenab, commit a main share of the water supply to this irrigation system. Reference [2] has shown that the livelihood of the people of Pakistan is

strongly dependent on the agriculture, which in turn is relying on the vast irrigation system of the country *i.e.* Indus Basin Irrigation system. Originating in Tibetan Plateau, the Indus River passes through the towering mountainous ranges of Hindukush-Karakoram-Himalaya (HKH). The catchment area upstream Tarbela reservoir is named as Upper Indus River Basin (UIB) (**Figure 1**). The catchment area is located in four countries of South Asia namely Pakistan, India, China and Afghanistan, with the largest part in Pakistan. Permanent ice caps including many of the world's largest glaciers cover ~11.5% of the total UIB area that makes it largest glaciated area out of Polar and Greenland regions [3,4].

Mountains bring the main water resource for the Indus Basin Irrigation System as a consequence of snow- and

*Remote sensing of snow cover variation in poorly gauged catchment.

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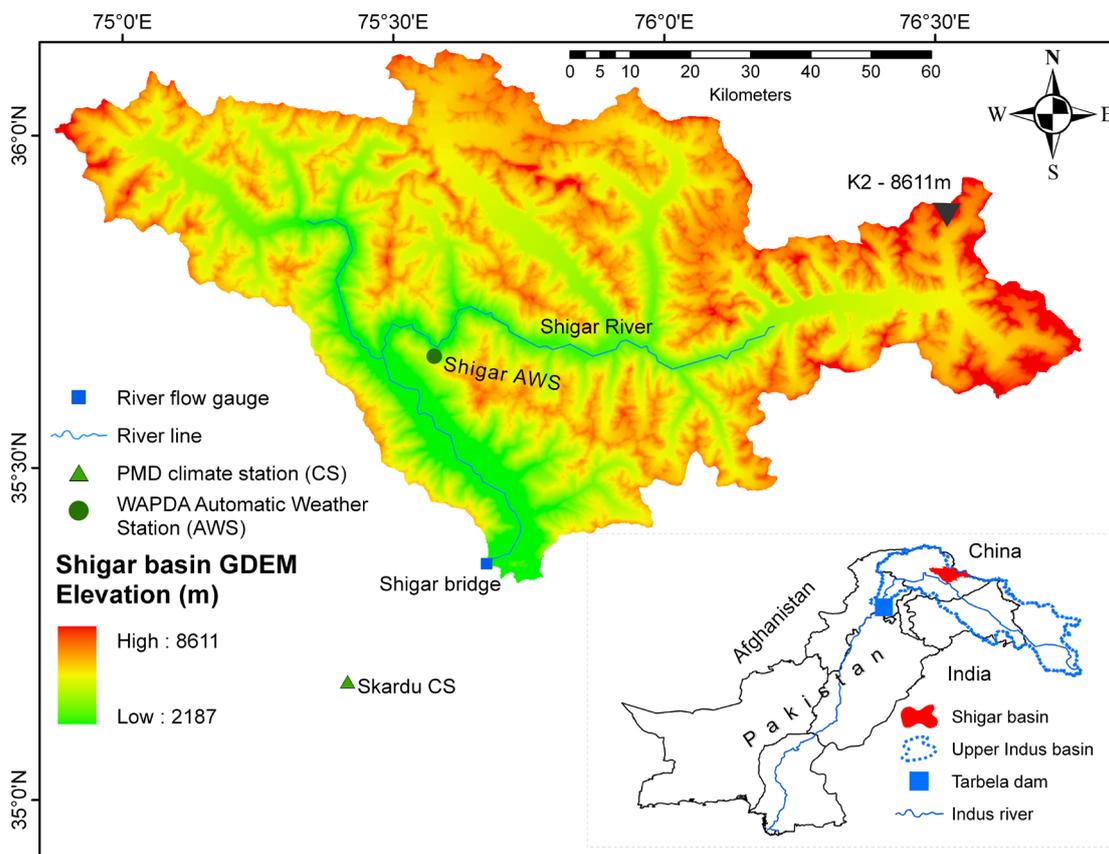


Figure 1. Location of the study area and its Global digital elevation model (GDEM).

glacier-melt water. The Indus river channel in mountains of northern-Pakistan contributes more than half the total flow upstream Tarbela Dam (key storage at Indus) (Figure 1). Indus River flow is dispensed by coalition of direct runoff from rainfall both during the winter and the summer monsoon seasons, and melted outflow from seasonal and permanent snow and ice fields [5]. Different studies (e.g. [6-11]) propose that the snow and glacier melt in the HKH range contributes more than 50% of annual flow in the Upper Indus River.

Deterioration of snow cover area (SCA) is a globally prevalent phenomenon since past few decades, which is accredited to global warming. The degradation of SCA has an intense influence on stream water availability in the river basins where snow and glacial melt constitute the main component of stream flow in summer. The status and condition of cryosphere is crucial in future water planning; providing more melt water initially on shrinking and then reducing it gradually till the glaciers disappearance. On the contrary, advancing glaciers may store solid-precipitation, reducing summer stream flow and can cause local hazards [1]. In the preceding century a clear effect of climate change has been observed on snow and ice globally [12]. Climatic factors such as precipitation and cloud cover also have an effect on the glacial

recede but air temperature is aforesought to be the greatest influential. Reference [13] has stated that changes in temperature are likely to govern the glacial contraction even in the regions where precipitation is expected to raise.

While accelerated ice cover melting has been proclaimed from the world including the neighbouring Greater Himalaya [14], the Karakoram Range shows a subtle situation as highlighted by the IPCC “Intergovernmental Panel on Climate Change” [12]. Central Karakoram is the biggest of those regions where augmentation of glaciers in length and mass is noticed by various researchers (e.g. [15-18]). Since mid-1990s, few of the substantial glaciers in the Karakoram Range have surged; 13 glaciers of intermediate size (10 - 20 km in length) and 16 high-altitude tributaries are perceived to be thickening [4,19]. These variations have been investigated only in the high altitude central Karakoram region. This discrepancy in glacier development indicates a different climate pattern in Karakoram from in the Greater Himalaya [20]. Different climatic regimes influence the UIB: the monsoon rainfall dominates the Southern Himalayan sub-catchments of UIB and snow and ice ablation is the main source of runoff from Karakoram regions of UIB [21]. Therefore, the Indus River can be very de-

licate to the climate change in HKH region which, if comes true, will significantly increase or decrease the Indus River discharge in future.

Snow cover has a momentous part in the system of Earth's climate. But the actual amount of precipitation in the form of snow received at high-altitudes is poorly gauged because of well known catching errors (e.g. strong winds at higher elevations) or even un-gauged due to the lack of observation stations in these remote areas. Shigar River basin (**Figure 1**) in HKH region is an example of inadequately gauged catchments, thus posing key concerns in flow forecast from snow and glacier melt. Reference [1] has reported that few measures from accumulation pits above 4000-meters above sea level (m.a.s.l.) in UIB varied from 1000-mm to more than 3000-mm annual precipitation, conditional upon the location. Mapping snow-cover area and snow volume as explained by [22] is another way to estimate the solid precipitation. Satellite remote sensing can be a very helpful tool to map and examine snow and glacier cover variation in such remote and inaccessible areas [23] and predict the seasonal flow from snowmelt. The use of remotely sensed satellite data for the mapping of snow-cover extent has a long history reaching back until the 1960s [22]. Reference [22] shows that the satellite remote sensing data can efficiently map snow-cover characteristics and snow mass in both high temporal and spatial resolutions. Reference [24] coupled the satellite remote sensing technique with ground observations to analyse successfully the influence of global warming on the Himalayan cryosphere.

The management of Tarbela reservoir (**Figure 1**) calculates largely on the summer influx conferred by the snow- and glacier-nourished tributaries of Indus River located in the high-altitudes of HKH range. It is, for this reason, crucial to estimate the seasonal snow cover in high-altitude snow-fed catchments using remotely sensed satellite data for various aims such as hydrometeorology, flood predictions and water resource management. Aforementioned study is one of the few to look into the annual cryosphere (snow and ice cover) change using the remotely sensed MODIS snow cover data (MOD10A2) in a snow- and glacier-fed River basin (Karakoram region). The main research contents of this paper are to investigate the:

- 1) Average annual snow and glacier cover variation in a high-altitude river catchment area situated in the HKH region using MODIS remote sensing snow product;
- 2) Dependence of River flow on annual cryosphere variation in the study area using satellite data and ground observations;

Correlation of River flow, climatic variables (mean temperature and precipitation) and snow cover variation in the study area.

2. Study Area

The geographical area taken into account for this study is Shigar River basin (**Figure 1**) (one of the UIB sub-catchments) situated in the northern areas (Karakoram region) of Pakistan. Some key characteristics of this river basin are presented in **Table 1**.

Shigar River basin ranges from 74.5° - 76.5°E in Longitude, and 35.2° - 36.38°N in Latitude. The catchment area of Shigar River is ~7000-km² at Shigar Bridge (flow gauge point of Shigar River) (**Figure 1**), as calculated from the Advanced Spaceborne Thermal Emission and Reflection Radiometer-Global Digital Elevation Model (ASTER-GDEM) in this study.

Its entire catchment is situated within Pakistan and is significant for evaluating the influence of climate change within the Karakoram Range of Pakistan. The peak elevation in this catchment area is reached by K2-Mountain (**Figure 1**) with 8611-m.a.s.l. and the lowest point is at Shigar Bridge at 2187-m.a.s.l (**Figure 1**). The mean elevation of the catchment is ~4705-m.a.s.l. (calculated from the hypsometry using ASTER-GDEM) (**Figure 2**) and ~35% of the area is over 5000-m.a.s.l. (calculated from the hypsometry using ASTER-GDEM) (**Figure 2**).

The major proportion (~80%, surface area of ~13,000-km²) of total Karakoram glaciers is located within Pakistan [25]. The most important are the Biafo (~63-km long) and Baltoro (~60-km long) (**Figure 3(a)**) situated in the Shigar River basin.

The hydrological regime in the Shigar River basin is, to some extent, influenced by monsoon while the snow and glacier melting contributes the major proportion. The Shigar River has a mean yearly flow of ~206 m³/s (*i.e.* 930-mm of water depth equivalent) gauged at Shigar Bridge (**Figure 1**), as calculated from the 15-years (1985-2001) flow record of the SWHP-WAPDA in this study. The governing sustenance for the glacier systems of the Karakoram Range is provided by the Westerlies precipitation system during winter [26]. There is one AWS (Automatic Weather Station) (**Figure 1**) installed in the Shigar basin and the other climate station (CS) is installed at Skardu (**Figure 1**) outside the catchment boundary of Shigar near the catchment outlet. The climate data used in this study is the averaged data of both AWS and CS. The mean total annual precipitation is ~216-mm at Skardu CS and ~405-mm at Shigar AWS according to the available data in the catchment. Being at higher-altitude (~3500-m.a.s.l. as estimated by superposing the AWS on GDEM—*exact value of altitude for AWS should be verified*), Shigar AWS receives more precipitation than Skardu CS (~2200-m.a.s.l.). However, the present total annual precipitation records at both climate stations are not illustrative of the runoff at the Shigar River outlet because of the climate data scarcity at altitudes above 4000-m and under-estimation of winter

Table 1. Key characteristics of the study area (Shigar River basin).

Catchment name	Shigar
River flow gauging station	Shigar Bridge
Latitude	35°25'12"N
Longitude	75°42'36"E
Elevation of river gauging station.	~2187-m
Drainage area (computed from ASTER GDEM in this study).	~7000-km ²
Glacier-covered area.	~2120-km ² (Calculated using, "World Glacier Inventory" data in this study) ~2774-km ² [1] ~2240-km ² (4)
Glacier cover percentage.	30% - 39% (Estimated from different sources mentioned above e.g. WGI, [1], Campbell)
Mean elevation (computed from ASTER GDEM in this study).	~4705-m
Area above 5000-m (computed from ASTER GDEM in this study).	~2460-km ² , ~35%
Meteorological station data used in this study.	1 (managed by PMD) – Skardu (~2210-m) 1 (managed by WAPDA) – Shigar AWS (~3500-m, estimated by super-posing the AWS on GDEM) – exact value of altitude for AWS should be verified

⁴Campbell JG (2004) Inventory of Glaciers, Glacial Lakes and the Identification of Potential Glacial Lake Outburst Floods (GLOFs) Affected by Global Warming in the Mountains of India, Pakistan and China/Tibet Autonomous Region, Final report for APN project 2004-03-CMY-Campbell. Kathmandu, Nepal: International Centre for Integrated Mountain Development; Kobe, Japan: Asia-Pacific Network for Global Change Research.

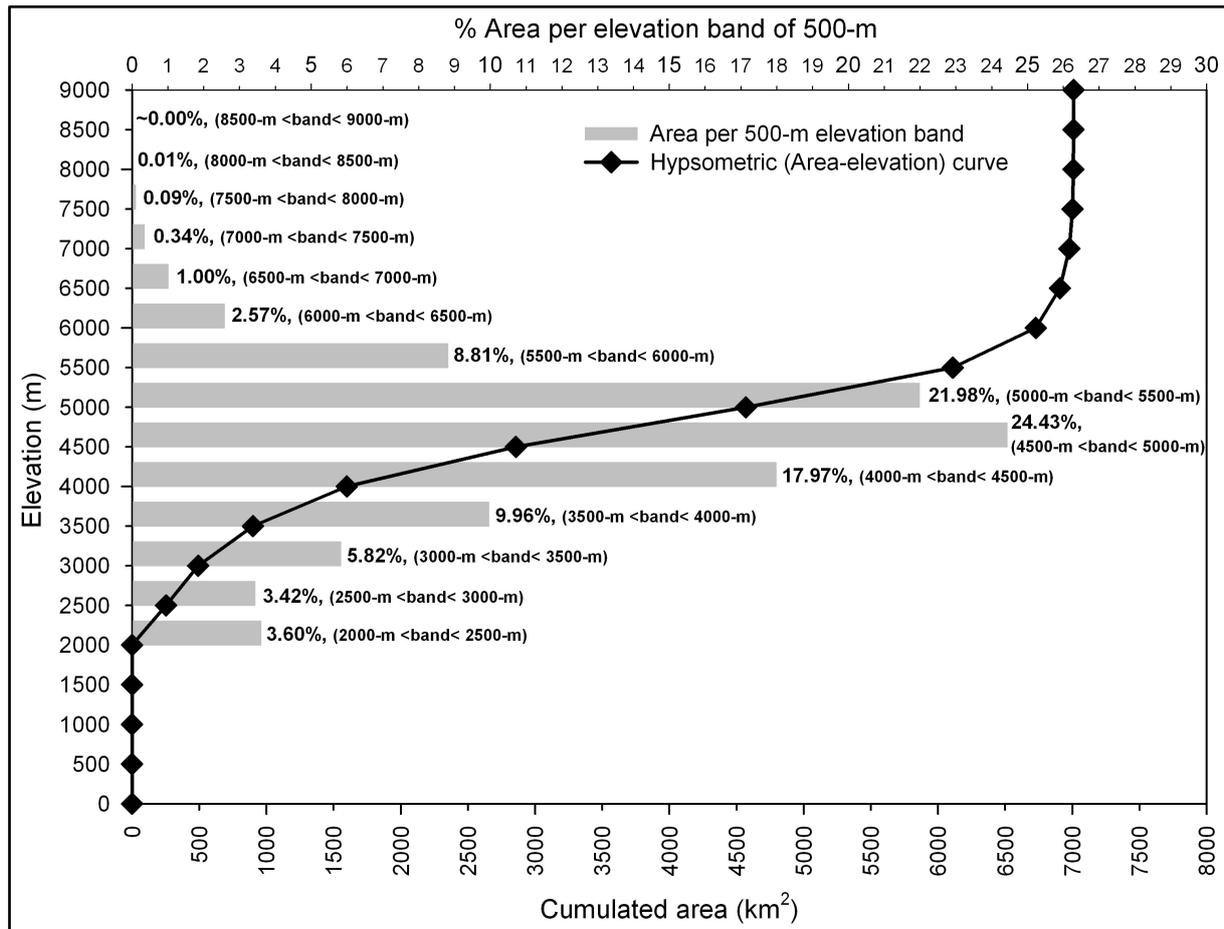


Figure 2. Hypsometric curve and the area under 500-m elevation band of the Shigar River basin.

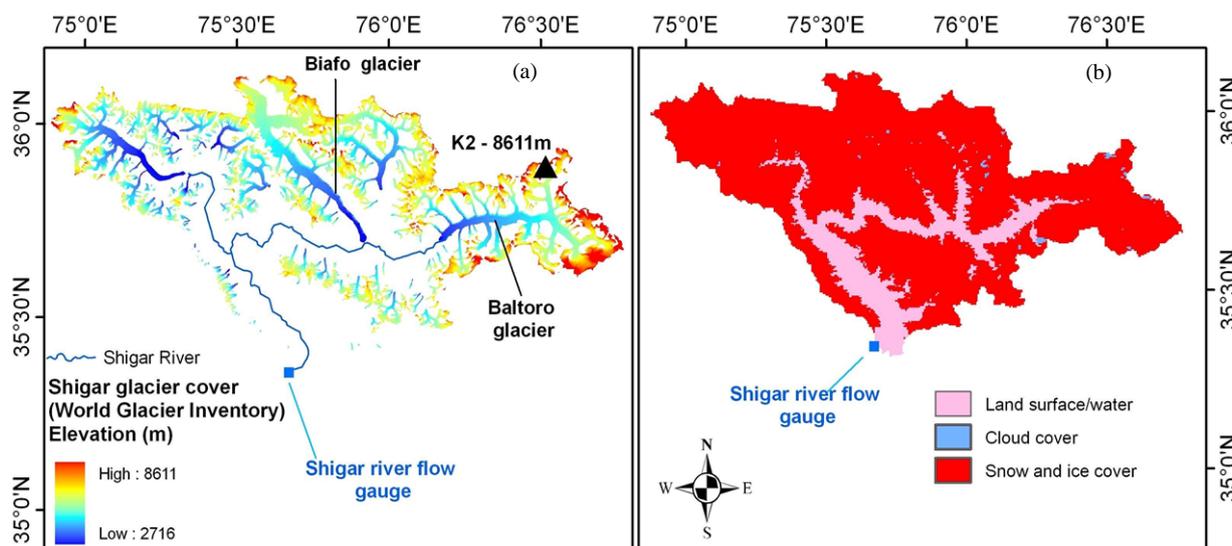


Figure 3. (a) GDEM showing glacier cover area using WGI (World Glacier Inventory) data and (b) An example of MODIS snow cover image for the Shigar River basin.

precipitation (snow) in this basin and may also be associated to the well-known gauging errors (wind induced, wetting loss, trace precipitation, blowing and drifting snow, and systematic mechanical errors etc.) in high mountain environment described by many authors, e.g. [27-29].

3. Data Sets and Treatment

In order to accomplish the study objectives, two types of data sets were obtained:

- 1) Satellite Remote Sensing Data (downloaded from the NASA website <http://reverb.echo.nasa.gov/reverb>).
 - ASTER-GDEM.
 - MODIS MOD10A2 snow product.
- 2) Hydro-meteorological Data (Stream flow, mean temperature and precipitation).

3.1. Satellite Remote Sensing Data

The satellite remote sensing data were obtained from two sources to be used for two different purposes. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)-Global Digital Elevation Model (GDEM) data was employed for sketching out the catchment area (Shigar Basin) (Figure 1) and calculating the hypsometric curve (area-elevation) (Figure 2). The ASTER-GDEM based on ASTER images is handy for high-latitude and steep mountainous areas not attained by SRTM3 [30]. It is set up on ASTER images and has a resolution of 30-m \times 30-m. It was referenced to WGS84/EGM96 coordinate system. The downloaded ASTER tiles were mosaicked and treated through a variety of steps using standard ARCMAP techniques (©1995-2012 ESRI) to draw the Shigar River catchment region. AS-

TER-GDEM was also treated to estimate the hypsometric-curve and the catchment area in every 500-m elevation band (Figure 2). World Glacier Inventory (WGI) data [31] was used along with ASTER-GDEM to extract the glacier cover (Figure 3(a)) from the catchment area.

Moderate Resolution Imaging Spectroradiometer MODIS/Terra Snow Cover 8-Day L3 Global 500-m Grid (MOD10A2) snow products for 10-years (2000- 2009) were utilized to estimate the snow cover variation in the study area. The monthly average values of SCA were estimated to analyse its relationship with hydro-meteorological variables. MODIS Snow products (MOD10A2) contain data fields for maximum snow cover extent over an 8-day composite time, projected with the **WGS 1984 UTM ZONE 43N** projection system. MOD10A2 is constituted of 1200-km \times 1200-km tiles of 500-m resolution data gridded in a sinusoidal map projection. MODIS cryosphere data is established on a snow-mapping algorithm that procures a Normalized Difference Snow Index (NDSI) and other criterion tests [32].

MODIS snow cover products have been extensively exploited to reckon the snow cover area (to couple it with hydrological models for flow simulation and forecasting) by various researchers (e.g. [33-37]) in numerous geographical areas of the world. Reference [38] correlated the accuracy of MODIS, NOAA and IRS Data and illustrated that MODIS data could be more effective for SCA evaluation, which is an important factor for snow-melt runoff modelling. Many researchers (e.g. [39-41]) evaluated MODIS/Terra daily snow-cover and meteorological product through comparability with ground investigations and found that the misclassified fractions of MOD10A1 were in general lesser at high elevations than at low elevations. Reference [41] observed the snow-

mapping correlation coefficient value of ~95% between seasonal MODIS daily snow maps and in-situ observations under clear-sky conditions. Reference [42] explained that the snow products derived from EOS-MODIS, AMSR-E and QSCAT data have been harmonised into a solo, worldwide, diurnal, user-friendly product via a latest developed Air Force Weather Agency (AFWA)/NASA Snow Algorithm (ANSA). A higher efficiency is also suggested for outlining snow-cover area with the MODIS product than with the AMSR product upon cloud-free MODIS images availability. Reference [42] used MODIS snow product as the default for estimating snow cover for this previously mentioned reason. The passive microwave product AMSR was preferred barely in those domains where MODIS data were not suitable due to clouds and darkness [42].

The snow-mapping algorithm differentiates pixels as snow, ice lakes, cloud, water, land or other. Snow extent is the variable of prime significance in this data set. The temporal search of snow cover through MOD10A2 was carried out through images downloaded from the above-mentioned NASA website. The study area (Shigar basin) was then extracted by mask function from the treated MODIS snow cover images (Figure 3(b)) using ARCMAP (©1995-2012 ESRI). Snow cover area was estimated from the cloud free images. If the cloud cover exceeded 15% on a specific date then the image was excluded from the time series. The snow cover on this date was then estimated by linearly interpolating between the previous and next cloud free image.

3.2. Hydro-Meteorological Data

The hydrological and meteorological data sets were obtained from WAPDA (Water and Power Development Authority) and Pakistan Meteorological Department (PMD), respectively. Surface Water Hydrology Project of Water and Power Development Authority (SWHP-WAPDA) mostly do stream flow assessment in Pakistan. PMD-CS has quite a long data series for climate variables while WAPDA-AWS are installed in 1995 and thus have shorter data series.

The monthly average stream flow was estimated from the available data of ~15-yr (1985-2001) in order to comprehend the correlation among stream flow and snow cover area of Shigar Basin. The available data on climatic variables including temperature (min. and max) and precipitation was averaged for the entire period of ~55-yr (1952-2007) for PMD-CS and ~11-yr (1996-2006) for WAPDA-AWS to get the monthly average values. The Pearson Product Moment correlation [43], Spearman Rank Order correlation [44] and Kendall's rank correlation [45,46] tests were performed (with a significance level of $p = 5\%$) to evaluate the relationship between monthly stream flow, monthly snow cover variation and

climate variables (monthly mean temperature and monthly total precipitation) to scrutinize the core regulating constituents of runoff from the Shigar River basin.

4. Results and Discussion

4.1. Snow Cover Variation in the Shigar River Basin

In the present study, the Snow Cover Area (SCA) for Shigar Basin was estimated through MODIS images over the 10-years period (2000-2009). The images were treated through ArcGIS software (©1995-2012 ESRI) and SCA percentage was calculated for each 8-days image. This SCA was then averaged to monthly time step to get the mean monthly values of SCA variation. MODIS images showing intra-annual SCA variation and its values in the Shigar River basin are presented in Figure 4. The average SCA varies from maximum in winter (December-January) to minimum in summer (July-August) (Figure 4). The snow accumulation begins in the months of September-October and the snow-covered area reached to maximum (~88%) in January (Figure 4). The maximum snowmelt (minimum snow-covered area ~10%) was observed in the month of August (Figure 4). This huge variation of SCA from ~88% to 10% can be reflected by high discharges in the Shigar River during snowmelt season because the large snow surface area may contain the higher depths too. This is supported by the study of [26] conducted on the neighbouring Hunza basin. This study [26] explains that the Central Karakoram region undergoes a snow cover change of about 40% - 70% where SCA is 70% - 80% in the winter (snow accumulation period), whereas, SCA is 30% - 40% in the summer (snowmelt period).

Thus these snow- and glacier-fed sub-catchments of Upper Indus River Basin (UIB) make this huge catchment dependent on the snow and glacier melt water. This result also proves the suitability of remote sensing snow products for the snow cover mapping in the un-gauged snow- and glacier-fed high-altitude river basins. Even if the ground observation stations are installed in these river basins; these are not able to catch the exact amounts of winter solid precipitations due to previously mentioned gauging errors (like strong winds) at high-altitudes. It is not possible to regularly monitor these high-altitude remote areas, due to severe climate conditions to cope-with, for the researchers. Therefore, the remote-sensing satellite snow images can be the best solution in these inaccessible regions (during certain seasons) to monitor the SCA on regular basis even in the severe climatic conditions.

The quality of these satellite snow cover datasets is already affirmed by many studies so these may be used for

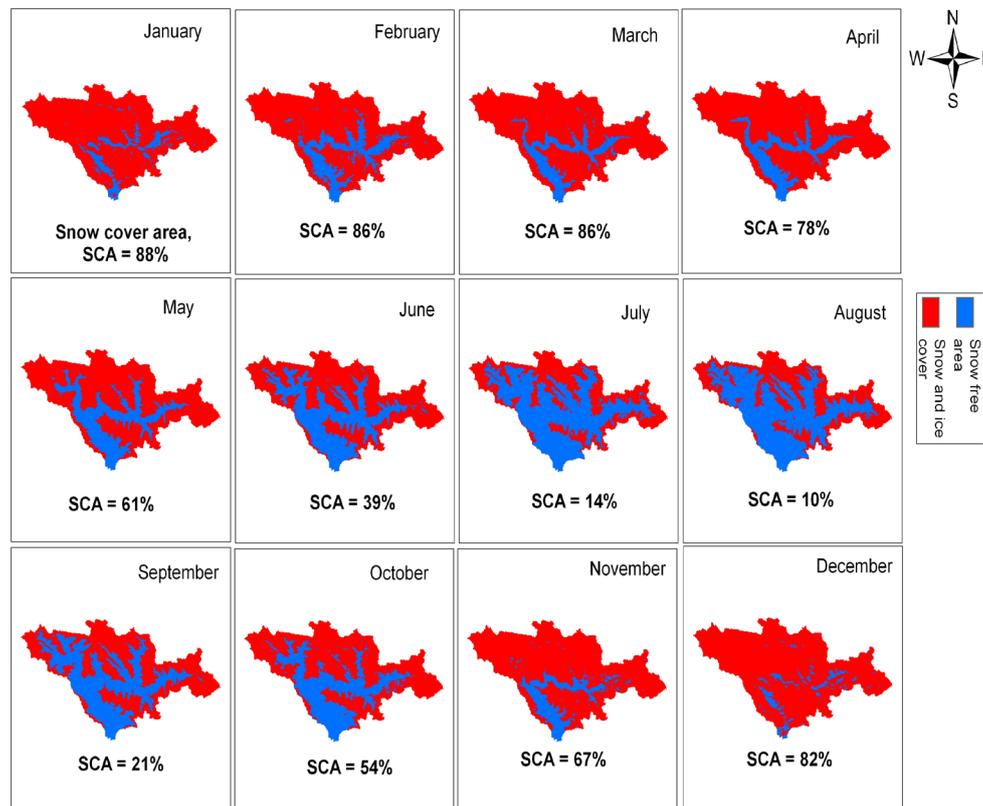


Figure 4. MODIS snow cover images showing intra-annual variation of snow cover for the period of 2000-2009 in Shigar River basin.

the snow mapping of larger areas like Upper Indus River Basin.

4.2. Dependence of Shigar River Discharge on the Snow Cover Variation

The correlation coefficient values showing the relationship of mean monthly Shigar river discharge and mean monthly SCA are presented in **Figure 5** and **Table 2**. High stream flow was observed from July to September when the snow cover area was at its minimum (*i.e.* in summer during the snow melt period) (**Figure 5**). A significant ($p = 0.05$) inverse correlation was observed between SCA and river discharge with $r = -0.87$ for Pearson product moment correlation test and $r = -0.95$ for Spearman rank order correlation test (**Figure 5** and **Table 2**). Kendall's rank correlation test indicated a coefficient value of $r = -0.82$ ($p = 0.05$) (**Table 2**). All these values were significant with a significance level of $p = 5\%$. Data reflect that January to April is the low flow period when the snow accumulates, and it begins to increase gradually when the snowmelt starts in the spring season. The peak river discharge is witnessed at minimum SCA in the months of July to September where the glacial melt and monsoon rainfall overlaps the snow melt. This peak discharge is also the result of $\sim 65\%$ drop in the

SCA from April ($\sim 78.3\%$) to July ($\sim 13.6\%$) that gradually increased the river discharge. Assessing the winter snow accumulation may be helpful to predict the following spring and summer season inflows in the Shigar River discharge.

Inter-relationship of river discharge, SCA, mean temperature and precipitation for the Shigar catchment area is presented in the next section.

4.3. Inter-Relationship of SCA, River Discharge and Climate Variables (Mean Temperature and Precipitation)

All the available data of SCA, river discharge and climate variables (mean temperature and monthly precipitation) was analysed to determine the inter-relationship between all these variables in the study area. Three different correlation tests (Pearson, Spearman and Kendall) were applied with a significance level of $p = 0.05$ (**Table 2**).

Correlation of SCA and mean Temperature: A strong inverse correlation was found between averaged monthly SCA and averaged monthly mean temperature. The correlation coefficient values of $r = -0.82$, -0.78 and -0.64 were found for Pearson, Spearman and Kendall's correlation tests (**Table 2**), respectively. All these values were

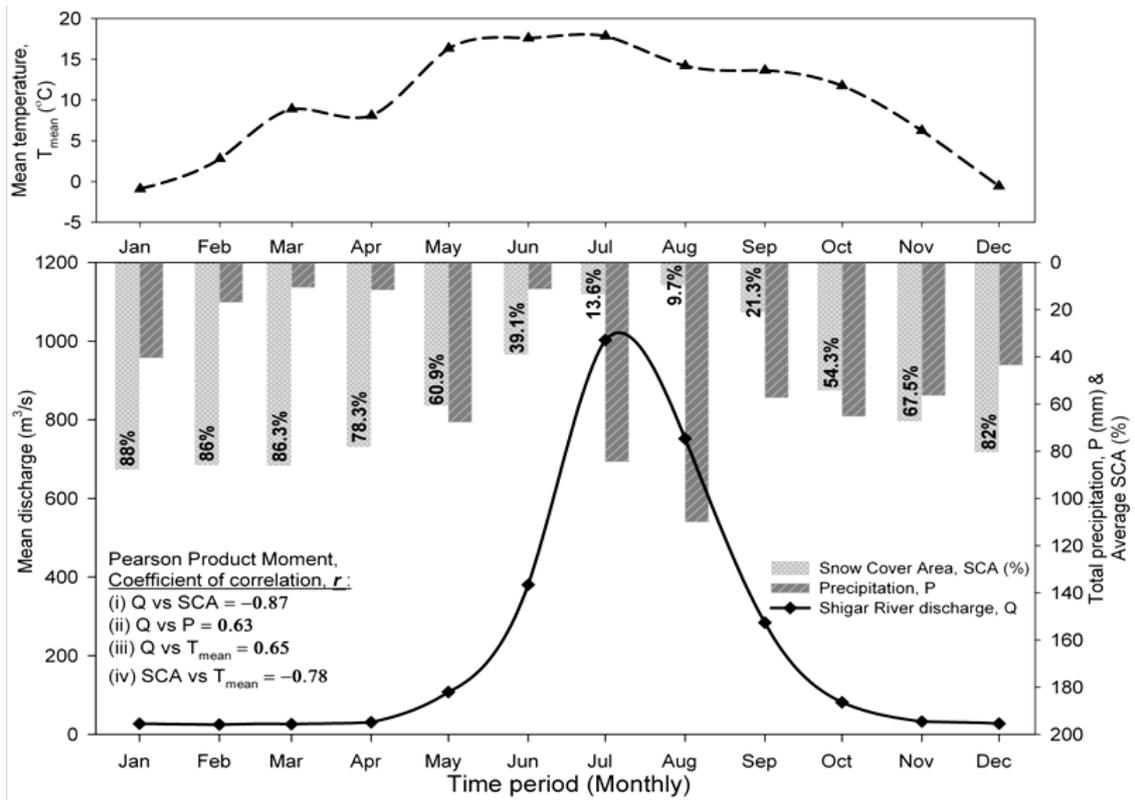


Figure 5. Relationship of mean snow cover area, mean River discharge, mean temperature and total precipitation (monthly time step) in the Shigar River basin.

Table 2. Correlation coefficient values between monthly values of Snow cover area (SCA), River discharge (Q), Precipitation (P) and Mean temperature (Tmean) in the Shigar River basin.

Variables	Kendall's rank correlation	Pearson Correlation	Spearman correlation
Q vs SCA	-0.82	-0.87	-0.95
Q vs P	0.54	0.63	0.66
Q vs Tmean	0.70	0.65	0.85
SCA vs Tmean	-0.64	-0.78	-0.82

All the correlation coefficient values in this table are significant at $p = 0.05$.

significant with a significance level of $p = 0.05$. The correlation graph indicated an inverse relationship between the mean temperature and SCA as shown in Figure 5, where an increase in monthly temperature leads to a reduced SCA and more snow melt and vice versa.

The snow cover is at maximum in the low temperature months from December until March, when the accumulation of snow is dominant over ablation that becomes prominent in the following warmer months June to September causing a marked decrease in the SCA. Minimum SCA is observed at higher mean temperatures in the months of July and August where the snow melt is at peak as discussed earlier.

Correlation of Shigar River discharge with Climatic Variables (mean temperature and precipitation): Figure 5 and Table 2 showed the correlation coefficient values between Shigar River discharge and mean temperature of the catchment area observed at Skardu and Shigar climate stations (Figure 1).

The significant ($p = 0.05$) correlation coefficient values of $r = 0.85$, 0.65 and 0.70 were found for Pearson, Spearman and Kendall's correlation tests (Table 2), respectively. The river discharge and mean temperature correlation curve reflected a direct correlation in the temperature and river discharge in the study area (Figure 5). The river flow starts increasing as the spring season starts and mean temperature tends to increase. The flow gets its peak in July when the mean temperature is at maximum of the year. The low flow periods are observed during low mean temperature periods and the flow is at minimum in the months of December and January when the mean temperature is below freezing point (Figure 5). The increase in mean temperature resulted in a coincident increase in the snow and glacial melt, which reflected in an increased river flow where the peak was observed at the maximum temperature in the month of July (Figure 5) in the study area.

The hydrograph of the Shigar River basin was presented in Figure 5 with the precipitation in the form of

inverted bars and river discharge shown in black solid-line curve. The peak discharge event occurred in the month of July, whereas, the maximum precipitation was received in the month of August (Figure 5). This may be due to the accumulation of precipitation at high-altitudes in the form of snowfall in August, which melts later in spring.

Table 2 presented the correlation coefficient values between Shigar River discharge and monthly precipitation of the catchment area observed at Skardu CS and Shigar AWS (Figure 1). The correlation coefficient values of $r = 0.66$, 0.63 and 0.54 were found for Pearson, Spearman and Kendall's correlation tests, respectively. All these values were significant with a significance level of $p = 0.05$. The peak river discharge and the maximum average rainfall do not coincide which indicates some other controlling factor for Shigar River discharge rather than precipitation. The comparative amount of rainfall in the months of July and August (peak monsoon) was higher than the other months of the year but yet it was much lower than the mean monthly discharge during these months. Reference [6] stated that as a component of the entire yearly discharge, the catchments of western Himalaya, Karakoram and Hindukush range (e.g. Indus River catchment) are sustained up to 50% by the snowmelt. The correlation values between SCA, stream flow and mean temperature are higher than those between the stream flow and precipitation.

The above correlation results indicate that the Shigar River flow is affected by the snow cover variation and temperature seasonality rather than by the monthly precipitation.

5. Conclusions

Located in the high-altitudes of Karakoram, the Shigar river discharge confides primarily on the amount of snow stored at high altitudes and energy influx, indirectly allied to mean temperature. This is proposing that the data estimation methods for climate variables should be upgraded and the remote sensing techniques should be adopted in un-gauged high-altitude catchments to understand the snow cover variation and runoff control factors, further efficaciously. Analyzing the results obtained in this study, can conclude the following statements:

- Remotely sensed MODIS snow products are useful to estimate the snow cover variation in the poorly-gauged/un-gauged high-altitude catchments of the Karakoram region. These are also useful at times of high snowfall during winter season that subsequently limits the accessibility in such high altitude remote areas.
- Shigar river discharge is largely controlled by the seasonal and annual snow cover area (SCA) variation that is directly linked to the temperature seasonality.
- Temperature variation strongly affects the snow cover change in the study area that subsequently affects the river discharge. Precipitation does not put forth profound effect in the river discharge in comparison of SCA and mean temperature.

A continuous monitoring of the snow cover dynamics is required on the high-altitude catchments of the Upper Indus region e.g. Gilgit, Hunza, Shigar and Shyok. These are chiefly snow- and glacier- nourished catchments that inject a hefty amount of discharge to the Indus River. The composite of satellite snow cover data and ground data (e.g. snow-pits and AWS) or information generated by snowmelt-runoff models may be a pertinent scheme to overwhelm the poor gauging of precipitation records at these high-altitudes. Eventually, present investigation may aid to better understand and, enhance the integrated water resource management at the Tarbela reservoir.

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