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# Spatio-Temporal Analysis of Land Use Land Cover Dynamics, Synergy of Land Surface Temperature and Snow Cover Fluctuations in Gilgit River Basin, North Pakistan

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This study explores the spatio-temporal dynamics of Land Use Land Cover (LULC), Land Surface Temperature (LST) and snow cover in the Gilgit River Basin (GRB), North Pakistan during the period 1995-2024 using remote sensing and GIS technologies. Multi-temporal Landsat satellite imagery (Landsat 5, 7, 8 and 9) was applied through Google Earth Engine (GEE) to analyze LULC changes, relationship of LST and snow cover variability. Supervised classification i.e. random forest algorithm revealed significant LULC transformations. Settlement expansion shows, rapid increases were recorded in urban sprawl and population growth (+6,736.92 ha). These changes in built-up area are concentrated in areas under farmland. This is because of the conversion of vegetation cover and agricultural land into built-up areas. In the context of vegetation cover, the region observed the degradation in area under forest cover and loss of agricultural land (-43,676.09 ha). Similarly, in case of snow cover, critical changes were observed (-169,211.68 ha). The resultant values illustrate glaciers retreat along with limited snow accumulation. This is largely attributed to climatic change and rising temperature in the HKH region. As a result, it has a direct impact on river discharge and water security. Furthermore, growth in barren land (+203,535.44 ha), where positive changes in almost all the land use classes. Consequently, desertification, land degradation and loss of snow and vegetation cover occurred. Additionally, slight rise has been seen in water bodies such as +86.74 ha and the minor changes are due to glacial melting which temporarily increases the surface water. As a result, small lakes i.e. glacial and glacio-fluvial lakes were also developed. The analysis revealed that LST exhibited a strong warming trend (+0.17°C/year, *p* < 0.0001), with Monte Carlo simulations confirming its robustness (95% CI: +0.12°C to +0.22°C/year). Whereas, the snow cover declined markedly (−137.5 km²/year, *p* < 0.0001), showing a strong inverse correlation with LST_max (*r* = −0.897, *p* = 0.000). The Mann-Kendall (MK) test and Pearson Correlation (PC) highlighted the climate-driven reduction in snow cover and its linkage to rising temperature. The key findings underscore the basin's vulnerability to climate change having significant implications for water security, hydrology and ecosystems. The study recommends integrated water management, land use regulations and climate-resilient agriculture to mitigate its adverse impacts. This research contributes to understanding elevation-dependent warming in mountainous regions and also to support policy formulation for sustainable resource management in the Upper Indus Basin.

**Keywords:** Land Surface Temperature, Snow Cover Dynamics, Remote Sensing, Google Earth Engine, Climate Change, Gilgit River Basin

## Introduction:

Globally, the Land Use Land Cover (LULC) changes, climatic variability and their possible impacts on land surface temperature (LST) along with snow cover dynamics are primarily responsible for the rapid environmental changes. These interactions are specifically noticeable in mountainous areas like Gilgit river basin, north Pakistan because of its fragile characteristics, altitudinal gradients and local communities' dependence on natural resources. This study uses RS and GIS technologies to examine the spatio-temporal pattern of snow cover, LST and LULC in Gilgit river basin. This study attempts to assess the changes occurring in the study area and their possible effects on hydrological and environmental sustainability by combining multi-temporal satellite data using statistical modeling. The LULC is the physical attribute of the earth's surface and the human uses of land respectively [1]. These modifications expresses how anthropogenic activities and natural ecosystems interact with each other. Urbanization, agricultural expansion, deforestation and socio-economic changes can contribute to the changes in land cover in the mountainous regions. Due to population pressure, tourism and infrastructure development, the land cover of the Himalayas and Karakoram regions were changed significantly [2]. Surface energy balance, ecosystem services and water cycles are all affected by LULC changes [3]. Deforestation and land degradation were increased in the Gilgit river basin due to growing infrastructure and human habitat.

In the context of climate science, land surface temperature represents dynamics of surface energy on earth. Land cover, vegetation cover, urban materials and the snow cover affect variations of LST [4][5]. Moreover, it is important for tracking thermal dynamics, snow melting along with glacier growth in high-altitude areas [6]. The surface urban heat island (SUHI) impact is a localized warming caused by changes in surface emission and heat retention qualities occurred due the urban and agricultural expansion [7][8]. Similarly, local warming might have an effect on snow accumulation and melting cycle in the Gilgit River Basin (GRB), which again had a great impact on river discharge. In mountainous areas, snow cover serves as a freshwater reservoir and climate regulator [9] To understand the climatic variability and water resource management in the Hindu Kush-Himalaya ranges, satellite-based snow cover monitoring has become an essential [10][11]. Early snow melting, changing runoff pattern and possible water shortages might be caused by warmer temperature shifts [12]. Thus, integrated watershed management and climate adaptation strategies require an understanding of the temporal and spatial dynamics of snow cover [13]. The GRB is a vital water resource for North Pakistan, providing freshwater to millions of individuals in the downstream areas.

Recent research studies have explained that the Himalayan rivers basins are experiencing unprecedented environmental changes in the scenario of climate change such as the escalated warming, glaciers melting, transformed runoff regimes and the fast LULC changes [14]. In the Hindu Kush-Himalaya (HKH) region, where the warming rate at higher altitudes mostly exceeds the global average, which intensify the snow cover loss and glacier retreat that create hydrological uncertainty [15]. Furthermore, recent evidences suggest that the changing of LST pattern is closely connected with the land degradation, snow cover variability and vegetation pressure that considerably affecting watershed hydrology and ecosystem [16].

In the Himalayan catchments, decreasing seasonal snow covers, changes in melting water contribution and the rising frequency of hydro-climatic extremes posed great threat to water resources and downstream livelihoods [17]. Similarly, the recent studies also insist that interactions among LULC dynamics and temperature anomalies remain inadequately explored at the basin scale, specifically in sub-basins i.e. Gilgit River Basin [18][19]. Additionally, satellite-based assessment by applying machine-learning approaches have enhanced the ability to monitor the land-atmosphere-cryosphere processes under the changing climatic circumstances [20][21][22].

An increase in land surface temperature over the last decades has led to an accelerated snow melting rate that might affect the natural seasonal hydrologic cycle. By examining the satellite data over the last three decades, researchers have managed to identify consistent warming trend in the concern basin and provide significant knowledge about future water scarcity. Snow decline is a serious threat to the nature-based water storage facilities, increasing the risk of early season of flood events due to rapid snow melting and the end-season drought caused by a great reduction in snow reserves [23][24][25]. By implementing the Normalized Difference Snow Index (NDSI), by mapping the snow for the period 1995-2024, significant variations in snow cover in terms of space and time were confirmed.

Furthermore, deforestation, agricultural land development and urbanization had a major impact on the basin's natural hydrology. The water cycle and ecosystem stability of the area are affected by these changes. The LULC maps for the period 1995-2004 and 2014-2024 has pointed out significance for monitoring the important environmental changes i.e. urbanization, vegetation loss and glacier retreat. In order to preserve natural balance and sustainable resource management, this monitoring aid in identifying important zones that require quick conservation actions.

## Material and Methods:

### The Study Area:

Generally, an important sub-catchment of Upper Indus Basin is the Gilgit River Basin that is situated in the north Pakistan. The basin is characterized by steep valleys, glaciated summits and rough terrain that crosses multiple ecological zones, ranging from alpine to sub-tropical. Geographically, the Gilgit River Basin lies between 35° 44' 10" to 37° 05' 21" North latitude and 72° 30' 45" to 75° 46' 42" East longitude (Figure 1). The study region is bordered by China in the north, district Shigar in the east, districts Darel, Tangir, Diamir and Astore in the south, while district Upper Chitral in the west. The basin is located in Gilgit-Baltistan (GB), Pakistan and covers an area of about 27,000 km². The features are very scenic and attractive including alpine regions, lowlands and glacier contents. Moreover, snow and glaciers greatly contribute to the Indus River. Because of its diverse topography, it is ideal for studying the dynamics of snow cover, LST and LULC. Alongside, its altitudinal fluctuation, the basin is home to a variety of plants and animals. In case of forests, Scrublands, juniper forests along with alpine meadows are frequently located. However, in the context of wild animals, snow leopards, Marco Polo sheep, Himalayan ibex and numerous other migratory birds are among the important species [26]. Furthermore, due to glacier contents, the Gilgit River has been originated from Karakoram and Hindu Kush lofty peaks, and the Astore, Ghizer and Hunza rivers are the important tributaries. The Indus River system, which sustains millions of people downstream, is greatly influenced by these rivers (Figure 2; Figure 3).

The study region is almost vulnerable to climate change [27]. In the study area, the backbone of agriculture is subsistence farming, which is mostly irrigated by glacier melting. Wheat, barley, potatoes and fruits like apples and apricots are examples of crops. Crop cycles and productivity are at risk because of recent climatic variability [28][29] Traditionally, Karez systems and glacier-fed waterways has been used to control irrigation system. The agriculture sector is extremely climate-sensitive, therefore, snow melting pattern has a direct impact on irrigation [30]. Aquamarine, ruby and topaz are among the precious and semi-precious stones that were found in the study area (Gilgit River Basin). However, the uncontrolled mining has the potential to disrupt the land cover and at the same time degrade the environment. Active faulting and geological instability make people more vulnerable to earthquakes and landslides. The basin encompasses districts like Gilgit, Hunza and Nagar as well as some portions of Ghizer and Astore districts located in Gilgit-Baltistan.

The complex terrain of Gilgit River Basin revealed by a Digital Elevation Model (DEM), which indicates varying elevations less than 1,500 meters at valley floor to more than 7,000 meters at snow-capped summits (Figure 4).

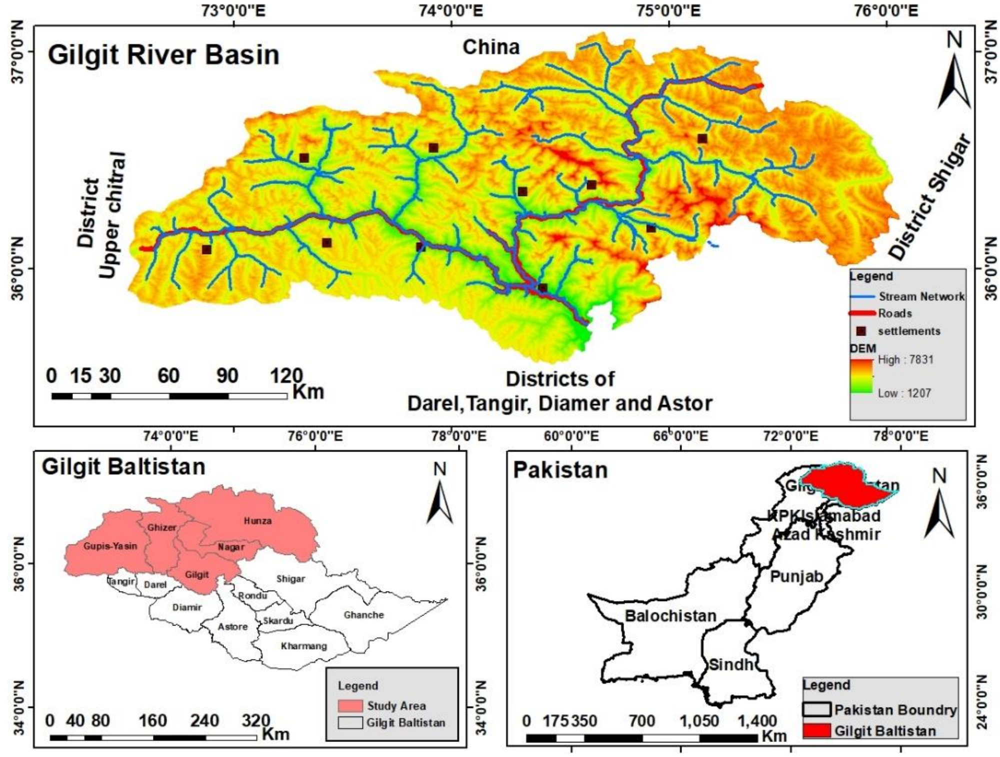

**Figure 1.** Location map of Gilgit River Basin

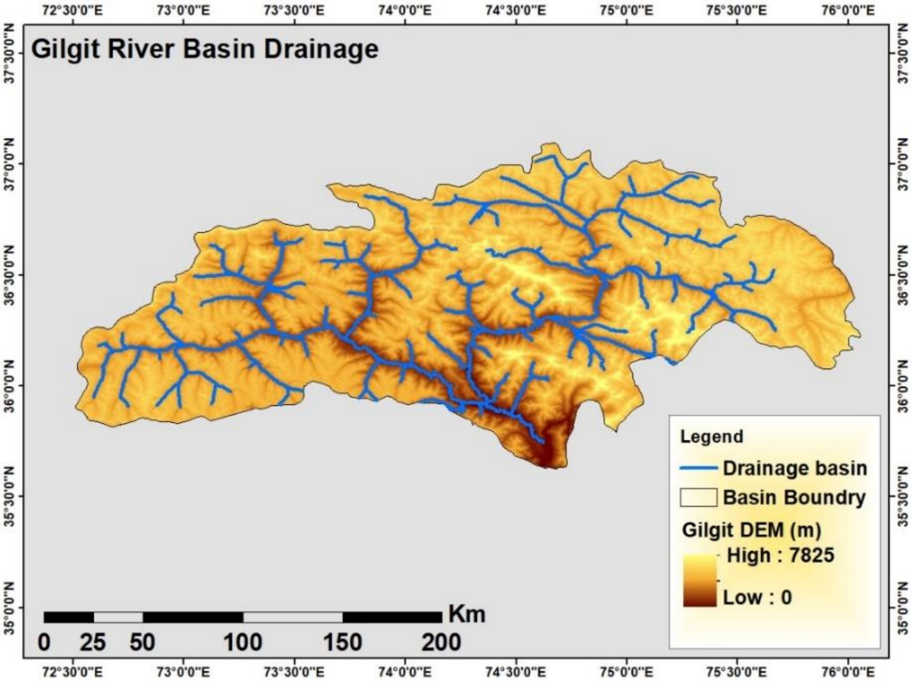

**Figure 2.** Drainage pattern of Gilgit River Basin (study area)

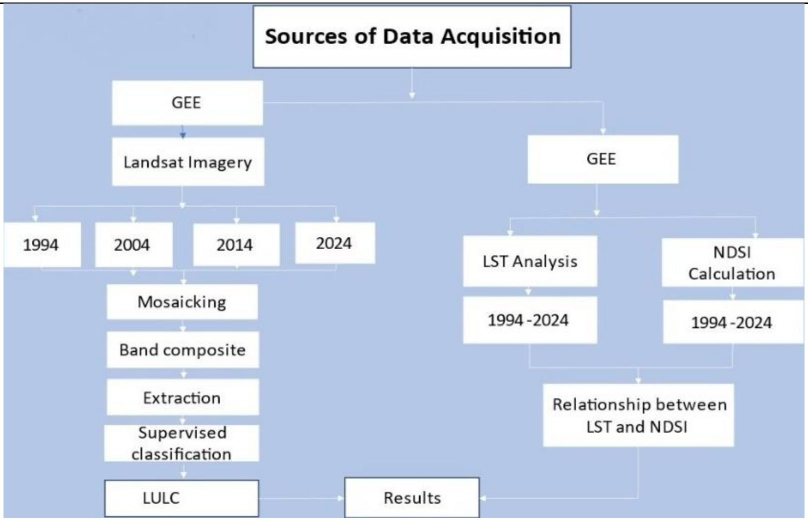

**Figure 3.** Research flowchart of the study

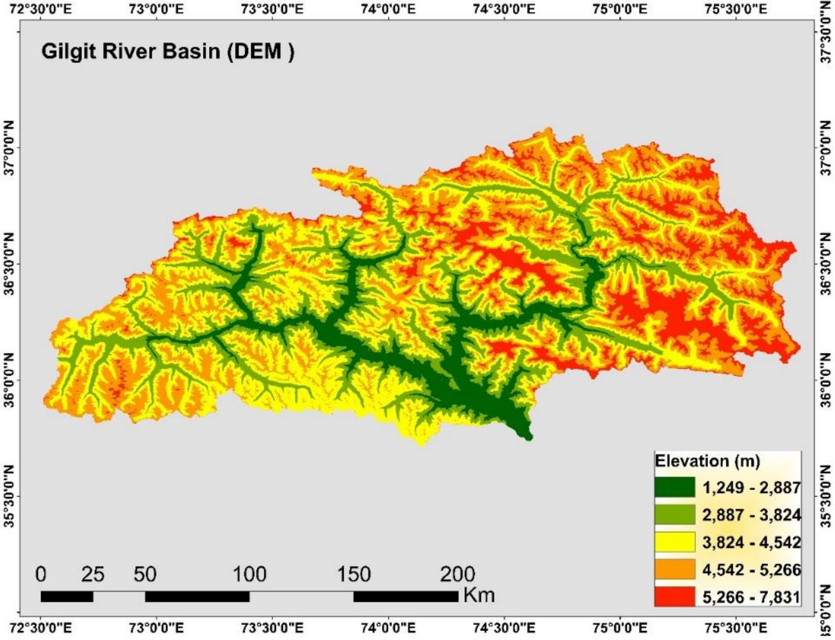

**Figure 4.** Digital Elevation Model of Gilgit River Basin

The concern basin presents a unique and fragile environment where the complex relationship among land use land cover changes, land surface temperature variations, and snow cover dynamics can be clearly observed. The diverse topography of the region, ecological setup and socio-economic dependency on natural resources make it highly sensitive to climate variability. The rapid urbanization, agricultural expansion, deforestation and mining activities are altering the physical landscape, while rising temperature and fluctuating precipitation pattern further create challenges. Therefore, to tackle these unpredictable climatic changes, the advanced tools like RS and GIS technologies should be applied to this research study.

**Data Collection and Analysis:**

This study focuses on to explore the spatio-temporal dynamics of land use land cover along with land surface temperature and snow cover in Gilgit River basin, Pakistan. Secondly, to evaluate the relationship between LST and snow cover variability. Contrary to dependent variables, the key independent variable is LST. It plays a crucial role in understanding surface energy balances and also had a direct association with environmental and climatic changes. Similarly, LST is used to assess that how temperature variations across different time intervals influence other geo-spatial phenomena within the basin.

### Data Sources and Tools:

To assess changes in case of land surface conditions over time, the study used satellite images from many landsat missions, including Landsat 5 (TM), Landsat 7 (ETM+), Landsat 8 (OLI/TIRS) and the latest Landsat 9. The Google Earth Engine (GEE) platform that provide a robust cloud-based capabilities for computing significant indicators including LST and Normalized Difference Snow Index (NDSI). The United States Geological Survey (USGS) earth explorer and the GEE data catalog, both offers high-resolution and open access images.

### Data Analysis:

In this research study, multispectral and thermal satellite data of multiple Landsat missions were used to conduct a detailed spatio-temporal study for the Gilgit basin for 30-years (1995-2024). Amongst all, Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) were used for the previous time periods. Actually, these satellites offer thermal band 6, which is essential for estimating LST. Moreover, the Near-Infrared (NIR) and red bands of such sensors were used to estimate vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Snow Index (NDSI). For recent years, the data from landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) and the new landsat 9 OLI-2/TIRS-2 were applied. Basically, these sensors provide thermal band 10 for deriving LST and to utilize band 5 (NIR) and band 4 (Red) for vegetation and snow cover classification. Band combinations i.e. 5-4-3 or 4-3-2 were utilized to form false-color or true-color images that improves visual interpretation like vegetation, water, snow, bare land and urban areas.

The present analysis was carried out by a step-by-step process by employing the cloud-based google earth engine platform having high computation capabilities in handling large datasets. This research had a time period 1995-2024 with average LST values in order to outline long term thermal trend that quantify the environmental and climatic changes in the region. The pre-processing was the initial step, in which only cloud free landsat images were chosen in order to validate the available data by eliminating pixels. Consequently, digital numbers of the thermal band were converted to top-of-atmosphere spectral radiance based on sensor-specific radiometric calibration. This radiance spectrum was then converted to brightness temperature in Kelvin by satellite-specific constants, K1 and K2, included in the image metadata. Alongside, NDVI was calculated as;

$$NDVI=NIR-RED/NIR+RED \quad \text{Eq.1}$$

This index was used as a substitute for vegetation density. Similarly, the vegetation proportion (Pv) was computed from NDVI data as follows;

$$Pv = ((NDVI - NDVI\_min) / (NDVI\_max - NDVI\_min))^2 \quad \text{Eq.2}$$

This step allows for quantification of vegetative cover that affect the surface thermal radiation. Consequently, the land surface emissivity (ε) was estimated as;

$$\varepsilon = 0.004 \times Pv + 0.986 \quad \text{Eq.3}$$

Accurate emissivity values are essential for the precise of calculations of LST. Alongside, the temperature has been measured in degree Celsius and was calculated as;

$$LST=1+(\varrho\lambda \cdot BT)\ \ln(\varepsilon) BT-273.15 \quad \text{.... Eq.4}$$

Where "BT" is the brightness temperature, "λ" is the thermal band wavelength (10.8 micrometers), "ϱ" is the Planck's law constant (14,388 μmk**)**, and **"**ε" is the surface emissivity. This attempt has been implemented with ad-hoc and google earth engine that allow automated processing of the multi-decadal dataset. The resulting maps regarding LST provide significant information in terms of climatic trends. Using satellite data offer temporal homogeneity and spectral comparability, supporting the robustness of the LST trend analysis across in the three decades. A snow-covered area, in Gilgit basin is quantified using NDSI whose spectral reflectance property is necessary to take advantage of the fact that snow reflects more in the green band but absorbs significantly in the shortwave infrared (SWIR) region. Numerically, NDSI can be derived as;

NDSI = Green – SWIR/Green +SWIR .... Eq.5

Moreover, pixels with an NDSI value of more than 0.4 were classified on threshold-based classification. Such pixels were extracted and masked to select snow zones in the associated basin. Additionally, the snow-covered area was computed in square kilometers by applying zonal statistics tools. This method provides snow extent information annually during the period 1995-2024, enabling a complete assessment of snow cover processes. The LULC classification of the Gilgit Basin was conducted using a supervised classification method under the google earth engine framework. This method was chosen because it could efficiently process large-scale geospatial data and perform cloud-based computing with the help of sophisticated machine learning algorithms. Satellite data utilized for the classification was obtained from USGS via google earth engine. Specifically, Landsat 5 Thematic Mapper was employed for the year 1995, Landsat 5 and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) were employed for 2004, Landsat 8 Operational Land Imager (OLI) was used for 2014 and the Landsat 9 OLI-2 was employed for the year-2024. The classification results of each year was thoroughly examined in GEE and the derived land cover maps were exported as Geo TIFF. The exported datasets were then imported into ArcMap 10.8 for additional processing, visualization and map design.

## Study Objectives:

To analyze the spatial and temporal LULC dynamics in the Gilgit River Basin by applying multi-temporal satellite imageries and Google Earth Engine (GEE) to detect historical trend and pattern of landscape changes.

To assess the Spatio-temporal flux of the land surface temperature and to examine its association with changing land use/land cover classes in the study region.

To evaluate the snow cover fluctuations and synergy with LULC dynamics and land surface temperature to explore the interaction among surface temperature variations, cryospheric changes and landscape changes in the Gilgit River Basin.

## Significance and Uniqueness of the Study:

This specific research offer a unique contribution in the context of mountain environmental change assessment along with cryosphere-climate relation. Alhough previous research studies have distinctly explored LULC transformation, LST variability in the HKH region and the integrated assessment link these three significant components inside a single analytical framework. The present research study fulfil the gap by providing a complete spatio-temporal evaluation of the synergy amongst LST variability, LULC dynamics and snow cover fluctuation in the selected Gilgit Basin by inserting Google Earth Engine (GEE). The basic novelty of the current research work lies by integrating multi-source Landsat archives i.e. Landsat 5, 7, 8 and 9 for the period of 30-years (1995–2024) using GEE in order to analyze the environmental changes in a uniform platform. Furthermore, an innovative characteristic of this research is the combining of machine learning-based random forest classification by applying specialized geostatistical approaches like MK trend test, SS estimator and Pearson correlation coefficient, to precisely quantify both the trend and synergies in the selected parameters. Moreover, this research study develop policy-relevant evidences for climate adaptation, watershed management and sustainable resource planning in the Gilgit River Basin.

## Analysis, Results and Discussion:

## Analysis of Land Use Land Cover (LULC):

Globally, LULC changes have reshaped the landscapes of the study region. Approximately, 32% of the earth's surface experiences LULC changes during the period 1960-2019. By the same token, numerous research studies have focused on the relationship between

LULC, LS and the altitudinal variability has been less explored particularly in the Himalayan ecosystem.

In this study, a comprehensive analysis regarding spatio-temporal dynamics of LST and snow cover in the Gilgit river basin for 30-year period i.e. 1995-2025 were carried out (Table 1). Using specialized statistical techniques such as Pearson correlation, Mann-Kendall (MK) trend test and Monte Carlo (MC) simulations [31][32][33] this study examines inter-annual variations and long-term trends in the scenario of LST. The analysis aim to understand the linkages between climatic variability and cryospheric changes within Himalayan sub-basin.

After generating spatial maps by applying GIS technology, Figure 5 (2015) represents the spatial distribution of Land Use Land Cover (LULC) in Gilgit River Basin (GRB) for the year-2015, however table 1 offers a comparative assessment for the two prominent periods i.e. 2015 and 2025 and ultimately provide change detection. Similarly, Figure 6 (2025) clearly explains the spatial distribution in the light of five major LULC classes (Table 2): In the selected river basin, the dominant class, mainly located in valleys, lower slopes, and river course that express the agricultural land, natural vegetation cover and forests cover. Similarly, the white color shows snow covered area that distributed in the northern, north-eastern and high elevation mountain zones. This revealed glaciers in the Hindu Kush-Karakoram (HKH) region.

In case of barren land showing by light brown color illustrate that in the southern regions and mid-altitude mainly in rugged terrain. Likewise, it also express exposed soil, rocky surfaces and the land having sparse vegetation. Similarly, different settlements indicated by red color through linear and clustered pattern across the transportation routes and river valleys. The settlements are concentrated in lower altitudinal zones that reflects resource availability and human accessibility. Moreover, the water bodies has been shown by blue color and limited extent and located mostly along the small lakes and river channels. In addition, it represent the hydrological network of the concern basin (GRB).

In case of expansion of settlements, rapid urban expansion reflects population growth (+6,736.92 ha). These settlements are concentrated in visible red zones. This is because of the conversion of vegetation cover and agricultural land into built-up areas. In the context of vegetation cover, the region revealed deforestation, agricultural pressure and land degradation (-43,676.09 ha). May also result from climate stress (temperature rise, reduced moisture). Similarly, in case of snow cover, critical changes were observed (-169,211.68 ha). The resultant values illustrate glaciers retreat along with limited snow accumulation. This strongly connected with climatic change and rise temperature in the HKH region. This has a direct impact on river discharge and water security. Furthermore, growth in barren land (+203,535.44 ha), major positive changes occurred among the land use classes. Consequently, desertification, land degradation and loss of snow and vegetation cover occurs.

Additionally, slight rise has been seen in water bodies such as +86.74 ha and the minor changes are due to glacial melting which temporarily increases the surface water. As a result, this also forms small lakes i.e. glacial lakes.

**Table 1.** Change detection of LULC classes in the GRB (2015-2025)

| Class | Area in hectares 2015 | Area in hectares 2025 | Change in hectares |
|---|---|---|---|
| Water Body | 8452.17 | 8538.91 | 86.74 |
| Settlements | 17627.31 | 24364.61 | 6736.92 |
| Vegetation | 1136054.69 | 1092378.6 | -43676.09 |
| Snow Cover | 826112.94 | 656901.26 | -169211.68 |
| Barren Land | 733782.27 | 937317.71 | 203535.44 |

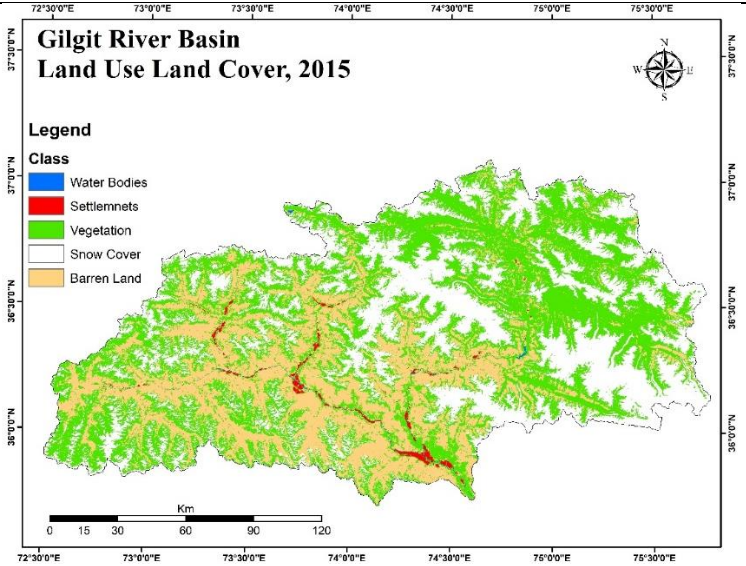

**Figure 5.** Land Use Land Cover (LULC), Gilgit River Basin (2015)

**Table 2.** Land Use/Land Cover Change Trend and Magnitude (2015-2025)

| Class | Change (Hectares) | Trend |
|---|---|---|
| Water Bodies | +86.74 | Slight increase |
| Settlements | +6736.92 | Strong increase |
| Vegetation | -43,676.09 | Significant decrease |
| Snow Cover | -169,211.68 | Very large decrease |
| Barren Land | +203,535.44 | Very large increase |

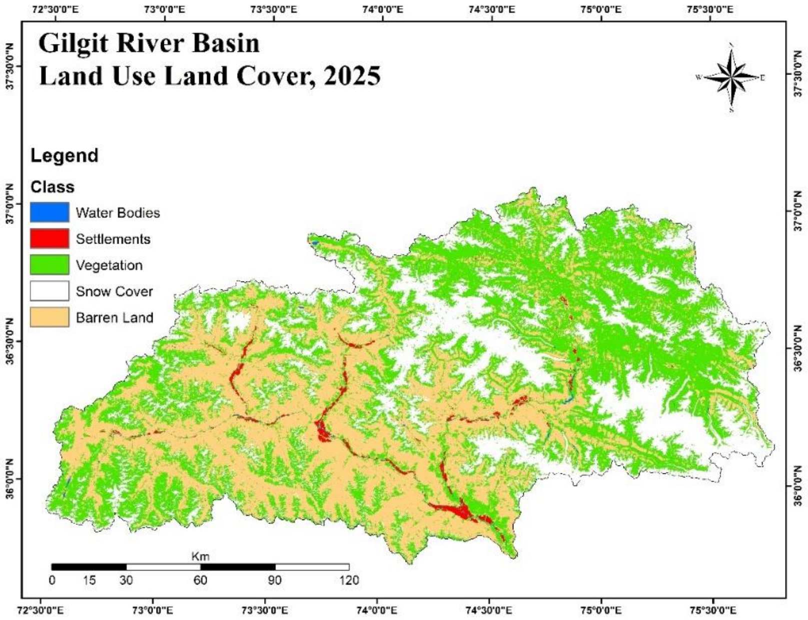

**Figure 6.** Land Use Land Cover (LULC), Gilgit River Basin (2025)

**Pattern of Land Surface Temperature:**

After analysis, significant inter-annual variations in LST and snow cover area was observed in the concern basin (GRB) for the period 2015 and 2025. The minimum LST is about -13.5°C was recorded in 1996 and the highest maximum temperature has been confirmed i.e. 14.8°C in the year-2000. The amount of snow cover varied greatly over this period, from a minimum of 13,100 km² (2000) to a maximum of 14,650 km² in 1998. The Snow cover increase in 1998 was accompanied by a noticeably lower maximum LST (12.4°C). Pointing to a potential inverse link between surface temperature and snow extent (Figure 7).

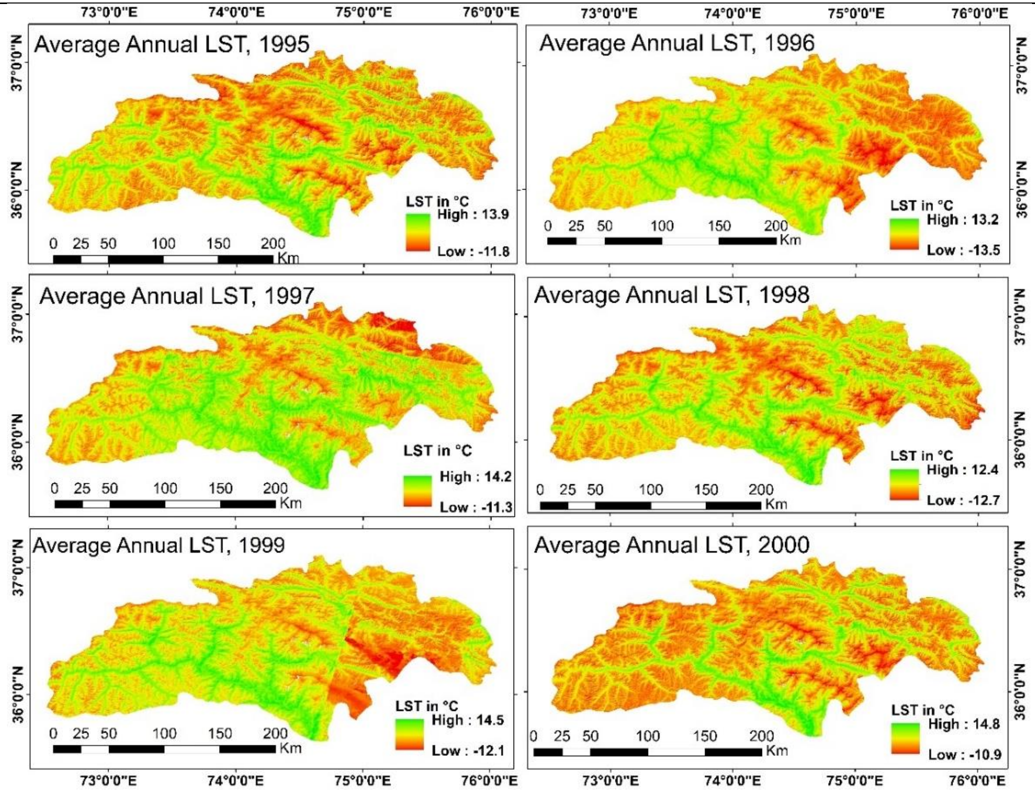

**Figure 7.** Average annual land surface temperature of Gilgit River Basin (1995-2000)

Both LST and the amount of snow cover in Gilgit basin continued to fluctuate gradually during the span 2001-2006. Likewise, the LST maps shows an evident rise in mean maximum temperature along with rising trend. The LST reached its lowest maximum of 14.9°C (2001), whereas in 2003, it reached its greatest point i.e. 20.7 °C. Less snow cover was noted with increase temperature, particularly in 2003, when the snow extent was at its lowest point such as 10,780 km². Opposite to this, snow cover somewhat improved, stabilizing at 12,369 km² by 2006 after hitting 12,960 km² (2001). The data emphasized how sensitive the cryosphere in the basin is to warming temperature by indicating a strong inverse association between snow cover and surface temperature (Figure 8).

Similarly, significant variations in the Gilgit basin's LST and amount of snow cover was observed between 2007 and 2012. With the maximum temperature rise from 15.7°C (2007) to 17°C (2012) and the lowest temperature ranging from -15.7°C to -9.4°C, the average annual LST demonstrated a slow warming trend. At the same time, snow cover also declined dramatically from 15,200 km² (2007) to 11,762 km² (2012). This steady decline in snow cover area indicate change in seasonal snow deposition and melting (Figure 9).

Moreover, Gilgit basin had notable changes in LST and slight variation in snow cover during 2013-2018. The area covered by snow was measured at 11,640 km² (2013), while it slightly shrank to 11,480 km² in 2014. Similarly, the year-2015 experiences a prominent increase of 12,562 km², before declining once more to 11,940 km² in 2016. Snow cover decreased even further in 2017 (11,159 km²), although it slightly increased in 2018 i.e. 11,849 km². Shifts in LST values reflected these variations with minimum temperature ranging from -14.8 °C to -8.2 °C and comparatively high temperature between 15.4 °C and 19.2 °C (Figure 10).

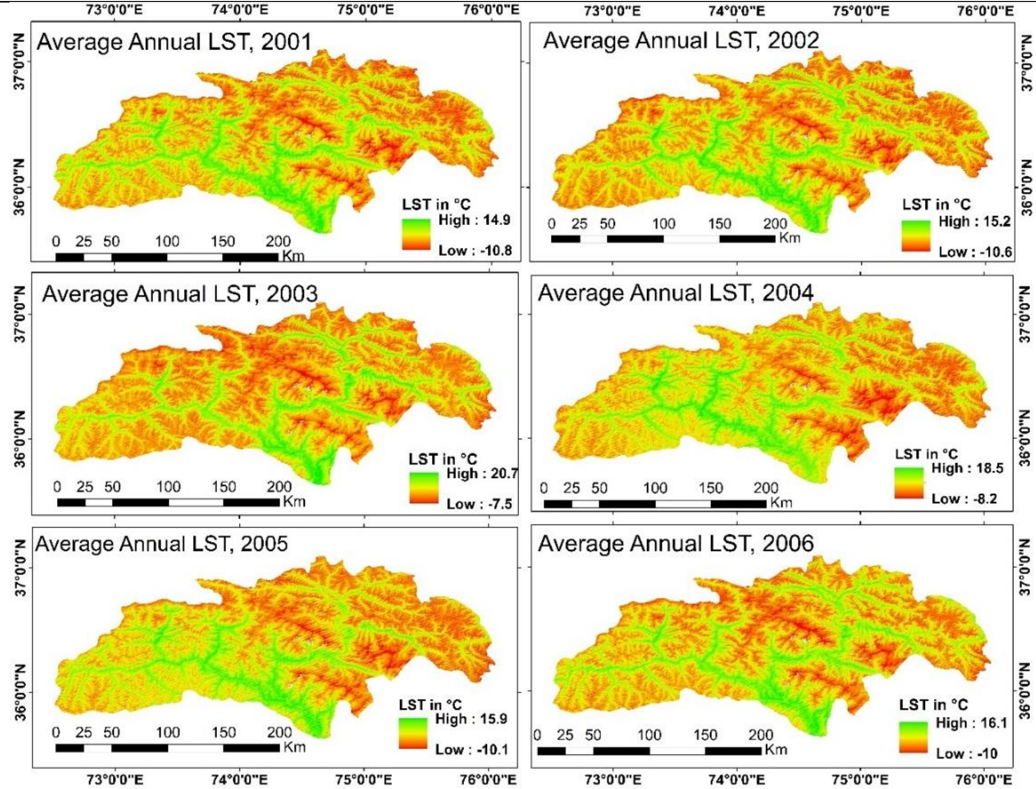
Average Annual LST, 2001
Average Annual LST, 2002
Average Annual LST, 2003
Average Annual LST, 2004
Average Annual LST, 2005
Average Annual LST, 2006

**Figure 8.** Average annual land surface temperature of Gilgit River Basin (2001-2006)

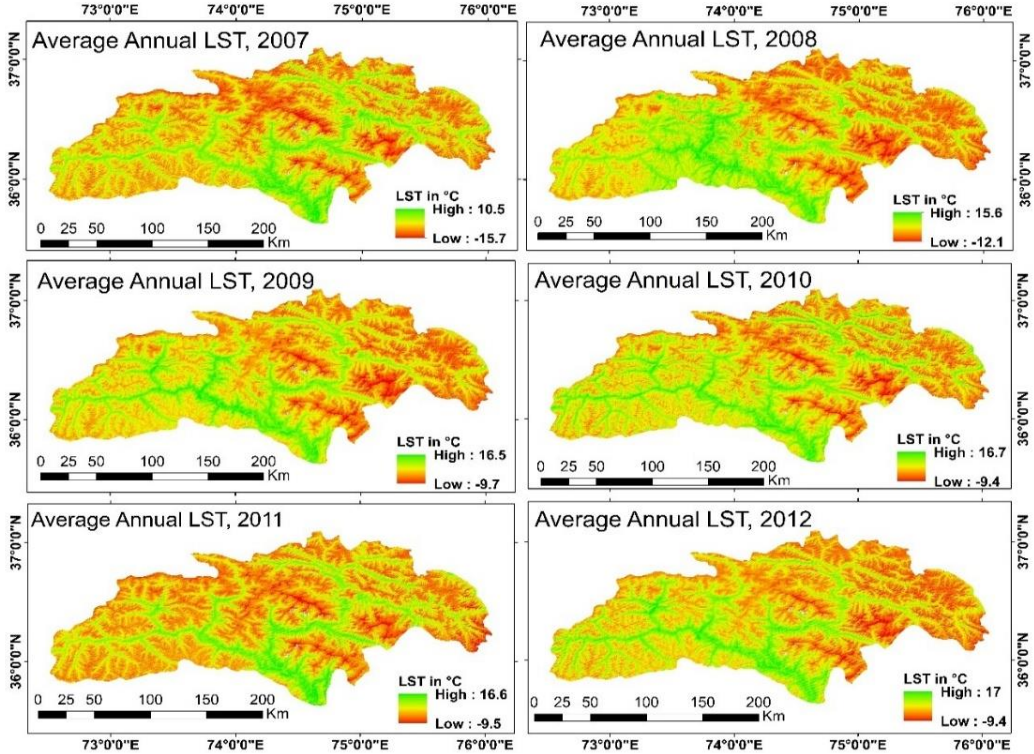
Average Annual LST, 2007
Average Annual LST, 2008
Average Annual LST, 2009
Average Annual LST, 2010
Average Annual LST, 2011
Average Annual LST, 2012

**Figure 9.** Average annual land surface temperature of Gilgit River Basin (2007-2012)

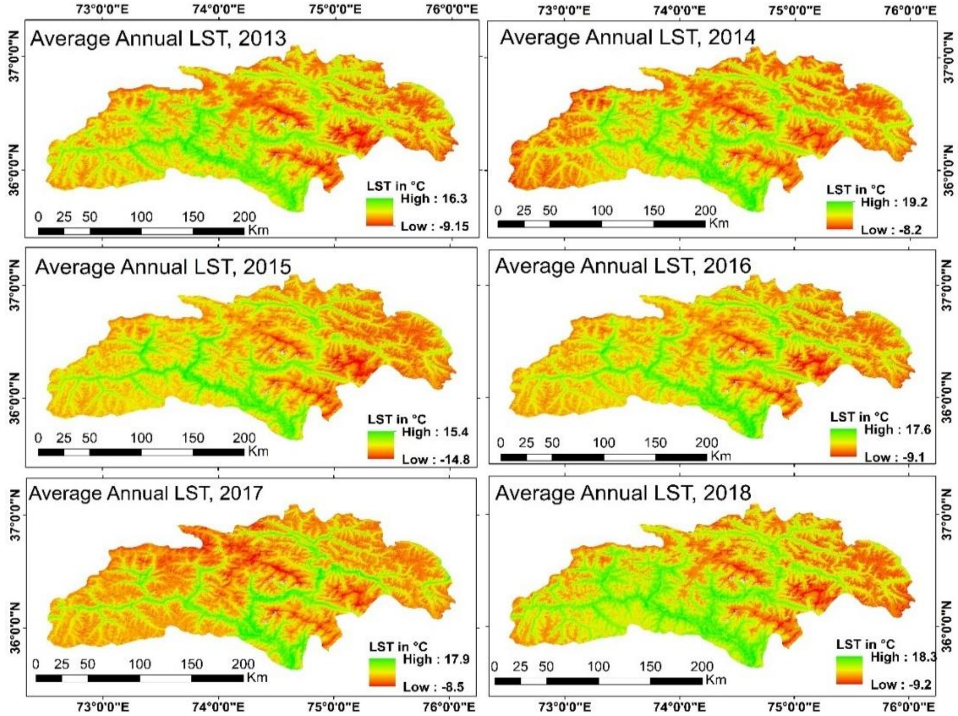

**Figure 10.** Average annual land surface temperature of Gilgit River Basin (2013-2018)

Additionally, the Gilgit basin in case of snow cover expressed a decreasing trend (2019-2024). The area covered by snow measured at 10,840 km² (2019), while in 2020 11,361 km². The amount of snow cover peaked in 2021 (12,099 km²). But in the years followed, there was a slow decrease i.e. 11,760 km² (2022) and 10,960 km² in 2023 respectively. The amount of snow cover has decreased to 10,278 km² by the year-2024. Changes in LST seemed to correspond with these variations, as their values varied throughout the same years (Figure 11).

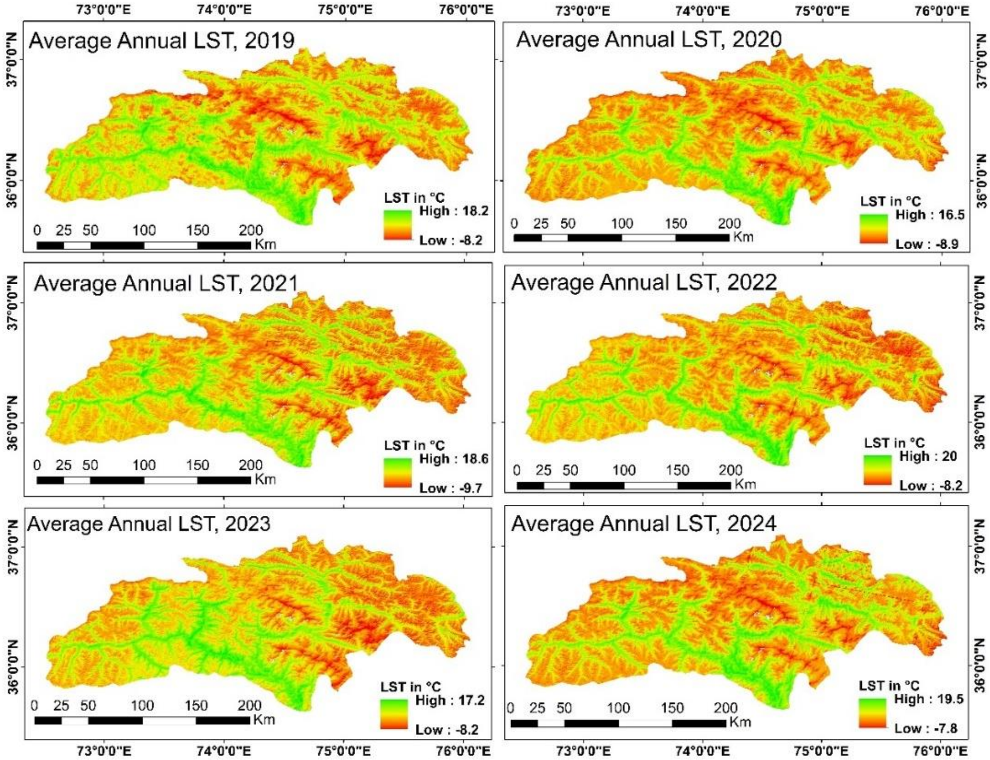

**Figure 11.** Average annual land surface temperature of Gilgit River Basin (2019-2024)

## Spatio-temporal Analysis of Snow Cover Dynamics:

The Gilgit river basin's snow cover area showed moderate inter-annual variability between 1995 and 2000. The area covered by snow was roughly 13,500 km² in the year-1995 and 13,560 km² in 1996, which mean a small increase is confirmed. In 1997, there was a little decrease occurred in coverage, falling to 13,400 km². However, 1998 saw a notable rise, peaking at 14,650 km$^2$, the greatest amount over the six-year span, which most likely denoted a wetter year. Later on, it decreased to 13,837 km² (1999) and then again to 13,100 km² (2000). These variations demonstrate the region's dynamic snow distribution and raise the possibility of connections to yearly climate shifts (Figure 12).

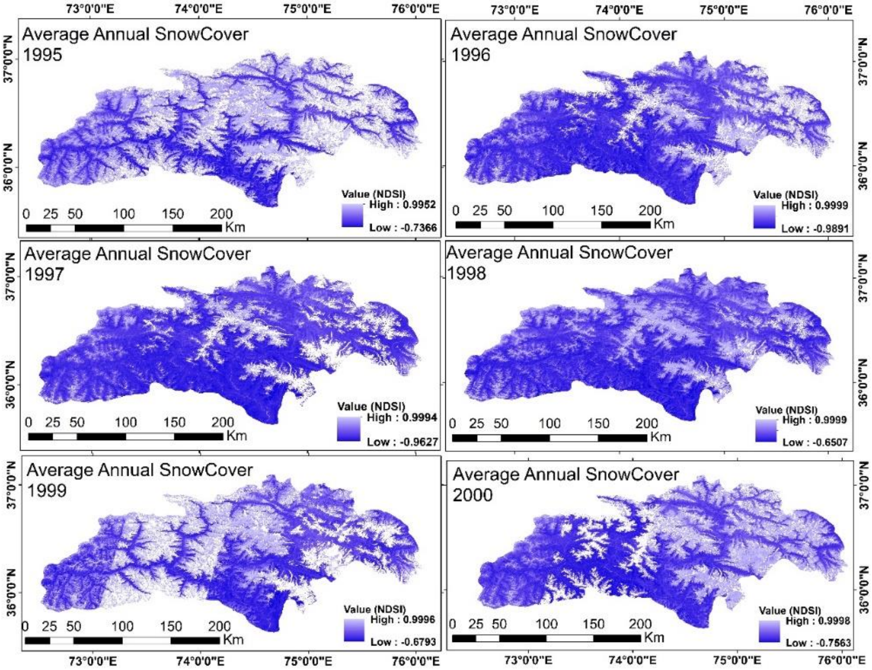

**Figure 12.** Average annual land surface temperature of Gilgit River Basin (1995-2000)

Similarly, in the concern basin, snow cover area decreased between 2001 and 2006, with noteworthy annual variations. The area covered by snow was measured at 12,960 km² in the year-2001 and then slightly decreased to 12,840 km² in 2002. The snow extent dropped significantly in 2003, reaching its lowest point of 10,780 km² due to the warmer temperature and less precipitation. In the year-2004, the snow cover increased slightly to 11,657 km² and in the year-2005, it increased even more to 12,440 km². At 12,369 km$^2$, the amount of snow cover was comparatively constant in 2006 (Figure 13).

Likewise, the Gilgit basin's snow cover expressed significant inter-annual variations from 2007 to 2012 as a result of a colder and significant peak was recorded in 2007 (15,200 km²). This was followed by a sharp drop to 13,700 km² in 2008 and another drop to 11,960 km² in 2009 with little variations, the snow extent was measured at 12,089 km² in 2010, 11,900 km² in 2011 and 11,762 km² in 2012. This indicates changing climatic conditions in response to snow cover (Figure 14).

Furthermore, snow cover of the concern basin has shown a consistent decreasing trend with periodic variations between 2013 and 2018. The area covered by snow was measured at 11,640 km² in 2013 and fell little to 11,480 km² in 2014, whereas 2015 confirmed a brief increase to 12,562 km$^2$. The snow extent decreased once more to 11,940 km² in 2016 and then again to 11,159 km² in 2017 indicating that this increase was short-lived. A slight rebound was noted in 2018, as the amount of snow covered increased to 11,849 km² (Figure 15).

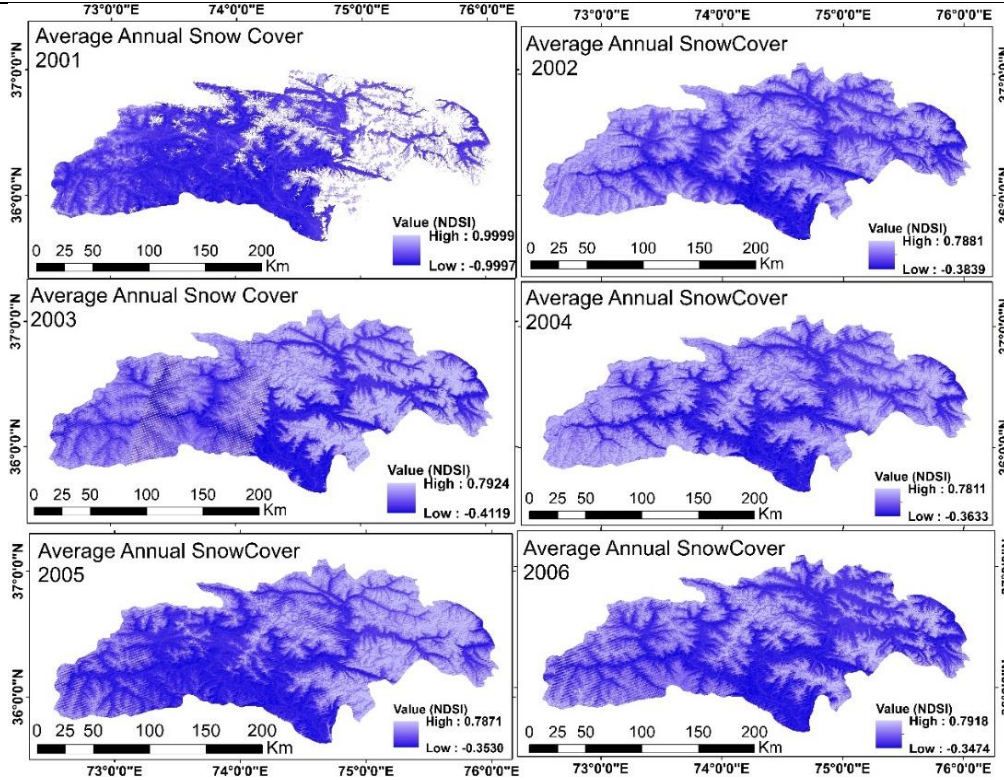

**Figure 13.** Average annual land surface temperature of Gilgit River Basin (2001-2006)

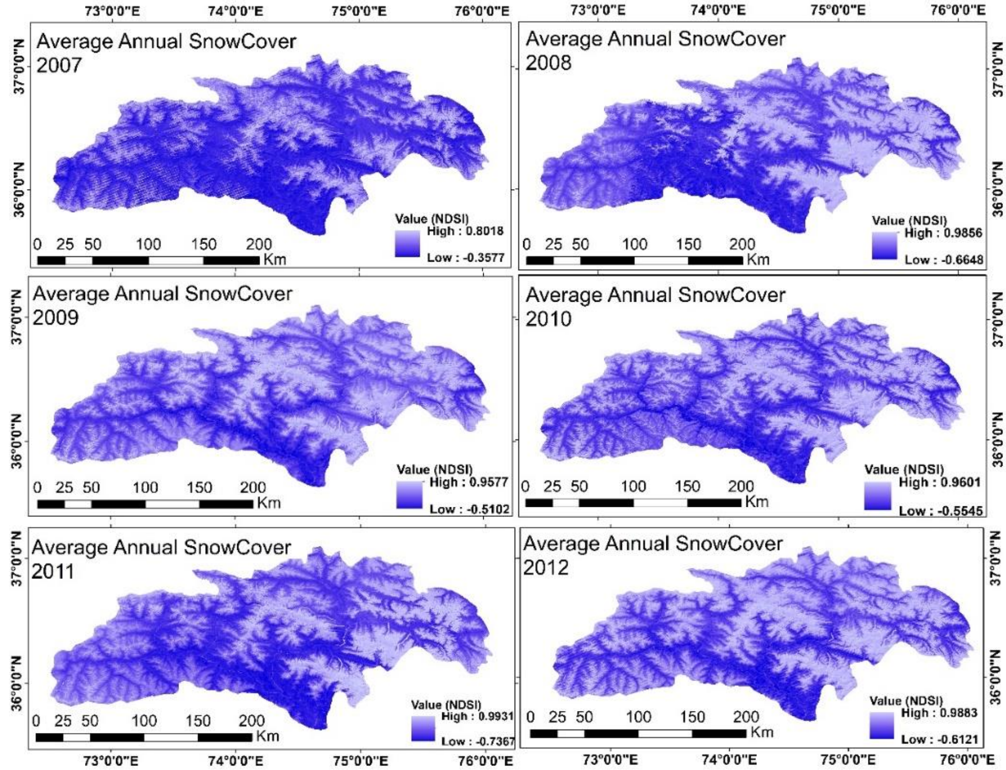

**Figure 14.** Average annual land surface temperature of Gilgit River Basin (2007-2012)

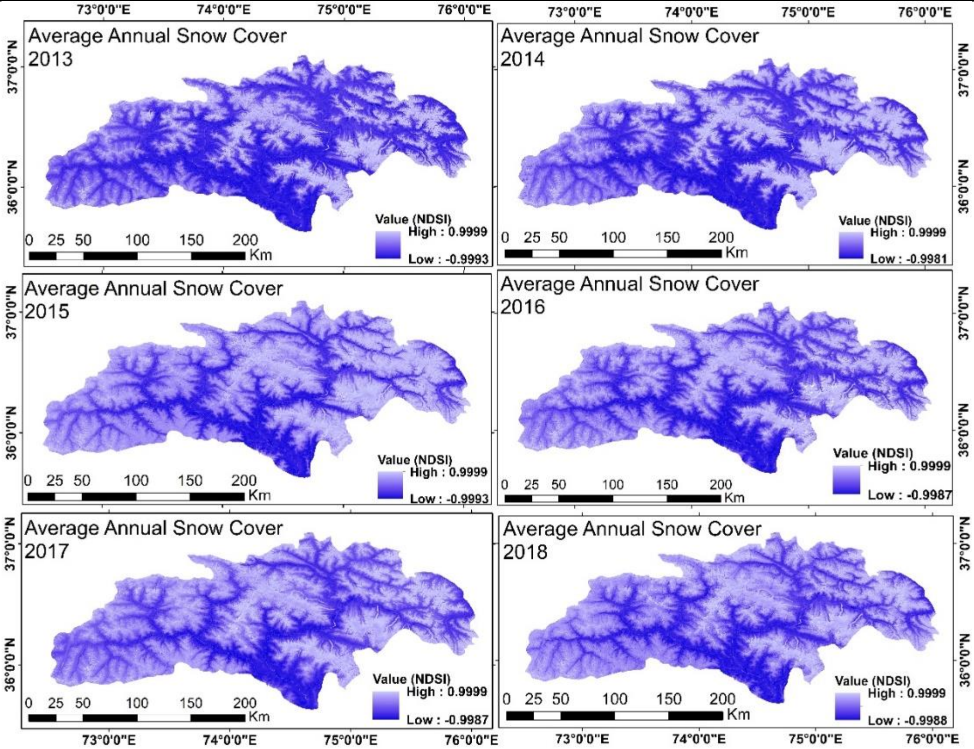
Average Annual Snow Cover 2013
Average Annual Snow Cover 2014
Average Annual Snow Cover 2015
Average Annual Snow Cover 2016
Average Annual Snow Cover 2017
Average Annual Snow Cover 2018

**Figure 15.** Average annual land surface temperature of Gilgit River Basin (2013-2018)

Moreover, the selected basin verified a visible decrease in snow cover between 2019 and 2024, which reveal a continuous climatic change. The amount of land covered by snow was 10,840 km² in 2019, 11,361 km² in 2020 and 12,099 km² in 2021. Following this brief increase, snow cover steadily decreased, falling to 11,760 km² in 2022, 10,960 km² in 2023 and 10,278 km² in 2024. These trends show increasing unpredictability and a general decline in snow extent, which is probably caused by the region's changing precipitation regimes and warming temperature (Figure 16).

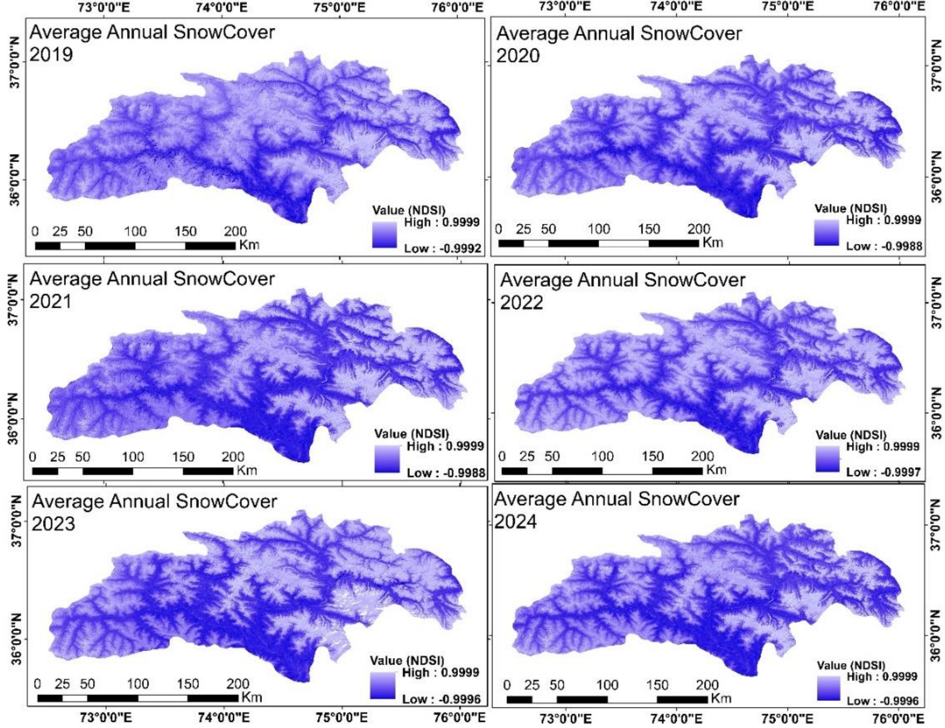
Average Annual SnowCover 2019
Average Annual SnowCover 2020
Average Annual SnowCover 2021
Average Annual SnowCover 2022
Average Annual SnowCover 2023
Average Annual SnowCover 2024

**Figure 16.** Average annual land surface temperature of Gilgit River Basin (2019-2024)

**Table 3.** Annual Snow cover and LST statistics for Gilgit River Basin (1995-2024).

| Year | Snow Cover (km$^2$) | MMin LST (°C) | MMax LST (°C) | Average LST (°C) |
|---|---|---|---|---|
| 1995 | 13,500 | -11.8 | 13.9 | 1.05 |
| 1996 | 13,560 | -13.5 | 13.2 | -0.15 |
| 1997 | 13,400 | -11.3 | 14.28 | 1.4 |
| 1998 | 14,650 | -12.7 | 12.4 | -0.15 |
| 1999 | 13,837 | -12.1 | 14.5 | 1.2 |
| 2000 | 13,100 | -10.9 | 14.8 | 1.9 |
| 2001 | 12,960 | -10.87 | 14.9 | 2.0 |
| 2002 | 12,840 | -10.6 | 15.2 | 2.3 |
| 2003 | 10,780 | -7.521 | 20.75 | 6.6 |
| 2004 | 11,657 | -8.22 | 18.5 | 5.1 |
| 2005 | 12,440 | -10.11 | 15.86 | 2.8 |
| 2006 | 12,369 | -10.01 | 16.09 | 3 |
| 2007 | 15,200 | -15.78 | 10.52 | 2.6 |
| 2008 | 13,700 | -12.13 | 15.61 | 1.7 |
| 2009 | 11,960 | -9.75 | 16.52 | 3.3 |
| 2010 | 12,089 | -9.4 | 16.73 | 3.6 |
| 2011 | 11,900 | -9.52 | 16.67 | 3.5 |
| 2012 | 11,762 | -9.48 | 17 | 3.7 |
| 2013 | 11,640 | -9.15 | 16.33 | 3.5 |
| 2014 | 11,480 | -8.2 | 19.2 | 5.5 |
| 2015 | 12,562 | -14.8 | 15.42 | 0.3 |
| 2016 | 11,940 | -9.1 | 17.62 | 4.2 |
| 2017 | 11,159 | -8.5 | 17.9 | 4.7 |
| 2018 | 11,849 | -9.28 | 18.34 | 4.5 |
| 2019 | 10,840 | -8.23 | 18.2 | 4.9 |
| 2020 | 11,361 | -8.99 | 16.51 | 3.7 |
| 2021 | 12,099 | -9.77 | 18.68 | 4.4 |
| 2022 | 11,760 | -8.2 | 20 | 5.9 |
| 2023 | 10,960 | -8.27 | 17.29 | 4.5 |
| 2024 | 10,278 | -7.8 | 19.5 | 5.8 |

### Snow Cover and Land Surface Temperature Trend:

Figure 17 illustrate the relationship between snow cover (km$^2$) and mean annual LST over a 30-year period, providing insights into long-term climatic pattern from 1994 to 2024. Both the MMAX and MMIN annual temperature trend lines exhibit a steady rise over time expressing a warming trend. The trend line indicate a consistent decrease that rising temperature causes a considerable amount of snow loss.

The line graph representing maximum LST that probably indicate an inverse association with snow cover, with lower temperature often corresponding to greater snow extent. Using SPSS, figure 17 express that years with an abundance of snow cover are associated with lower MMAX LST values having high negative correlation i.e. $r = -0.897$. Opposite to this, the second line represent the MMIN LST having weak correlation i.e. $r = 0.056$, $p = 0.765$.

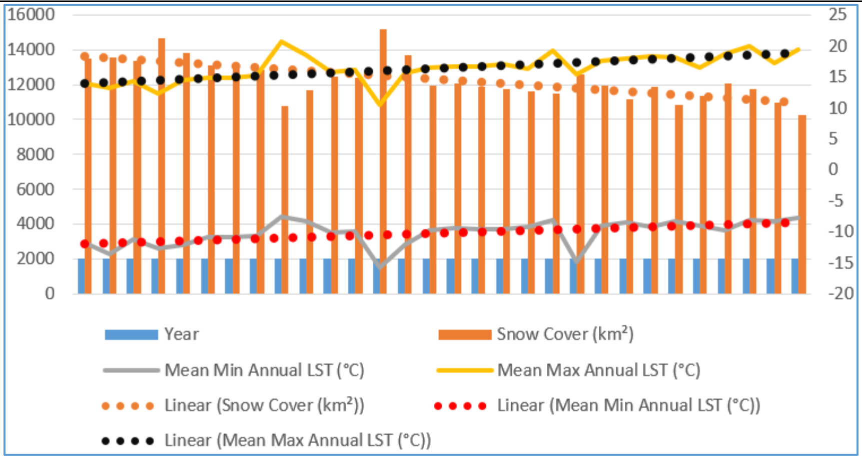

**Figure 17.** Average annual land surface temperature of Gilgit River Basin (1995-2024)

### Pearson Correlation Results: Snow Cover vs Land Surface Temperature:

Using SPSS software, the Pearson correlation ran on data to examine the association between snow cover and LST. Two important LST variables were particularly the subject of the analysis. LST_ max, which stands for the maximum daily land surface temperature and LST_ min, which stands for the minimum daily land surface temperature. To ensure statistical reliability, a robust sample size of 30 observations such as N=30 was applied to the dataset.

In addition, snow cover and LST_max were found to be strongly negatively correlated, with a Pearson correlation coefficient (r) of -0.897. This implies that the maximum daily land surface temperature tends to drop considerably with increase in snow cover. This correlation emphasize that how important snow cover is in regulating daytime surface temperature. A p-value of 0.000, which is highly significant at $p < 0.01$, support the statistical importance of this association and verifies that the observed correlation is highly significant (Table 4).

**Table 4.** Snow cover vs LST maximum temperature

| **Correlations** | | | |
|---|---|---|---|
| | | **snow** | **LST_max** |
| **Snow** | Pearson Correlation | 1 | -.897 |
| | Sig. (2-tailed) | | .000 |
| | N | 31 | 31 |
| **LST_max** | Pearson Correlation | -.897** | 1 |
| | Sig. (2-tailed) | .000 | |
| | N | 30 | 30 |

Correlation is significant at the 0.01 level (2-tailed).

Contrary to this, a very weak positive association between snow cover and LST_min was detected as the estimated Pearson correlation coefficient was very low (0.056). This express that the relationship between snow cover and land surface temperature is essentially nonlinear. The correlation value is close to zero, suggesting that other environmental factors are also necessary in predicting minimum surface temperature. With a p-value of 0.765, the resultant statistical significance is also uncertain, suggesting that the correlation is insignificant between the two variables (Table 5).

A highly significant p-value of less than 0.0001 and a test statistic value of 355 were found in the trend analysis of average land surface temperature. This suggest that the average LST increased significantly. This increasing tendency is further quantified by the Sen's slope estimation, which indicate an approximate annual increase of 0.17°C.

**Table 5.** Snow cover vs LST minimum temperature

| Correlations | | | |
|---|---|---|---|
| | | **snow** | **LST_max** |
| **Snow** | Pearson Correlation | 1 | .056 |
| | Sig. (2-tailed) | | .765 |
| | N | 31 | 31 |
| **LST_max** | Pearson Correlation | .056 | 1 |
| | Sig. (2-tailed) | .765 | |
| | N | 30 | 30 |

The average snow cover trend analysis revealed a highly significant p-value of less than 0.0001 and a test statistic of -356. This demonstrate that during the study period, the amount of snow cover decreased significantly. The SS estimator indicate a significant decrease in the amount of snow in the study area, with an estimated annual decline of 137.5 km². A highly significant increasing trend in land surface temperature over the period 1995-2024. A highly significant decreasing trend in snow cover over the same period. The strong negative correlation between these two variables suggest that as temperature rise, snow cover is decreasing that align with expected climate change pattern.

To achieve objectives of the study, MK was applied in case of LST and snow cover during the period 1995-2024. This method provide confidence intervals of p=0.05 (95%) to determine whether the observed trend is significant of not. After modelling, the evidences revealed that warming and snow loss trend is significant in the Gilgit River Basin.

The MK test yielded the initial SS estimate, which was +0.17°C year. The 95% confidence interval generated by the MK trend test was between +0.12°C and +0.22°C per annum. This means that there is a 95% chance that this range contain the actual warming trend and the trend is regarded as statistically significant.

After applying MK test, at 95% confidence interval the snow loss expected to fall was -180.2 km² to -95.3 km² per year. The decrease in snow cover is regarded as statistically significant and represent a declining trend because the interval does not include zero. With an annual warming rate of 0.17°C, the LST trend is dependable and well supported by MK test, suggesting that it is not the consequence of chance. In a similar vein, the about 137.5 km² annual drop in snow cover is statistically significant.

## Conclusion:

The Mann-Kendall (MK) test demonstrated a statistically significant rise in land surface temperature, with a Sen's slope of +0.17°C/year (*p* < 0.0001). This was confirmed by MK trend test with 95% confidence level +0.12°C to +0.22°C/year, confirming the strength of the warming. In the context of spatial variability, warming was strongest in the lower-elevation areas, where the maximum temperature increased by some 20 °C in extreme years such as 2003 and 2024. The regions located at higher altitudes expressed less intense temperature but persistent warming, consistent with global evidence of elevation dependent warming in mountainous terrain. Moreover, a notable decline in snow extent was recorded with average annual loss being 137.5 km² ($p < 0.0001$). MK test confirmed this pattern of about 95% confidence that the actual reduction should range between 95.3 and 180.2 km² annually. In addition, Pearson correlation was applied to the data and the analysis revealed a very high negative relationship between snow cover and LST_ max i.e. $r = -0.897$ ($p = 0.000$), which confirm that increasing temperature is one of the key factors responsible for snow loss. Conversely, LST_ min was not correlated with snow cover i.e. $r = 0.056$ ($p = 0.765$), reflecting the known fact that night time temperature is less affected by snow behavior.

The analysis reveals clear evidence of significant climatic shifts within the Gilgit River Basin over the past three decades. LST has exhibited a strongly increasing trend of approximately +0.17°C per year, while the snow cover has declined at a rate of about -137.5 km² per annum. These trends are statistically significant and robust, as confirmed by MK trend test (Dawood et al., 2018b). A strong inverse correlation between snow cover and maximum LST suggests that warming temperatures are directly influencing snow loss in the basin. The study further highlight sensitivity of the Gilgit River Basin to climatic change, indicating rapid climate change with significant consequences for regional hydrology and ecosystem. Major research findings express a dramatic rise in LST, particularly at higher elevations. To mitigate the rising LST and its associated impact on snow cover reduction, integrated environmental and land management policies are essential. Strengthening local resilience to rising LST and declining snow cover involves community-based climate adaptation. Encouraging the cultivation of drought-resistant crops like millets, buckwheat, and barley, and modernizing ancient irrigation systems like the Karez can significantly boost water-use efficiency.

## Policy Implications for Water Security, Hydrology and Sustainable Ecosystem:

The key findings of the current study hold significant implications for water governance, hydrological planning and resilient ecosystem in the study region (Gilgit River Basin). The considerable increase in land surface temperature i.e. +0.17°C year$^{-1}$ and the decline in snow cover express escalating cryospheric change that can alter magnitude of the streamflow (−137.5 km² year$^{-1}$). Therefore, seasonal glacier melting consists of substantial freshwater sources for agriculture in the downstream areas, domestic usage and hydropower generation. Hence, the observed snow loss actually poses great threat to the water security. Similarly, this research study also have significant ecological implications. The snow cover reduction and rise in temperature might disturb biodiversity habitats, fragile mountainous ecosystems and the vegetation pattern. These outcomes of the current research study illustrate the need for ecosystem-based adaptation strategies comprises of afforestation, watershed conservation, restoration of rangeland and the protection of mountainous habitats.

From a policy point of view, this study fully support the developing of water management and climate-responsive land policies. The Integrated Water Management techniques must be encouraged to improve water usage efficiency and also to enhance resilience against hydro-climatic fluctuation. Likewise, the planning regarding land use should manage the unplanned urban expansion, deforestation. Moreover, key findings also contribute evidences for the regional climate adaptation policies in Gilgit Basin by illustrating how elevation depends warming and snow decline that directly impact ecosystem and hydrology of the study region. Therefore, the present research study offers a scientific base particularly for water managers, environmental agencies and policymakers to develop suitable strategies for disaster risk reduction and water security.

## Recommendations for Integrated Water Management, Land Use Regulation and Climate-Resilient Agriculture:

In the scenario of warming trend, decreasing snow cover and linked environmental changes in the Gilgit Basin, the below recommendations were proposed to delivered climate resilience along with long term sustainability:

### Integrated Water Management Recommendations:

The already noticed reduction in snow cover reserves along with altering melting dynamics point out the quick need for integrated water resource management (IWRM) strategies. Similarly, basin-scale water resource planning should monitor snow and glacier along with climate forecasting to reduce water insecurity in future.

### Land Use Regulation Recommendations:

A rapid land use changes comprising of urban expansion, infrastructure development and deforestation need comparatively stronger land use regulations. Similarly, sustainable land use zonation must be applied to reduce ecological degradation particularly in forested slopes, recharge zones and fragile mountainous environment. Parallel to this, policies promoting watershed restoration, afforestation and the unplanned settlement growth should be controlled on priority basis.

**Climate-Resilient Agriculture Recommendations:**

Due to growing climatic change variability along with changing hydrological circumstances, promoting climate-resilient agriculture is needed to diminish livelihood vulnerability. Alongside, the farmers might be encouraged so that to adopt drought-resistant crops for instance barley and other similar climate-adapted varieties that are suitable for mountain ecosystems.

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