**ORIGINAL ARTICLE** 



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# Spatio-Temporal Analysis of Early Twenty-First Century Areal Changes in the Kabul River Basin Cryosphere

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#### Abstract

Climate change is a common concern globally and the Kabul River Basin, a transboundary basin between Pakistan and Afghanistan, is no exception. Rising temperatures cause snow and glaciers to melt rapidly, which increases the variability of river flows that may affect the water resource management between the two countries. For this purpose, it is necessary to study snow and glaciers, the main source of river flow. The goal of this research is to assess and analyze the basin-scale and elevation-zonal variation in the areal extent of snow and glacier cover for the years 2001-2016, on daily, monthly, seasonal and yearly basis. The basin was distributed into eight elevation zones; and snow cover for the whole basin and each elevation zone was then extracted by utilizing the Moderate Resolution Imaging Spectroradiometer (MODIS), Onboard TERRA Satellite, 8-daily, 500 m resolution images. As per average climatology of the basin, snow cover is minimum in August because of higher summer temperatures and maximum in February owing to lower winter temperatures and higher westerly precipitation in solid form. Based on the basin-scale analysis of changes in the daily snow-covered areal extents, it is found that snow cover significantly increases in the three lowest elevation zones, whereas in the mid elevation zones (Zone 4 and 5) and the highest elevation zone (Zone 8) a negligible decreasing trend is found. Moreover, non-significant but decreasing trend in Zone 8 may hint either at decrease in solid precipitation in the high elevation region or a slight retreat of the glaciers which may become significant in the coming years. In addition, there is a significant decreasing trend of snow covered area in Zones 6 and 7 which gives a similar indication. Our seasonal and annual analysis indicates that there is an overall slight increasing trend in the basin for all analyzed seasons and also on annual basis. The results concluded that a detailed hydro-climate modeling analysis should be carried out for this basin to find the changes in water availability under the future climate scenarios.

Keywords Snow cover · Climate change · Transboundary river basin · Remote sensing

# 1 Introduction

Outside the polar region, the Hindu-Kush Karakoram Himalayan (HKH) range, also known as the 'Third Pole', comprises some of the highest mountain peaks and largest

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amount of ice reserves (Hewitt et al. 1989). These large reserves supply water to about 1.3 billion people, from ten leading river basins in Asia (Yao et al. 2012). Climate changes, specifically rising temperatures, play a prominent role in fast glacier melting, more intense and more frequent extreme weather events and shifts in monsoon currents (Shrestha et al. 2015). Wijngaard et al. (2017) showed increasing trend in the magnitude of climate means and extremes at the end of twenty-first century. Consequently, water availability for agriculture, municipal needs, and industry and hydropower generation is largely impacted. Lutz et al. (2016) concluded in their study that water availability of the Upper Indus Basin (UIB) is extremely uncertain in Pakistan for future because of dispersed precipitation projections. Hence, the cryosphere changes are very important to understand to determine and avoid the implications for the

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region's water resources. Numerous researches have been carried out in the HKH region of Pakistan to assess how the snow and glacier cover vary and its contribution to runoff (Immerzeel and Bierkens 2012; Immerzeel et al. 2015; Hasson et al. 2014; Immerzeel et al. 2009; Mukhopadhyay and Khan 2015; Archer and Fowler 2004; Shrestha et al. 2015; Tahir et al. 2011; Bolch et al. 2017; Brun et al. 2017; Lin et al. 2017; Zhou et al. 2017; Cogley 2011; Pellicciotti et al. 2012). Hewitt et al. (1989) and Archer and Fowler (2004) noted that 80–90% of the Indus River flow above Tarbela Dam is generated from seasonal and permanent snowfields and glaciers.

In the Gilgit River Basin (12,656 km<sup>2</sup> area), a sub basin in the western UIB, the trend in snow covered area and the recent changes were calculated on monthly basis (Tahir et al. 2016) and concluded to be stable and showed a small increasing trend of snow cover in UIB. Snow cover is an essential part of the cryosphere, and assessment of its spatiotemporal variations is indispensable for knowing its effect on water resources and impact on climate change in the Indus River flow system (Chu 2018). By utilizing the MODIS MOD10A1 C6 daily snow product, Malmrosa et al. (2018) examined spatio-temporal trends in snow cover extent, snow cover duration, and snow albedo for the period from 2000 to 2016 for Chilean and Argentinean Andes. MODIS 8-day snow product between 2000 and 2016 has also been used by Shafiq et al. (2018) to carry out a research study for assessment of snow cover area between 2000 and 2016 and ascertained that climate has a prominent role in controlling the snow-covered area. Tahir et al. (2011) with MODIS MOD10A2 database of snow products analyzed the changes in snow covers in Hunza River Basin (one of the highest snow and glacier covered sub-basin in Indus River), from March 2000 to December 2009. A slight expansion of cryosphere in the area was shown by the investigation of inaccessible cryosphere data in comparison to many world regions where snow and glaciers are receding speedily.

Climate change is occurring in the transboundary Kabul River Basin like everywhere on the globe. This basin is a part of the HKH mountainous region, shared by Pakistan and Afghanistan, having a catchment area of about 91,297 km<sup>2</sup>. Rising temperatures may cause rapid snow and glacier melt in the basin, due to that, variability of river flows is likely to increase, affecting the water resources management between the two countries. Owing to law and order situation for more than two decades in Afghanistan, there is not sufficient information on the Kabul basin river (Lashkaripour and Hussaini 2007). In addition, there is no water/benefit sharing related treaty between Pakistan and Afghanistan. Hence, to make an efficient water resource management strategy between the two countries, a proper agreement/understanding of water resources development on both sides is necessary to avoid any negative impacts of climate change on water availability

in the basin and resulting conflicts between the two nations. For this purpose, it is necessary to know the changes in river flows and sources of these flows such as snow and glacier which are dominant contributors in the Kabul River. The main goal of this research is to assess and analyze the basin-scale and elevation-zonal variation in the areal extent of snow and glacier cover for the years 2001–2016, on daily, monthly, seasonal and yearly basis to determine whether there is a significant areal change in this basin during the early part of the twenty-first century.

## 1.1 Study Area

The Kabul River Basin is located at 65–75° east and 32.5–37.5° north, has an area of 91,297 km<sup>2</sup> and is shared between Pakistan and Afghanistan. The two countries are both upper and lower riparian simultaneously. The melting snow and glaciers from the northern mountains is the main source of discharge. The total length of the Kabul River is 700 km, of which 560 km is in Afghanistan. Due to its versatile and transboundary nature, it is one of the important rivers in Afghanistan, although not the biggest one (http://www.encyclopedia.jrank.org/Jan\_KHA/KABUL).

The basin's climate is dry and strongly continental. Most of climate data in Afghanistan is available from 1957 to 1977. Later, owing to war; law and order situation, many stations were destroyed and data could not be collected. According to Tunnemeier and Houben (2005), the average annual precipitation is 330 mm based on the available recorded data, while the annual average temperature ranges from 10 to 13 °C. In the northern mountainous areas, the maximum precipitation is more than 1600 mm, most of which is in solid (snow) form that melts during the spring and summer seasons enhancing the river flow of the basin. This study recorded a maximum elevation of 7701 m above mean sea level (amsl) in the northeastern basin, and a minimum of about 266 m amsl near the outlet of the Kabul River at Nowshera as shown in Fig. 1. A Digital Elevation Model (DEM) for the basin using Shuttle Radar Topography Mission (SRTM), with a spatial resolution of 30 m, has been prepared for the analysis of this study as shown in Fig. 1.

#### 2 Methodology

#### 2.1 Data Sources and Analysis

#### 2.1.1 Topography

SRTM DEM was utilized to delineate the watershed boundary and is obtained from the website; http://www. srtm.csi.cgiar.org/. DEM tiles were mozaiked, and then processed further using GIS (Geographic Information



Fig. 1 Digital elevation model (DEM) of Kabul River Basin. Sources for shape file and background imagery: (i) https://www.usgs.gov/products/ data-and-tools/data-and-tools-topics, (ii) Online library of Arcmap)

| Bands | Elevation zones<br>(m) | Mean<br>elevation<br>(m) | Area (km <sup>2</sup> ) | Percent zone area |
|-------|------------------------|--------------------------|-------------------------|-------------------|
| 1     | 266-1000               | 700                      | 12,017                  | 13.2              |
| 2     | 1001-1667              | 1350                     | 12,278                  | 13.4              |
| 3     | 1668–2335              | 2000                     | 15,268                  | 16.7              |
| 4     | 2336-3002              | 2500                     | 16,246                  | 17.8              |
| 5     | 3003-3669              | 3350                     | 15,347                  | 16.8              |
| 6     | 3670-4337              | 4000                     | 10,665                  | 11.7              |
| 7     | 4338-5003              | 4700                     | 7260                    | 8.0               |
| 8     | 5004-7701              | 5500                     | 2212                    | 2.4               |
| Total |                        |                          | 91,297                  | 100.0             |

System) techniques to demarcate the required basin. Eight elevation zones were defined for detailed analysis of cryosphere changes. Table 1 explains the different zones' characteristics. Hypsometric elevation of each zone was plotted between hypsometric mean elevations (hypsometric mean elevations mean an equivalent area above and below the elevation of the zone) and cumulative areas of zones as shown in Fig. 2.

#### 2.1.2 Snow Cover

Snow cover analysis was performed by utilizing data of the Moderate Resolution Imaging Spectroradiometer (MODIS), Onboard TERRA Satellite, 8-daily, 500 m resolution images using the software package ArcGIS 10.0. The snow cover has been masked out for the whole Kabul River Basin. The data set from http://nsidc.org/cgi-bin/ snowi/search.pl was downloaded. It contains MOD10A2 (V005 processed images from January 2001 to December 2016. The WGS 1984 UTM ZONE 43N projection system was used to mosaic and process the MODIS images. To investigate cryosphere area changes, the Kabul River Basin was then extracted from the mosaic scenes. Some assumptions were used in the calculation of snow covered area: (i) Cloud cover over snow-covered area is taken as snow-covered area, (ii) cloud cover over land surface is ignored, and (iii) lake ice area is always added in the snow covered area. If cloud cover becomes greater than 20% on a particular day, the record of that day was not counted and the mean snow cover on that specific day was calculated by linear interpolation between the previous and the next cloud-free images. The cryosphere changes were also assessed for different elevation zones and the trend in the snow covered area has been calculated on daily, monthly, seasonal and annual basis.



Fig. 2 Hypsometric curve of the Kabul River Basin and spread of percentage area per elevation zone

#### 2.1.3 Description of Moderate Resolution Imaging Spectroradiometer (MODIS)

The launch of the Terra satellite was carried out on 18th December, 1999 with its five instruments which included MODIS. Snow cover product is one of the MODIS derived products from many geophysical products. The National Snow and Ice Data Center (NSIDC) Distributed Active Archive Center (DAAC) has been providing snow data products to the MODIS. Potential improvement to currently obtainable functional products is represented by MODIS snow cover products, due to the products being global and of 500 m resolution. Owing to the automated algorithms of MODIS snow cover mapping, the generated data set is suitable for long-term climate-related research involving data of snow cover. The product comes stocked with Large Quality Assurance (QA). In terms of the spatial characteristics of the MODIS snow cover map, it has a 500 m resolution and 2330 km swath, with an integer-based sinusoidal grid that produces a daily and 8-daily (beginning at first day of each year) composite tile products (Hall et al. 2002). The snow cover data is further divided into 6 sub-categories/classes each assigned a unique value. The categories are 'No Snow', 'Lake', 'Ocean', 'Cloud', 'Lake Ice' and 'Snow cover'. The corresponding values assigned are 25, 37, 39, 50, 100 and 200, respectively. Figure 3 presents the MODIS sinusoidal grid tiles; the research of this paper used tiles of h25 v6.

## **3** Results and Discussion

#### 3.1 Snow Cover Dynamics for the Kabul River Basin

Table 2 and Fig. 4 explain the annual variability of snowcovered areas in Kabul River Basin. Annually, on average, the total basin area changes from 10 to 66%. The minimum snow-covered area includes the glacier cover in the basin and also the perennial or left over seasonal snow. In 2001, lowest minimum snow-covered area about 8% of catchment area was observed while the highest maximum 77% was observed in 2005 as shown in Table 2 and Fig. 4. Monthly variation of snow-covered area for Kabul River Basin over the period from 2001 to 2016 is shown in Fig. 5. The snow-covered area starts increasing from August and keeps on increasing till February and then it decreases from February to August. Minimum snow cover is during the period of July to September due to high summer temperatures and liquid precipitation while it is maximum in December, January and February, due to westerly precipitation (mostly in solid form) and low temperatures.

Table 3 shows estimation of trends of the daily percentage of snow-covered area over the 16 years period in all the eight elevation zones. Examination of Table 3 reveals that there is a statistically significant increasing trend in Zone 1–3. In addition, a non-significant decreasing trend in Zones 4–8. Moreover, non-significant but



Fig. 3 MODIS sinusoidal grid tiles (https://nsidc.org/data/MOD10A1/versions/6)

Table 2 Snow-covered area for Kabul River Basin

| Area        | km <sup>2</sup> | Percentage | Years     |
|-------------|-----------------|------------|-----------|
| Total       | 91,297          |            |           |
| Average min | 9421.81         | 10.32      | 2001-2016 |
| Average max | 60,608.81       | 66.39      | 2001-2016 |
| Lowest min  | 7415.4          | 8.12       | 2001      |
| Highest max | 70,283.4        | 76.98      | 2005      |

decreasing trend in Zone 8 may hint either at decrease in solid precipitation in the high elevation region or a slight retreat of the glaciers which may become significant in the coming years. In addition, there is a significant decreasing trend of snow-covered area in Zones 6 and 7 which also gives a similar indication. A typical spatial variation of daily snow-covered area for the Kabul River Basin is shown in Fig. 6; taking the data of year 2001 as a sample.



Fig. 4 Annual variability of snow-covered areas km<sup>2</sup> for the period 2000–2016



Fig. 5 Monthly variation of snow-covered area for Kabul River Basin over the period 2000-2016

 Table 3
 Mann–Kendall trend analysis of the daily snow-covered area

 in the whole basin
 Image: Control of the daily snow-covered area

| Elevation zone | P value   | Tau      | Trend signal | Sig/non-sig          |
|----------------|-----------|----------|--------------|----------------------|
| Z1             | 0.0032    | 0.0294   | Increasing   | Significant          |
| Z2             | <2.22e-16 | 0.072    | Increasing   | Significant          |
| Z3             | 0.0059    | 0.0247   | Increasing   | Significant          |
| Z4             | 0.3889    | -0.00766 | Decreasing   | Non-signif-<br>icant |
| Z5             | 0.1398    | -0.0131  | Decreasing   | Non-signif-<br>icant |
| Z6             | 0.0374    | -0.019   | Decreasing   | Significant          |
| Z7             | 0.0033    | -0.0279  | Decreasing   | Significant          |
| Z8             | 0.3077    | -0.0102  | Decreasing   | Non-signif-<br>icant |

Examination of this figure reveals the concentration of glaciers in the northern highest elevation part of the basin; snow cover during the period of July to September shows minimum extent.

### 3.2 Glacial and Leftover/Perennial Snow Area

For determination of glacial and leftover/perennial snowcovered area, Conventional Depletion Curve (CDC) "the ratio of snow covered area in a zone to the total area of that zone" analysis is used. CDC analysis showed that Zone 8 has around 84% minimum snow-covered area average over 16 years (2001–2016) while minimum snow cover in Zone 7 goes as low as around 30% average over same 16 years. Zone 7 has the area of 7261  $\text{km}^2$ , so 30% of the area makes it around 2178 km<sup>2</sup>. Zone 8 area is above 5000 m elevation that is why it has maximum accumulated area of perennial snow and glacier, while Zone 7 has area above and below 5000; thus, less area of perennial snow and glacier as compared to Zone 8. According to studies by Wi et al. (2015) and Pfeffer et al. (2014), glacier extent was found as 2.9% of catchment area (67,370 km<sup>2</sup>) estimated by Randolph Glacier Inventory. In our case, we have a watershed area of 91,297  $\rm km^2$  and our calculated glacier area is 4.39% which is proportionally a close agreement. This gives us enough confidence that the assumptions we have made to analyze glacier-covered area change are quite reasonable. Table 4 shows our estimation of the glacial cover over the entire Kabul River Basin.

Seasonal analysis of the snow-covered area is presented in Fig. 7. In this figure, six curves are introduced as NDJF (November, December, January and February), MA (March and April), MJJA (May, June, July and August), SO (September and October), minimum snow cover (we take as an approximation of the glacierized 'Gl' area) and average annual snow cover 'Avg Annual'. Westerly precipitation (mostly in solid form) is the main source of seasonal snow cover for NDJF while the maximum snow melting takes place during the period (MJJA) because of high summer temperatures. For the months of March and April, snow cover starts decreasing as temperatures begin increasing in the area while in September and October melting starts decreasing as summer gets over.



Fig. 6 Typical spatial variation of snow-covered area for Kabul River Basin for a sample year (2001)

Table 4 Calculation of glacier-covered area

| Zones            | Total area (Km <sup>2</sup> ) | Glacial<br>cover<br>(Km <sup>2</sup> ) | Total gla-<br>cial cover<br>(Km <sup>2</sup> ) | Total<br>water-<br>shed area<br>(Km <sup>2</sup> ) | Percentage<br>of glacial<br>cover |
|------------------|-------------------------------|--|--|--|-----------------------------------|
| Zone 7<br>Zone 8 | 7261<br>2212                  | 2178<br>1858                           | 4036   | 91,926   | 4.39%                             |

To calculate the annual average, the snow-covered area for the whole year is averaged and then each year's average value is plotted over the 16 years' time period. Based on the assumption that the minimum snow-covered area of the basin is a close approximation of the glacier-covered area of the basin, its annual values are plotted in Fig. 7. The interannual variation and trend provide a rough indication of any changes in the areal extent of the basin's glacier cover. It is evident in Fig. 7 that all the curves representing seasonal and annual variation are showing an increasing trend, though negligible. Almost no trend of the minimum snow-covered area indicates that on annual basis, the glacier-covered area in the basin seems to be stable.

# 4 Conclusions and Recommendations

This study endeavored to analyze the variations of snowcovered areal extent, spatially, temporally and at different elevation zones in the Kabul River Basin. Thus, this unique study presents a useful insight for estimating the impact of climate change on the transboundary Kabul River Basin and helping the two riparian countries to take informed decisions. During the analysis of daily changes in the snowcovered area data, a significantly increasing trend in the three lowest elevation zones was observed and the middle elevation zones (Zones 4, 5) and the highest elevation zone (Zone 8) showed a negligible decreasing trend. Moreover, non-significant but decreasing trend in Zone 8 may hint either at decrease in solid precipitation in the high elevation region or a slight retreat of the glaciers which may become significant in the coming years. In addition, there is a significant decreasing trend of snow-covered area in Zones 6 and 7 which gives a similar indication. Our seasonal and annual analysis indicates that there is an overall slight increasing trend in the basin for all analyzed seasons and also on annual basis. The results of this study recommend that a detailed hydro-climate modeling analysis should be carried out for this basin to find the changes in water availability under the future climate scenarios. In addition, although our results are in close agreement with previous studies' results but for more accurate validation of MODIS results, snow and glacier cover analysis may also be carried out through some other satellite images such as ASTER or LANDSAT.

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Fig. 7 Annual and seasonal snow cover distribution for the Kabul River Basin over the period 2001–2016

#### **Compliance With Ethical Standards**

**Conflict of Interest** There is no of conflict of interest of any kind among the authors.

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water mass.

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