Variability of Hydro-Meteorological Fluxes in North West Himalayan Basins for Hydrological and Sustainability Studies

Rachit[1], Abhay Masiwal[1], Sanyam Singla[1], Gaurish Singhal[1], Praveen K. Thakur[1], Vaibhav Garg[1], Shakil Romshoo[2,3]

[1] Indian Institute of Remote Sensing, ISRO, 248001, 4-Kalidas Road, Dehradun, Uttarakhand, India - (rachit, abhaym, sanyam, gaurishsinghal, praveen, vaibhav)@iirs.gov.in; rachit.knl@gmail.com
[2]Islamic University of Science and Technology, Pulwama, Jammu and Kashmir, India
[3]University of Kashmir, Hazratbal, Srinagar, Jammu & Kashmir, India, 190006 - shakilrom@kashmiruniversity.ac.in

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Abstract

The Himalayas are a crucial source of food, water, and habitat for a wide range of ecosystems in the northern Indian subcontinent. This research focuses on utilizing remote sensing data to analyze hydrological and meteorological factors—such as precipitation, temperature, runoff, evapotranspiration (ET), soil moisture and snow depth—for nine watersheds in the North West Himalayas (NWH): Jhelum, Tawi, Beas, Parbati, Suketi, Gangotri, Aglar, Asan, and Henval. The study employs near real-time (~1-day latency) hydrological flux data from the Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) at a spatial resolution of 0.01°. To gain further insights, the trend in snow cover area (SCA) for the NWH region is analyzed using Interactive Multisensor Snow and Ice Mapping System (IMS) data from the United States National Ice Center (USNIC), disseminated by the National Oceanic and Atmospheric Administration (NOAA) via the National Snow and Ice Data Center (NSIDC). The analysis covers water balance components for these basins from 2001 to 2023. Monthly and annual averages are computed to reveal overall watershed behavior and distribution, which is closely linked to the land use and land cover (LULC) in the area. For instance, the Gangotri basin, with over 50% snow coverage, shows low ET throughout the year, a trend reflected in the long-term annual average ET values. Similarly, basins with higher SCA exhibit lower ET percentages, resulting in increased runoff and a strong correlation between rainfall and runoff patterns. A regional analysis of snow cover from 2014 to 2024, encompassing the union territories of Jammu and Kashmir, Ladakh, and the states of Himachal Pradesh and Uttarakhand, indicates a significant decrease in relative SCA. For the peak winter months of December and January, SCA dropped by about 50% from January 2023 (~2,94,635 km²) to January 2024 (~1,48,225 km²). Additionally, the Indian Meteorological Department's (IMD) daily rainfall data for Jammu and Kashmir from December 1, 2023, to January 31, 2024, shows lower rainfall compared to the previous year, likely due to reduced north-west disturbances. This prolonged snow drought poses challenges to water security and increases the risk of wildfire disasters in these regions.

1. Introduction

The Himalayas are one of the most significant sources of food, water and shelter for a variety of ecological diversity in the northern Indian sub-continent region (Singh et al., 2021). They are a highly dependable resource for the population residing in the Indo-Gangetic Plain (IGP) which hosts around 9 % of the global number and contributes largely to agricultural crop production in India, Pakistan, and Bangladesh in the west (Rawal et al., 2013). The north-west part of the Himalayas particularly can be differentiated from the rest as it witnesses the origination and flow of life sustaining glaciers and rivers. Therefore, the study of its changing hydrology becomes imperative for assessing the impacts on life dependent on them. To understand the hydrology, it is basic to understand and estimate the variation of various components of hydrological cycle. The major components of hydrological cycles are precipitation, evapotranspiration, soil moisture and infiltration (Balasubramanian, A. & Nagaraju, D., 2015). The main challenge that exits in the study of these parameters is the availability of the dataset specifically for mountainous terrain The distribution and variability of mountain precipitation are influenced by the interaction of orography with large-scale atmospheric circulation systems, zonal climate processes, and local evapotranspiration rates (Nesbitt & Anders, 2009).

One of the most critical parameter that governs the variations of these parameter is temperature. Several studies (Bhattacharya et al., 2020; Tiwari et al. 2018), have demonstrated the benefits of using reanalysis temperature products for snowmelt modelling and streamflow simulation in high-altitude, rugged regions where observational networks are not accessible. Land use Land cover over the area also effects the values of varies component of the hydrological cycle. Impact of LULC on the behaviour of watershed. Land use land cover also effects the hydrology of the watershed, there are several studies that focuses on the effect of changed LULC on the watershed hydrological response (Woldesenbet et al., 2017). Gashaw et al estimated that increasing built up areas at the expense of forest, grassland and shrub lands results in increased surface runoff (9.3%) and reduced evapotranspiration (0.3%) (Gashaw et al., 2018).

The behaviour of glaciated and non-glaciated watershed is very much different in terms of hydrological response. The contribution of different component varies with increase in glacier presence inside the watershed. The trend of glacier runoff in various catchments differs based on the proportion of glaciation, the size of the glaciers, and the climatic features of the catchments (Liu et al., 2021). There are studies which estimated the change in evapotranspiration due the presence of glacier. Relative contribution of climate variables and vegetation greening shows the changes in rate of evapotranspiration (Hu & Mo, 2021).

In order to address the long-term effects of hydrological changes in the Himalayan Region, a comprehensive strategy for adaptation that strengthens the adaptive skills of communities at risk and concentrates policy efforts in critical areas must be devised.

This contribution has been peer-reviewed.
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The main objective of the study is understanding the variability in hydro-metrological fluxes for different watershed. These watersheds generally differ from each other in terms of land use land cover. To achieve this, we have evaluated the usage of latest and finest open-source modelled datasets for hydrological studies on north-western region. The idea to study the different basin in the Himalayan region their importance and their variability in terms of land use land cover.

2. Study Area and Datasets

The study area primarily focuses on the northwestern part of the Himalayas. For analysis purpose 9 basins lying in the NWH region were considered. The basins are Jhelum, Tawi, Beas, Parbati, Suketi, Gangotri, Aglar, Asan and Henval. The watersheds were delineated using Multi-Error-Removed Improved-Terrain (MERIT) DEM in Geographical Information System (GIS) software according to the locations of monitoring sites and the outlet locations to be studied.

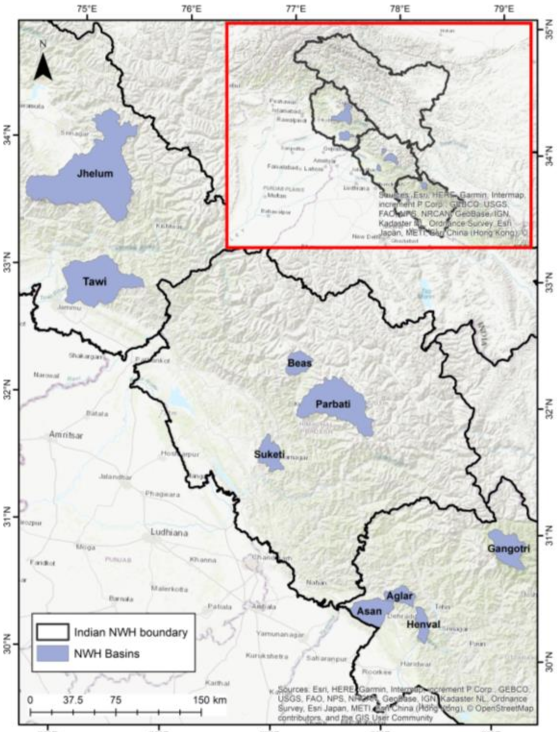


Figure 1. Study area basins of NWH region.

This study comprises the utilization of remote sensing retrieved hydrological and meteorological parameters such as precipitation, temperature, runoff, evapotranspiration (ET), soil moisture and snow depth for the basins from the year 2001 to 2023. For this, Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) hydrological fluxes outputs at near real-time (~1-day latency) over the Central Asian region at 0.01° spatial resolution have been used (McNally et al., 2022). The Land Information System (LIS) developed by NASA facilitates to generate various land surface model outputs, one of whose custom instances is FLDAS – Central Asia modelling system. The model uses observational datasets and advanced techniques along with data assimilation methods to generate high quality land surface parameters and fluxes. For better understanding, the snow cover area (SCA) trend for the NWH region has been studied using Interactive Multisensor Snow and Ice Mapping System (IMS) data produced by United States National Ice Center (USNIC), disseminated by National Oceanic and Atmospheric Administration (NOAA) at National Snow and Ice Data Center (NSIDC) platform. This 1-kilometer resolution product is particularly useful for snow and glacier related studies.

Snow depth product from FLDAS data streams has also been utilized. Glacier boundaries from Randolph Glacier Inventory version 6 were overlaid to evaluate the raster and visualize the glaciated area in the basin along with the spatial variation of snow depth (Figure 9, 11 and 13).

LULC product prepared by Roy et al., 2005 i.e. Decadal Land Use and Land Cover Classifications across India for the year 2005 has been utilzed to see prevalent land use land cover classes distribution for the basins under study.

3. Methodology

The method or processes performed for the analysis in the study were as follows:

1. The watersheds were delineated by processing DEM in GIS software according to the locations of monitoring sites and the outlet locations to be studied.
2. Precipitation, temperature, runoff, ET, soil moisture and snow depth data taken from FLDAS datasets were clipped according to the nine NWH basins shapefiles generated after delineation.
3. The snow depth rasters were overlaid with the glacier boundary from Randolf glacier inventory and maps were generated.
4. Long term annual average maps for a basin provide an overall behaviour and distribution of the watershed which can precisely be associated with the LULC prevalent in the area. So, the maps generated were analysed and the spatial variation was seen, which is further shown and discussed in results and conclusion.
5. IMS Snow Cover product was used to see the change in snow cover for the last 10 years in the NWH region and particularly for the winter i.e. January month of 2024.

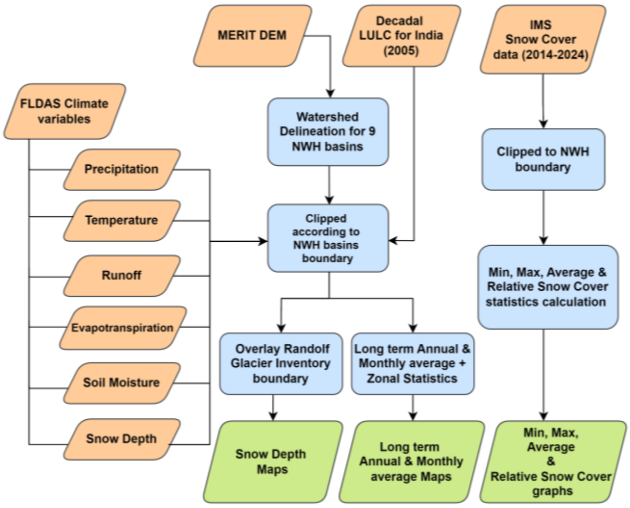


Figure 2. Flowchart of the study.

4. Results and Discussion

The water balance components for the mentioned basins were analysed, starting from the year 2001 till 2023. The long term monthly and annual averages were computed for each basin. The monthly average statistics and rasters (not included here) for each watershed were generated, to bring out the spatial variation of all these components within the watershed. The various basins have varied percentages of SCA. Out of the nine river basins chosen, three have a significant amount of area covered with snow namely Beas, Parbati and Gangotri.

The results of the study are discussed for each hydro-climatic parameter analysed for the different basins in the NWH region.
The long term annual average rasters of each parameter for non-glaciated basins that are Jhelum (Figure 3), Asan (Figure 4), Aglar, Henval, Suketi and Tawi (Appendix-I) and glaciated basins that are Beas, Gangotri and Parbati were computed and mapped. Table 1 represents the minimum and maximum values of three water balance components for each basin in consideration. The negative ET values can be associated with the presence of snow cover.

	Precipitation (mm)		ET (mm)		Runoff (mm)	
Basins	min	max	min	max	min	max
Aglar	1198.46	1795.66	639.37	941.43	126.05	403.87
Asan	790.13	1414.58	0.69	871.55	33.13	1339.68
Beas	734.39	2818.97	0.67	1198.61	15.54	1661.53
Gangotri	0.00	1552.12	-0.19	576.26	0.00	2398.83
Jhelum	197.60	2742.55	0.57	1052.59	65.25	3476.15
Henval	1295.52	1839.41	714.79	1005.69	152.84	394.36
Parbati	4.71	1208.37	-6.00	804.04	0.00	1837.21
Suketi	552.60	1404.64	0.73	879.52	13.93	783.42
Tawi	734.39	2818.97	0.67	1198.61	15.54	1661.53

Table 1. Long term annual average minimum and maximum values of three water balance parameters in NWH basins

4.1 Results for non-glaciated basins

Areas under each class in LULC for non-glaciated basins is shown in Table 2.

LULC classes	Aglar	Asan	Henval	Jhelum	Suketi	Tawi
Cropland	12.18	178.59	20.12	1372.48	233.57	296.78
Built-up Land	0.32	21.99	-	55.98	4.49	54.13
Mixed Forest	48.75	5.51	28.79	-	9.32	-
Shrubland	0.19	-	17.4	169.07	-	555.48
Fallow Land	56.46	11.48	39.68	-	-	-
Wasteland	-	-	-	17.36	-	-
Water Bodies	0.87	43.3	1.77	77.44	3.41	49.94
Plantations	-	18.49	-	-	99.84	-
Grassland	4.34	-	-	828.08	16.35	61.3
Deciduous Broadleaf Forest		317.87	7.65	-	-	-
Evergreen Broadleaf Forest	178.03	-	-	1683.28	59.23	946.08
Evergreen Needleleaf Forest	-	53.41	139.05	-	-	-
Snow & Ice	-	-	-	134.67	-	-
Total	**301.14**	**650.64**	**254.46**	**4338.36**	**426.21**	**1963.71**

Table 2. LULC classes area (km^2) in selected non-glaciated basin of North West Himalayas

Jhelum basin in Jammu territory of NWH, with land cover dominated by cropland, evergreen broadleaf forest and grassland receives a majority of the precipitation in its easternmost region where vegetation and water bodies can mostly be seen (Figure 3). Temperature and ET, on the other hand, show their high range in the central region which is fairly dominated by cropland and settlements. Runoff can be related to the precipitation variability as it shows higher values in areas where high annual average precipitation is observed. Soil moisture, however showed much less variation over the whole Jhelum area.
From the monthly plot, it was evident that the peaks of precipitation and ET occurred in July and August months of the year which is quite evident phenomenon for the monsoon season months. Similar analyses were done for all other basins to understand the water balance component for each basin.

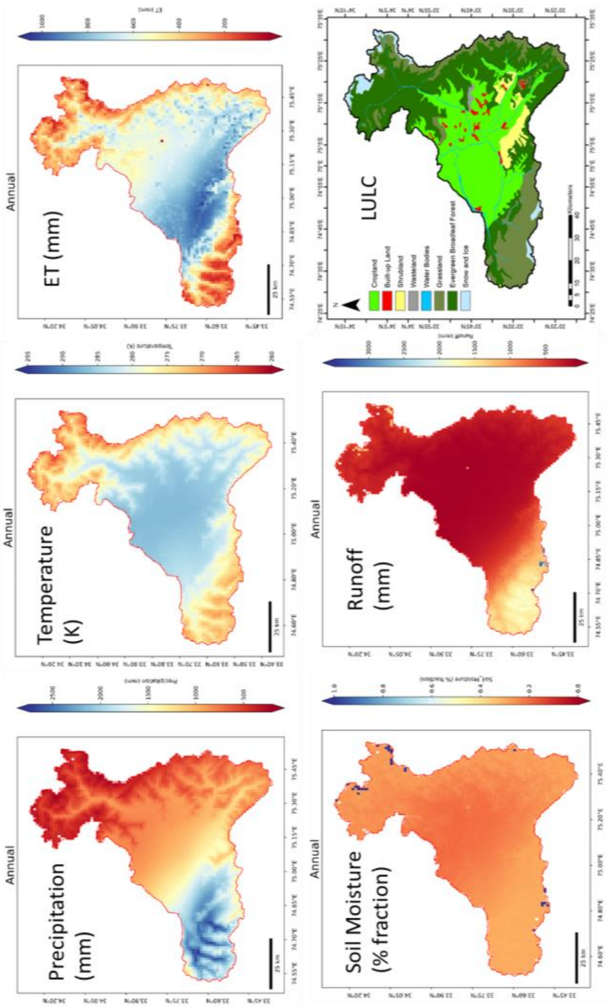


Figure 3. Jhelum annual average hydro-meteorological parameters and LULC map

In case of Asan watershed, it is apparent from Figure 4 that the annual average precipitation is higher on the northeastern side of the area where there is presence of evergreen needleleaf forest. The temperature map shows that overall, the more cooler areas are there in the higher mountainous regions with presence of evergreen needleleaf forest and mixed forest. ET is lower in built-up region and higher in forest cover dominated areas of the basin. Soil Moisture and Runoff are higher in the built-up region. The runoff, in this case seems to more affected by the land use and land cover distribution in the area, while soil moisture variability is more aligned according to the precipitation variability in the Asan basin.

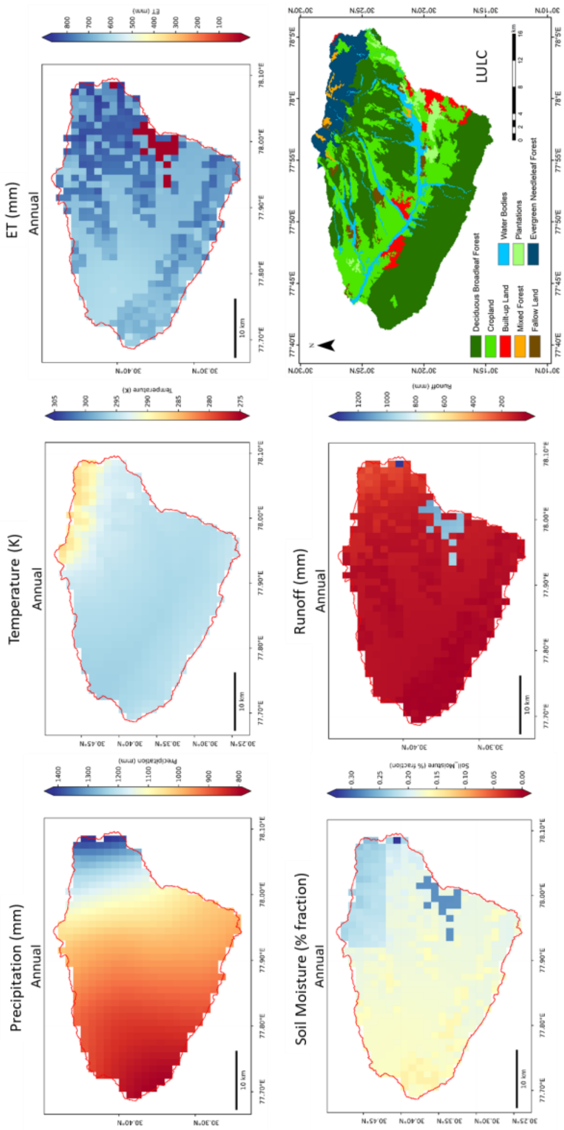


Figure 4. Asan annual average hydro-meteorological parameters and LULC map

4.2 Results for glaciated basins

The LULC classes and the area under each class in glaciated basins is shown in Table 3.

LULC classes	Beas	Gangotri	Parbati
Cropland	10.21	-	37.52
Built-up Land	-	-	0.19
Mixed Forest	1.05	-	3.86
Shrubland	-	10.43	23.96
Barren Land	-	63.54	-
Wasteland	-	6.41	-
Water Bodies	6.04	1.4	10.24
Plantations	11.94	-	43.07
Grassland	117.43	-	420.75
Evergreen Broadleaf Forest	95.93	-	416.63
Evergreen Needleleaf Forest	-	44.23	-
Snow & Ice	98.86	565.22	809.52
Total	**341.46**	**691.23**	**1765.74**

Table 3. LULC classes area (km^2) in selected glaciated basin of NWH.

Beas, Gangotri and Parbati are the glaciated or snow cover dominated basins in the NWH region under study.

The ET parameter in these basins is affected by the presence of snow and shows a lower relative percentage with respect to precipitation when compared to other basins having no or little snow cover.

Similarly, Beas and Parbati basins with higher SCA shows a lesser percentage of ET, which leads to higher values of runoff and high similarity between the curvature of rainfall and runoff as shown through graphs in Figure 5, 6 and 7. While the basins which are having lesser amounts of SCA shows higher percentages of ET. The increased ET value leads to a decrease in the value of runoff.

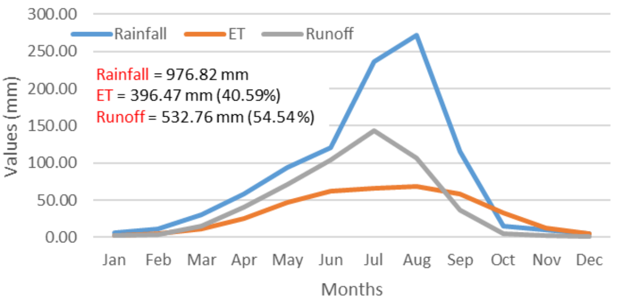


Figure 5. Long term monthly average of rainfall, runoff and ET for Beas basin

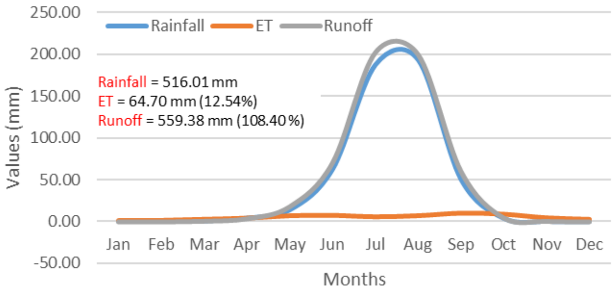


Figure 6. Long term monthly average of rainfall, runoff and ET for Gangotri basin

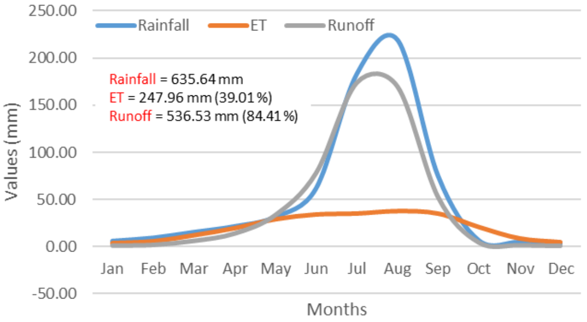


Figure 7. Long term monthly average of rainfall, runoff and ET for Parbati basin

The runoff in these basins in monsoon season is quite higher than ET, i.e. more than 50% and even higher for Gangotri basin having more than 80% of its area dominated by snow and ice.

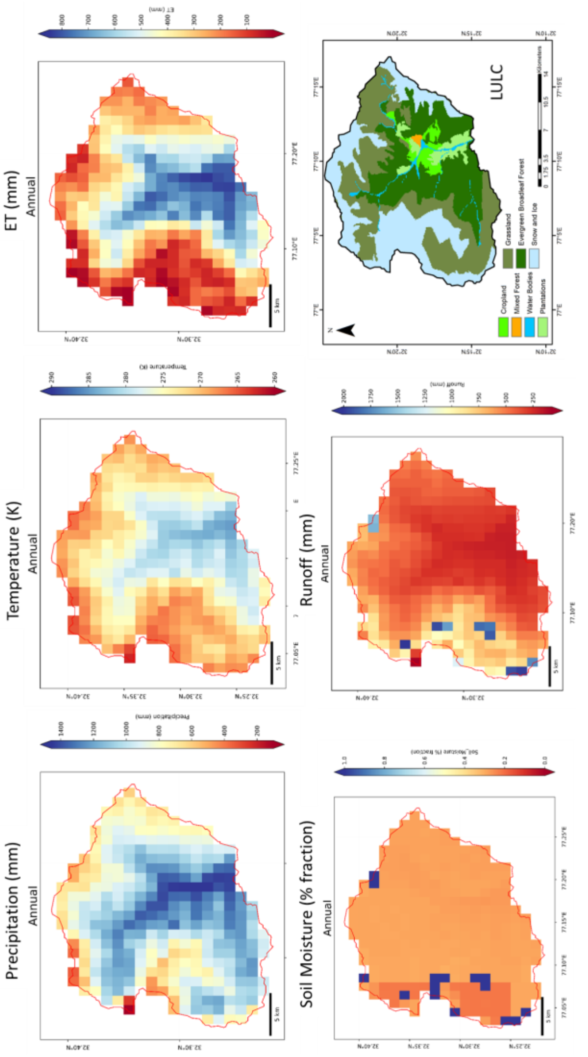


Figure 8. Beas annual average hydro-meteorological parameters and LULC map

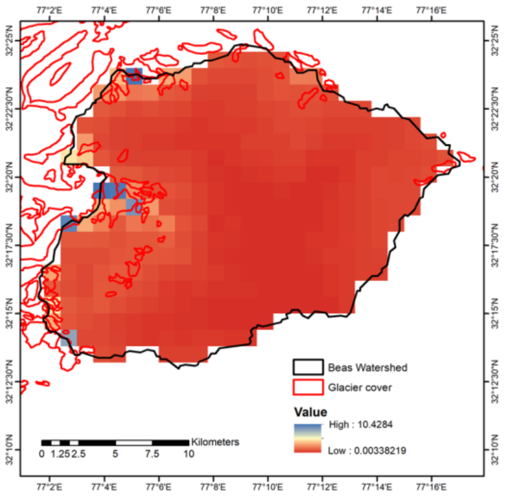


Figure 9. Annual average snow depth (in meters) and glacier cover map of Beas basin

Gangotri basin has over 50% of its area covered by snow, leading to low ET throughout the year, and the same trend can be observed in the long-term annual average of ET values. The snow depth map for Gangotri (Figure 11) shows the higher values of snow depth coinciding with the glacier cover boundary. Similar variability can be seen in the Parbati basin from Figure 12 and Figure 13.

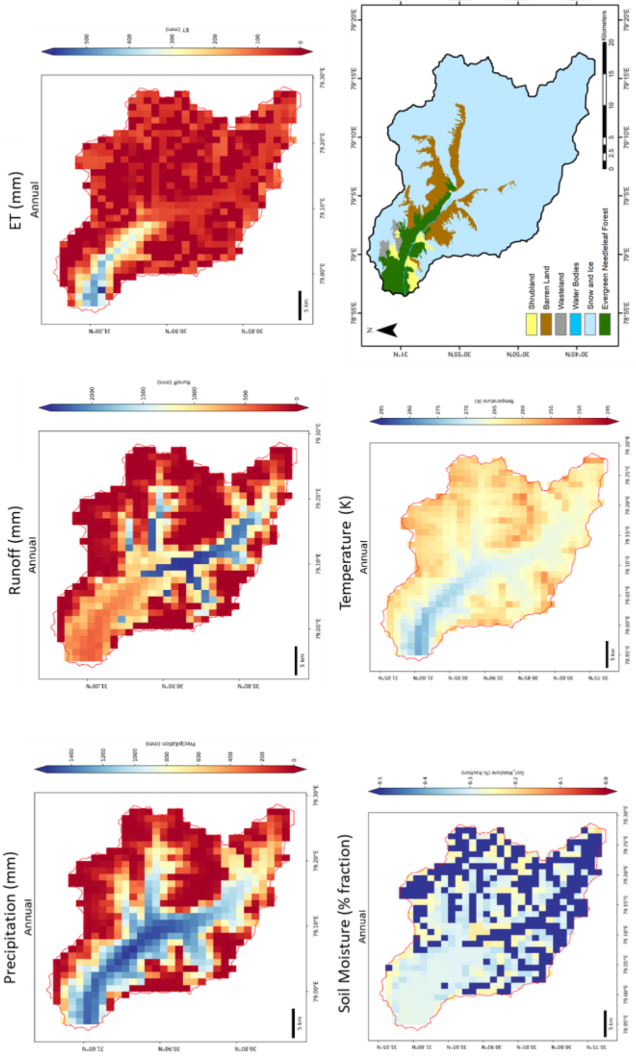


Figure 10. Gangotri annual average hydro-meteorological parameters and LULC map

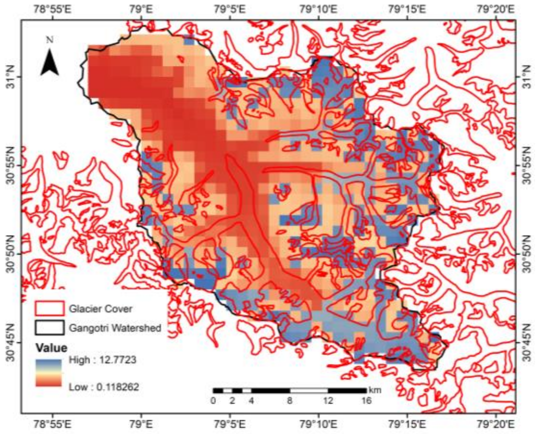


Figure 11. Annual average snow depth (in meters) and glacier cover map of Gangotri basin

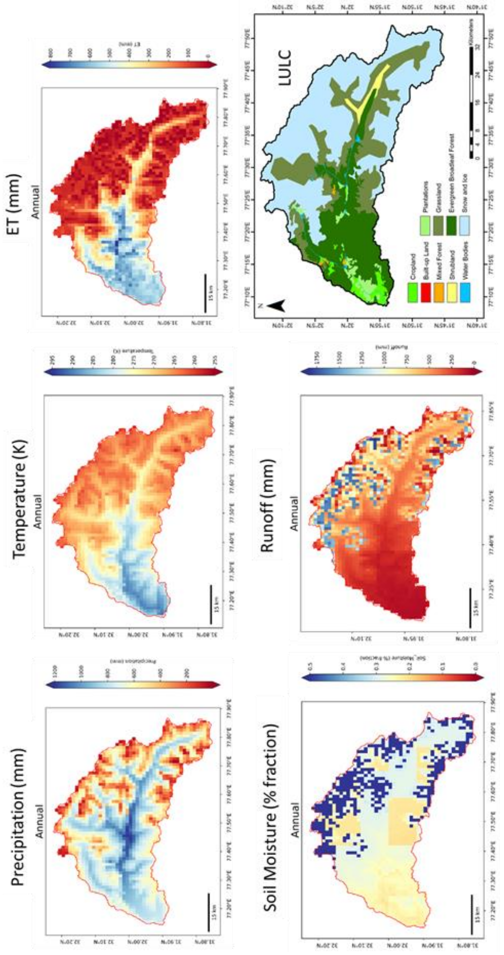


Figure 12. Parbati annual average hydro-meteorological parameters and LULC map

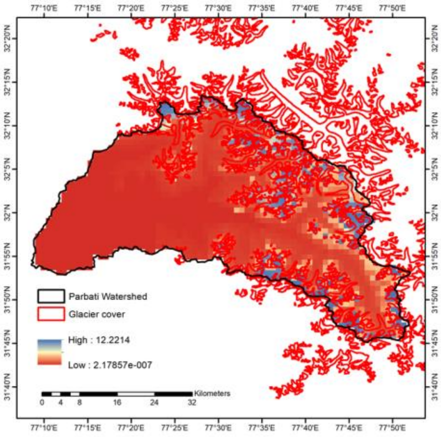


Figure 13. Annual average snow depth (in meters) and glacier cover map of Parbati basin

4.3 Results for Snow Cover Area

In terms of snow cover, for the whole NWH region comprising union territories of Jammu and Kashmir, Ladakh, and states Himachal Pradesh and Uttarakhand, analysis from 2014 till 2024 was carried out. The minimum, maximum and average snow cover plots for this period (Figure 14) shows the lowest values in the year 2024 and 2016. While the minimum snow cover area was observed in year 2016, the average SCA remained lowest in 2024 i.e. less than 40%. It was observed for the peak winter months i.e. December and January relative SCA in this region has decreased by approximately 50% in January 2024 (~1,48,225 km²) as compared to January 2023 (~2,94,635 km²). Moreover, the daily rainfall (in mm) trends of Indian Meteorological Department (IMD) 0.25° x 0.25° gridded dataset for Jammu and Kashmir, from 01-Dec-2023 to 31-Jan-2024 showed that the rainfall was comparatively lower as compared to the previous year for the same duration which can be attributed to due to reduced North-West disturbances. As, fresh snowfall was observed on January 31 and February 01, 2024, in North West Himalayan Region, the SCA has increased to ~2,19,669 km^2, (45.7%) on 31st January 2024 as compared to SCA of 30% on 23rd January 2024, ending the dry winters but remained lower as compared to previous year (Figure 15).

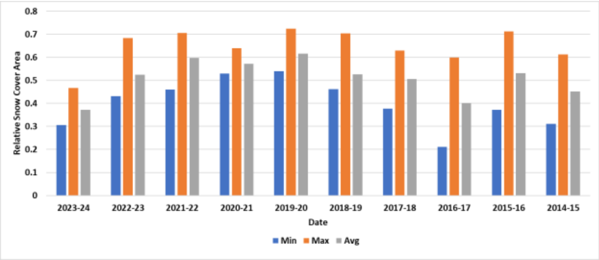


Figure 14. Minimum, Maximum and Average Snow Cover area in NWH for Dec & Jan (2014 to 2024)

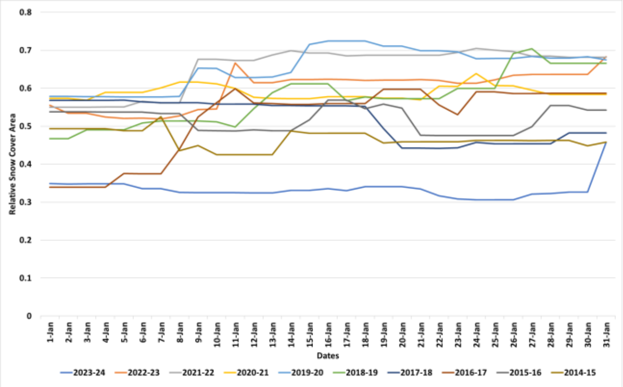
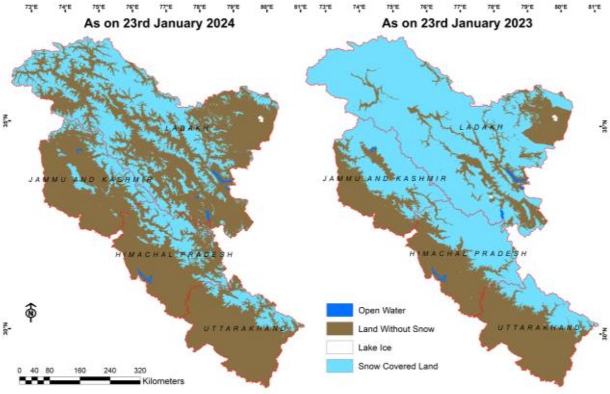


Figure 15. Relative Snow Cover area in NWH for January month (2014 to 2024)



Data Source: U.S. National Ice Center. (2008).

Figure 16. Snow Cover Comparison of year 2023 with 2024 in NWH region for 23rd January.

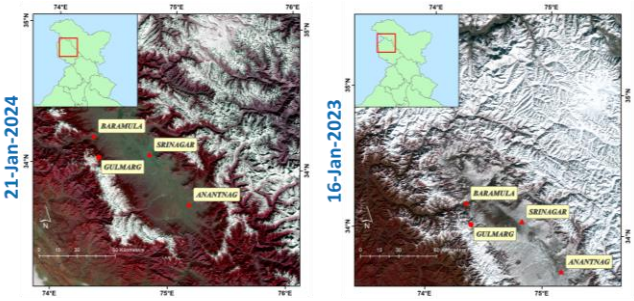


Figure 17. Standard False Colour Composite of J&K districts in January 2023 and 2024. Source: Resourcesat-2A AWiFS Imagery

5. Conclusions and Future Scope

This study primarily focuses on using the modelled products and compare the hydrological parameters of different basin depicting the different conditions on the grounds. The key observations were the behaviour of different LULC classes dominated NWH basins towards the hydrology of the area. It is evident that the glaciated basins tend to generate more runoff and less ET than the non-glaciated ones with respect to the rainfall. The ET values in the glaciated basins are almost less than 50% of the rainfall long term monthly average values. For validation purpose, setting up a hydrological or land surface model for the regions can be done and results compared. Moreover, the change in LULC over the period of study should be considered for more accurate long term average assessment of variability in the hydro-meteorological parameters. In the snow cover area prevalent in the peak winter months, the variation in the snow cover has seen a significant reduction in years 2024 and 2016. Further study is needed to evaluate its relationship with the occurrence of El Nino and LULC changes over NWH region in this period.

As data scarcity and inaccessibility of water balance components in hilly and mountainous terrains affect significantly on the accuracy of the analysis, this study suggests that the detailed analysis of water balance parameters at finer resolution of land, water, and atmospheric data products particularly for smaller catchments situated in hilly and undulating terrain would be useful for implementation of Sustainable Water Resource management with better estimation of water availability, distribution, and demand. There is a strong need to address the concerns as the prolonged snow drought is a challenge to water security and increases the chances of wildfire disasters in these regions

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Appendix – I

In this section, in Figure 18, 19, 20 and 21, the results of remaining four non-glaciated basins of NWH have been presented. Figure 18 shows the variability of hydro-meteorological parameters in Aglar basin which is dominated by Evergreen Broadleaf Forest. High ET can be observed in forest and cropland region.

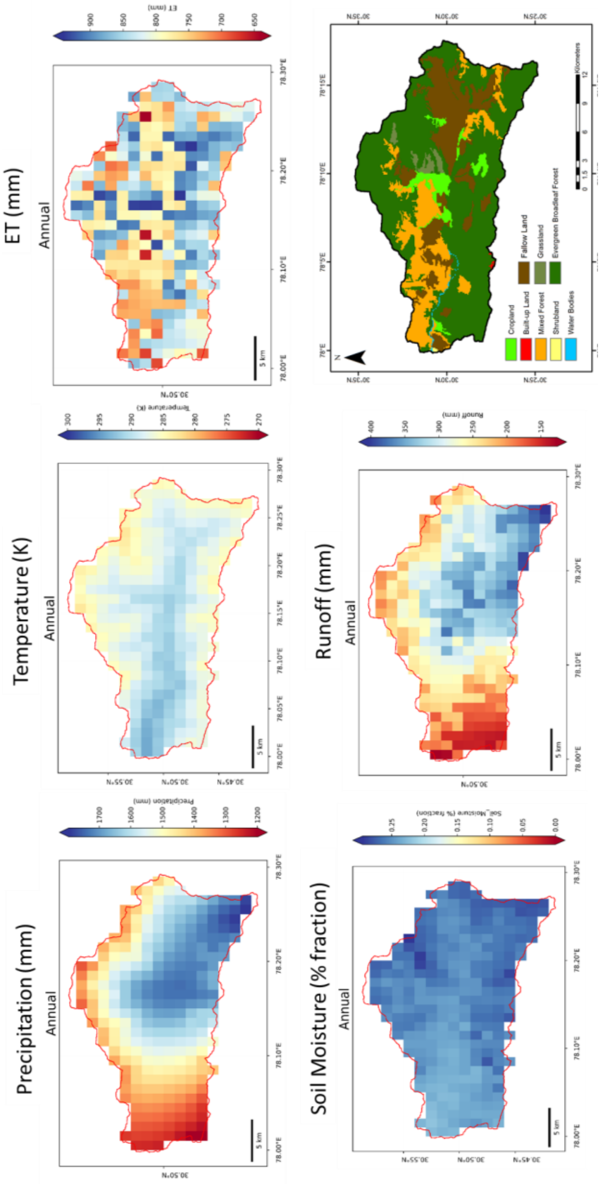

Figure 18. Aglar annual average hydro-meteorological parameters and LULC map

In Tawi basin (Figure 19), the variability of the fluxes such as precipitation and runoff can also be associated with the LULC classes. Similarly for Henval and Suketi (Figure 20 and 21), the variation in runoff and precipitation can be associated. However, in case of Suketi an abnormal behaviour in terms of ET, runoff and soil moisture can be seen in form of an anomaly near the built-up area pixels.

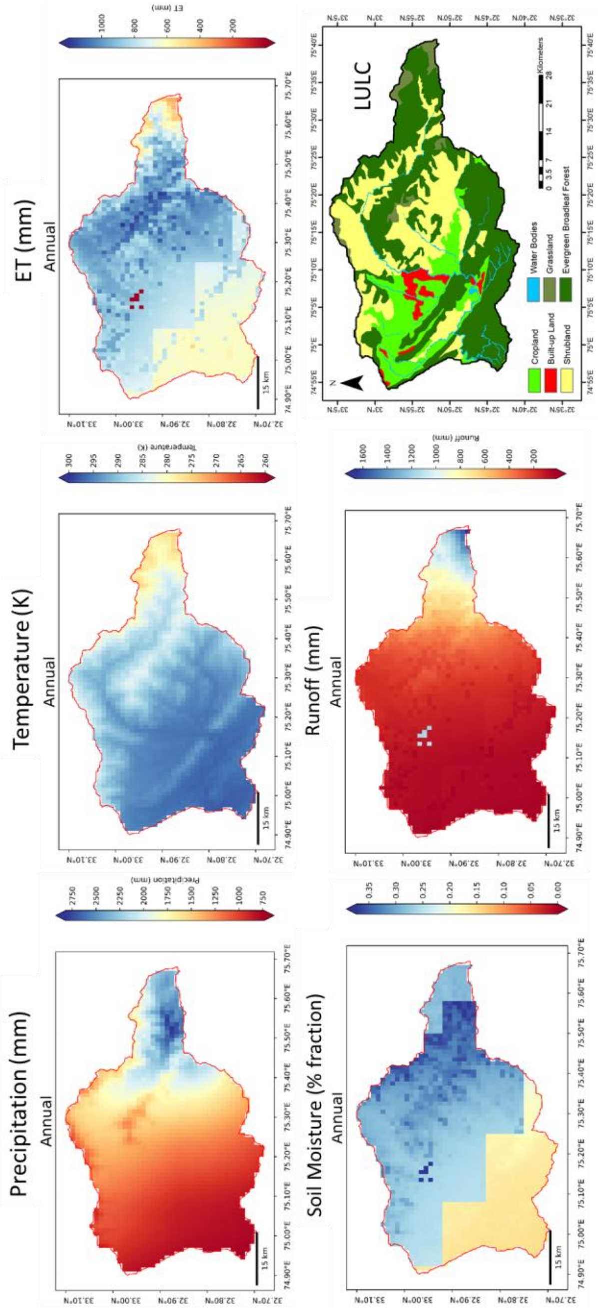

Figure 19. Tawi annual average hydro-meteorological parameters and LULC map

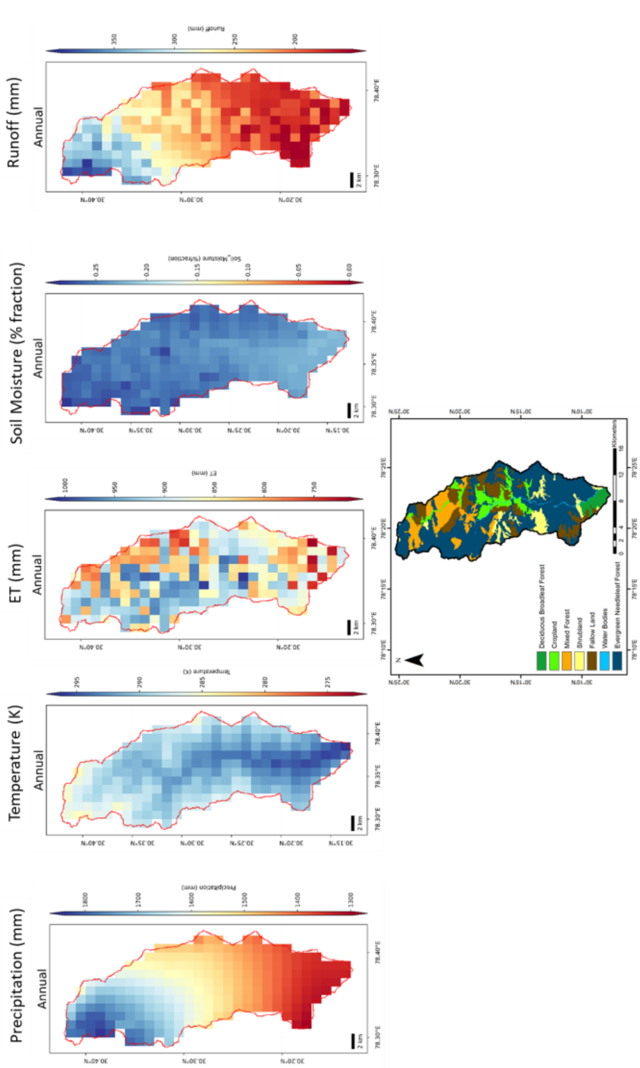

Figure 20. Henval annual average hydro-meteorological parameters and LULC map

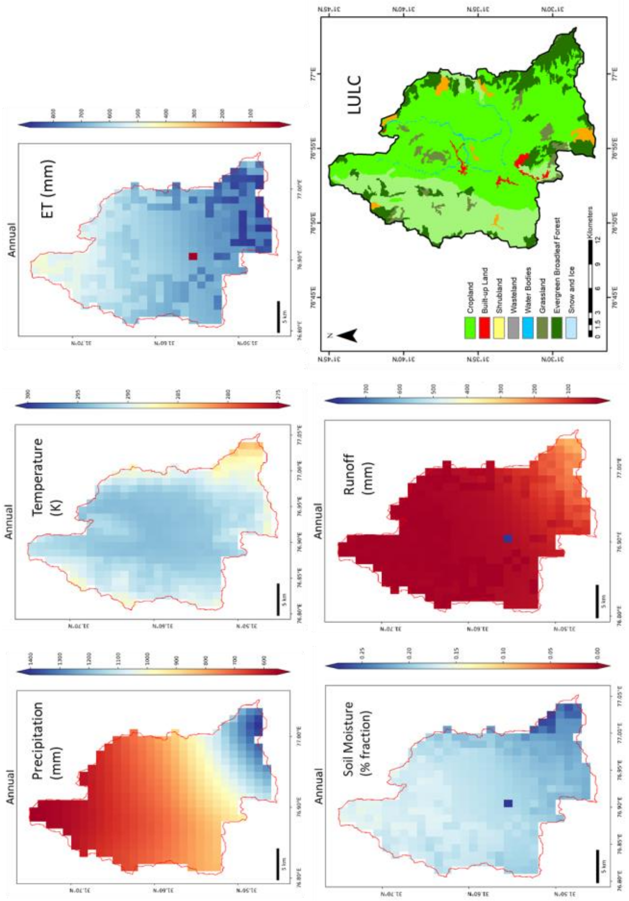

Figure 21. Suketi annual average hydro-meteorological parameters and LULC map