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# Snow cover dynamics and hydrological regime of the Hunza River basin, Karakoram Range, Northern Pakistan

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## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

A major proportion of flow in the Indus River is contributed by its snow- and glacier-fed river catchments situated in the Himalaya, Karakoram and Hindukush ranges. It is therefore essential to understand the cryosphere dynamics in this area for water resource management. The MODIS MOD10A2 remote-sensing database of snow cover products from March 2000 to December 2009 was selected to analyse the snow cover changes in the Hunza River basin (the snow- and glacier-fed sub-catchment of the Indus River). A database of daily flows for the Hunza River at Dainyor Bridge over a period of 40 years and climate data (precipitation and temperature) for 10 years from three meteorological stations within the catchment was made available to investigate the hydrological regime in the area. Analysis of remotely sensed cryosphere (snow and ice cover) data showed a slight expansion of snow cover in the area in contrast to most of the regions in the world where glaciers are melting rapidly. This increase in snow cover may be the result of an increase in winter precipitation caused by westerly circulation. The impact of global warming is not effective because a large part of the basin area lies under high altitudes where the temperature remains negative throughout most of the year.

## 1 Introduction and background

An agricultural country, Pakistan is highly dependent on the Indus irrigation system, one of the largest irrigation networks in the world (SIHP, 1990). The Indus River emerges from the Tibetan Plateau and flows toward northern areas of Pakistan where it changes its direction toward the south and flows into the Arabian Sea (Fig. 1). It has a controlling storage at Tarbela dam as the river descends from the mountains. The catchment area upstream of Tarbela reservoir is called the Upper Indus River basin (UIB) (Fig. 1), which contributes the main inflow to the main course of the Indus River at high elevations as a result of snow and glacier melt; the lower catchment is rain-fed. Tarbela is the first major

### **Snow cover dynamics and hydrological regime**

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



structure on the Indus River and supplies the flow to the Indus Irrigation System to irrigate the agricultural lands of Punjab (a province of Pakistan), the dominant producer of agriculture products in the country. Inflow to Tarbela is measured at Besham Qila, situated approximately 80 km upstream of Tarbela (Fig. 2), with a mean annual flow of  $2410 \text{ m}^3 \text{ s}^{-1}$  according to the SWHP (Surface Water Hydrology Project) flow records from 1969 to 2008.

The UIB has a total catchment area of  $206\,000 \text{ km}^2$  as calculated in this study. Nearly 11.5% of the total area ( $22\,000 \text{ km}^2$ ) of the UIB is covered by perennial glacial ice including most of the largest valley glaciers, the largest area outside the polar and Greenland regions (Hewitt, 2001, 2007). The Greater Karakoram Range (Fig. 1), situated in UIB, has an extensive formation of glaciers due to high altitudes (Young and Hewitt, 1990), covering an area of  $16\,300 \text{ km}^2$  with about  $13\,000 \text{ km}^2$  of cover within Pakistan (Mercer, 1975). Most of the annual precipitation in the UIB falls in the winter and spring and originates from the west (Young and Hewitt, 1990). The high mountains of Hindukush-Karakoram-Himalaya (HKH) in the UIB decrease the effect of the monsoon in the catchment area, whose influence weakens northwestward; therefore, the climatic records in the UIB are different from the eastern Himalayas (Fowler and Archer, 2005a; Young and Hewitt, 1990).

The main active hydrological zone for the Upper Indus River basin is situated in the high-altitude Karakoram ranges. Archer (2003) explained that the Indus River catchment at Partab Bridge (Fig. 2) has nearly 36% of its area above 5000 m in elevation and is mainly fed by glaciers and snow melt in this area. Several authors (Hewitt et al., 1989; Wake, 1989; Young and Hewitt, 1990) reported that 80% of the flow of the Upper Indus River is contributed by less than 20% of its area, essentially from the zones of heavy snowfall and glacierised basins above 3500 m in elevation. Liniger et al. (1998) stated that some 90% of the lowland flow of the Indus River System originates from the Hindukush, Karakoram and western Himalaya mountain areas. Maurer et al. (2003) stated that the presence of snow in a river catchment area strongly affects the moisture that is stored at the surface and available for future runoff. The summer

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



runoff is highly correlated with the summer mean temperature in these high-altitude sub-catchments of the UIB, mostly covered with permanent snow pack and glaciers (Archer, 2003). Linear regression analysis by Archer (2003) indicates that a 1 °C rise in mean summer temperature would result in a 16% increase in summer runoff into the Hunza River.

Satellite image observation is very helpful in these remote regions of the world to examine cryosphere dynamics. Sirguey et al. (2009) reported that satellite remote sensing is a powerful tool to estimate the snow-covered area in remote and inaccessible areas. MODIS snow cover products have been widely used to estimate the snow cover area by researchers in several regions of the world. Tekeli et al. (2005) compared the MODIS snow cover images with ground observations and found that MODIS determined the snow cover satisfactorily even in the rough terrain river basin located in eastern Turkey. Maurer et al. (2003) found a significant improvement in snow cover determination using MODIS snow cover products, especially in topographically complex portions of the Columbia River basin, as compared to the operational NOHRSC (National Operational Hydrologic Remote Sensing Center) snow cover images. Immerzeel et al. (2009) investigated the effects of snow cover dynamics on the discharge of the upper Indus River and concluded that stream flows can be predicted with a high degree of accuracy using MODIS snow cover data in a hydrological runoff model. Lee et al. (2005) reported that MODIS snow cover products have sufficient accuracy for stream flow prediction using the Snowmelt Runoff model (SRM) in the snowmelt-dominated basin of the Upper Rio Grande basin.

As highlighted by the IPCC's 4th synthesis report (IPCC, 2007), while the rapid melting of the ice cover is reported from High Asia, the Karakoram Range shows a more nuanced picture. Hewitt (2005) reported that central Karakoram is the largest of those very few areas where expansion of glaciers has been noted. Some of the largest glaciers in the Karakoram Range have undergone rapid thickening since the mid-1990s; 13 glaciers of intermediate size (10–20 km in length) and 16 high-altitude tributaries were observed to be advancing (Hewitt, 2005, 2007). These changes were

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

---

**Snow cover dynamics and hydrological regime**A. A. Tahir et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

observed only in the highest central parts of the Karakoram. This is contrary to most of the glaciers in the world reported to be shrinking for the last several decades, including the neighbouring Greater Himalaya analysed by Berthier et al. (2007). This contrast in glacier evolution shows a climate change pattern in Karakoram that differs from that in the Greater Himalaya (Fowler and Archer, 2005b). Hewitt (2005, 2007) stated that a unique climate regime in this area and exceptionally high-altitude ranges of the ice masses may be the important factors in this expansion, contrary to other regions.

The management of Tarbela reservoir depends to a large extent on the summer inflow contributed by the snow- and glacier-fed tributaries situated in the Karakoram Range. The Hunza River at Dainyor Bridge is representative of the moderately high runoff catchments in the centre of the Karakoram where a significant proportion of the flow is derived from cryosphere melt. It nearly doubles the runoff rate along with the Gilgit River in the overall Indus catchment at Partab Bridge station (Fig. 2), i.e. at its confluence point with the Indus River. It is, therefore, important to monitor the seasonal snow cover in snow-fed catchments for several purposes such as hydrometeorology, flood forecasting and water resource management. This study is the first to detail and to investigate the cryosphere dynamics based on the remotely sensed MODIS snow cover data (MOD10A2) over a period of 10 years in the Hunza River basin (situated in the central Karakoram region). The main objectives of this study were to investigate:

1. The climate variations within the Hunza River basin;
2. The relevance and validity of remotely sensed MODIS snow cover data in the catchment;
3. The hydrological behaviour of the catchment in response to climate variables (precipitation and temperature);
4. The cryosphere dynamics and impact of climate change on the cryosphere in the high-elevation mountainous Hunza River basin;

5. The annual and seasonal correlation between snow cover dynamics, mean temperatures and stream flow in the Hunza River basin.

The study area is described in Sect. 2 of this paper followed by the description of the data sets and analysis of the data in Sect. 3. The results obtained from this study are described and discussed in Sect. 4. Section 5 presents the conclusions drawn from this study.

## 2 Study Area (Hunza River basin)

The present analysis of cryosphere dynamics was undertaken in the Hunza River basin (basin area, 13 733 km<sup>2</sup>) (Fig. 2), situated in the high mountainous region of central Karakoram, with approximately 4463 km<sup>2</sup> of catchment area at an elevation over 5000 m. The area distribution in different elevation bands in the catchment is shown by the hypsometric curve in Fig. 3.

Some key features of the Hunza River basin are given in Table 1. The snow cover area in winter is approximately 80% and decreases to 30% in summer. The mean total annual precipitation is 170 mm at Khunjerab (4730 m), 225 mm at Ziarat (3669 m) and 680 mm at Naltar (2858 m) according to the 10-year record (1999–2008) of the three climatic stations in the catchment. The Hunza River has a mean annual flow of 323 m<sup>3</sup> s<sup>-1</sup> (i.e. 742 mm of water depth equivalent) gauged at Dainyor Bridge (Fig. 2), according to the 40-year (1966–2008) flow record of the SWHP-WAPDA. However, the present precipitation records are not representative of the runoff at the outlet. There are two main explanations for this problem.

1. The most active hydrological region for the Hunza River lies above 5000 m in elevation where maximum snowfall and accumulation occurs, as confirmed by Young and Hewitt (1990). All the major meteorological stations of the region are located below this altitude range and we have no data records of the water equivalent of the snow accumulation in this elevation zone. Hewitt (2005, 2007) reported that

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



---

**Snow cover dynamics and hydrological regime**A. A. Tahir et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

there is a five- to tenfold increase in precipitation over the elevation of 5000 m, and a large drop in temperature. Hewitt (2007) stated that about 90% of the total glaciated area in the Karakoram Range lies between 5000 and 6000 m, where most of the accumulation zones lie. The Karakoram Range receives maximum precipitation at elevations greater than 3500 m (Hewitt, 1986). Precipitation in the form of snow contributes the large moisture surplus for the UIB (Wake, 1989). The Batura Glacier Investigation Group, BGIG (1976) recorded a net winter accumulation of 1030 mm water equivalent (w.e.) at 4840 m on Batura Glacier situated in the Hunza River basin. An annual snow accumulation ranging from 900 mm to 1900 mm w.e. in the 4900- to 5400-m elevation range was reported by Hewitt et al. (1989) and Wake (1989) in the Biafo Glacier basin of the Karakoram Range. Winiger et al. (2005) derived the total annual precipitation for different altitudinal zones using a combined snow cover and ablation model. The estimated precipitation for northwest Karakoram was more than 1700 mm year<sup>-1</sup> above 5500 m.

2. The other factor that marks this contrast is the fact that the precipitation gauges present at high altitudes can catch only 20–30% of the precipitation, while the rest is distributed outside the gauges by strong winds. This factor may be the reason for the low precipitation level recorded at the Khunjerab climate station situated just below 5000 m in elevation. According to Sevruk (1985, 1989) and Førland et al. (1996), the most greatest of the systematic errors in precipitation gauging is wind-induced error (flow distortion), especially in the case of snowfall where losses can be on average 10–50%, despite the many gauges equipped with wind shields.

### 3 Data: sources and analysis

#### 3.1 Topography

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Global Digital Elevation Model (GDEM) was used to delineate the catchment boundary studied. The ASTER GDEM is available for high-latitude and steep mountainous areas not covered by SRTM3 (METI and NASA, 2009). It is based on ASTER images (see Sect. 3.3).

Nine downloaded ASTER GDEM tiles were mosaicked and then treated further using the ARC Map tool (version 9.3, © ESRI) to delimit the Hunza River basin. The study area was then extracted and superimposed by the gauging stations and other necessary feature layers. Three different altitudinal zones were extracted from the GDEM study area for detailed analysis of snow cover distribution. Each of the three zones contains one climate station so we can study each zone snow cover dynamics in relation to its own climate. The characteristics of these zones are given in Table 2.

#### 3.2 Hydrometeorology

The database of daily flows for the Hunza River gauged at Dainyor Bridge was made available for this analysis from 1966 to 2008, with deficient data from 2005 to 2007. Stream flow measurement in Pakistan is mostly carried out by the Surface Water Hydrology Project of the Water and Power Development Authority (SWHP-WAPDA), with the earliest records beginning in 1960.

The temperature and precipitation records at Gilgit just outside the basin have been used by the researchers in past years for testing runoff controls because there were no climatic stations within the basin. We used the meteorological data available at three high-altitude stations (Fig. 2 and Table 1) from 1999 to 2008 within the Hunza River basin established by WAPDA, although the records for these data were not particularly long (~10 years).

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The available hydrological and meteorological data were entered in the Hydraccess database, © IRD, developed by Vauchel (2005), for easy use in the future. Regression analysis was performed on the climate data (temperature and precipitation) available at high-altitude stations (Naltar, Ziarat and Khunjerab) within the Hunza basin and the Gilgit climate station (Fig. 2) just outside the catchment boundary, to investigate the climate correlations between these stations.

Regression analysis was also performed between annual and seasonal (summer and winter) stream flow data at Dainyor and climate data from the Hunza basin climate stations and the Gilgit station to identify the climate station that was the most representative of discharge at Dainyor. Moreover, this analysis was performed to investigate the main controlling factors of runoff for the Hunza River at Dainyor Bridge. The Pearson correlation (Rodgers and Nicewander, 1988) and Kendall rank correlation (Kendall, 1975; Kendall and Gibbons, 1990) tests were used to evaluate the relationship between different hydrological and climate variables of all the gauging stations mentioned above. An analysis of mean monthly temperatures and monthly precipitation magnitude variation between the Hunza basin climate stations and the Gilgit climate station is presented in Figs. 4 and 5, respectively. A non-parametric Mann-Kendall trend test (Kendall, 1975; Mann, 1945) was applied to identify the trends in time series data; the values of this trend test are represented by Kendall's tau ( $\tau$ ) coefficient. This coefficient value varies between +1 and -1. A positive coefficient value denotes the increasing trend in time series data and versa negative coefficient value the contrary. A coefficient value of 0 denotes no trend in time series data.

### 3.3 Snow cover

The Moderate Resolution Imaging Spectroradiometer (MODIS) snow products were selected to calculate the snow cover percentage on our study area. The MODIS/Terra Snow Cover 8-Day L3 Global 500 m Grid (MOD10A2) used for this study contains data fields for maximum snow cover extent over an 8-day repeated period (Hall et al., 2006, updated weekly) and has a resolution of approximately 500 m covering the Hunza River

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



basin completely. A data set of 450 processed MOD10A2 (V005) images available from March 2000 to December 2009 was downloaded from <http://nsidc.org/cgi-bin/snow/search.pl>.

The available MODIS images, from the 2000–2009 period on an 8-day classification basis, were mosaicked and projected with the WGS 1984 UTM ZONE 43N projection system. The Hunza River basin area was then extracted from this mosaicked scene to assess the snow and ice cover (cryosphere) percentage in the study area over a 10-year period. When the percentage of cloud cover exceeded 20% on a specific date, the record was eliminated and the average snow cover on this date was estimated by interpolating linearly between the previous and the next available cloud-free images. The snow cover area was also calculated for the different altitudinal zones to investigate the snow cover dynamics in these zones over a period from 2000 to 2009. A non-parametric Mann-Kendall trend test (Kendall, 1975; Mann, 1945) was applied to identify the trends in time series data; the values of this trend test are represented by Kendall's tau ( $\tau$ ) coefficient.

Fine-resolution ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images were used for snow cover extent extraction to validate MODIS snow cover products. The ASTER instrument operates in different spectral regions that have 15-m, 30-m and 90-m spatial resolutions (Lopez, 2007; Sarwar and Bill, 2003). Four ASTER images, nearly cloud-free, in different seasons, were downloaded from <http://glovis.usgs.gov/ImgViewer/Java2ImgViewer.html> for use in this study. The dates of these images are 16 July 2000, 30 April 2001, 26 June 2001 and 28 February 2002.

The Normalized Difference Snow Index (NDSI) has been widely used for effective snow cover mapping using various sensors (Dankers and de Jong, 2004; Nagler et al., 2008; Sirguey et al., 2008; Hall et al., 2002). The aim of this spectral index is to enhance the snow and ice targets and distinguish them from vegetation, bare ground and clouds. The NDSI index does not differentiate between snow and snow-covered ice as stated by Lopez (2007), so both of them are included in the results obtained with the NDSI.

---

**Snow cover  
dynamics and  
hydrological regime**

A. A. Tahir et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 4 Results and discussion

### Climate data variation analysis

Correlation coefficient values for the trend of different climate variables (monthly temperatures and precipitation) between the Hunza basin climate stations and the Gilgit climate station are given in Table 3. Pearson and Kendall rank correlation tests (significance level,  $p = 5\%$ ) were applied to evaluate the relationship between these variables. A highly significant correlation was found for maximum, minimum and mean temperature trends between all the stations of the Hunza basin and the mean temperatures at the neighbouring Gilgit climate station. The correlation coefficient value was at least 0.97 in each case. Regression analysis of seasonal and annual temperatures at three Hunza basin climate stations ranging in elevation from 2858 m to 4730 m gives lapse rates ranging from 0.64 to 0.77 °C/100 m. The magnitude of mean temperature observed at the Hunza basin climate stations is well below those at the Gilgit climate station, as shown in Fig. 4.

Correlation coefficient values for monthly precipitation show that there is a significant correlation between the Hunza basin climate stations (Table 3). A maximum correlation was found between Ziarat and Naltar ( $r = 0.37$ ). The minimum correlation for monthly precipitation was found between Ziarat and Khunjerab ( $r = 0.25$ ). Almost the same behaviour was shown by the monthly precipitation correlation between the Gilgit climate station and the Hunza valley stations and a maximum significant correlation ( $r = 0.62$ ) was found between the Gilgit and Naltar climate stations. Monthly variation of precipitation at all the climate stations in the Hunza basin and the Gilgit station is presented in Fig. 5. The quantity of total annual precipitation received at all these climate stations varied significantly due to the effect of elevation. Nearly 98% of the Hunza River basin has an elevation greater than 2000 m and the Gilgit station (~1460 m) does not suitably represent the high-altitude climate conditions of the catchment, which receives much more snow at high altitudes than the Gilgit River basin.

### Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The altitude within the Hunza River basin varies greatly, which is why the climate records at different stations within the basin are not strongly correlated. Moreover, the Hunza basin climate stations are situated at much higher altitudes than the Gilgit station and therefore better represent the climate records (temperature, precipitation, etc.) of the Hunza River basin at different varying elevations.

## MODIS snow cover product validation

The snow cover area on cloud-free ASTER images was compared with MODIS images on the same dates (seasonally significant) to validate the MODIS snow cover product as given in Table 4. The validation of MODIS images with ASTER images (which have finer resolution than MODIS) suggests that MODIS snow products are reliable in estimating the snow cover area in the Hunza River basin. The NDSI was applied to ASTER images and the index (threshold) values greater than or equal to 0.82 were considered as snow and ice cover. The index value was calibrated by visual and pixel inspection of two ASTER and MODIS images. In comparison, the index value of 0.9 was used to calculate the snow cover extent from ASTER images over the Pamir region (Afghanistan) by Haritashya et al. (2009). Comparison of MODIS and ASTER images taken on 28 February 2002 (Fig. 6) showed nearly the same percentage of snow cover area.

## Hydrological behaviour of the Hunza River basin

The Pearson and Kendall rank correlation coefficient values ( $p = 5\%$ ) obtained for the correlation between annual and seasonal stream flow at Dainyor and the climate data from the Hunza basin climate stations and the Gilgit station are given in Table 5. No highly significant correlation was found between annual precipitation of all the climate stations analysed and the stream flow at Dainyor Bridge. The maximum correlation

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



coefficient value was found between annual precipitation at Khunjerab and runoff at Dainyor ( $r = 0.26$ ). An analysis of seasonal runoff and precipitation showed no significant correlation between summer precipitation and runoff at Dainyor for almost all the climate stations except Khunjerab, as given in Table 5. A significant inverse correlation was found between summer precipitation at Gilgit and runoff at Dainyor ( $r = -0.22$ ). The reason for this negative correlation may be associated with the precipitation decrease in summer while runoff increases due to increasing temperature and melt. This may also be attributable to the minimum effect of the monsoon regime in the Hunza basin because of the Karakoram high mountainous barrier. A significant inverse correlation between Gilgit summer precipitation and Hunza River runoff was found by Archer (2003).

A significant positive correlation was found between winter and spring precipitation, for almost all the climate stations of the Hunza basin and summer stream flow at Dainyor (Table 5). This correlation was expected because most of the precipitation in this period falls in the form of snow and accumulates at high altitudes in the Hunza River basin. This snow contributes to the runoff on melting in summer when the temperature increases in the valley. The highest correlation was found between winter precipitation at Khunjerab and summer flow at Dainyor. This result is supported by the fact that almost 60% area of the Hunza River basin has an altitude greater than 4500 m and only the Khunjerab climate station is situated above this altitude (Table 2) to represent the climate of this altitudinal zone. In addition, the highest correlation value describing this zone can also be explained by the fact that almost all the winter and spring precipitation received above an elevation of 4500 m is in the form of snow and melts only in summer when the mean temperatures rise above  $0^{\circ}\text{C}$  in this zone represented by the Khunjerab climate station.

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



---

**Snow cover  
dynamics and  
hydrological regime**A. A. Tahir et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Analysis of correlation coefficient values suggests that there is a significant positive correlation between the annual and seasonal temperature records and discharge at Dainyor (Table 5), which indicates that river flows are driven by snowmelt in the catchment. The maximum correlation coefficient value ( $r = 0.79$ ) was found for annual correlation between runoff at Dainyor and mean temperatures at Khunjerab, Ziarat and Gilgit. For summer temperature and runoff, the Gilgit climate station (situated outside the basin) showed a strongly significant correlation ( $r = 0.89$ ). Khunjerab ( $r = 0.81$ ) and Ziarat ( $r = 0.81$ ) (situated within the basin) also had significant positive correlations with runoff at Dainyor. The correlation coefficient between winter and spring temperatures and runoff was also found to be significantly positive and the coefficient value was not less than 0.61 for any station. This result suggests that Hunza River runoff is controlled by temperature seasonality and mainly fed by glaciers and snow that melt in relation to increasing temperatures in summer. Hewitt et al. (1989) and Wake (1989) stated that the annual precipitation for Hunza River basin above 5000 m in elevation is on the order of 1800–2000 mm. This elevation and precipitation are instrumental in creating large glaciers and perennial snow, which slowly moves down to the ablation zone and contributes to the river flow in summer.

The climate variables (temperature and precipitation) observed at all the climate stations in the Hunza River basin are almost as well correlated with Hunza river runoff as the Gilgit climate station variables (Table 5). These results and the high-altitude variation of the Hunza River basin suggest that the Gilgit climate station can be replaced with the Hunza basin climate stations for current and future studies of the Hunza river catchment.

The regression analysis results presented in Table 5 and Fig. 7 suggest that zone C (corresponding to the Khunjerab climate station) is the most active hydrological zone for Hunza River flows. Both the correlation coefficient values for precipitation and mean temperature at Khunjerab and runoff at Dainyor are higher than or equal to other catchment stations (Naltar and Ziarat). This result can also be observed in Fig. 7, where zone B (corresponding to the Ziarat climate station) and zone C (corresponding to the

Khunjerab climate station) present a significant contribution to river flow in the form of snow melt in summer (April to September). Zone C has the largest proportion (64%) of the Hunza basin area and hence a small drop in the percentage of snow cover in zone C in summer will have a significant impact on catchment runoff.

## 5 Snow cover dynamics in the Hunza River basin

MODIS image analysis for snow cover dynamics over a 10-year period suggests that the cryosphere areas in the Hunza River basin are expanding slightly, as shown in Fig. 7. Analysis of Kendall's tau ( $\tau$ ) coefficient value indicates a significant expansion of the snow cover area in zone C over an elevation of 4300 m. This expansion is more significant in the maximum snow periods from November to February in all the altitudinal zones, notably in zone C ( $\tau = 0.25$ ) (Fig. 7). In the minimum snow cover periods from June to September, a slight increasing trend is noted in zone C ( $\tau = 0.02$ ) (Fig. 7); this expansion may result from the constancy in the mean temperatures and an increasing trend in the catchment's annual precipitation. An analysis of the temperature variations (Fig. 4) from 1999 to 2008 using Kendall's tau ( $\tau$ ) coefficient value indicates a constant trend at Naltar and Gilgit but a slight increasing trend at Ziarat and Khunjerab. Analysis of total annual precipitation (Fig. 8) by Kendall's tau ( $\tau$ ) coefficient value at all three climate stations of the Hunza basin indicates a slight increasing trend at Ziarat (corresponding to zone B) and Khunjerab (corresponding to zone C) over the period from 1999 to 2007. The increasing trend is not significant but continues to feed the high altitudes, particularly zone C, and results in the form of expanding snow cover in the area. A greater proportion of the catchment area (i.e. almost 32.5% of the catchment area) is higher than 5000 m in elevation, as shown in Fig. 3 and presented in Table 1 and nearly the same percentage of area (30%–40%) is snow covered all year, as illustrated by the snow cover distribution in Fig. 9. This is the area where the mean temperature remains below freezing throughout the year and the snow cover is expanding as a result of the increasing precipitation trend. This is

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



also explained by Hewitt (2005, 2007), who found that the central Karakoram Range is one of the few areas where glaciers are growing. The longer records of climate data at high-altitude weather stations and satellite images may help researchers to understand the dynamics of snow cover in the area. In the future, automatic weather stations or snow pillows should be installed over 5000 m in elevation to assess the precipitation patterns in the most active hydrological zone of the Karakoram Range (WAPDA, personal communication, 2009).

The current hypothesis for this phenomenon of increasing snow cover is an increase in winter precipitation mainly due to westerly circulation, as observed in this study and explained by Hewitt (2005). The impact of global warming is not noticeable because of the high altitudes in the Hunza River basin. Even if global warming is real, the mean temperature remains negative or very low over a large part of the basin area. The increasing precipitation in the form of snowfall continues to feed the snow cover and the accumulation zones of glaciers in zones B and C.

### **Correlation between snow cover change, climate variables and stream flow in the Hunza River basin**

Snow cover in the area is at a maximum 70–80% in the winter and spring seasons (December to April) and at a minimum 30–40% in the summer (July to September), as shown in Fig. 9. This change in the snow cover has a significant inverse correlation with the mean temperatures and discharge in the Hunza River basin, as shown in Fig. 10 and Table 6. The relationship between standardised values of four variables (precipitation, snow cover, mean temperature and discharge) is presented in Fig. 10. The values were standardised using the normal deviate formula, i.e. the distance of one data point from the mean, divided by the standard deviation of the distribution. This indicates a continuous depletion in the snow cover in summer as the average temperature in the area increases, resulting in increasing discharge. In winter, as the temperature decreases, the snow cover starts to increase and hence discharge decreases.

## **Snow cover dynamics and hydrological regime**

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The monthly difference in the Hunza River discharge at Dainyor is inversely correlated (Pearson's correlation coefficient =  $-0.73$ ; Kendall's rank correlation =  $-0.56$ ) with the monthly difference in the snow cover, as shown in Fig. 11, which indicates that the change in Hunza River discharge is dependent on the snow cover change in the area.

Pearson and Kendall's rank correlation coefficient values ( $p = 5\%$ ) were used to evaluate the correlation between the snow cover dynamics and (a) climate variables (the mean temperature, precipitation) and (b) stream flow in the Hunza River, as given in Table 6. No significant correlation was found between the snow cover dynamics and precipitation in the Hunza basin. This may be due to the fact that the precipitation gauges are mostly under sampled in the high-altitude catchments due to a number of errors, as explained by Førland et al. (1996) and therefore cannot efficiently represent the snow cover dynamics at high altitudes. The maximum inverse correlation was found between the snow cover change in the Hunza basin and the mean temperatures observed at Khunjerab and Ziarat. A high significant inverse correlation was found between snow cover change as well as between summer and annual discharges. This correlation indicates that the stream flow in the Hunza River strongly depends on the snow cover dynamics and the mean temperatures in the catchment.

The analysis of 25 years of flow records (1980–2004) for the Hunza River shows that annual flow decreases with time, as shown in Fig. 12. A declining river flow at Dainyor suggests long-term storage of snow and ice at the higher altitudes. With shorter time-series, (Archer and Fowler, 2004) also associated the decreasing river discharges of the high-altitude central Karakoram catchments with the long-term storage of additional ice.

## 5 Conclusions

The Hunza River basin is one of the main tributaries of the Indus river irrigation system that contributes nearly one-fifth of the Upper Indus flow at Partab Bridge. Situated in the high-elevation zone of central Karakoram, the Hunza river flow depends mainly on

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the accumulation of snow at high altitudes and energy input indirectly related to temperature. This suggests that meteorological data collection methods should be improved at the high-altitude stations present within the basin area to study the snow cover dynamics and runoff controlling factors more effectively. The following conclusions can be drawn by analysing the results obtained in this study:

- The climate stations present within the Hunza River catchment area can replace the Gilgit climate station to study the behaviour of stream flow at Dainyor Bridge in the future.
- The MODIS MOD10A2 remote sensing cryosphere product is free of charge and easy to treat and therefore is a good option to assess the percentage cryosphere areas in the Hunza River basin over the long term.
- The stream flow in the Hunza River is influenced mainly by winter precipitation, but also by the mean summer and winter temperatures of its catchment. Moreover, the most active hydrological region of the Hunza River basin is present above an elevation of 4500 m in zone C.
- The 10-year analysis of the remotely sensed cryosphere data, an increasing precipitation trend, constancy in mean temperatures and declining discharge trend in the Hunza River basin suggest that the Hunza River basin is a region undergoing a slight expansion in the cryosphere area, especially at high elevations.
- The study of annual and seasonal snow cover dynamics suggests that the snow cover change has a highly inverse correlation with the catchment's summer mean temperatures, which results in a large amount of stream flow. Therefore, it is very important to estimate the winter snow accumulations at high altitudes to forecast the summer flow and ultimately to improve the management of the Tarbela reservoir.

A detailed study is needed on the other high-altitude catchments of the Upper Indus region (e.g. Shigar and Shyok) that contribute a substantial amount of flow to the Indus

**Snow cover dynamics and hydrological regime**

A. A. Tahir et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



River and are mainly snow- and glacier-fed. Snow depletion curves calculated in this study for each altitudinal zone of the Hunza River basin can further be used as input to the hydrological models with a snow component, e.g. the Snowmelt Runoff Model developed by Martinec (1975), to simulate and forecast the stream flow at Dainyori Bridge as well as to study the climate change impact on snow cover and stream flow dynamics in the future. Ultimately, this study will help to improve integrated water resource management in the Tarbela reservoir.

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## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Table 1.** Characteristics of the study area (Hunza River basin).

River flow gauging station	Dainyor Bridge		
Latitude	35°56' N		
Longitude	74°23' E		
Elevation of gauging station	1450 m		
Drainage area	13 733 km <sup>2</sup>		
Glacier-covered area	4688 km <sup>2</sup> Akhtar et al. (2008)		
Glacier cover percentage	34%		
Mean elevation (computed from ASTER GDEM using ARCMAP)	4631 m		
Area above 5000 m	32.5%		
No. of meteorological stations	3 (Installed by WAPDA)		
	Khunjerab	Ziarat	Naltar
	4730 m	3669 m	2858 m

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Table 2.** Characteristics of the three elevation zones extracted from the GDEM of the Hunza River basin and their corresponding climate station.

Zone	Elevation range (m)	Mean elevation (m)	Area (%)	Area (km <sup>2</sup> )	Climate station
A	1432–3300	2365.5	11	1541	Naltar
B	3301–4300	3800.5	25	3413	Ziarat
C	4301–7849	6075.0	64	8779	Khunjerab
Total			100%	13 733	

(Elevation range and mean elevation for each zone was computed from ASTER GDEM using ARCMAP tool.)

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

**Table 3.** Monthly climate data (precipitation and temperature) correlation coefficients between three climate stations of the Hunza River basin (1999–2008) and Gilgit climate station (1999–2007).

Precipitation	Ziarat			Naltar			Gilgit
Khunjerab	<b>0.25 (0.32)</b>			<b>0.33 (0.26)</b>			<b>0.29 (0.33)</b>
Ziarat				<b>0.37 (0.31)</b>			<b>0.38 (0.29)</b>
Naltar				–			<b>0.62 (0.47)</b>
Mean precipitation in the Hunza River basin							<b>0.62 (0.45)</b>
Temperature	Ziarat			Naltar			Gilgit
	$T_{\max}$	$T_{\min}$	Mean $T$	$T_{\max}$	$T_{\min}$	Mean $T$	Tavg
Khunjerab	<b>0.99 (0.92)</b>	<b>0.97 (0.88)</b>	<b>0.99 (0.92)</b>	<b>0.99 (0.92)</b>	<b>0.99 (0.92)</b>	<b>0.99 (0.92)</b>	<b>0.98 (0.88)</b>
Ziarat	–	–		<b>0.99 (0.92)</b>	<b>0.97 (0.89)</b>	<b>0.99 (0.92)</b>	<b>0.98 (0.87)</b>
Naltar			–	–	–	–	<b>0.99 (0.88)</b>
Avg. of Hunza basin climate stations mean temperature							<b>0.98 (0.88)</b>

$T_{\max}$  = Daily maximum temperature,  $T_{\min}$  = Daily minimum temperature, Mean  $T$  = Daily mean temperature, Tavg = Monthly mean temperature Values outside and within the ( ) are Pearson and Kendall rank correlation coefficient values, respectively. All the values are different from 0 with  $p = 0.05$ .

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


**Table 5.** Annual and seasonal correlation coefficients between stream flow data at Dainyor (1966–2008) and (a) daily climate data (precipitation and temperature) of Hunza basin climate stations (1999–2008), (b) monthly climate data (precipitation and temperature) of Gilgit station (1966–2007).

Climate data	Stream flow in Hunza River at Dainyor Bridge		
	Annual correlation (January to December)	Summer correlation (April to September)	Winter and spring correlation (October to March)
<b>(a) Hunza climate stations</b>			
Precipitation			
Khunjerab	<b>0.26 (0.17)</b>	<b>0.17 (0.11)</b>	<b>0.10 (0.00)</b>
Ziarat	0.02 (0.05)	−0.01 (0.01)	0.02 (0.02)
Naltar	0.03 (0.02)	−0.04 (−0.01)	−0.01 (−0.05)
Avg. of Hunza basin climate stations	<b>0.08 (0.08)</b>	−(0.04)	0.01 (−0.04)
Winter precipitation (Oct–Mar)		Summer stream flow (Apr–Sep)	
Khunjerab	−	<b>0.12 (0.06)</b>	−
Ziarat	−	<b>0.08 (0.06)</b>	−
Naltar	−	<b>0.07 (0.00)</b>	−
Avg. of Hunza basin climate stations		<b>0.10 (0.03)</b>	
Daily mean temperature			
Khunjerab	<b>0.79 (0.69)</b>	<b>0.80 (0.66)</b>	<b>0.64 (0.36)</b>
Ziarat	<b>0.79 (0.67)</b>	<b>0.81 (0.66)</b>	<b>0.61 (0.32)</b>
Naltar	<b>0.77 (0.66)</b>	<b>0.73 (0.56)</b>	<b>0.64 (0.36)</b>
Avg. of Hunza basin climate stations	<b>0.79 (0.69)</b>	<b>0.81 (0.66)</b>	<b>0.65 (0.36)</b>
<b>(b) Gilgit climate station</b>			
Precipitation	0.04 (0.1)	−0.22 (−0.1)	−0.01(−0.18)
Winter precipitation (Oct–Mar)	−	−0.04 (−0.06)	−
Daily mean temperature	<b>0.79 (0.68)</b>	<b>0.89 (0.81)</b>	<b>0.70 (0.26)</b>

Values outside and within the ( ) are Pearson and Kendall rank correlation coefficient values, respectively. (Bold figures: values are different from 0 with  $p = 0.05$ ).

## Snow cover dynamics and hydrological regime

A. A. Tahir et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

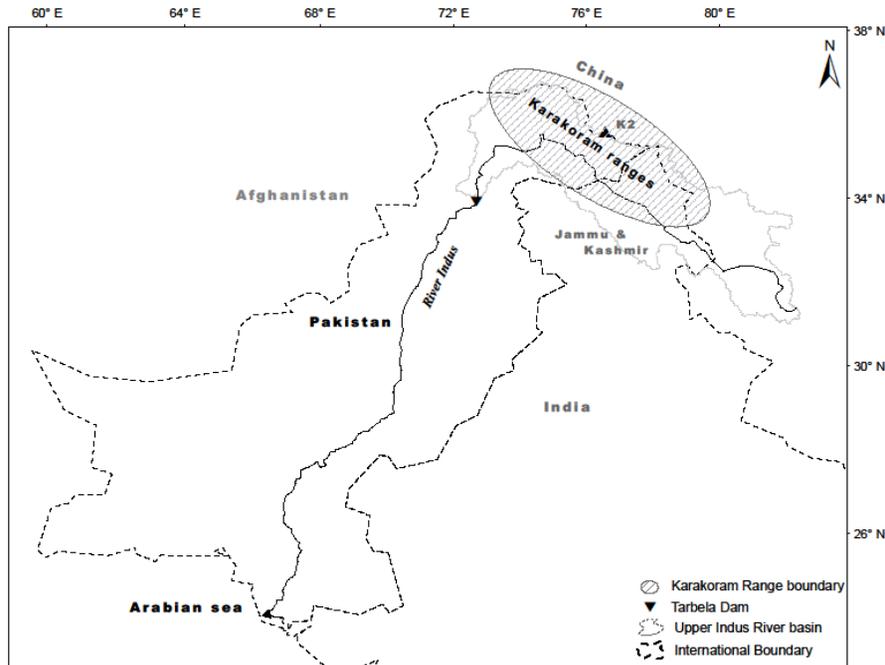
Interactive Discussion



**Table 6.** Annual and seasonal correlation coefficients between snow cover dynamics, Hunza River basin (2000–2009), and (a) daily climate data (precipitation and temperature) (1999–2008), (b) daily stream flow data at Dainyor bridge (1966–2008).

Climate data	Snow cover dynamics in the Hunza River basin		
	Annual correlation (January to December)	Summer correlation (April to September)	Winter and spring correlation (October to March)
(a) Hunza climate stations			
Precipitation			
Khunjerab	<b>-0.26 (-0.18)</b>	<b>-0.17 (-0.11)</b>	<b>-0.09 (-0.09)</b>
Ziarat	-0.02 ( <b>-0.05</b> )	-0.01 (-0.03)	0.04 (0.01)
Naltar	-0.01 (-0.02)	<b>0.07 (0.02)</b>	0.01 (0.00)
Avg. of Hunza basin climate stations	<b>-0.07 (-0.08)</b>	0.01 (-0.04)	0.01 (-0.01)
Daily mean temperature			
Khunjerab	<b>-0.80 (-0.56)</b>	<b>-0.78 (-0.56)</b>	<b>-0.42 (-0.21)</b>
Ziarat	<b>-0.80 (-0.57)</b>	<b>-0.80 (-0.57)</b>	<b>-0.43 (-0.25)</b>
Naltar	<b>-0.78 (-0.54)</b>	<b>-0.72 (-0.48)</b>	<b>-0.40 (-0.21)</b>
Avg. of Hunza basin climate stations	<b>-0.80 (-0.56)</b>	<b>-0.80 (-0.56)</b>	<b>-0.43 (0.23)</b>
(b) Stream flow			
	<b>-0.88 (-0.65)</b>	<b>-0.81 (-0.68)</b>	<b>-0.64 (-0.26)</b>

Values outside and within the ( ) are Pearson and Kendall rank correlation coefficient values, respectively. (Bold figures: values are different from 0 with  $p = 0.05$ ).



**Fig. 1.** Location of the Upper Indus River basin with main controlling storage at Tarbela Dam.

**Snow cover dynamics and hydrological regime**

A. A. Tahir et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

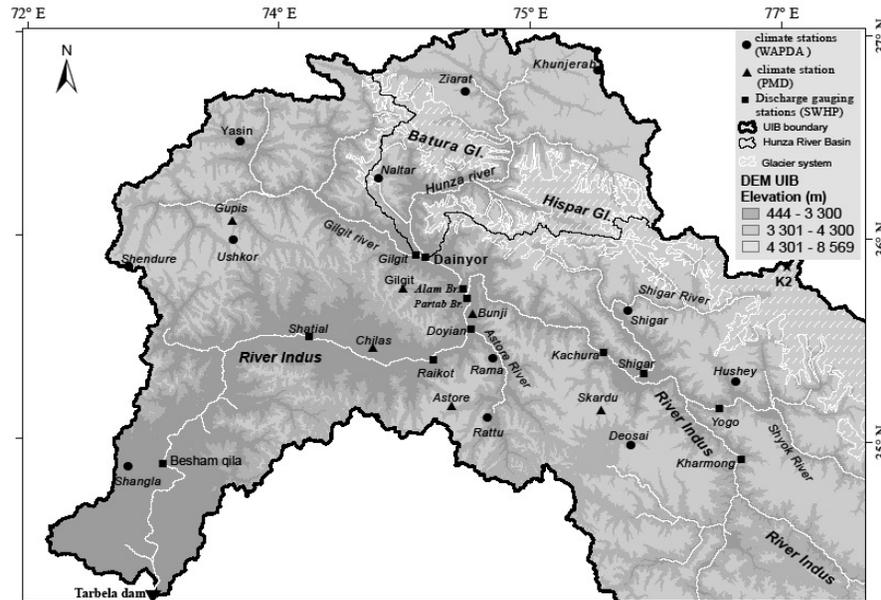
Printer-friendly Version

Interactive Discussion



## Snow cover dynamics and hydrological regime

A. A. Tahir et al.



**Fig. 2.** ASTER Global digital elevation model (GDEM) of the Upper Indus River basin and gauging station network within the boundary of Pakistan (Hunza River catchment location in the UIB is shown with a thin boundary line). The projection of the map is WGS1984 UTM 43N.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

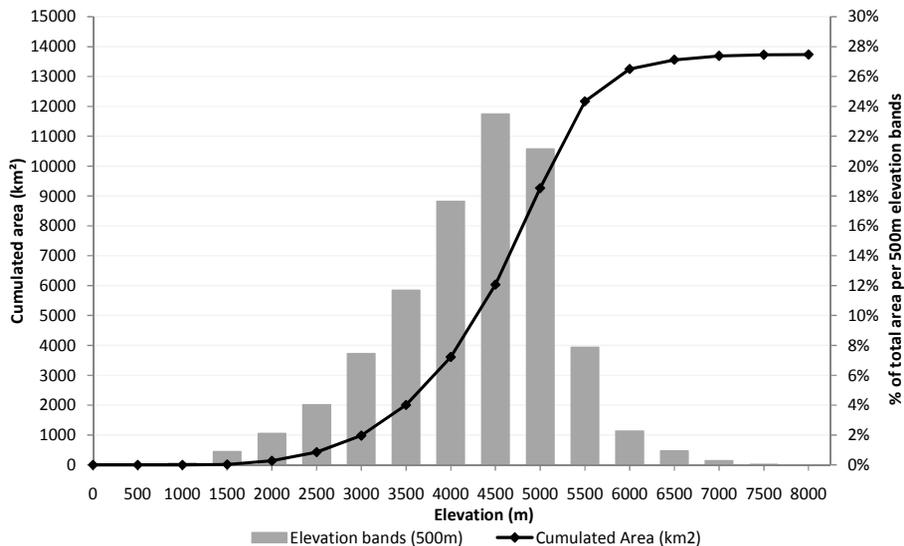
Printer-friendly Version

Interactive Discussion



## Snow cover dynamics and hydrological regime

A. A. Tahir et al.



**Fig. 3.** Hypsometric curve of the Hunza River basin and distribution of the area by layer under each 500-m elevation band.

[Title Page](#)

[Abstract](#) | [Introduction](#)

[Conclusions](#) | [References](#)

[Tables](#) | [Figures](#)

[◀](#) | [▶](#)

[◀](#) | [▶](#)

[Back](#) | [Close](#)

[Full Screen / Esc](#)

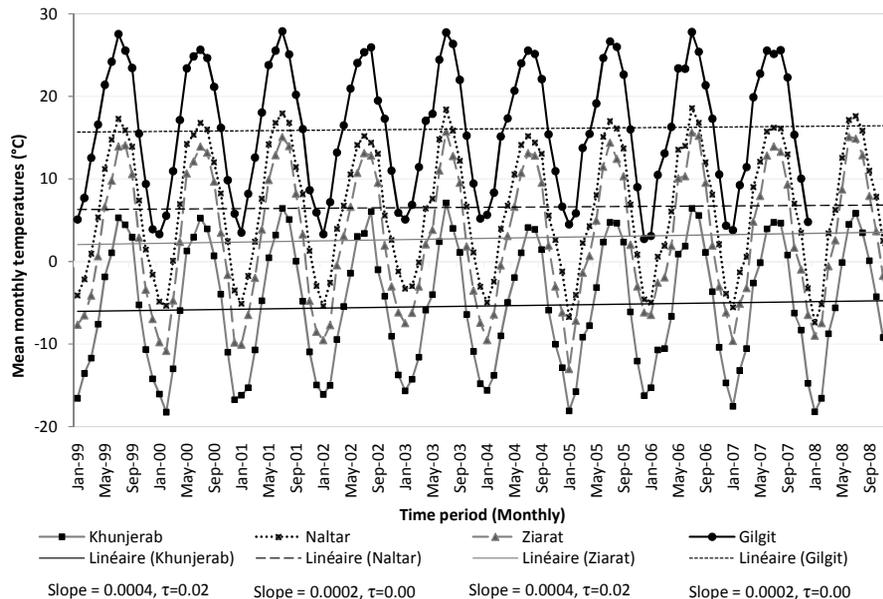
[Printer-friendly Version](#)

[Interactive Discussion](#)



## Snow cover dynamics and hydrological regime

A. A. Tahir et al.



**Fig. 4.** Mean monthly temperatures variation between the Hunza River basin climate stations and Gilgit station. (Kendall's tau ( $\tau$ ) coefficient values presented in bold figures indicate a significant trend with  $p < 0.05$ ).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

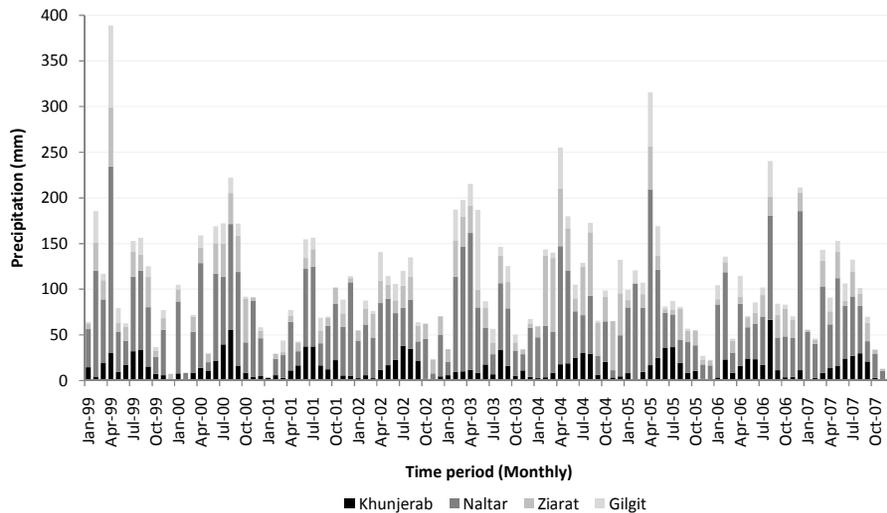
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 5.** Monthly variations of precipitation at the Hunza River basin climate stations and Gilgit climate station.

**Snow cover dynamics and hydrological regime**

A. A. Tahir et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

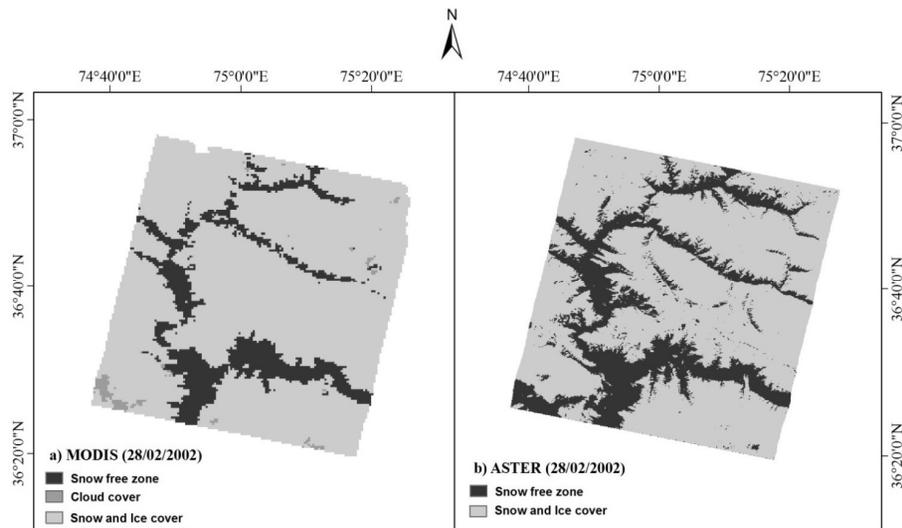
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 6.** (a) MODIS snow cover image and (b) ASTER snow cover image for the Hunza River basin.

**Snow cover dynamics and hydrological regime**

A. A. Tahir et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

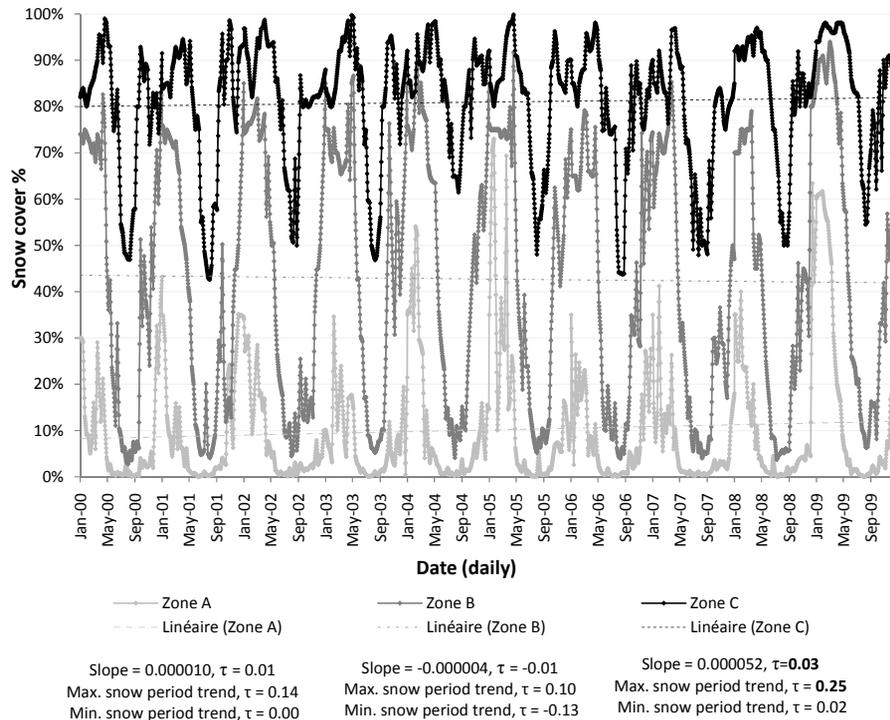
Printer-friendly Version

Interactive Discussion



## Snow cover dynamics and hydrological regime

A. A. Tahir et al.



**Fig. 7.** Snow cover distribution in three different altitudinal zones of the Hunza River basin. Significant expansion can be noted in zone C. Temporal trend is also presented for maximum and minimum snow cover periods. (Kendall's tau ( $\tau$ ) coefficient values presented in bold figures indicate a significant trend with  $p < 0.05$ ).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

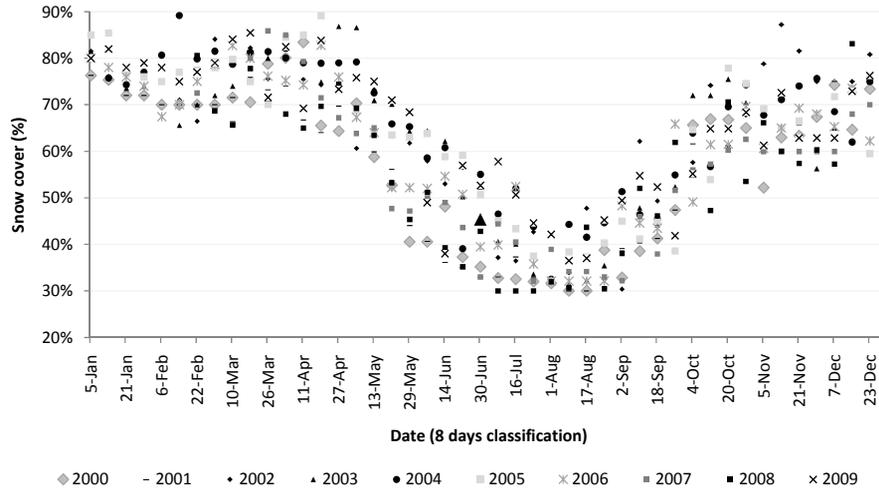
Interactive Discussion





## Snow cover dynamics and hydrological regime

A. A. Tahir et al.



**Fig. 9.** Percentage snow cover in the Hunza River basin calculated by analysing 450 MODIS images.

[Title Page](#)

[Abstract](#)   [Introduction](#)

[Conclusions](#)   [References](#)

[Tables](#)   [Figures](#)

[◀](#)   [▶](#)

[◀](#)   [▶](#)

[Back](#)   [Close](#)

[Full Screen / Esc](#)

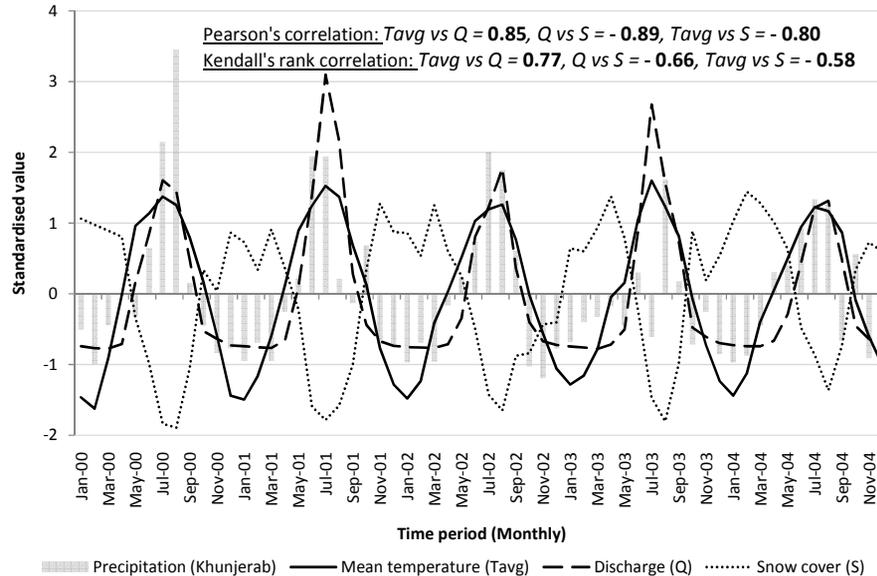
[Printer-friendly Version](#)

[Interactive Discussion](#)



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A. A. Tahir et al.



**Fig. 10.** Correlation between standardised values of precipitation (Khunjerab), snow cover, average temperature and discharge (at Dainyor) in the Hunza River basin (on a monthly basis). (Correlation coefficient values presented in bold figures are significant with a significance level,  $p < 0.05$ .)

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

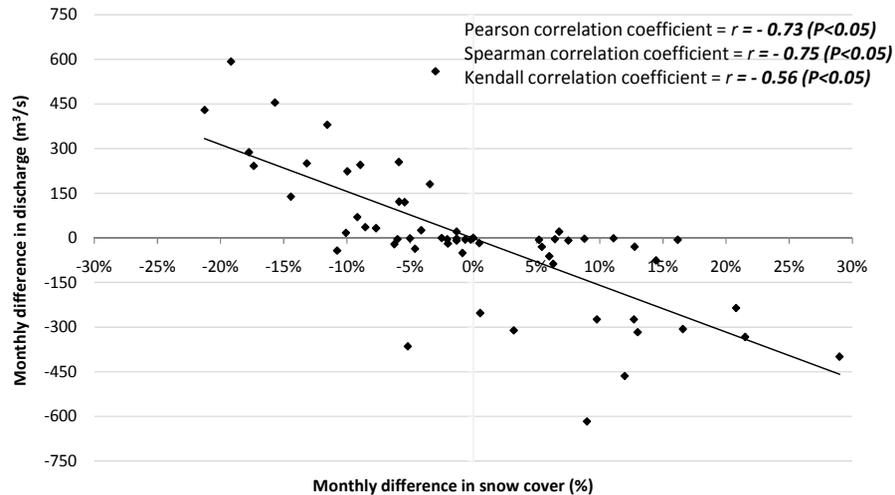
Printer-friendly Version

Interactive Discussion



**Snow cover dynamics and hydrological regime**

A. A. Tahir et al.



**Fig. 11.** Correlation between monthly difference in snow cover and monthly difference in discharge at Dainyor in the Hunza River basin.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

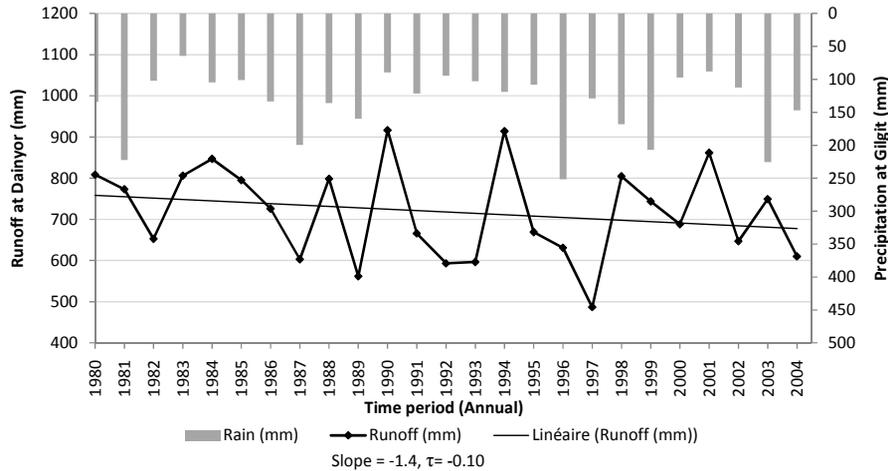
Printer-friendly Version

Interactive Discussion



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A. A. Tahir et al.



**Fig. 12.** Annual flow trend in Hunza River at Dainyor Bridge and total annual precipitation at Gilgit over 25 years (1980–2004). (Kendall’s tau ( $\tau$ ) coefficients values presented in bold figures indicate a significant trend with  $p < 0.05$ ).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

