Plant Archives **Vol. 25, Special Issue (ICTPAIRS-JAU, Junagadh) Jan. 2025 pp. 173-180**
e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.SP.ICTPAIRS-028

SPATIOTEMPORAL COMPARATIVE STUDY OF SNOW COVER VARIABILITY OVER THE HIMALAYAN REGION BY USING MODIS SATELLITE DATA

Surendra P. Singh[1]* and Swagatika Jena[2]

[1]Department of Basic Engineering and Applied Science, College of Agricultural Engineering and Technology,
Navsari Agricultural University, Dediapada, Gujarat, India.
[2]Department of Farm Machinery and Power Engineering, College of Agricultural Engineering and Technology,
Navsari Agricultural University, Dediapada, Gujarat, India.
*Corresponding author E-mail : pratap2583@gmail.com

ABSTRACT

Himalayan rivers are the paramount source of water supply to millions of people for drinking, irrigation and hydropower generation. Several researchers reported that the hydrological regime of these Himalayan rivers is vulnerable to climate change and its impacts on its stream flow runoff and evapotranspiration. In this study of long-term time series spatiotemporal (1982-2021) in the coverage of snow cover and climatic variables for the different zone (Western, Central, & Eastern) Himalayan region by using satellite data at 0.10-degree grid resolution from NASA archives. The Mann-Kendall test with variance corrections is used to detect the trend, and Sen's slope estimator is calculated to quantify monthly, seasonal and annual trends. The result suggests that there is a significant increasing trend for mean temperature and minimum temperature, while no remarkable trend is identified for maximum temperature. Similarly, sensitivity concerning these climatic variables a significant increasing trend was observed in the annual mean runoff with Sen's slope rate= +0.0022 mm year^{-1} ($p<0.05$), +0.0019 mm year^{-1} ($p<0.05$), +0.009 mm year^{-1} ($p<0.05$) western, central and eastern zone, respectively. Snow cover is a major source of fresh water for the region and downstream area and is depleting at an alarming rate. In summary, this study describes the relations of climatic variables (surface temperature with snow cover fraction, surface runoff, and evapotranspiration (ET). Outcomes of the results in the last decade's variability of snow cover have drastically changed over all three zones of the Himalayan. The findings of this study would be useful for sustainable water resources planning and management of agriculture in hilly regions, the availability of water in downstream areas and the development of adaptation strategies in adverse climatic conditions.

Key words : Agriculture, Climate Change, Climate variables, Himalayas, Mann-Kendall Test, Snow cover.

Introduction

The Himalayas are known as Asia's Water Tower (Xu *et al.*, 2009). A large portion of the high-elevated mountains are glaciated, and they are a prominent feature of this region, contributing to the region's river systems. This zone includes the world's major river basins, including the Ganges, Indus, Brahmaputra and serves as the backbone of the region's economy, which is home to approximately 60 million people. The annual precipitation in India is approximately 1170 mm (4000 km^3), but its distribution varies greatly over time and space. Water demand has increased at twice the rate of population growth as a result of the rising population (FAO, 2015). India has 18% of the world's population and 4% of the world's water resources. The basic hydrological unit for assessing, planning, and developing water resources is the river catchment. Climate change poses a significant threat to India's water resources (Yao *et al.*, 2022). Water availability will be impacted further by rising population, urbanization, and rapid industrialization. Climate change will have an impact on hydrology in the Indian subcontinent, which will reflect in its water resources and agricultural economy (Nie *et al*., 2021). The Indus and its tributaries receive a large portion of their runoff from snowmelt and glaciers, making this river system vulnerable to climate change (Singh, 2008; Chen *et al.*, 2021). Snow and ice melt are important for river runoff and a critical resource for agriculture, indirectly via irrigation and groundwater flow generated by snowmelt, and for all living species (Tsering, 2010; Azizi and Akhtar, 2022). Among these incidents, the decrease in SCA (Snow Cover area) has recently gained significant attention from the global scientific community due to the associated chain of drastic event of climate change, and floods (Thapa *et al*., 2020). Literature showed that the Himalayan region has detected both rising and declining trends in SCA owing to different altitudinal variations. Bookhagen and Burbank (2010) and Kour *et al.* (2016) have detected a rise in the SCA of the western Himalayan region due to the influence of winter westerlies. Himalaya is acutely vulnerable to climate change due to the expansive coverage of snow (Maskey *et al*., 2011; Wang *et al*., 2023). Over the last few years, images and products of remote sensing have been widely employed to investigate the variation of snow cover in the Western Himalayan cryosphere (Liang *et al*., 2008; Jain *et al.*, 2009; Gurung *et al.*, 2011; Birajdar *et al*., 2016; Barman and Bhattacharjya, 2015; Kour *et al*., 2016; Negi *et al*., 2017; Shafiq *et al*., 2019). The Western Indian Himalayas experienced a 0.9°C increase from 1901 to 2003 (Dash *et al.*, 2007; Dimri and Dash, 2011**)**. Annual average maximum temperatures in the western Himalayas increased by 1.1 to 2.5°C from 1975 to 2006. Temperatures in the northwest Himalayas have risen at a rate of 0.16 °C per decade over the last century, according to Bhutiyani *et al.* (2007). Maximum temperatures and the seasonal average of daily maximum temperatures increased in the northwest Indian Himalayas for all seasons except monsoons (Singh *et al.,* 2008). Increasing temperatures were discovered to be more prevalent in the Himalayan region's winters (Shrestha, 1999; Bhutiyani *et al*., 2010). The majority of the researchers have found evidence of warming in the eastern Indian Himalayas.

A study Jhajharia and Singh (2011) found that average, maximum, and minimum temperatures were rising at rates of 0.2–0.8°C/decade, 0.1–0.9°C/decade, & 0.1–0.6°C/decade, respectively. Temperature rises studies in the Himalayas revealed that the region is vulnerable to warming rates faster than the global average. These results will majorly affect SCA and water resource availability in the face of future climate change. The massive snow and ice cover has an impact on the region's major rivers and tributaries, including the Brahmaputra, Ganges and Indus. They contribute to the region's economy through agriculture, water supply, tourism and hydropower. The effects of climate change are clearly visible in the Himalayas, with increasing floods, droughts, landslides, biodiversity changes, endangered species, agriculture livelihood, threatening challenges to food security and so on (Barnett *et al.,* 2005; Xu *et al.,* 2009; Kumar and Gautam, 2014; Mir *et al.*, 2019). Temperatures in the Himalayan region have risen, but the variation is time and region-dependent. Climate change is occurring globally (IPCC, 2007) and is alleged to cause changes in climatic variables, such as relative humidity, precipitation, air temperature, and solar radiation and in the hydrological cycle by affecting precipitation and evaporation (Yu *et al.,* 2013). Researchers have concluded that the rate of temperature increase in the last few decades has been faster than in the previous century (Brohan *et al*., 2006; Diodato *et al*., 2011). Winter maximum temperatures increased at rates of 0.45, 0.42 and 0.23°C/decade for the upper, middle and lower basins, respectively, from 1967 to 2005 (Khattak *et al*., 2011).

Statistical techniques, such as the non-parametric Mann-Kendall test and Sen's slope were employed to estimate and quantify the trend in the data. These methods are widely used for detecting trends in time series data. Nonparametric tests are useful in the presence of non-normality and are resistant to outliers and missing data. This study looks at the long-term, seasonal and annual trends of climatic variable with snow cover fraction, surface runoff, & evapotranspiration in different parts of Himalayan zones. To detect the trend, the Mann-Kendall test with variance corrections is used, and Sen's slope estimator is calculated to quantify the trend. Trend analysis is useful for predicting future extreme weather and evaluating the effectiveness of climate change mitigation efforts.

Materials and Methods

Himalayan Region

The whole of the Himalayas covering 20-38° N and 70-98° E Teotia (S. S. *et al*., 1997). These are divided into three climatic zones western Himalayas (WH) 30-38° N latitude, 70-78° E longitude central Himalayas (CH) 28-38° N latitude and 78-98° E longitude eastern Himalayas (NH) 20-28° N latitude and 88-98° E longitude (Gupta *et al*., 1986). The Himalaya has a topographic, variability from south to north and east to west with a regional scale weather pattern. This region contains high mountains with considerable snow and ice extent and glaciers, including the top 14 peaks of the world. The lives of hundreds of millions of people living downstream

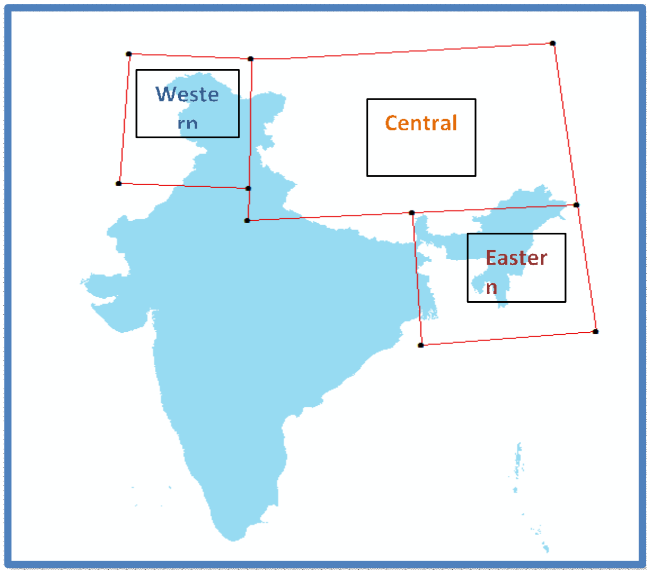

Fig. 1 : Map of India showing the study areas of Himalayan Zones Western (WH), Central (CH) & Eastern (EH).

of this region depend on the discharge from these rivers (Wester *et al.*, 2019).

Data collection

Dataset used for this research work land surface parameters simulated from the Noah 3.6.1 model in the Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS). The data are in (0.10) degree resolution and range from (1982 to June 2021) and for MODIS Satellite data (2000 to 2021).

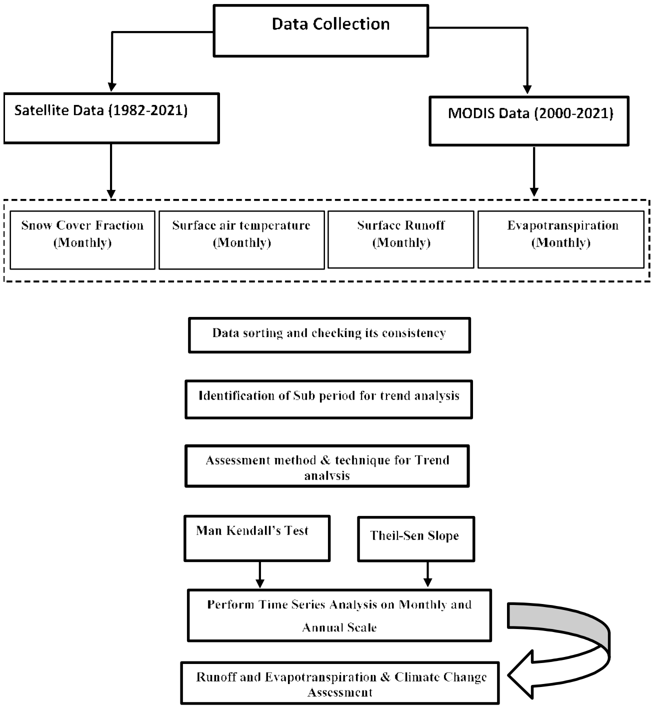

Fig. 2 : Methodology of Trend analysis for different parameter (Surface Runoff, Evapotranspiration, Snow cover fraction & Surface temperature over the period of time for Climate Change Assessment).

Trend analysis with the Mann-Kendall test

For trend analysis, a widely used nonparametric Mann-Kendall (MK) trend test with a 5% significance level ($p = 0.05$) for Kendall's tau (τ) coefficient Mann (1945) and Theil-Sen estimator as known as Sen's slope (S) Sen (1968) was performed to estimate whether there exists a significant trend in the time series of snow cover fraction, surface air temperature, surface runoff and evapotranspiration. The MK test was applied for trend analysis at the annual and seasonal variation levels in all parameters mentioned above.

Results and Discussion

In the present study, an assessment of snow cover variability for the three zones of Himalayan has been carried out using trend analysis of representative variables *i.e.*, snow cover fraction, surface air temperature, surface runoff and evapotranspiration. Detailed trend analysis has been carried out for annual, snow accumulation (November to March), snow melting (April to June) and seasonal variation as classified by the India Meteorological Department (IMD) in four parts *i.e.*, Winter (December-February) Premonsoon (March-May) Post monsoon (October to November) and Monsoon (June to September) periods of the mean using 40-year time series data (1982–June 2021) and for MODIS data (2000 to 2021). Non-parametric Mann-Kendall (MK) and Sen's slope estimator have been used for trend analysis. Results have been discussed in detail, as in Tables 1-2. and Figs. 4-5.

Trends in the annual mean time scale

The trend analysis has been done at the annual mean to ascertain the possible spatiotemporal variability in snow cover and change in climate relating to surface air temperature. The MK trend analysis techniques have been used to find the trend at the annual mean for all three zones of the Himalayan region. The results are presented in Table 1 as shown in Fig. 3.

The MK trend analysis techniques have been used to find the trend at the annual mean for all three zones of the Himalayan region. In the case of surface air temperature, a non-significantly increase at the rate of MK (τ) = +0.82 ($p>0.05$) and Sen's slope (S) = +0.08 $^{\circ}$C year^{-1}, and a significant increase at the rate of MK (τ) = +2.51 ($p<0.05$) and Sen's slope (S) = +0.05 $^{\circ}$C year^{-1} for central and western zones, respectively.

However, the eastern zone shows a significant decrease at the rate of MK (τ) = -0.02 ($p<0.05$) and Sen's slope (S) = -0.00013 $^{\circ}$C year^{-1}.

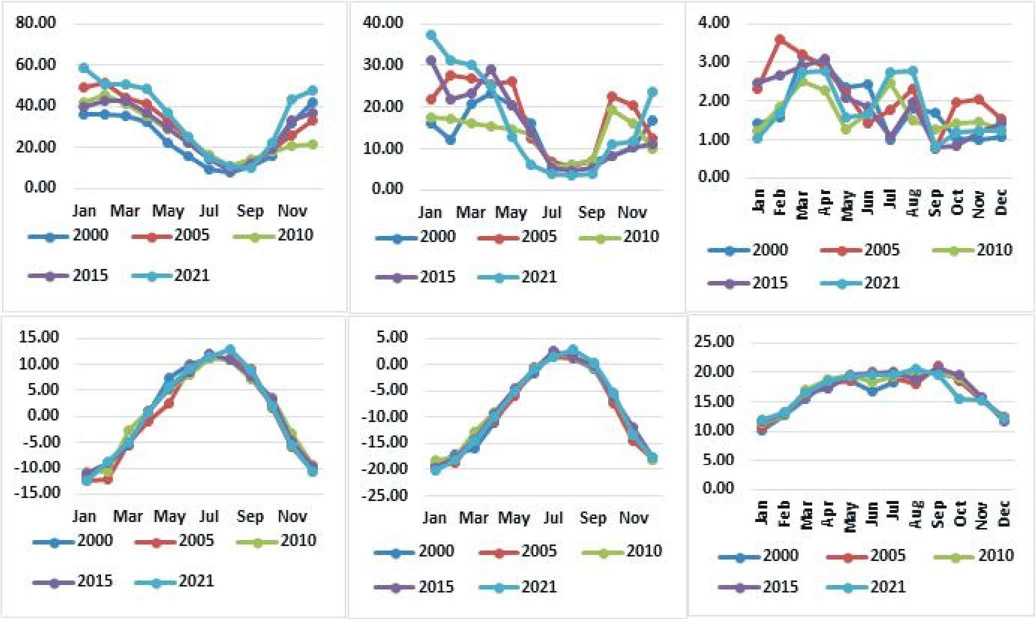

Fig. 3 : Monthly variation in the time-series analysis of fractional snow cover (row-1), surface temperature night (row-2) in the Himalayan zones Western (WH), Central (CH) and Eastern (EH) for the period from (2000-2021) by MODIS Data.

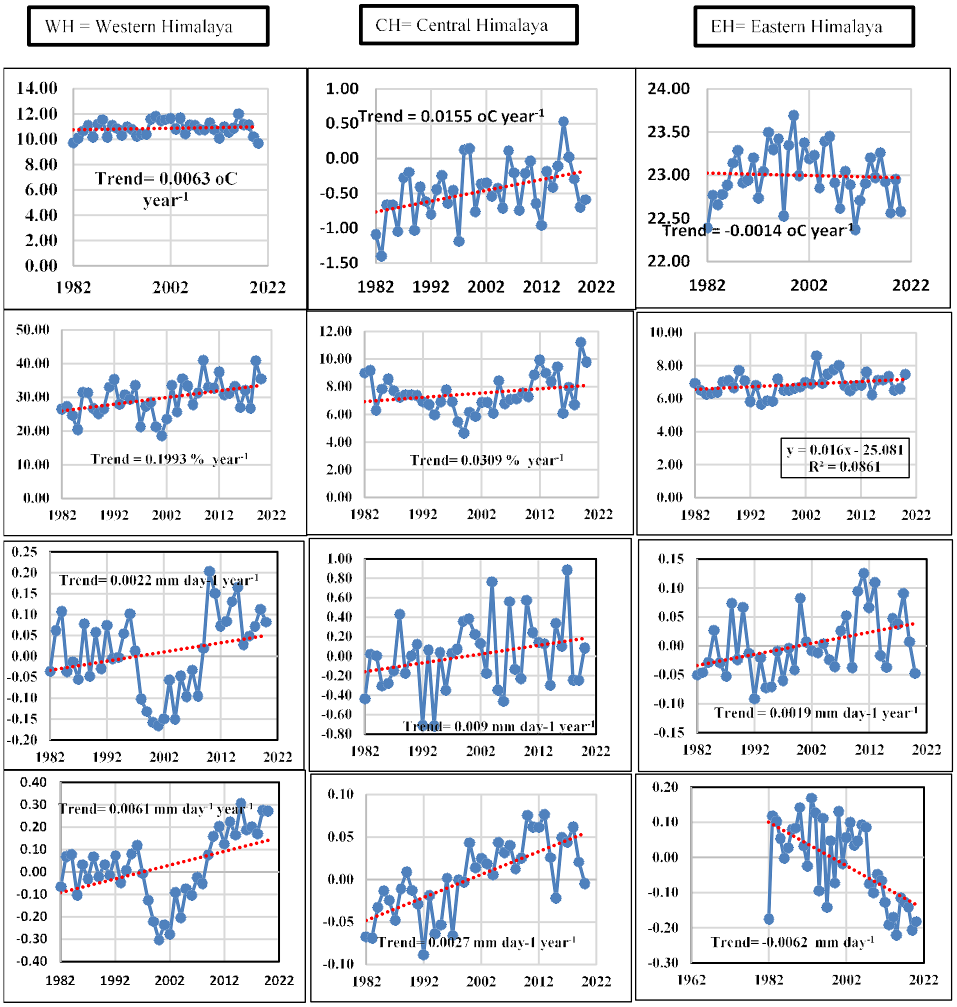

Fig. 4 : Annual monthly mean time-series analysis of land surface temperature, snow cover fraction, and surface runoff, in the Himalayan Zones Western (WH), Central (CH) and Eastern (EH) for the period from (1982 to 2000) by Satellite Data. (Data source: https://disc.gsfc.nasa.gov).

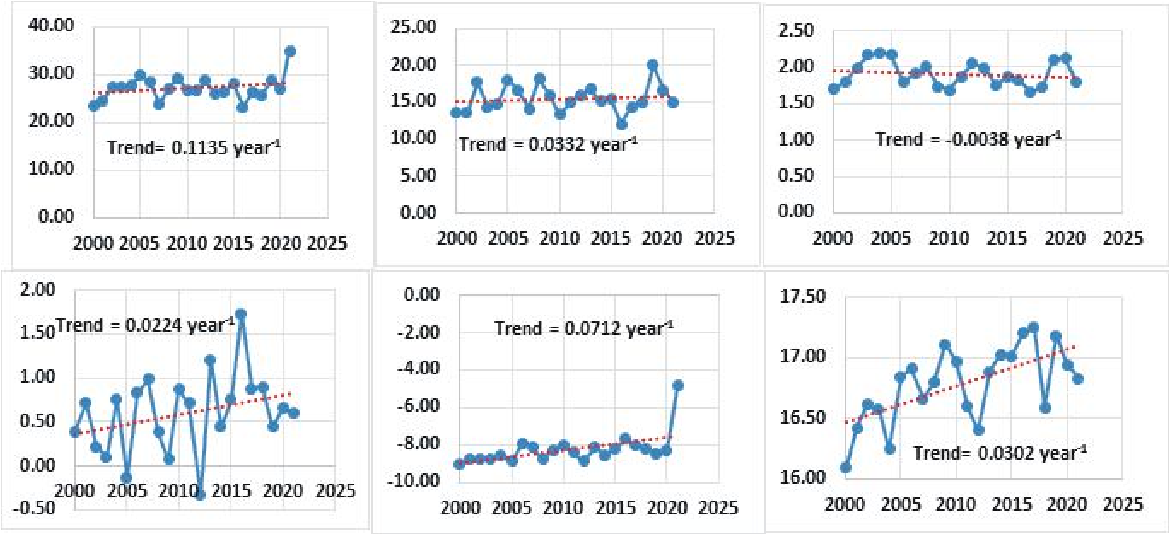

Fig. 5 : Annual mean sub-period (April to June) during melting time-series analysis of fractional snow cover (row-1) and surface temperature night (row-2) in the Himalayan zone Western (WH), Central (CH) and Eastern (EH) for the period from 2000-2021 by MODIS Data.

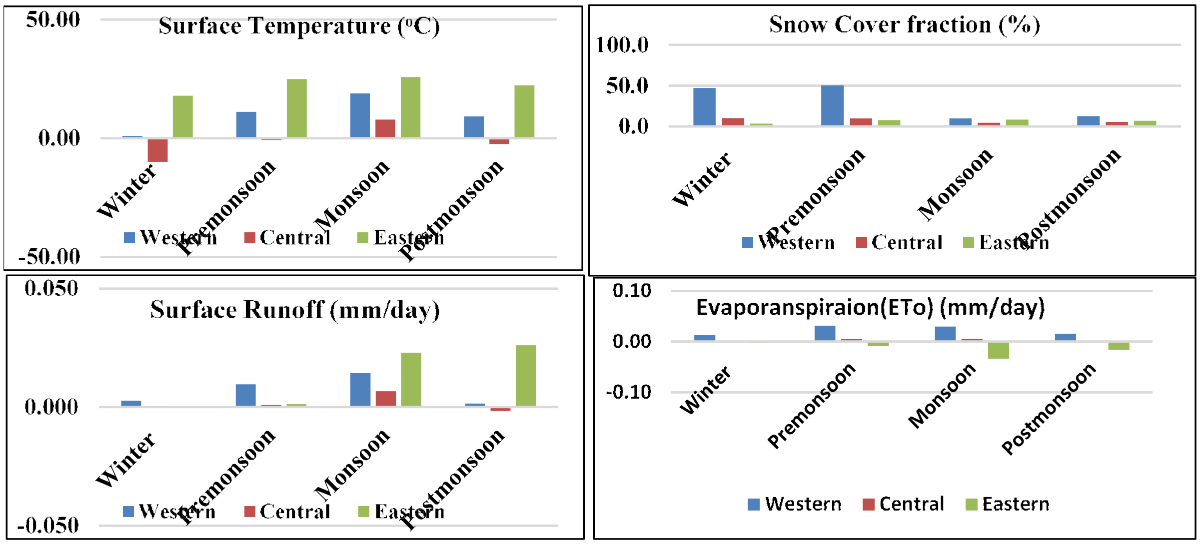

Fig. 6 : Seasonal and spatial variation in surface air temperature, snow cover fraction, and surface runoff for the period (1982-2020) in three zones of the Himalayas.

Table 1 : Trend in mean annual for different land parameters at monthly time step for Himalayan region for snow accumulation of time period.

Land parameters	Western Himalayas			Central Himalayas			Eastern Himalayas		
	MK value	Sen's Slope	*P-value*	MK value	Sen's Slope	*P-value*	MK value	Sen's Slope	*P-value*
Surface Temp.	2.51	0.05	**0.05**	0.82	0.08	0.091	-0.024	-0.00013	**0.008**
Snow Cover	2.58	0.20	**0.009**	0.823	0.020	0.158	1.887	0.017	0.150
Surface runoff	1.54	0.002	0.11	1.887	0.017	0.150	1.74	0.007	0.082
Evapotranspiration	2.90	0.006	**0.000**	4.887	0.002	0.00	1.74	0.007	0.000

*Numerical in bold highlighted indicate the significant trends at 95% confidence interval.

Similarly, in the case of snow cover fraction, a non-significantly increase at the rate of MK (τ) = +0.823 (p>0.05) and Sen's slope (S) = +0.02% year^{-1} and MK (τ) = +1.88 (p>0.05) and Sen's slope (S) = +0.017% year^{-1}, for central and eastern zones, respectively. On the other hand, a significant increase at the rate of MK

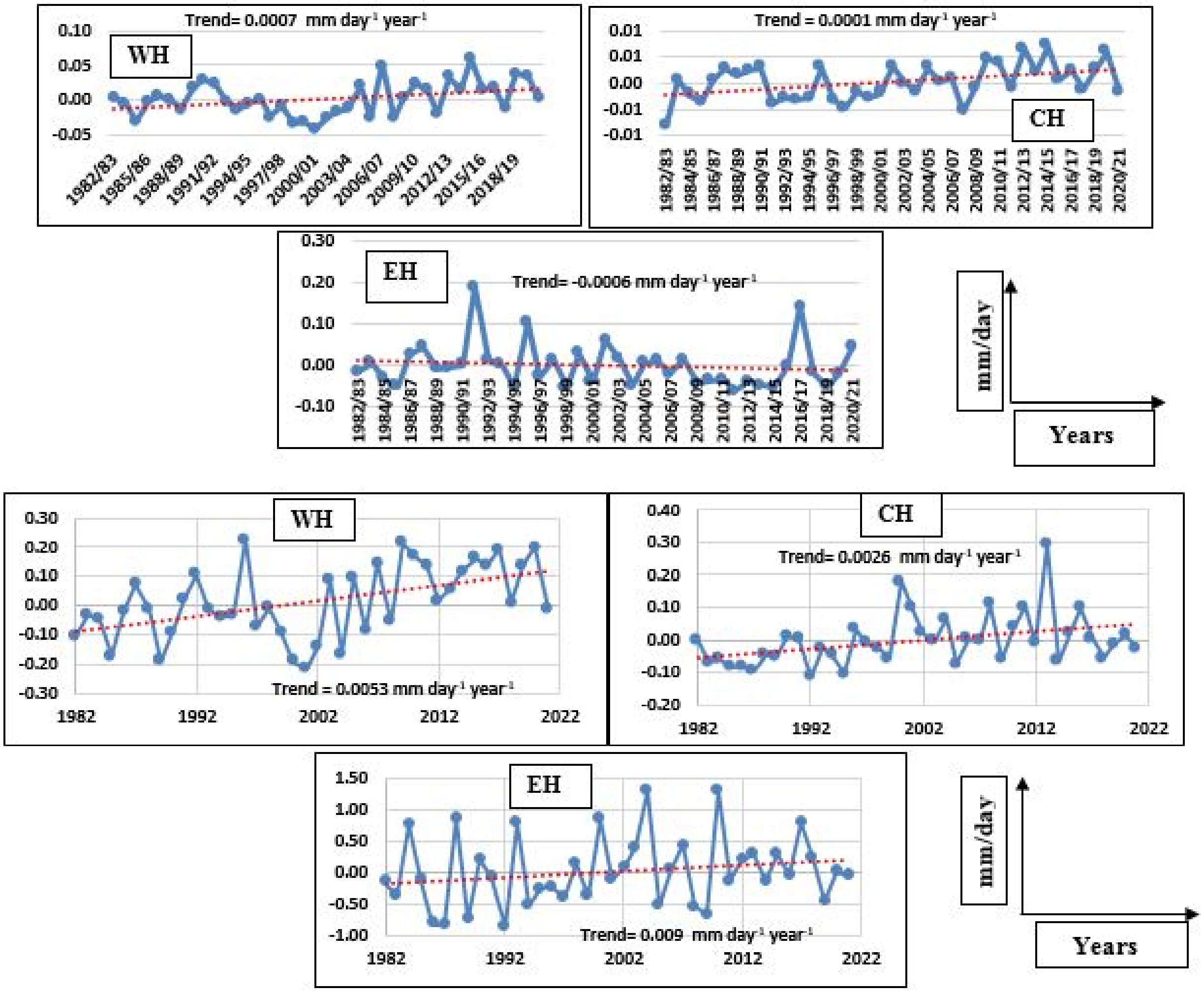

Fig. 7 : Trend graph in mean surface runoff at monthly time step for (i) Snow accumulation (Nov–March) and (ii) Snow melting (April–June) period from (1982-June2021) for three zones of the Himalayas region (Western, Central and Eastern).

Table 2 : Trend in mean surface runoff at monthly time step for snow accumulation (Nov–March) and snow melting (April–June) time period from (1982-June 2021) for three zones of Himalayas region (Western, Central and Eastern).

Himalayan Zones	**Snow accumulation period surface runoff**			**Snow melting period surface runoff**		
	MK value	**Sen's Slope**	***P-value***	**MK value**	**Sen's Slope**	***P-value***
Western	1.69	0.007	**0.03**	3.064	0.0057	**0.0001**
Central	2.54	0.0001	**0.009**	2.482	0.0022	**0.015**
Eastern	-1.21	-0.007	0.419	1.433	0.010	0.244

*Numerical in bold indicate the significant trends at 95% confidence interval.

(τ) = +2.58 ($p<0.05$) and Sen's slope (S) = +0.20% year^{-1} was found in the western zone of the Himalayas.

Surface runoff experienced a significantly increased at the rate of MK (τ) = +2.49 ($p<0.05$) and Sen's slope (S) = +0.0001 mm/day year^{-1} and a non-significant MK (τ) = +1.54 ($p>0.05$) and Sen's slope (S) = +0.0024 mm/day year^{-1} and MK (τ) = +1.74 ($p>0.05$) and Sen's slope (S) = +0.0007 year^{-1} for the mean annual of central, western and eastern respectively.

Similarly, in the case of evapotranspiration, a significant increase at the rate of MK (τ) = +2.90($p<0.05$) and Sen's slope (S) =+0.0067 mm/day year^{-1}, MK (τ) =+4.887 ($p<0.05$) and Sen's slope (S) = +0.0028 mm/day year^{-1} & MK (τ) =+1.74($p<0.05$) and Sen's slope (S) =+0.007 mm/day year^{-1} for the mean annual of central, western, and eastern, respectively.

Conclusion

The following conclusions are derived from the foregoing study:

(i) Variability in the meteorological parameters especially air surface temperature is probably the main cause of snow cover retreat in the Himalayan region (Krishnan *et al*., 2020).

(ii) Snowmelt runoff increases in winter and the early melt season (December–May) and decreases during the late melt season (June–September) as a result of the earlier onset of snowmelt due to increasing temperature (Singh *et al*., 2021).

(iii) Runoff could increase in the initial decades and then decrease or cease due to a substantial decrease in glacier area in three zones of the Himalayas Bliss *et al*., 2014; Lutz *et al*., 2014 and Bolch *et al*., 2012).

(iv) Surface runoff mean indicate an increasing tendency for all three zones of Himalayan throughout the snow accumulation period (November to March) and snow melting phase (April to June) from 1982 to June 2021.

(v) Similarly, evapotranspiration mean shows increasing trend in two zones western and central part of the Himalayas whereas eastern part is decreasing. Therefore, climate change will disturb the hydrological cycle mainly through evapotranspiration (Pandey *et al*., 2016).

The findings of this study will be valuable in understanding the status of climate change in different zones of the Himalayan region and managing the watershed sustainably, as well as depicting the relationships between climatic factors, snow cover, surface runoff and evapotranspiration.

Acknowledgments

The authors are grateful to Vice Chancellor, Navsari Agriculture University, Gujarat for providing the necessary facilities to carry out this research study. Authors are also thankful that the datasets have been downloaded from <disc.gsfc.nasa.gov>. The authors acknowledge the Open and freely available NASA Earth Observations Data Source Platform.

References

Azizi, A.H. and Akhtar F. (2022). Analysis of spatiotemporal variation in the snow cover in Western Hindukush-Himalaya region. *Geocarto International*, **37(22)**, 6602-6624.

Bhutiyani, M.R., Kale V. and Pawar N.J. (2010). Climate change and the precipitation variations in the Northwestern Himalaya: 1866–2006. *Int J Climatol*., **30**, 535–548.

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*, **438**, 303–309

Brohan, P., Kennedy J.J., Harris I., Tett S.F.B. and Jones P.D. (2006). Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J Geophys Res*., **111**, D12106.

Bliss, A., Hock R. and Radiæ V. (2014). Global response of glacier runoff to twenty first century climate change. *J. Geophysical Res*.: *Earth Surface*, **119(4)**, 717-730.

Bolch, T., Kulkarni A., Kääb A., Huggel C., Paul F., Cogley J.G. and Stoffel M. (2012). The state and fate of Himalayan glaciers. *Science*, **336(6079)**, 310-314.

Bhutiyani, M.R , Kale V.S. and Pawar N.J. (2007). Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. *Clim Change*, **85**, 159–177.

Barman, S. and Bhattacharjya R.K. (2015). Change in snow cover area of Brahmaputra river basin and its sensitivity to temperature. *Environ. Syst. Res.*, **4**, 1-10.

Birajdar, F., Venkataraman G. and Samant H. (2016). Monitoring snow cover area using different algorithms on indian remote sensing data. In : *Geostatistical and Geospatial Approaches for the Characterization of Natural Resources in the Environment: Challenges, Processes and Strategies*, 749-753.

Bookhagen, B. and Burbank D.W. (2010). Toward a complete Himalayan hydrological budget: spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *J Phys Res*., **115**, 3–19.

Chen, W., White L., Leblanc S.G., Latifovic R. and Olthof I. (2021). Elevation-dependent changes to plant phenology in Canada's Arctic detected using long-term satellite observations. *Atmosphere*, **12(9)**, 1133.

Diodato, N., Bellocchi G. and Tartari G. (2011). How do Himalayan areas respond to global warming. *Int J Climatol*., **32**, 975–982.

Dash, S.K., Jenamani R.K., Kalsi S.R. and Panda S.K. (2007). Some evidence of climate change in Twentieth-century India. *Clim Change*, **85**, 299–321.

Dimri, A.P. and Dash S.K. (2011). Wintertime climatic trends in the western Himalayas. *Clim Change*, **111**, 775–800.

FAO (2015). AQUASTAT country profile—India. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Gupta, H.K. and Rajendran K. (1986). Large artificial water reservoirs in the vicinity of the Himalayan foothills and reservoir-induced seismicity. *Bull. Seismological Soc. America*, **76(1)**, 205-215.

Gurung, D.R., Maharjan S.B., Shrestha A.B., Shrestha M.S., Bajracharya S.R. and Murthy M.S.R. (2017). Climate and topographic controls on snow cover dynamics in the Hindu Kush Himalaya. *Int. J. Climatol*., **37(10)**, 3873-3882.

Parry, M.L. (Ed.). (2007). Climate change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC (Vol. **4**). Cambridge University Press.

Jhajharia, D. and Singh V.P. (2011). Trends in temperature, diurnal temperature range and sunshine duration in northeast India. *Int J Climatol*., **31**, 1353–1367.

Jain, S.K., Goswami A. and Saraf A.K. (2009). Role of elevation and aspect in snow distribution in Western Himalaya. *Water Resources Manage.,* **23**, 71-83.

Kumar, R. and Gautam H.R. (2014). Climate change and its impact on agricultural productivity in India. *J Climatol Weather Forecast,* **2(109)**.

Khattak, M.S., Babel M.S. and Sharif M. (2011). Hydro-meteorological trends in the upper Indus River basin in Pakistan. *Clim Res.*, **46**, 103–119.

Krishnan, R., Gnanaseelan C., Sanjay J., Swapna P., Dhara C., Sabin T.P. and Niyogi D. (2020). Introduction to climate change over the Indian region. In : *Assessment of Climate Change over the Indian Region* (pp. 1-20). Springer, Singapore.

Kour, R., Patel N. and Krishna A.P. (2016). Assessment of temporal dynamics of snow cover and its validation with hydro-meteorological data in parts of the Chenab Basin, western Himalayas. *Sci China Earth Sci.*, **59**, 1081–1094.

Lutz, A.F., Immerzeel W.W., Shrestha A.B. and Bierkens M.F.P. (2014). Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, **4(7)**, 587-592.

Liang, T.G., Huang X.D., Wu C.X., Liu X.Y., Li W.L., Guo Z.G. and Ren J.Z. (2008). An application of MODIS data to snow cover monitoring in a pastoral area: A case study in Northern Xinjiang, China. *Remote Sensing of Environment*, **112(4)**, 1514-1526.

Mir, B.H., Kumar R. and Rather N.A. (2019a). Water resources scenario of Himalayan Region, applied agricultural practices for mitigating climate change, vol **2**, 1st Edition, Ch. 18. CRC Press, Taylor & Francis Group, Boca Raton, London, New York.

Maskey, S., Uhlenbrook S. and Ojha S. (2011). An analysis of snow cover changes in the Himalayan region using MODIS snow products and *in-situ* temperature data. *Clim Change*, **108(1)**, 391–400.

Negi, H.S., Shekhar M.S., Gusain H.S. and Ganju A. (2018). Winter climate and snow cover variability over north-west Himalaya. Science and Geopolitics of The White World: Arctic-Antarctic-Himalaya, 127-142.

Nie, Y., Pritchard H.D., Liu Q., Hennig T., Wang W., Wang X., Liu S., Nepal S., Samyn D. and Hewitt K. (2021). Glacial change and hydrological implications in the Himalaya and Karakoram. *Nat Rev Earth Environ.,* **2(2)**, 91–106.

Pandey, P.K., Dabral P.P. and Pandey V. (2016). Evaluation of reference evapotranspiration methods for the northeastern region of India. *Int. Soil Water Conser. Res.*, **4(1)**, 52-63.

Singh, P., Umesh K.H. and Kumar N. (2008). Modeling and estimation of different components of stream flow for Gangotri Glacier basin, Himalayas/Modélisationet estimation des different escomposante de l'écoulement fluviatile du bassin du Glacier Gangotri, Himalaya. *Hydrol Sci J.*, **53**, 309–322.

Shrestha, A.B., Wake C.P., Mayewski P.A. and Dibb J.E. (1999). Maximum temperature trends in the Himalaya and its vicinity: an analysis based on temperature records from Nepal for the period 1971-94. *J Clim.*, **12**, 2775–2786.

Singh, V., Jain S.K. and Shukla S. (2021). Glacier change and glacier runoff variation in the Himalayan Baspa river basin. *J. Hydrol.,* **593**, 125918.

Shafiq, M.U., Ahmed P., Islam Z.U., Joshi P.K. and Bhat W.A. (2019). Snow cover area change and its relations with climatic variability in Kashmir Himalayas, India. *Geocarto Int.,* **34(6)**, 688-702.

Sen, P.K. (1968). Estimates of the regression coefficient based on Kendall's tau. *J. Amer. Stat. Assoc.*, **63(324)**, 1379-1389.

Tsering, K., Sharma E., Chettri N. and Shrestha A. (2010). Climate change vulnerability of mountain ecosystems in the Eastern Himalayas— synthesis report. Kathmandu, ICIMOD, ISBN 978-92-9115-141-7.

Teotia, S.S., Khattri K.N. and Roy P.K. (1997). Multifractal analysis of seismicity of the Himalayan region. *Curr. Sci.*, 359-366.

Thapa, S., Li B., Fu D., Shi X., Tang B., Qi H. and Wang K. (2020). Trend analysis of climatic variables and their relation to snow cover and water availability in the Central Himalayas: A case study of Langtang Basin, Nepal. *Theoret. Appl. Climatol.,* **140**, 891-903.

Wester, P., Mishra A., Mukherji A. and Shrestha A.B. (2019). The Hindu Kush Himalaya assessment: mountains, climate change, sustainability and people (p. 627). Springer Nature.

Wang, J., Tang Z., Deng G., Hu G., You Y. and Zhao Y. (2023). Landsat satellites observed dynamics of snowline altitude at the end of the melting season, Himalayas, 1991–2022. *Remote Sens.*, **15(10)**, 2534.

Xu, J., Grumbine R.E., Shrestha A., Eriksson M., Yang X., Wang Y. and Wilkes A. (2009). The melting Himalayas: cascading effects of climate change on water, biodiversity and livelihoods. *Conserv Biol.,* **23**, 520–530.

Yao, T., Bolch T., Chen D., Gao J., Immerzeel W., Piao S. and Zhao P. (2022). The imbalance of the Asian water tower. *Nat. Rev. Earth Environ.,* **3(10)**, 618-632.

Yu, L.L., Xia Z.Q., Li J.K. and Cai T. (2013). Climate change characteristics of Amur River. *Water Sci. Engg.,* **6(2)**, 131-144.