Shahid Beheshti University

Researches in Earth Sciences

Journal homepage: https://esrj.sbu.ac.ir

Research Article

Snow cover changes and affecting hydro-climate variables in Sabalan Mountainous region in Northwest Iran

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Received: 12 Jul 2025 Accepted: 20 Jul 2025

Abstract

Snow, a key part of the water balance in mountains, supports flow in snow-fed streams. This study aims to investigate snow cover variations and the effects of hydro-climatic variables on it in the Sabalan mountain region of Ardabil province, Iran. Snow cover changes were assessed through interpretation of Landsat satellite images. The Mann-Kendall test analyzed trends in temperature, precipitation, and discharge, while Pearson correlation assessed their relationship with snow cover. The results showed that snow cover decreased by 12.7% in the period between 1991 and 2003, and by 65.1% for the study period (1991-2015). Discharge had a decreasing trend in all hydrometric stations except Lay station in December, with significant reductions observed at Pole-Soltani and Nir hydrometric stations at 99% and 95% confidence levels, respectively. Additionally, Meshgin-Shahr hydrometric station showed an increasing trend in December discharge, while precipitation at Nir rain gauge station in January increased significantly. Although the temperature of both Meshgin-Shahr and Nir meteorological stations increased, correlation analysis did not identify a significant relationship between snow cover and hydro-climatic variables in the region. The study reveals a significant decline in snow cover in the Sabalan mountain region, with a 65.1% reduction from 1991 to 2015, indicating potential impacts on water availability. Despite rising temperatures and varying trends in precipitation and discharge, no strong correlation was found between snow cover and hydro-climatic variables. This suggests that other factors, possibly local microclimates or land use changes, may influence snow dynamics. The results revealed the complexity of snow-hydroclimate interactions and the need for integrated monitoring to manage future water resources.

Keywords: Discharge variation, Mann-Kendall test, River regime, Climate change, Snow cover.

Citation: Mostafazadeh, R. et al, 2025. Snow cover changes and affecting hydro-climate variables in Sabalan, *Res. Earth. Sci:* 16(Special Issue), (18-30) DOI: 10.48308/esrj.2025.240655.1287

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Introduction

Snowmelt runoff plays a significant role in the runoff and water yiled during spring and summer in mountainous regions, which, despite covering a small part of the Earth's surface, are critical in the hydrological perspective of river basins (Hanich et al, 2022). In many areas, snow cover in mountains is the primary source of overland and underground water supply, making it important for agriculture, domestic use, and underground aquifers (Sharma et al, 2012; Morshedi and Hoseini Boroujeni, 2021). Additionally, snow is crucial for mitigating natural hazards such as avalanches and floods (Bühler et al, 2015). Snow is the product of interactions among regional and global climate systems, with variability in its amount having significant consequences. Hydro-climatic variations can have a direct impact on snow cover variability, which in turn affects snowmelt runoff and water cycle balances (Sood et al, 2020). Therefore, identifying the temporal and spatial properties of snow and recognizing the effective parameters on snow cover are essential for appropriate water resource management (Ahmadi et al, 2014). Elevation, slope, slope direction, sunlight, snow depth, snow reflection, temperature, wind speed, vapor pressure and precipitation are among the most important variables that affect snow cover and snowmelt amounts (Huang et al, 2022). Climate change is one of the most significant environmental challenges in recent decades, causing fluctuations in weather patterns in a region. Global warming is currently considered a part of climate change (Guan et al, 2023). Studies have shown that this phenomenon has already affected biological and physical systems worldwide, and its impacts will continue to be felt in the future (Moen and Fredman, 2007; Sood et al, 2020). In recent years, snow cover has decreased in most regions, especially during the spring and summer. According to the Intergovernmental Panel on Climate Change's 2008 report, rising temperatures over decades have led to significant changes in the hydrological cycle, such as increased atmospheric vapor, changes in precipitation intensity and patterns, changes in extreme weather events, reduced snow cover, and massive melting of ice and soil moisture, leading to changes in runoff (Stern, 2007). As previously mentioned, snow precipitation in drainage basins is a stable and consistent source of overland and underground water that sustains the flow of rivers, streams, and qanats, and is also used during dry seasons (Jafarli, 2019; Song et al, 2022). Monitoring the status of snow cover at snow gauge stations can be challenging (Thakur et al, 2023), which has led to the use of remote sensing technology to monitor and evaluate characteristics of snow models at regional and global levels. Numerous studies around the world have applied this tool for snow surveys (Lindsay et al, 2015; Marti et al, 2016; Xia et al, 2019; Aghelpour et al, 2020; Singh et al, 2022; Thaler et al, 2023). The relationship between hydro-climatic variables and snow has attracted significant research attention worldwide. Vahvilinin and Luhvanso (2009) used the GISS model to assess climate change effects on snow cover and discharge in Finland, projecting a 2–6°C temperature rise and increased precipitation. Results showed a 20–50% rise in flow and reduced snow cover in southern Finland. Yang et al. (2003) found a strong link between snow cover changes and spring runoff in Siberia. Wang et al. (2015) studied the Tuotuo River basin and observed increased snow cover and variability at high altitudes, with earlier snowmelt starts and delayed ends due to warmer, wetter conditions. Knowles (2015) analyzed climate data from 1950–2010 and reported a significant decline in snow cover days. Tang et al. (2017) used MODIS data (2001–2015) to study snow cover in the Tian-Shan Mountains, revealing spatial variability, with decreases up to 9.5% and increases up to 2.81% in some areas. Ma et al. (2019) studied snow-cover area and runoff variation in the West Kunlun Mountains under climate change. They analyzed 60 years of temperature, precipitation, and snow data. Results indicated rising temperature and precipitation trends, especially in the Karakax and Yurungkax basins. Snow-cover fraction varied among the basins, and runoff depth increased in all of them. Misra et al. (2020) explored the influence of topography and climate on seasonal snow cover and its role in melt-runoff within ungauged Himalayan basins. They emphasized how snow cover area varies with elevation, slope, and aspect, and indicates the importance of temperature lapse rates in estimating melt-runoff. Aghelpour et al. (2020) researched the effects of drought on snow cover in Iran's Alborz Mountains using MODIS sensor images and meteorological data from 2000 to 2014. Utilizing statistical models and drought indices, they established a positive relationship between drought and snow cover. The study revealed that drought impacts on the snow cover area persisted for up to six months, with the highest impact occurring after two months. Banerjee et al. (2021) analyzed 2000–2020 trends in precipitation, temperature, and snow cover in the central Himalayas, finding increased precipitation (except in November) and a strong correlation ($R^2 = 0.78$) between snow cover and precipitation. Li et al. (2021) linked snow depth (Nov–Mar) to spring runoff increases in the Yellow River source region. Rößler et al. (2021) observed snow cover variability and its impact on runoff and flooding in northern Fenno-Scandia due to rising temperatures. Chen (2023) reported a 9.34% decline in glacier and snow-covered areas near O'Higgins Lake between 2000 and 2020. Previous studies across various mountainous regions worldwide have demonstrated that climate change significantly affects snow cover and runoff regimes.

Research from Europe, Asia, and South America has reported declining snow cover, rising temperatures, and shifts in the timing of snowmelt, all leading to altered surface water availability. However, most of these studies have been conducted outside Iran, and there is limited research specifically examining the impact of hydro-climatic variables on snow cover in regions like the Sabalan Mountains. Given the critical role of snow cover in sustaining water resources in northwestern Iran, especially for snow-fed rivers, there is a clear need to analyze temporal trends and the relationship between snow cover and climatic factors in this area. Therefore, the present study aims to fill this knowledge gap and provide essential insights for regional water resource management. Sabalan Mountain in Ardabil province, Iran, is a vital water source, with its snow cover crucial for regulating water supply. Recent studies indicate that snow cover on Sabalan is changing due to climate variations, impacting drinking, agricultural, and industrial water availability in the region. The region's hydrology is dominated by snowmelt runoff from the mountain, which feeds several rivers and streams in the area. Recent studies show that climate and land use changes are impacting river flow regimes in the Sabalan Mountains (Mostafazadeh and Mehri, 2018; Tavakoli et al, 2018; Namdar et al, 2020). Sabalan Mountain is one of the pristine, protected, and ecologically important regions of Ardabil province. The main hypothesis of this research is that snow cover in the Sabalan mountainous region has significantly changed over time due to variations in hydro-climatic variables such as temperature, precipitation, and river discharge. It is assumed that these changes in snow cover directly affect the hydrology of snow-fed streams in the region. The study tests whether trends in these climatic and hydrological factors are correlated with observed snow cover variations, aiming to understand the driving forces behind snow dynamics and their potential impact on water resources. Considering the important role of snow in supplying water in mountain regions, the main purpose of this study is to investigate changes in snow cover and hydro-climatic factors affecting these changes (precipitation, discharge, and temperature) within the Sabalan mountain region.

Materials and Methods

Study area

Sabalan Mountain, which has a height of 4811 meters, is the third highest mountain in Iran after Damavand and Alam-kuh. It is located in the northwest of Ardabil Province, 35 km west of Ardabil and 25 km southeast of Meshgin-Shahr, and is situated on the border between the central part of Ardabil city and Lahrud district of Meshgin-Shahr (Talebi Khiavi and Mostafazadeh, 2021). The study area is located between latitudes 38° 7' to 38° 36' north and longitudes 47° 36' to 47° 58' east. The topography of the study area includes hillslopes of Sabalan Mountain, and the climate, based on Emberger method, is semi-arid and cold-to-frozen, with an annual precipitation of around 360 mm (Ghafari et al, 2018; Asgari et al, 2025). Precipitation is mostly observed in autumn and winter, commonly as snowfall, and increases with elevation while temperature decreases (Sharifi et al, 2012). Figure 1 shows the location of Sabalan Mountain in Ardabil Province, along with the location of rainfall and hydrometric stations.

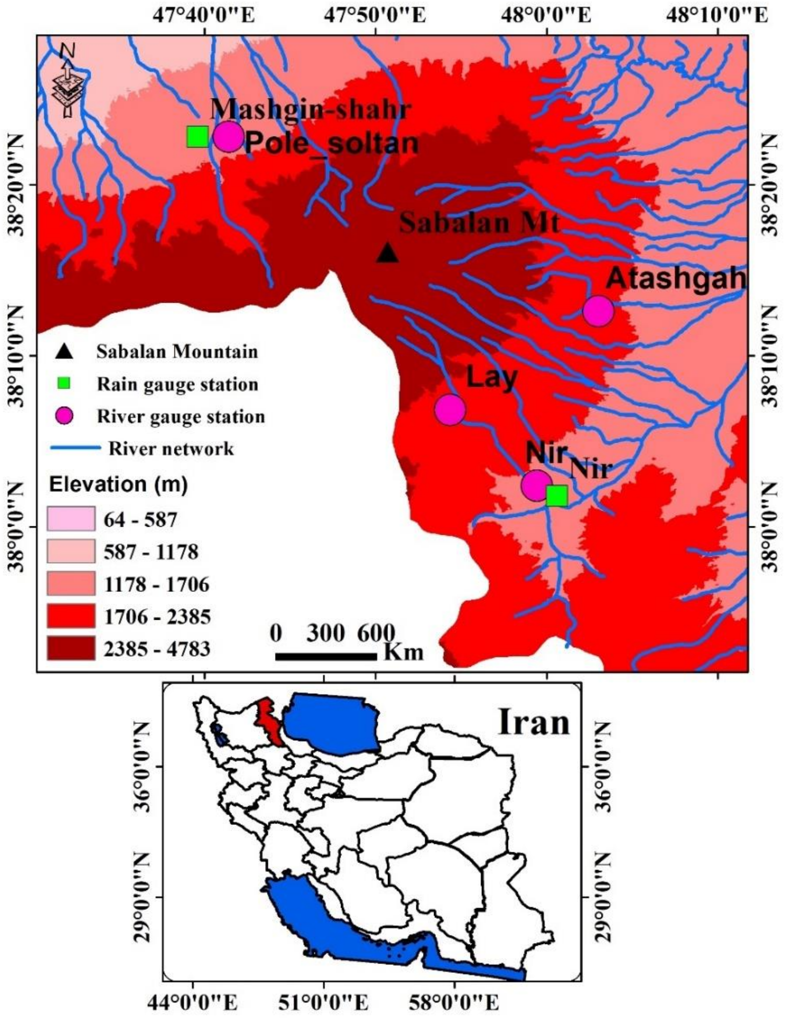

Fig. 1: Location of the study region and hydrometric and rain gauge stations in Ardabil Province

Methodology

- Delineation of snow cover using satellite imagery

To analyze temporal changes in snow cover, five Landsat satellite images from May 1991, 1998, 2003, 2009, and 2015 were used. These images, acquired from Landsat 4 and 7 satellites over paths 33 and 34, were selected based on minimal cloud cover and comparable seasonal timing to ensure consistency in snow cover interpretation. Table 1 presents the technical specifications, including sun azimuth and elevation angles, for each acquisition. The consistent acquisition period in May helped to capture the late-season snow cover extent before complete melting. This approach allowed for reliable comparison of snow cover variations over the study period.

Table 1: Specifications of satellite imagery used for snow cover changes evaluation

Date	28.05.1991	07.05.1998	13.05.2003	13.05.2009	30.05.2015
Landsat number/pass 33	Landsat 4	Landsat 4	Landsat 7	Landsat 7	Landsat 7
Landsat number/pass 34	Landsat 4	Landsat 4	Landsat 7	Landsat 7	Landsat 7
Sun Azimuth/Pass 33	115/640	128/278	130/517	131/069	129/734
Sun Elevation/Pass 33	58/959	58/914	61/781	62/139	65/916
Sun Azimuth/Pass 34	113/096	125/913	127/895	128/426	126/599
Sun Elevation/Pass 34	59/310	59/560	62/483	62/851	66/593

The Sabalan mountain range, due to its special geographical location, is located in 33 and 34 passes in Landsat satellite images, which cover Ardabil province and parts of East Azerbaijan province, respectively. The essential images were obtained from the United

States Geological Survey. The Landsat satellite is a valuable tool for monitoring snow cover in mountainous areas, as it can provide high-resolution images with a wide coverage area (Hall et al, 2016). The image preparation steps were accomplished in IMAGINE V.2014 ERDAS software to determine the snow cover in different periods. The steps are presented as follows: First of all, the gap among the used images was corrected, then, the bands of images regarding Ardabil and East Azerbaijan were merged. The false color composite for images including several bands was formed. False color composites are often used to enhance the visual contrast between different land covers and facilitate the identification of snow cover (Vidot et al, 2017). In the next phase, the photo mosaics were prepared and the boundaries of the images in 33 and 34 passes were assimilated in a single layer; afterwards, the radiometric modification and Supervised Classification were applied to classify and determine the snow cover and non-snowy areas (Lillesand et al, 2015). Based on collected and compared spectral curves, the evaluation and merging of the spectral curves of different land covers were carried out and finally classified. Spectral curves characterize the reflectance of different land covers in different wavelengths and are essential for image classification (Richards and Jia, 2006). For verification of the image classification, the Kappa index was delineated. The Kappa index is a statistical measure used to evaluate the accuracy of image classification and is widely used in remote sensing studies (Congalton and Green, 2019). Eventually, the boundary of the area was crossed over satellite images. This step likely involved the use of geospatial software such as ArcMap to define the study area and extract relevant data from satellite imagery (ESRI, 2021).

-Data sources

The current study benefited the recorded hydro-climatic data regarding monthly precipitation and temperature of Meshgin-Shahr and Nir meteorological stations, and discharge data of Atashgah, Lay, Nir and Pole-Soltani hydrometric stations during 1991, 1998, 2003, 2005, and 2015 years.

-Mann-Kendall test for hydro-climatic variables trend analysis

One of the advantages of this method is its suitability for temporal series which do not follow a particular statistical distribution. Besides, mentioned method neglects impressive of the extreme values observed in some data series, as well (Partal and Kaya, 2005). To assess the variability of hydro-climatic variables, monthly data on precipitation, temperature, and discharge from the study hydrometric stations were analyzed using the non-parametric Mann-Kendall test. The non-parametric Man-Kendall test is one of the methods for monitoring the change in the data trend, which was first used by Man (1945) and then in 1975 Kendall expanded it. The non-parametric M-K test offers diagnostic accuracy comparable to parametric tests without assuming a specific data distribution (Lettenmaier et al, 1994; Baig et al, 2021).

The test's null hypothesis assumes no trend and random data, while the alternative indicates a trend (Ahmad et al, 2015; Towfiqul Islam et al, 2020). Data are first ordered chronologically, then each value is compared to subsequent ones (Mohammad et al, 2022). The S statistic is commonly used to measure this in time series (Kisi and Ay, 2014; Parchami et al, 2024).

Eq. 1)

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_k)$$

Eq. 2)

$$sign(\theta) = \begin{cases} +1 & if(x_j - x_k) > 0 \\ 0 & if(x_j - x_k) = 0 \\ -1 & if(x_j - x_k) < 0 \end{cases}$$

In our study, with 20 data points, the normal approximation (Kendall's Z) is applied since n ≥ 10. This requires calculating the variance of S, VAR(S) (Chattopadhyay et al, 2012).

Eq. 3)

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_p(t_p - 1)(2t_p + 5)\right]$$

The equation accounts for tied values, where "n" is the total data count, "m" is the number of tied groups, and "tp" is the size of each group. The Kendall test statistic (Z-value) is calculated using S and VAR(S) (Chattopadhyay et al, 2012).

Eq. 4)

$$Z_s = \begin{cases} \frac{S-1}{VAR(S)}; & if S > 0 \\ 0; & if S = 0 \\ \frac{S+1}{VAR(S)}; & if S < 0 \end{cases}$$

If no relationship is found, the null hypothesis of no trend is accepted.

Eq. 5)

$$|\mathrm{MK}| \leq \mathrm{Z}_{s/2}$$

Trends are significant if the Mann-Kendall test statistic exceeds 1.96 (5%) or 2.56 (1%). A positive Z indicates an increasing trend, and a negative Z indicates a decreasing trend.

- Analysis of snow cover changes with hydro-climatic variables

In the same way, the values of hydroclimatic variables (temperature, precipitation and flow discharge) were analyzed. Hydroclimatic variables influence watershed water balance and help assess climate change impacts on water resources (Tan et al, 2022). In the analysis, it was tried to interpret the relationship between climatic components and flow rate. This step likely involved the use of statistical methods such as correlation analysis to identify the relationship between hydroclimatic variables and streamflow (Chiew et al, 1998; Mostafazadeh et al, 2023). In the following step, the correlation diagram between snow cover and the studied hydro-climatic variables was plotted and analyzed using R programming (R Core Team, 2024).

Results and Discussion

The purpose of this study is to investigate snow cover changes in Sabalan mountain region and the relationship between hydro-climatic variables (precipitation, temperature, and discharge) affecting snow cover changes. Additionally, regarding snow cover information is also presented in Table (2). The results of snow cover resulted from using satellite images of various temporal periods are presented in Figure 2.

Table 2: the snow cover area of Sabalan Mountain in study temporal periods

Year	1991	1998	2003	2009	2015
Snow Cover Area (km^2)	155.47	131.04	135.60	136.621	54.16

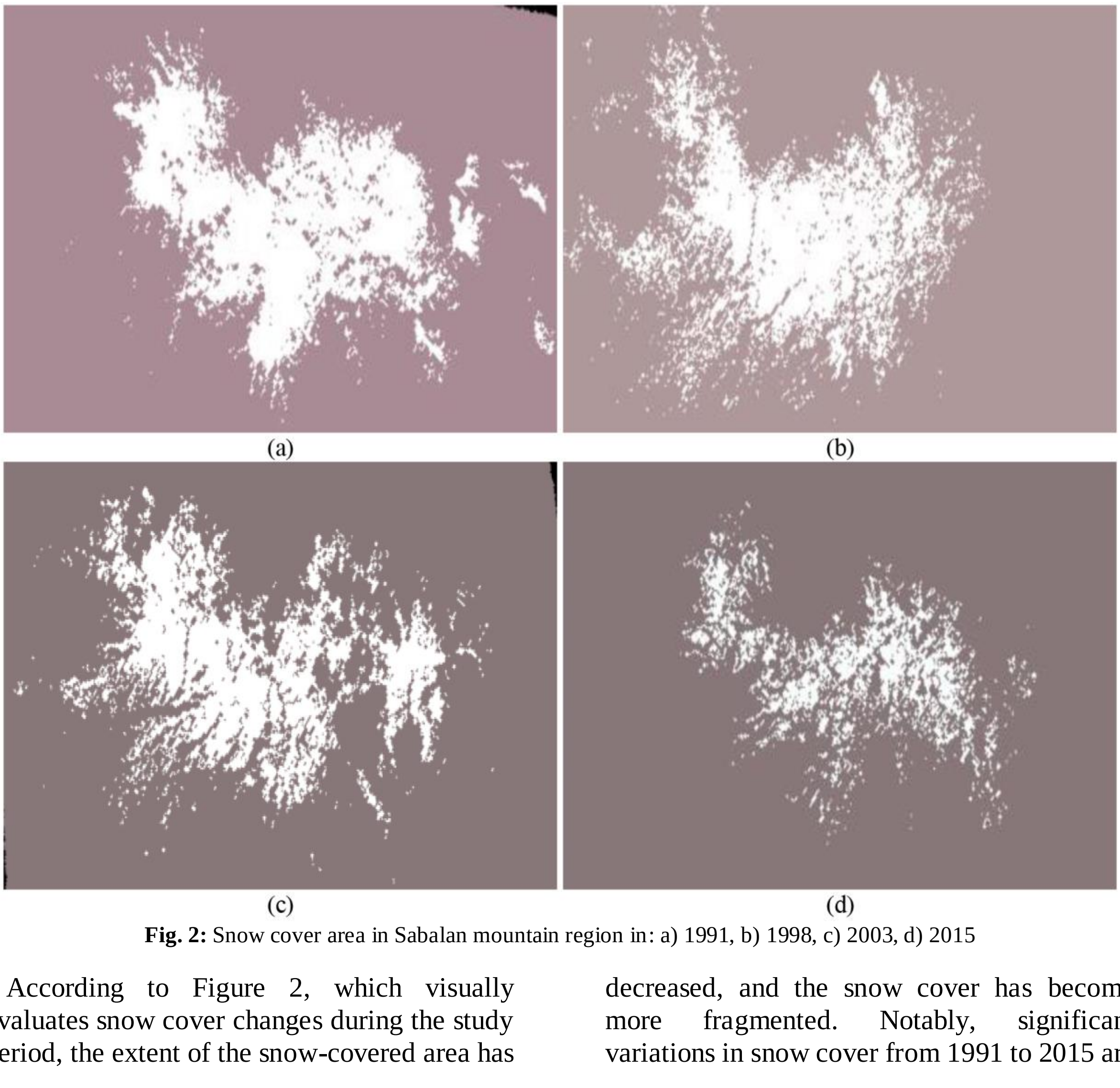
(a) (b) (c) (d)

Fig. 2: Snow cover area in Sabalan mountain region in: a) 1991, b) 1998, c) 2003, d) 2015

According to Figure 2, which visually evaluates snow cover changes during the study period, the extent of the snow-covered area has decreased, and the snow cover has become more fragmented. Notably, significant variations in snow cover from 1991 to 2015 are observed, with a significant change between the first and last periods, while changes in the middle periods are less distinct. Table 2 shows that the snow cover area has declined between 1991 and 2015, with a considerable difference between the beginning and end of the study period. However, the snow cover in the middle years slightly increased, and changes in these periods were not very noticeable.

The results of the verification test performed in the IMAGINE V.2014 ERDAS software are showin in Table 3.

Table 3: The accuracy assessment criteria in snow cover change detection in Sabalan mountain region

Year	1991	1998	2003	2009	2015
Kappa Index	0.7073	0.8339	0.7895	0.9091	0.9155
Total accuracy index	90.00	96.00	94.12	97.62	98.61

The Kappa index is a statistical measure of agreement between observed and predicted values in classification analysis. The Kappa index values in this study suggest reasonably accurate and reliable classification results. Analyzing changes in snow-covered area extent over time reveals key insights into snow cover dynamics in the study region. Comparing the snow cover extent in different years or seasons can identify trends and patterns in snow cover changes over time. Table 3 shows that all classification errors are acceptable, with the highest and least accuracy observed in 2015 and 1991, respectively, indicating good agreement between the classification and real conditions in the study area. Trend analysis of hydro-climatic variables (discharge, precipitation, and temperature) was conducted using the Mann-Kendall test and MAKSENS software, and the results are illustrated in Table 4.

Table 4: Mann-Kendall test values for hydro-climatic variables of the study meteorological stations

Variable	**Station**	**November**	**December**	**Test Z November**	**Test Z December**
Discharge	Atashgah	ns	ns	-0.77	-1.58
	Lay	ns	ns	0.84	-0.05
	Nir	*p-value<0.05	ns	-2.37	-1.76
	Pole-Soltani	**p-value<0.01	**p-value<0.01	-2.73	-2.94
Precipitation	Meshgin-Shahr	*p-value<0.05	ns	1.99	0.43
	Nir	ns	*p-value<0.05	0.00	-1.99
Temperature	Meshgin-Shahr	ns	ns	1.46	0.62
	Nir	ns	ns	0.89	0.41

ns= not significant, *=p-value less than 0.05, **=p-value less than 0.01

The table displays the results of the Mann - Kendall trend test for hydro-climatic variables at various study stations. For the Discharge and Precipitation variables, the table indicates significant trends at some stations. For instance, at Pole-Soltani station, there is a significant decreasing trend in both November and December, with a p-value of less than 0.01. At the Meshgin-Shahr station, there is a significant increasing trend in November for Precipitation (p-value<0.05). However, for the Temperature variable, there are no significant trends at any station, as indicated by the lack of stars in the table. Overall, the table suggests that certain study stations have significant trends in hydro - climatic variables. Nevertheless, it is essential to note that the M-K test is a univariate test and does not account for potential interactions or dependencies among the variables (Hamed, 2008). Hence, further analysis may be necessary to fully understand the implications of these trends.

Figure 3 shows the results of changes in discharge values compared with snow cover extent corresponding to the related month.

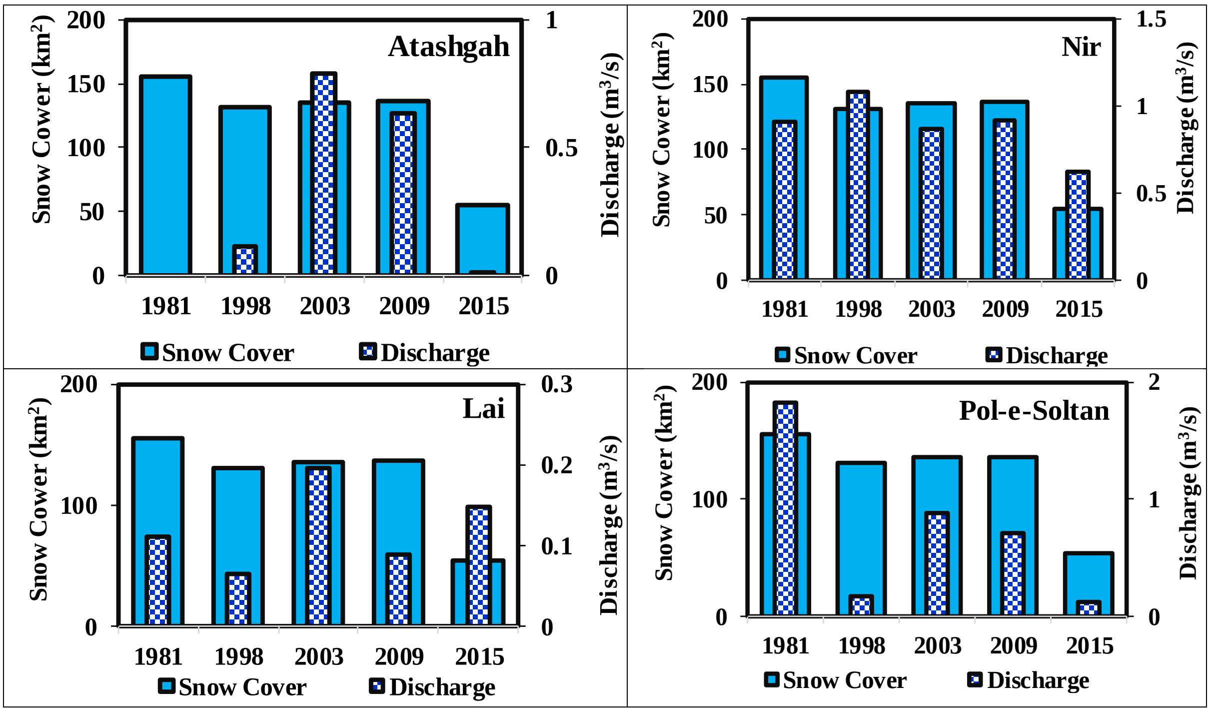

Fig. 3: Changes in river flow data simultaneous with the snow cover over different river gauge stations

Figure 3 illustrates changes in river flow data and snow cover in the study area over time. Concerning the changes in runoff, it can be observed that Atashgah and Lay hydrometric stations show a gradually increasing trend during the study period, while Nir and Pole Almas hydrometric stations do not follow a specific trend. It is noteworthy that a decrease in snow cover may result in a reduction in runoff. The discharge trends at the Atashgah, Nir, and Pole-Soltani hydrometric stations are relatively similar, indicating consistent hydrological response in the study area. Figure 4 shows the results of changes in precipitation values compared with snow cover extent corresponding to the related month.

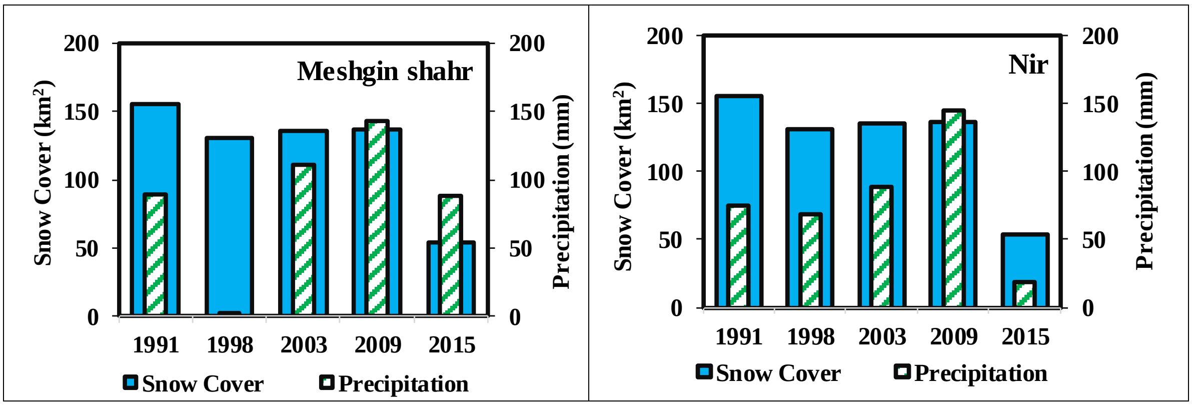

Fig. 4: Changes in precipitation data simultaneous with the snow cover over different river gauge stations

The precipitation diagrams indicate a decreasing trend over time at the Nir rain gauge station. Figure 4 also shows that at the Meshgin-Shahr rain gauge station, although precipitation amounts fluctuated, a clear decrease is observed in the later periods (2009 - 2015). These results suggest that the study area is experiencing a decrease in precipitation, which could have significant impacts on water resources in the region. Figure 5 presents the results of changes in precipitation values compared with snow cover extent corresponding to the related month.

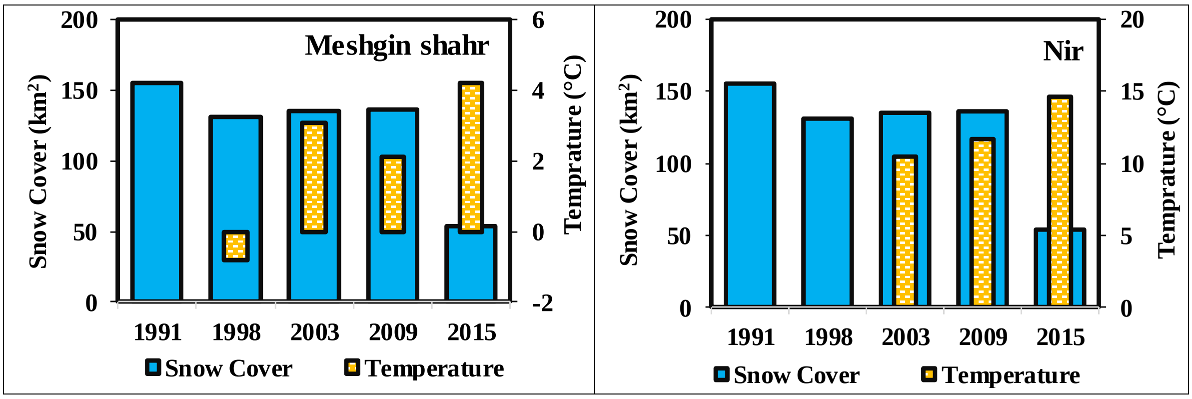

Fig. 5: Changes in temperature data simultaneous with the snow cover over different river gauge stations

Figure 5 displays an increasing trend in temperature at both Meshgin-Shahr and Nir meteorological stations, indicating a warming trend in the study area. This warming trend affects snow cover, as presented in Figure 2, where the snow cover amount gradually decreases during the study period. The significant temperature rises from 2009 to 2015 shows climate change's impact on regional snow cover and water resources. Discharge values shows fluctuations over time, depending on various factors such as precipitation as rain and snowmelt in the study months. To further evaluate the relationship among hydro-climatic variables and snow cover in the study region, a Pearson correlation test was conducted using the R language programming as shown in Figure 6. The Pearson correlation test can provide insights into the strength and direction of the relationships among the variables and help to identify potential causal relationships among them.

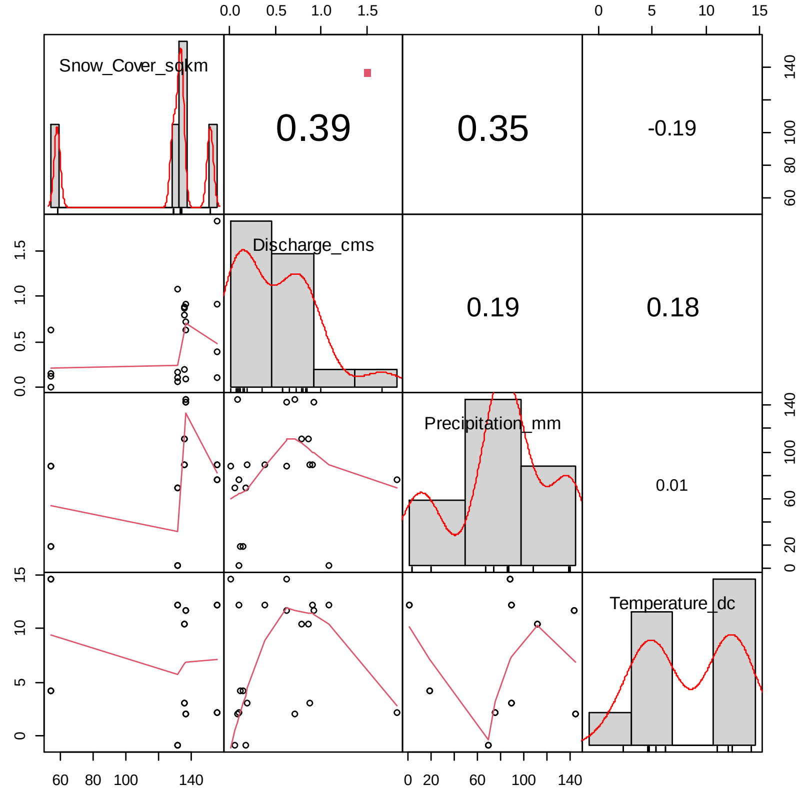

Fig. 6: Correlation matrix and dependencies between snow cover and multiple hydro-climatological variables

Based on the results in Figure 6, there is a positive correlation between snow cover and discharge, but it is not statistically significant. An increase in snow cover and consequently snowmelt will lead to an increase in discharge, but the delay in snowmelt during the month under study may reduce the correlation between these variables. Figure 6 shows that the correlation between precipitation and snow cover is positive, indicating that the value of the dependent variable increases with an increase in the independent variable (precipitation). However, the low amount of correlation coefficient suggests that the increase in snow cover as a dependent variable does not solely depend on precipitation values and may be in response to other independent parameters. A negative correlation exists between temperature and snow cover, indicating that temperature influences snow cover changes. However, it should be noted that the presented graphs and correlation values are based on the data from the surrounding stations of the study area. Due to the difference in the direction of the range of these values, the correlations may be somewhat lower overall. Another important point is that there is no precipitation and temperature measurement station near the Sabalan crest in the highlands of the study area, which can significantly reduce the significance of the independent variables affecting the snow cover. It is obvious that if measurement stations existed in the highlands, it would be possible to achieve higher correlation relationships. Generally, in the Sabalan mountain region, as precipitation increases, snow cover also increases, and with an increase in temperature, snow cover decreases. Recent studies have reported similar results to the current study regarding the positive correlation between snow cover and discharge in mountainous regions.

Conclusion

The trend analysis of hydro-climatic variables, including precipitation, discharge, and temperature, and their effect on snow cover in the Sabalan mountain region resulted in the following results. Snow cover variations in the study region were observed using classified images, and the Kappa index was used to verify the results, which showed acceptable coefficients. Discharge and precipitation showed decreasing trends, while temperature increased, reflecting expected climate change effects. The significance of these variables was examined at 95% and 99% confidence levels. In some cases, the non-significant trend of the data was due to the shortage or lack of data in the present study. The hydro-climatic parameters histogram and satellite image classification demonstrated decreasing changes for snow cover and precipitation, increasing changes for temperature values, and fluctuating variations for discharge. Correlation diagrams and the use of Pearson's correlation coefficient indicated that an increase in temperature led to a decrease in snow cover, and a decrease in precipitation also resulted in a decrease in snow cover. Additionally, in three out of four hydrometric stations, a decrease in precipitation led to a decrease in discharge, which was confirmed by their correlation coefficients. To evaluate the changes, it is suggested to use simultaneous data from snow gauges. The use of other satellites in shorter periods of time would also be helpful for better interpreting the results. As temperatures continue to rise, snow cover is expected to decrease, which will have significant implications for river flow. Therefore, it is essential to understand how climate change will affect the relationship between snow cover and meteorological variables and how this will impact river flow regime. Different rivers have different seasonal patterns, and understanding how these patterns interact with snow cover and meteorological variables can provide insights into the complex relationships between these variables and river flow. The increasing frequency and intensity of extreme events due to climate change can have significant impacts on snow cover, river flow, and water availability. Therefore, understanding how extreme events affect the relationship between snow cover and meteorological variables is crucial for managing water resources in the future.

Acknowledgment

The authors of this article did not receive any financial support from any organization or institution.

References

Aghelpour, P., Guan, Y., Bahrami-Pichaghchi, H., Mohammadi, B., Kisi, O. and Zhang, D., 2020. Using the MODIS sensor for snow cover modeling and the assessment of drought effects on snow cover in a mountainous area. Remote Sensing, v. 12(20), DOI: 10.3390/rs12203437.

Ahmad, I., Tang, D., Wang, T., Wang, M. and Wagan, B., 2015. Precipitation trends over time using Mann-Kendall and spearman’s rho tests in swat river basin, Pakistan. Advances in Meteorology, v.2, p. 1-15, DOI: 10.1155/2015/431860.

Asgari, E., Mostafazadeh, R. and Talebi Khiavi, H., 2025. Projecting the Climate Change Impact on

Water Yield in a Cold Mountainous Watershed, Ardabil. Journal of the Earth and Space Physics, v. 50(4).

Baig, M.R.I., Shahfahad, Naikoo, M.W., Ansari, A.H., Ahmad, S. and Rahman, A., 2021. Spatio-temporal analysis of precipitation pattern and trend using standardized precipitation index and Mann–Kendall test in coastal Andhra Pradesh. Modeling Earth Systems and Environment, v. 8(1), DOI: 10.1007/s40808-021-01262-w.

Banerjee, A., Chen, R., Meadows, M.E., Sengupta, D., Pathak, S., Xia, Z. and Mal, S., 2021. Tracking 21st century climate dynamics of the Third Pole: An analysis of topo-climate impacts on snow cover in the central Himalaya using Google Earth Engine. International Journal of Applied Earth Observation and Geoinformation, v. 103, 102490.

Barnett, T.P., Adam, J.C. and Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, v. 438, p. 303-309.

Bühler, Y., Marty, M., Egli, L., Veitinger, J., Jonas, T., Thee, P. and Ginzler, C., 2015. Snow depth mapping in high-alpine catchments using digital photogrammetry. The Cryosphere, v. 9(1), p. 229-243.

Chattopadhyay, G., Chakraborthy, P. and Chattopadhyay, S., 2012. Mann–Kendall trend analysis of tropospheric ozone and its modeling using ARIMA. Theoretical and Applied Climatology, v. 110, p. 321-328.

Chen, J., 2022. Glacierized and snow-cover area variation in O'Higgins lake area from 2000 to 2020. In Advances in Measurement Technology, Disaster Prevention and Mitigation, p. 56-64. CRC Press.

Chiew, F.H., Piechota, T.C., Dracup, J.A. and McMahon, T.A., 1998. El Nino/Southern Oscillation and Australian rainfall, streamflow and drought: Links and potential for forecasting. Journal of hydrology, v. 204(1-4), p. 138-149.

Congalton, R.G. and Green, K., 2019. Assessing the accuracy of remotely sensed data: principles and practices. CRC press.

Demir, V., Esra, U.R.A.Y., Orhan, O., Yavariabdi, A. and Kusetogullari, H., 2021. Trend analysis of ground-water levels and the effect of effective soil stress change: the case study of Konya closed basin. Avrupa Bilim ve Teknoloji Dergisi, v. 24, p. 515-522.

Ghafari, S., Ghorbani, A., Moameri, M., Mostafazadeh, R. and Bidarlord, M., 2018. Composition and structure of species along altitude gradient in Moghan-Sabalan rangelands, Iran. Journal of Mountain Science, v. 15(6), p. 1209-1228.

Guan, X., Zeng, X., Shi, R., Chen, H. and Wei, Z., 2023. Changes in snow parameterization over typical vegetation in the Northern Hemisphere. Atmospheric and Oceanic Science Letters, v. 16(2), 100325.

Hall, D.K., Riggs, G.A. and Salomonson, V.V., 2016. MODIS/terra snow cover daily L3 global 500m grid, version 6. Boulder, CO: NASA National Snow and Ice Data Center Distributed Active Archive Center. Doi: 10.5067/MODIS/MOD10A1.006

Hamed, K.H., 2008. Trend detection in hydrologic data: The Mann-Kendall trend test under the scaling hypothesis. Journal of Hydrology, v. 349(3-4), p. 350-363. Doi: 10.1016/j.jhydrol.2007.11.009

Hanich, L., Chehbouni, A., Gascoin, S., Boudhar, A., Jarlan, L., Tramblay, Y. and Khabba, S., 2022. Snow hydrology in the Moroccan Atlas Mountains. Journal of Hydrology: Regional Studies, v. 42, 101101.

Huang, Y., Xu, J., Xu, J., Zhao, Y., Yu, B., Liu, H. and Zheng, Z., 2022. HMRFS-TP: long-term daily gap-free snow cover products over the Tibetan Plateau from 2002 to 2021 based on Hidden Markov Random Field model. Earth System Science Data Discussions, p. 1-27.

Jafarli, J., 2019. Conditions for the formation of underground waters in the Turyanchay and Girdimanchay river basins. Journal of Technical and Natural Sciences, v. 4, p. 68-72.

Kakavand, M. and Bonyadi, Z., 2022. Evaluation of alteration zones around Parmagasu copper indication, Kuh Zar, Damghan, Iran, using ASTER satellite data. Geocarto International, v. 37(27), p. 16827-16845.

Kisi, O. and Ay, M., 2014. Comparison of Mann–Kendall and innovative trend method for water quality parameters of the Kizilirmak River, Turkey, Journal of Hydrology, v. 513, p. 362-375.

Knowles, N., 2015. Trends in snow cover and related quantities at weather stations in the conterminous United States, Journal of Climate, v. 28(19), p. 7518-7528.

Lettenmaier, D.P., Wood, E.F. and Wallis, J.R., 1994. Hydro-climatological trends in the continental United States, 1948-88, Journal of Climate, v. 7(4), p. 586-607.

Li, Z. et al, 2021. Climate and snow cover's impact on spring runoff in the Yellow River source region. Science of the Total Environment, v. 799, 149503.

Lillesand, T., Kiefer, R.W. and Chipman, J., 2015. Remote sensing and image interpretation. John Wiley & Sons.

Lindsay, C., Zhu, J., Miller, A. E., Kirchner, P., & Wilson, T. L. (2015). Deriving snow cover metrics for Alaska from MODIS. Remote sensing, v. 7(10), p. 12961-12985.

Ma, X., Yan, W., Zhao, C. and Kundzewicz, Z.W., 2019. Snow-Cover Area and Runoff Variation under Climate Change in the West Kunlun Mountains. Water, v. 11(11), 2246.

Marti, R., Gascoin, S., Berthier, E., De Pinel, M., Houet, T. and Laffly, D., 2016. Mapping snow depth in open alpine terrain from stereo satellite imagery. The Cryosphere, v. 10(4), p. 1361-1380.

Misra, A., Kumar, A., Bhambri, R., Haritashya, U.K., Verma, A., Dobhal, D.P., Gupta, A.K., Gupta, G. and Upadhyay, R., 2020. Topographic and climatic influence on seasonal snow cover: Implications for the hydrology of ungauged Himalayan basins, India, Journal of Hydrology, v. 585, 124716.

Moen, J. and Fredman, P., 2007. Effects of Climate Change on Alpine Skiing in Sweden, Journal of SustainableTourism, v. 15(4), p. 418-437.

Mohammad, L., Mondal, I., Bandyopadhyay, J., Pham, Q.B., Nguyen, X.C., Dinh, C.D. and Al-Quraishi, A.M.F., 2022. Assessment of spatio-temporal trends of satellite-based aerosol optical depth using Mann–Kendall test and Sen's slope estimator model. Geomatics, Natural Hazards and Risk, v. 13(1), p. 1270-1298.

Morshedi, A. and Hoseini Boroujeni, B., 2021. Monitoring and comparing NDSI changes using MODIS and ETM+ sensor data to estimate snow cover in North Karun Basin. Water and Soil Management and Modelling, v. 1(4), p. 68-82. Doi: 10.22098/mmws.2021.9453.1045

Mostafazadeh, R. and Mehri, S., 2018. Trends in variability of flood coefficient in river gauge stations of Ardabil Province, Iran. Journal of Watershed Management Research, v. 9(17), p. 82-95.

Mostafazadeh, R., Talebi Khiavi, H., Esmali-Ouri, A. and Golshan, M., 2023. Surface runoff and sediment yield response under the rainfall simulation condition controlled by soil variables of a semi-arid landscape. Environment, Development and Sustainability, v. 25(11), p. 12339-12356.

Namdar, F., Mahmoudi, S., Ouri, A.E. and Pazira, E., 2020. Investigating the effect of land use changes on soil erosion using RS-GIS and AHP-Fuzzy based techniques (Case Study: Qaresu Watershed, Ardabil, Iran). Nexo Scientific Journal, v. 33(02), p. 525-538.

Parchami, N., Mostafazadeh, R., Ouri, A.E. and Imani, R., 2024. Spatio-temporal analysis of river flow master recession curve characteristics over Ardabil province rivers. Physics and Chemistry of the Earth, Parts A/B/C, v. 134, 103586.

Partal, T. and Kahya, E., 2006. Trend analysis in Turkish precipitation data. Hydrological Processes: An International Journal, v. 20(9), p. 2011-2026.

R Core Team., 2024. R: A language and environment for statistical computing (Version 4.3.0). R Foundation for Statistical Computing. https://www.R-project.org

Robler, S., Witt, M.S., Ikonen, J., Brown, I.A. and Dietz, A.J., 2021. Remote sensing of snow cover variability and its influence on the runoff of Sápmi's Rivers, Geosciences, v. 11(3), Doi. org/10.3390/geosciences11030130.

Setzer, J. and Higham, C., 2022. Global trends in climate change litigation: 2022 snapshot.

Sharifi, J., Jalili, A., Gasimov, S., Naqinezhad, A. and Azimi Motem, F., 2012. Study on floristic, life form and plant chorology of wetlands in northern and eastern slopes of Sabalan mountains. Taxonomy and Biosystematics, v. 4(10), p. 41-52.

Sharma, V., Mishra, V. and Joshi, P., 2012. Snow cover variation and streamflow simulation in a snow-fed river basin of the Northwest Himalaya. Journal of Mountain Science, v. 9(6), p. 853-868.

Singh, K.K., Singh, D.K., Thakur, N.K., Dewali, S.K., Negi, H.S., Snehmani, and Mishra, V.D., 2022. Detection and mapping of snow avalanche debris from Western Himalaya, India using remote sensing satellite images. Geocarto International, v. 37(9), p. 2561-2579.

Song, Y., Li, Z., Gu, Y. and Xiao, Z., 2022. Impact of Solar Activity on Snow Cover Variation over the Tibetan Plateau and Linkage to the Summer Precipitation in China. Frontiers in Earth Science, v. 9, 756762.

Sood, V., Singh, S., Taloor, A.K., Prashar, S. and Kaur, R., 2020. Monitoring and mapping of snow cover variability using topographically derived NDSI model over north Indian Himalayas during the period 2008–19. Applied Computing and Geosciences, v. 8, 100040.

Stern, N., 2007. The economics of climate change: The Stern Review, Cambridge University Press, Cambridge, p. 1-556.

Talebi Khiavi, H. and Mostafazadeh, R., 2021. Land use change dynamics assessment in the Khiavchai region, the hillside of Sabalan mountainous area. Arabian Journal of Geosciences, v. 14(22), 2257.

Tan, X., Liu, B., Tan, X. and Chen, X., 2022. Long-term water imbalances of watersheds resulting from biases in hydroclimatic data sets for water budget analyses. Water Resources Research, v. 58(3), e2021WR031209.

Tang, Z., Wang, X., Wang, J., Wang, X., Li, H. and Jiang, Z., 2017. Spatiotemporal variation of snow cover in Tianshan Mountains, Central Asia, based on cloud-free MODIS fractional snow cover product, 2001–2015. Remote Sensing, v. 9(10), 1045.

Thakur, A., Sharma, A. and Thakural, L.N., 2023. Assessment of Snow Cover Changes Over the Tons River Basin During Last Two Decades (2000–2019). In Climate Change and

Environmental Impacts: Past, Present and Future Perspective, p. 287-294, Cham: Springer International Publishing.

Thaler, E.A., Crumley, R.L. and Bennett, K.E., 2023. Estimating snow cover from high-resolution satellite imagery by thresholding blue wavelengths. Remote Sensing of Environment, v. 285, 113403.

Tavakoli Ghazi Jahani, M., Raoof, M., Rasoulzadeh, A. and Mirzayi, S., 2018. Evaluation of Effect of Land Use Change on Flood Hydrograph and Peak of Flow in Atashgah Basin of Ardabil. Iranian Journal of Rainwater Catchment Systems, v. 5(4), p. 59-71.

Towfiqul Islam, A.R.M., Rahman, M.S., Khatun, R. and Hu, Z., 2020. Spatiotemporal trends in the frequency of daily rainfall in Bangladesh during 1975–2017. Theoretical and Applied Climatology, v. 141, p. 869-887.

Vehviläinen, B. and Lohvansuu, J., 1991. The effects of climate change on discharges and snow cover in Finland. Hydrological Sciences Journal, v. 36(2), p. 109-121.

Vidot, J., Bellec, B., Dumont, M. and Brunel, P., 2017. A daytime VIIRS RGB pseudo composite for snow detection. Remote Sensing of Environment, v. 196, p. 134-139.

Wang, R., Yao, Z., Liu, Z., Wu, S., Jiang, L. and Wang, L., 2015. Snow cover variability and snowmelt in a high-altitude ungauged catchment. Hydrological Processes, v. 29(12), p. 2672-2684. https://doi.org/10.1002/hyp.10472

Xia, M., Liu, W.A., Shi, B., Weng, L. and Liu, J., 2019. Cloud/snow recognition for multispectral satellite imagery based on a multidimensional deep residual network. International Journal of Remote Sensing, v. 40(1), p. 156-170.

Yang, D., Robinson, D., Zhao, Y., Estilow, T. and Ye, B., 2003. Streamflow response to seasonal snow cover extent changes in large Siberian watersheds, Journal of Geophysical Research, v. 108(D18), p. 1-14.

Zhang, R., Xu, Z., Zuo, D. and Ban, C., 2020. Hydro-meteorological trends in the Yarlung Zangbo River Basin and possible associations with large-scale circulation. Water, v. 12(1), 344, DOI: 10.3390/w17030344.