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Highlights:

- MNDWI and Landsat imagery were used to assess hydrological and land cover changes in the Upper Indus Basin from 2005 to 2020.
- Permanent water bodies/Glacier area declined, while vegetation and fallow lands showed notable increases.
- Annual rainfall dropped by from 2005 to 2020, reflecting climatic variability.
- Permanent water bodies reduced significantly, raising concerns over long-term water availability.
- The study highlights remote sensing as a key tool for sustainable water resource management.

Keywords:

MNDWI
Upper Indus Basin
Land use land cover
Water resources
Remote sensing

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Spatiotemporal Analysis of Hydrological and Land Cover Transformations in the Upper Indus Basin Insights from MNDWI

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Abstract The Upper Indus Basin (UIB) is a crucial freshwater source for millions of people in South Asia, although its water resources are increasingly threatened by climate change, population increase, and land-use changes. Effective monitoring and management of these resources are essential for long-term sustainability. This study employs the Modified Normalized Difference Water Index (MNDWI) and remote sensing techniques to assess spatiotemporal variations in water resources and land cover from 2005 to 2020. Using a region-specific empirical formula, rainfall intensity in the UIB was estimated while statistical approaches using logarithmic trends and polynomial equations quantified rainfall probability and return periods to forecast extreme events. The results illustrate (i) a significant reduction in permanent water bodies and glaciers together with an increase in barren land and vegetation cover, consequently highlighting the influence of climate variability and anthropogenic activities specifically, permanent water bodies/ Glaciers decreased from 22,216.2 km^2 in 2005 to 18,816.4 km^2 in 2020, marking a decline of 3,399.8 km^2 (2%), (ii) fallow land increased from 69,684.8 km^2 in 2005 to 83,568.2 km^2 in 2020, while, (iii) vegetation land expanded from 35,346.2 km^2 in 2005 to 36,257.9 km^2 in 2020, reflecting a 16% rise, (iv) the rainfall probability analysis revealed annual precipitation fluctuations, with the maximum recorded as 830.45 mm in 2000 and the lowest at 399.34 mm in 2013, representing a reduction in annual rainfall. This study highlights the importance of geospatial approaches in hydrological management, contributing to the development of sustainable strategies for the UIB.

1. Introduction

Millions of people across South Asia rely entirely on the Upper Indus Basin for their water supply making it one of earth's most glaciated and vital water basins (Malla & Ariya, 2024). The UIB includes extensive mountainous land which makes its water resources essential for Pakistan (Shresta et al., 2019). The rivers at Indus basin headwaters provide essential water resources needed to sustain people living in the downstream areas of Pakistan (Yaseen et al., 2020). Water resources face a real challenge because of fast-growing populations and food security issues (Lakshmi, 2024; Tapas et al., 2024). The UIB provides essential understanding for hydrological patterns, assessing water availability, and ensuring sustainable management effectively through Spatiotemporal methods (Kumar et al., 2024). Spatiotemporal method, such as the Modified Normalized Difference Water Index (MNDWI), is highly effective for detecting and analyzing surface water dynamics over time, particularly in complex and data-scarce regions (Xu et al., 2006). Spatial and temporal distribution of precipitation, has lead to more frequent or extreme precipitation events due to accelerated hydrological cycle (Marshall eta al., 2025; Le et al., 2023). The rapid changes in land cover affect local water flow patterns and increase flooding or drought threats throughout the globe and also at regional scale (Zhang et al., 2011; Zhang et al., 2009). Comprehensive investigation, mapping, and monitoring of water resources are essential to ensure their availability, accessibility, equitable utilization, and sustainable management (Swain et al., 2022; Nruthya et al., 2015; Sulugodu & Deka, 2019).

Water for agricultural and rural water supply is undoubtedly a top priority in developing countries (Anusha et al., 2022). The UIB has been the subject of extensive research because of its vital role in providing freshwater resources to a population that has grown rapidly. Recent advancement in GIS and remote sensing technology have revolutionized our capability to track and evaluate the UIB's water resources. Recently, remote sensing datasets, such as different precipitation products (Aryal et al., 2023), digital elevation models (DEMs) (Nguyen et al., 2023), and land use/land cover data (Saber et al., 2023), have been predominantly utilized in the development of hydrological models (Tran et al., 2023). The Glaciers and snowmelt influence the flow of the Indus River which makes hydrological models necessary to forecast water resources (Immerzeel, et al., 2010). When hydrological simulations are coupled with remote sensing data allows us to understand how water resources change overtime (Do et al., 2024; Nguye et al., 2024). Recent studies highlight significant hydrological changes within the UIB, driven by changing climate patterns and water resource dynamics. Ali et al. (2023) evaluated hydrological responses in the Astore River Basin, a sub-basin of the UIB. Their analysis predicts an increase in mean annual flows. Additionally, the study forecasts a substantial rise in extreme flood events, with an estimated increase of 50% to over 100%, indicating a heightened risk of flooding in the region. Similarly, Dharpure et al. (2025) analyzed groundwater storage trends in the Indus Basin and revealed a decline in groundwater storage, particularly in the UIB, attributed to decreasing precipitation, reduced runoff, and rising evapotranspiration alongside an expansion of vegetation cover. Before wide utilization of GIS and RS technologies, drainage systems within basins or sub-basins were identified using traditional methods and topographic maps (Akhtar et al., 2021; Ozdemir & Bird, 2009). Nowadays, modern technologies are effectively employed to create highly accurate representations of water resources (Khan et al., 2008). High resolution remotely sensed data, combined with advanced topographical data processing techniques, serves as a powerful instrument for comprehending and monitoring natural resources (Ahiwar et al., 2021; Guptha et al., 2021; Patel et al., 2022). It provides real-time and accurate insights into diverse geographical formations and landforms, while also aiding in the identification of drainage systems modified by the natural influences of human activity (Taloor et al., 202; Kumar et al., 2021).

The increasing population, urbanization, better agricultural productivity, and climate change are the key factors that have hindered the balance between water demand and supply (Hasan et al., 2020). There is a consensus within the scientific community that the challenges associated with water resources have become increasingly complex (Sherif et al., 2023). Pakistan is distinguished by its abundance of land yet faces challenges with water scarcity, experiencing occasional surpluses during the monsoon season. Consequently, enhancing and optimizing water efficiency is essential to meet future needs (Khan et., 2008). The solutions require the incorporation of various interdisciplinary techniques, including hydrological modelling, remote sensing, and geophysics.

This study therefore employs geospatial techniques, with a particular focus on the Modified Normalized Difference Water Index (MNDWI), to analyze surface water dynamics over a fifteen-year period. The research offers valuable insights into land cover changes and their implications for sustainable water resource management. Additionally, the study emphasizes the development of alternative thematic maps by utilizing a comprehensive archive of regional-scale remote sensing data. This research has the following objectives: (i) to analyze surface water dynamics and land cover changes in the Upper Indus Basin using geospatial techniques, with a focus on the Modified Normalized Difference Water Index (MNDWI), and (ii) to develop thematic maps and assess water resource patterns through the integration of regional-scale remote sensing data and advanced RS-GIS.

2. Materials and Methods

2.1. Study area

The Upper Indus Basin (UIB), is a critical transboundary watershed in the South and Central Asia. The UIB extends from the Tibetan Plateau (China) in the east to northern Pakistan in the west, covering parts of Gilgit-Baltistan, Khyber Pakhtunkhwa (KPK), and the northern fringes of Azad Jammu and Kashmir (AJK). Geographically, the UIB lies between latitudes 33°40′ to 37°12′ N and longitudes 70°30′ to 77°30′ E, encompassing the mountainous terrains of the Hindu Kush, Karakoram, Himalayas, and the Tibetan Plateau (Hasson, 2016). This region hosts around 11,000 glaciers (Bajracharya, 2013), making it one of the most glaciated areas on earth, with an estimated glacier coverage of approximately 22,000 km² (Lutz et al., 2016). The elevation within the UIB ranges from 200 meters to 8,633 meters above mean sea level as shown in (Figure 1). The basin serves as Pakistan's primary freshwater source, playing a crucial role in the country's economic sustainability and development. The climate of the UIB is classified as high-altitude alpine, with strong seasonal and elevational gradients. Precipitation is bimodal, primarily driven by winter westerlies and summer monsoons. The basin receives an average annual precipitation ranging from 200 mm in the western arid regions to over 1,000 mm in the central-eastern mountainous areas, with higher precipitation generally recorded on windward slopes. Temperatures show wide variability, with mean monthly maximum temperature ranging from sub-zero values in winter to over 30°C in summer at lower elevations. The UIB features a diverse land cover mosaic, consisting of permanent snow/glaciers, barren land, natural vegetation, cultivated fields, urban settlements, and various water bodies.

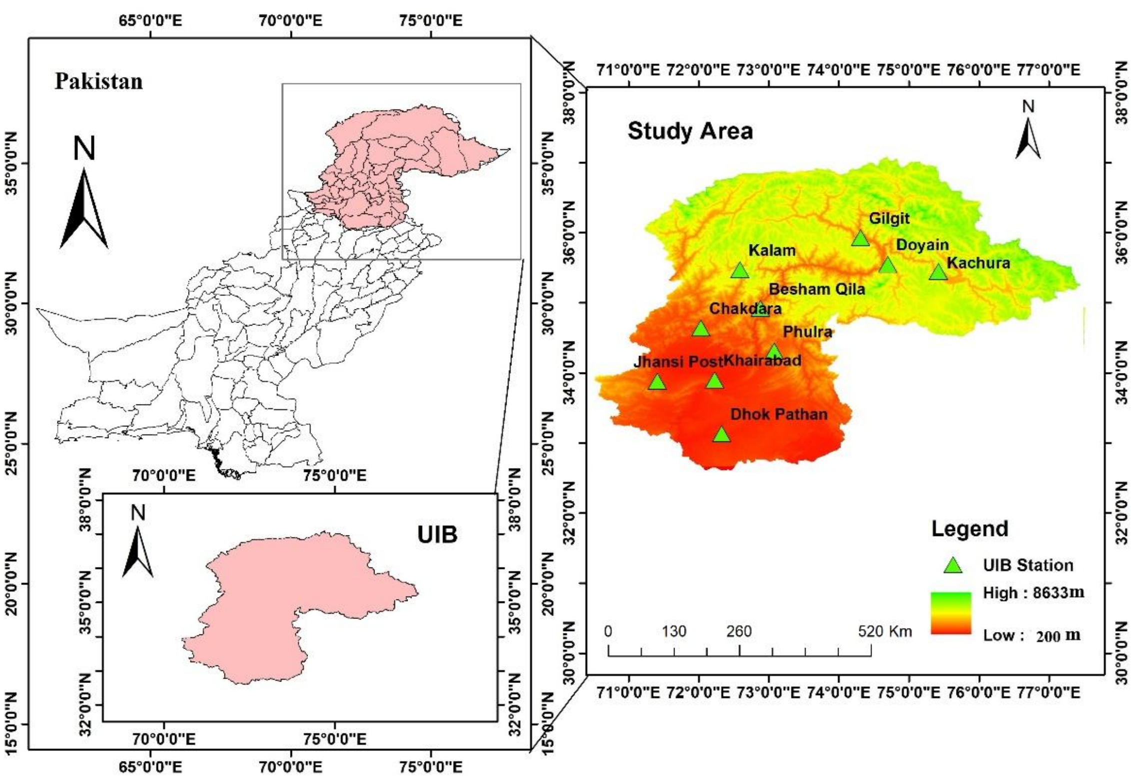

Fig. 1 Geographical location of Upper Indus Basin (UIB) along topographic information

2.2. Datasets and Methodology Framework

Freely available satellite data such as Landsat 7 ETM+ (2005), Landsat 8 OLI/TIRS (2010, 2015, and 2020), and ASTER DEM with a 30-meter resolution were acquired from the USGS Earth Explorer. These datasets were further processed and analyzed using ArcGIS 10.8, ERDAS IMAGINE 2014, and Google Earth Engine. To effectively map and monitor water resources, six thematic maps were prepared, including geology, geomorphology, soils, slope, rainfall, and the Modified Normalized Difference Water Index (MNDWI). The geological map was developed using Geological Survey FAO maps, while the soil texture map was derived from NBSS/LUP data at a 1:50,000 scale. The slope map was generated using the topography, and rainfall data were sourced from CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data). MNDWI maps spanning from 2005 to 2020 were developed using the mentioned remote sensing data in ArcGIS. All thematic layers were georeferenced and processed forming a comprehensive database for monitoring water resources in the upper Indus basin and study area is shown in Figure 1.

Such analyses are vital for flood risk assessment and water resource management in the UIB, where extreme events can have significant impacts on downstream communities. Understanding these patterns is essential for effective water resource planning and mitigating the impacts of climate variability in the Upper Indus Basin. The methodology flow chart below (Figure 2) shows the details to achieve the study objectives.

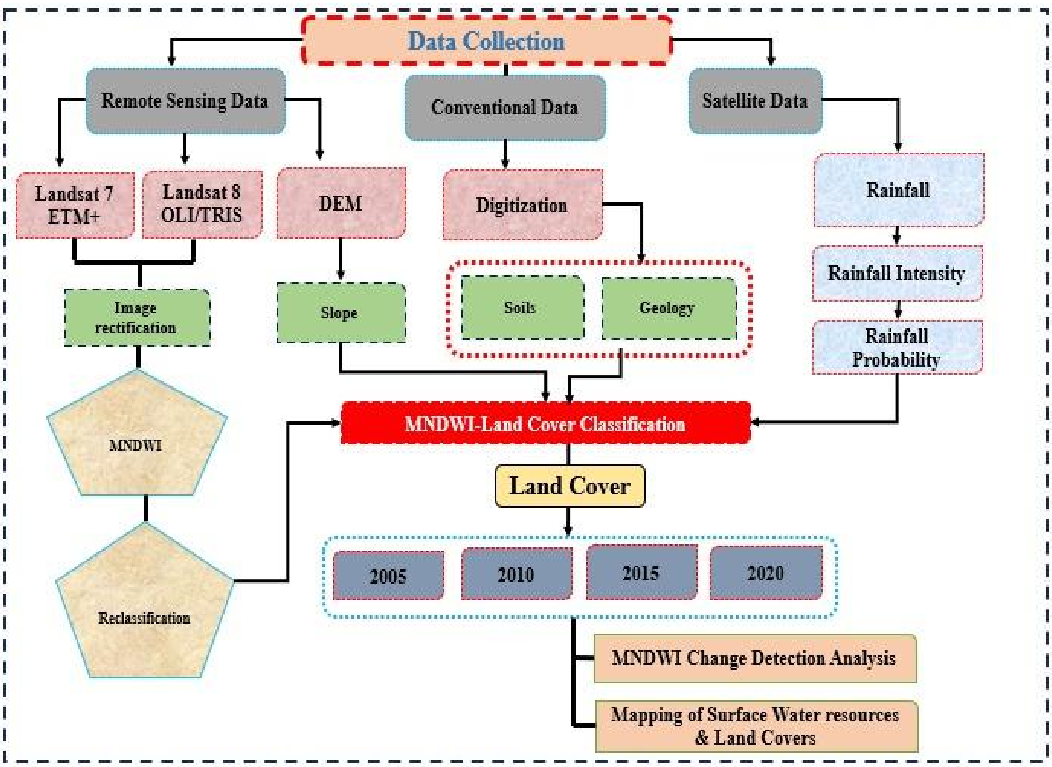

Fig. 2 A detailed methodology describing datasets retrieval, processing and analysis in the UIB

2.2.1. Rainfall intensity and probability

The UIB experiences significant fluctuations in precipitation, with certain periods witnessing intense rainfall while others face extended dry spells. This variability complicates agricultural planning and water resource management. Moreover, accurate identification of dry and wet spells requires systematic analysis of extensive hydrological data. The UIB exhibits diverse climatic conditions, with annual precipitation ranging from approximately 100–200 mm in the northern valley floors to about 600 mm at elevations around 4,400 meters (Krakauer et al., 2019; Hussain et al., 2021). Rainfall intensity in the UIB was estimated using empirical formula tailored to the UIB's climatic conditions with a general form of:

$$p = 254a/ (t + b) \text{ mm/hr} \qquad (1)$$

where, t = duration of storm in minutes, p = rainfall intensity (mm/hr), a and b = empirical constants. The area under study receives an average annual precipitation of approximately 500 mm (Krakauer et al., 2019) which indicates a humid climate zone. Precipitation is influenced by orographic effects and synoptic processes, particularly during winter months when western disturbances play a significant role (Baudouin et al., 2021). Utilizing long-term precipitation records, researchers have identified trends and variability in both annual and seasonal rainfalls over the UIB (Latif et al., 2018). The probability was calculated using p = m/(N+1), and the return period (T) was determined as T = 1/P, where m represents the rank and N is the total number of years in the dataset. Logarithmic trend lines and regression analyses have been employed to model rainfall probabilities, aiding in the prediction of future precipitation patterns. Return periods (e.g., 5, 10, 15, 20 years) were calculated using second degree polynomial equation to estimate the likelihood of extreme rainfall events.

2.2.2. Modified Normalized Difference Water Index (MNDWI)

The Modified Normalized Difference Water Index (MNDWI) is a dimensionless index ranging between −1 and 1, used to enhance open water features in remote sensing imagery. Values below 0 indicate low water content, encompassing soil and vegetation, while values above 0 signify high water content and varying water levels. MNDWI is calculated using the Green and Shortwave Infrared (SWIR) bands, specifically within the wavelengths of 0.55–0.57µm and 1.23–1.25µm, respectively.

$$MNDWI = \frac{Green - SWIR}{Green + SWIR} \quad (2)$$

The MNDWI provides more details about open water compared to the NDWI, which is essential for identifying significant variations in water quality (Xu, H. 2006). Du et al., (2016) showed the effectiveness of MNDWI in water mapping applications. Sentinel-2 imagery has shown that MNDWI improves the ability to sense water bodies and suppresses built-up features more effectively than typical NDWI. For this work, we used the MNDWI formulation in conjunction with Landsat 7 ETM+ (2005) and Landsat 8 OLI/TIRS (2010, 2015, and 2020) to monitor and map water resources in the study area. The MNDWI approach was developed using the arc toolbox, resulting in MNDWI raster picture with pixel values ranging from -1 to +1. The MNDWI image was then reclassified in the ArcGIS environment and classified into five categories.

2.2.3. Geology

The Upper Indus Basin (UIB) in Pakistan exhibits a complex geological framework shaped by diverse lithological units and a significant tectonic activity. This region's geology profoundly influences its hydrology, natural resources, and susceptibility to geohazards. Using ArcGIS, lithological units were digitized, and a detailed geological map was generated (Fig. 3) to accurately represent the region's geological composition. The UIB features extensive exposures of Paleocene–Eocene sedimentary rocks, particularly along east–west-trending fold-and-thrust belts in areas (Afzal et al., 2009). Lower Cenozoic sediments are prominent in the Kohat-Potwar Plateau, comprising formations like marl, calcareous shale, and argillaceous limestone (Yasin et al., 2021). The region is delineated by significant faults, including the Kurram thrust fault to the west and the Pezu wrench fault, which separates the Upper and Lower Indus Basins (Afzal et al., 2009). East–west-trending fold-and-thrust belts characterize the basin's structural geology, influencing sediment deposition and landscape evolution. The diverse lithology results in varying infiltration capacities. For instance, dolomite formations exhibit high permeability, facilitating significant groundwater recharge, whereas shale units, due to their low porosity, restrict infiltration. The presence of hard rocks in the region suggests restricted infiltration, resulting in prolonged surface water retention and altering river flow regimes.

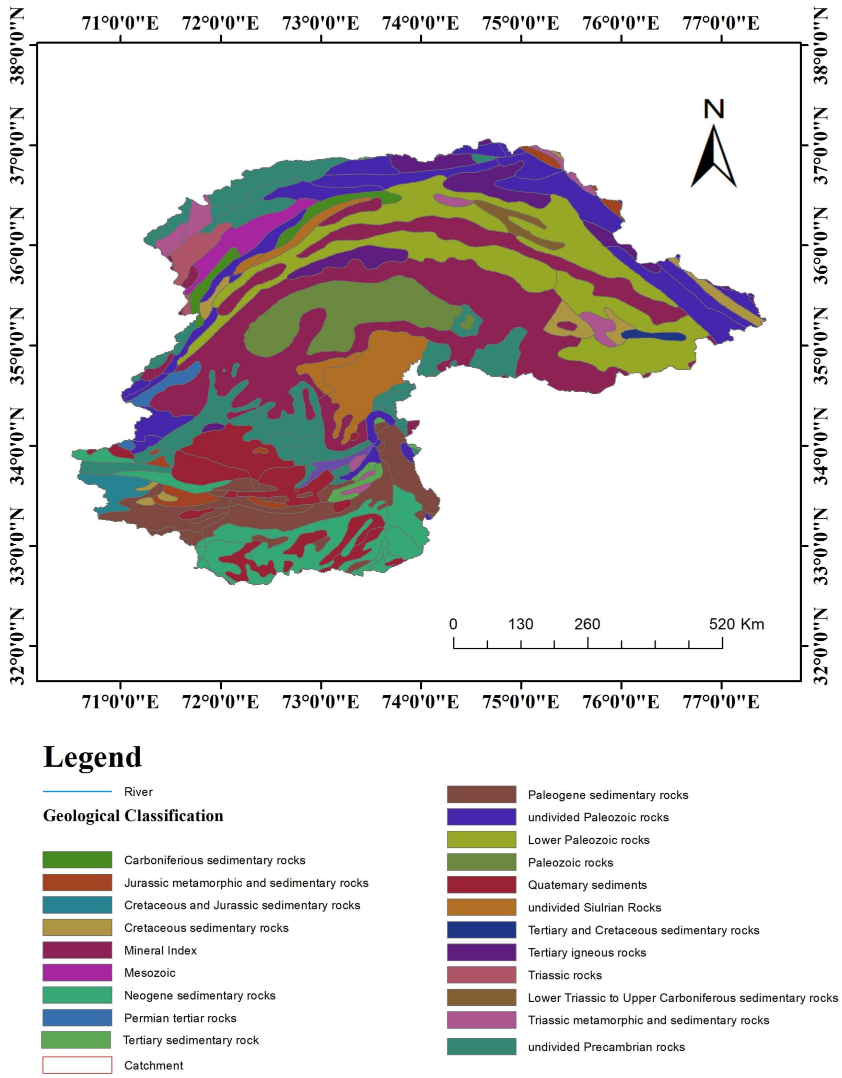

Fig. 3 Geological map of the study area

2.2.4. Soil Classification

The Upper Indus Basin (UIB) in Pakistan contains a broad spectrum of soil types that have a significant impact on water resource management. Understanding these soil characteristics is critical for effective irrigation, groundwater recharge, and resolving issues like salinity and waterlogging. The soil map, at a 1:50,000 scale was created using NBSS which displays fundamental soil classifications (Fig. 4). Alluvial soils commonly found in the UIB are created from riverine deposits and are generally fertile, allowing for substantial agricultural operations. Their texture and structure provide adequate water retention and drainage, making them suitable for a variety of crops (Rodrigo et al., 2023). However, their management requires careful consideration of flood risks and sedimentation rates. A significant portion of the Indus Basin faces soil salinization issues. Approximately 24% of the area is affected by salinity and sodicity, with 11% classified as saline (Mohanavelu et al., 2021). The fertility of alluvial soils supports intensive agriculture. However, inefficient irrigation practices can lead to over-abstraction of groundwater and exacerbate salinity and waterlogging (Hakami et al., 2024). Sustainable groundwater management strategies are critical for preserving the balance between recharge and extraction and maintaining long-term water availability.

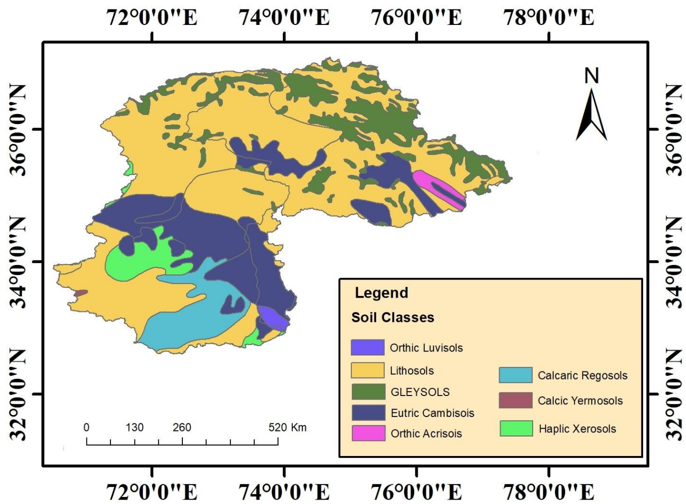

Fig. 4 Soil texture map of the study area

2.2.5. Slope Classification

In the Upper Indus Basin (UIB), geomorphic units are classified based on slope surface cover and soil orientation. Following the recommendations of the International Geographical Union working groups, the slopes in the study area are categorized into five classes: (0 – 2%) Very gentle slopes, primarily flat terrain, often associated with alluvial and colluvial deposits. These areas support higher infiltration rates and agricultural activities; (2 – 5%) Slightly inclined slopes, commonly found in Pedi plain regions, making them suitable for cultivation with minimal erosion risk; (5 – 15%) Moderately inclined slopes, corresponding to dissected pediments. These areas may require erosion control measures due to increased runoff; (15 – 35%) Steeply inclined slopes, usually associated with denudational hills, limit land usage and increase susceptibility to soil erosion; >35% Very steep slopes, indicating rough mountainous terrain with a significant erosion risk and limited suitability for human activity (Figure 5). North-facing slopes tend to retain more snow and ice due to reduced solar radiation, leading to prolonged meltwater contribution to rivers. Conversely, south-facing slopes receive more sunlight, causing faster snowmelt and increased evaporation rates, which can affect water availability during warmer months (Orr et al., 2022). The infiltration rate in the UIB varies dramatically between various slope classes. Gentle slopes (0-5%) improve groundwater recharge, but steeper slopes (>15%) increase surface runoff, resulting in soil erosion and less water retention. A recent study estimates future water demand scenarios in the UIB, focusing on issues such as high population growth and increased irrigation, emphasizing the necessity for sustainable water management measures (Ahmad et al., 2025; Zahra et al., 2023). Moreover, research emphasizes the importance of enhancing water-use efficiency and implementing sustainable strategies for managing both groundwater and surface water resources in the UIB.

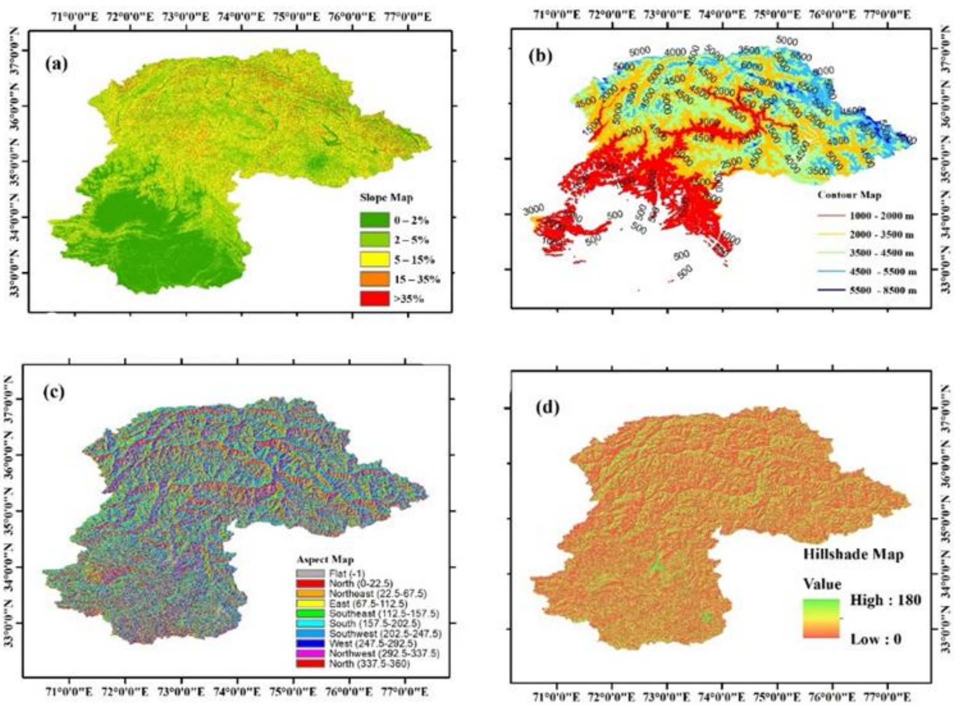

Fig. 5 Topographic analysis of the study area: (a) Slope map, (b) Contour map, (c) Aspect map, and (d) Hillshade map.

3. Results

3.1. Estimation of Rainfall probability and recurrence interval

Rainfall intensity is determined as the average rainfall rate in mm/h or mm/min for a specific duration and a selected frequency. In many regions, rainfall intensity data are available with sufficient spatial and temporal resolution, often expressed as rainfall height for a defined period. Based on the available data, annual rainfall in the study area has varied significantly over time. The analysis of the dataset reveals that in the year 2000, the recorded annual rainfall was approximately 830.45 mm. This annual average rainfall value decreased to 690.45 mm 2005 and 727.46 mm in 2010. The downward trend continued, with rainfall dropping to 567.38 mm in 2015. However, in 2020, the annual rainfall decreased again, reaching 477.961 mm. The highest rainfall intensities were observed in 2000 and 2010, indicating periods of very heavy rainfall, while the years 2011, 2013, and 2020 experienced moderate to lower rainfall events. The temporal variability is shown in (Figure 6).

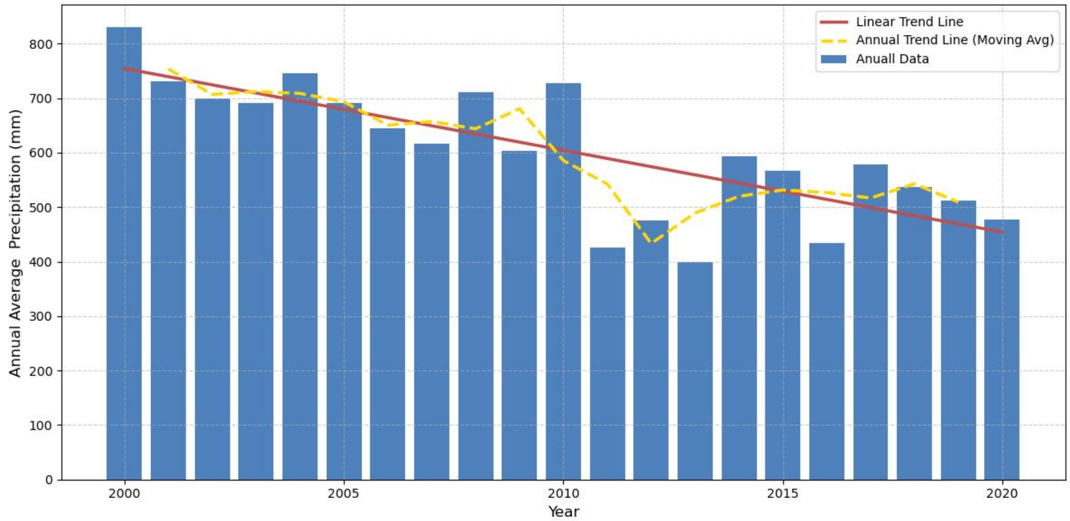

Fig. 6 Rainfall annual trends and temporal variability

A probability and recurrence interval analysis were conducted to assess rainfall trends, which is crucial for monitoring surface water resources and flood risk assessment in the study region. The rainfall data analysis shows that the highest annual rainfall (830.45 mm) has a return period of 22 years, indicating a rare event, while the lowest (399.35 mm) occurs frequently with a 1.05-year return period. Rainfall above 745 mm is rare (T >10 years), whereas values below 538 mm are common (T <1.5 years). Moderate rainfall between 690–710 mm occurs occasionally with return periods of 2.75–4.4 years. Key thresholds were identified: 677.9 mm, 740.9 mm, 754.9 mm, and 760.8 mm for 5, 10, 15, and 20-year return periods respectively (Table1). These findings highlight a predominance of low to moderate rainfall events, with only a few high-rainfall years occurring at long intervals.

Table 1. Probability Analysis of Annual Rainfall

Rank (M)	*Annual Rainfall (mm)*	*P = m/N+1*	*T = 1/P*
1	830.45	0.045	22
2	745.47	0.091	11
3	730.40	0.136	7.33
4	727.41	0.182	5.5
5	710.64	0.227	4.4
6	700.10	0.273	3.67
7	690.56	0.318	3.14
8	690.45	0.364	2.75
9	643.98	0.409	2.44
10	616.98	0.455	2.2
11	604.06	0.500	2
12	592.94	0.545	1.83
13	578.64	0.591	1.69
14	567.38	0.636	1.57
15	537.64	0.682	1.47
16	512.00	0.727	1.38
17	477.96	0.773	1.29
18	475.28	0.818	1.22
19	434.12	0.864	1.16
20	425.04	0.909	1.1
21	399.35	0.955	1.05

3.2. Extreme Value Analysis Using GEV Distribution

To address methodological limitations, we implemented a Generalized Extreme Value (GEV) analysis of monthly maxima. Our updated extreme value analysis employs a Generalized Extreme Value (GEV) distribution fitted to annual maximum monthly rainfall values (2000-2020), with parameters estimated via maximum likelihood (shape *c* = 0.10, location = 103.1 mm, scale = 25.1 mm). To rigorously quantify uncertainty, we performed 1,000 bootstrap resamples, yielding the following return level estimates with 95% confidence intervals. The GEV distribution fitted to annual maximum monthly rainfall data from 2000 to 2020 provided a good statistical representation of extreme events in the UIB as shown in Table 2. The 20-year return level was estimated at 167.7 mm with a 95% confidence interval of 157.3–167.7 mm, reflecting increased uncertainty in long-period extrapolations. The return level plot shows close agreement between the modeled and the observed values, supporting the reliability of the GEV model for flood-risk estimation within the observed data range.

Table 2. Return period estimates with uncertainty quantification

Return Period (Years)	*Estimate (mm)*	*Lower 95% CI (mm)*	*Upper 95% CI (mm)*
5	138.11	128.01	138.11
10	153.76	138.83	153.76
15	162.08	149.17	162.08
20	167.7	157.32	167.7

The accompanying return level plot (Figure 7) demonstrates good agreement between the observed annual maxima (blue points) and the GEV model (red line), with uncertainty bands (shaded region) widening substantially beyond the observation period.

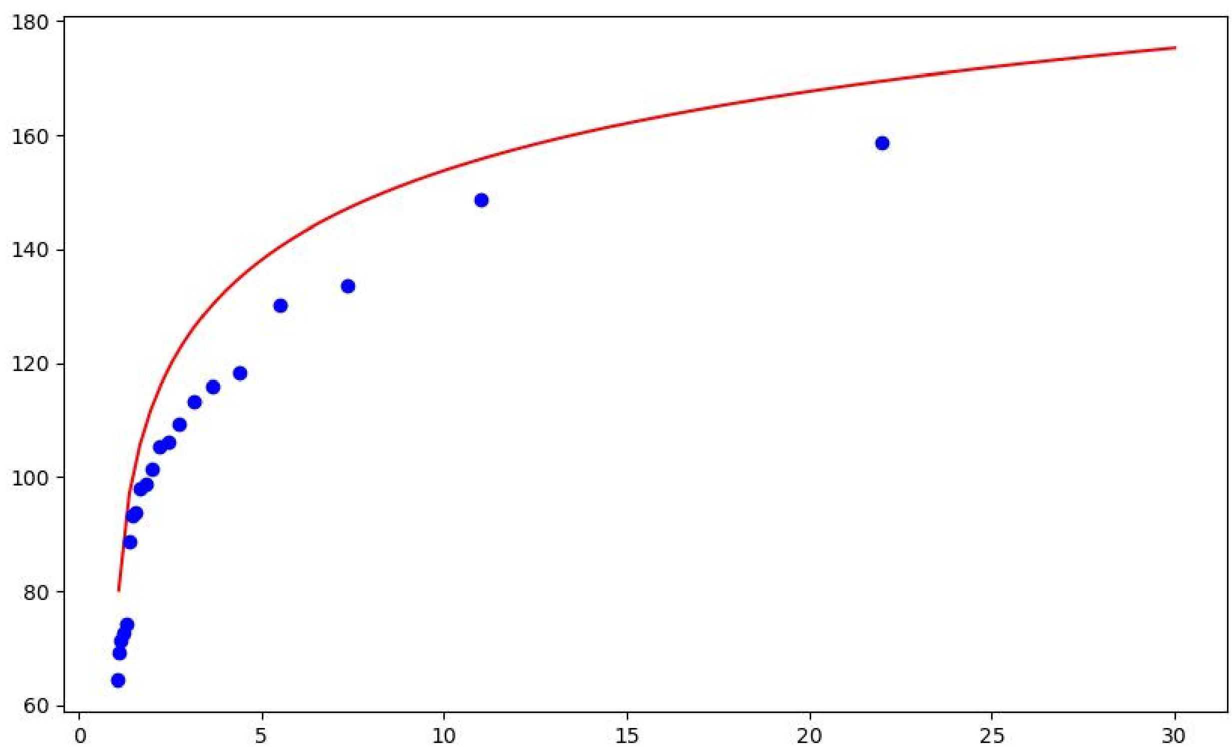

Fig. 7 Return level plot showing observed annual maxima, GEV fit, and 95% confidence intervals

3.3. Projected temperature changes in UIB under SSP-4.5 and SSP-8.5 scenarios

Based on the projected temperature data from 2021 to 2100, all stations in the Upper Indus Basin exhibit a consistent upward trend in maximum temperatures, with a steeper rise under the SSP-8.5 scenario compared to SSP-4.5. Saidu Sharif shows a moderate increase in temperature, with an annual average rise of approximately 0.0257 °C under SSP-4.5 and a sharper 0.0787 °C/year under SSP-8.5. Similar warming patterns are observed in Drosh, Kalam, Dir, and Lower Dir as shown in Figure 8. Notably, while the SSP-4.5 projections suggest a gradual increase across all stations, SSP-8.5 presents a more accelerated warming trajectory, highlighting the potential intensification of heat extremes toward the end of the century.

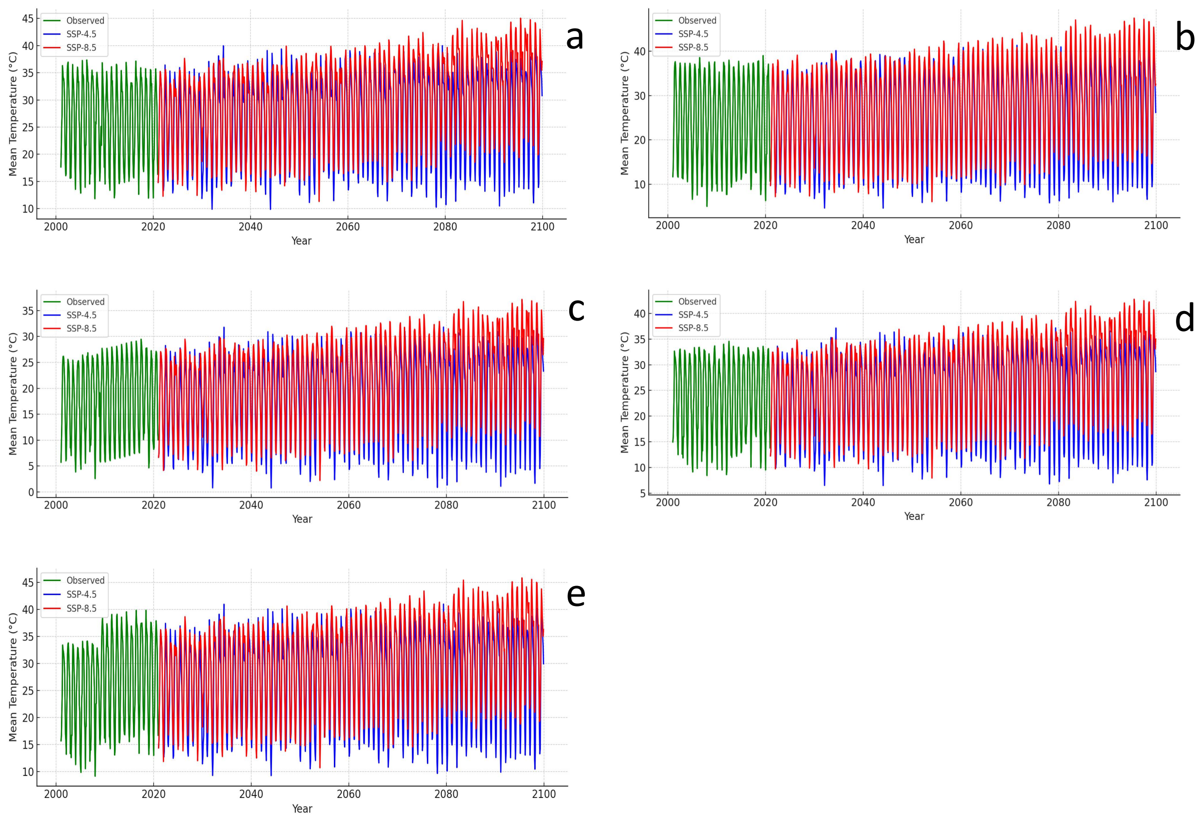

Fig. 8 Comparison of mean maximum temperature changes for the observed (2001-2020), intermediate (SSP-4.5) and very high greenhouse gas emission (SSP-8.5) climate change scenarios (2021-2100) indicating higher forecasted temperature in future in all the five climate data stations (a- Saidu Sharif, b-Drosh, c-Kalam, d- Dir, and e- Lower Dir) located in the UIB

3.4. Temporal variations in Land cover changes of MNDWI

In the initial stage of the study period (2005), the MNDWI was derived using Landsat 7 ETM+ satellite imagery, and land cover classifications were computed (Table 3). In 2005, the estimated land cover distribution was as follows: fallow land covered 69,684.8 km^2 (34.3%), vegetation land occupied 38,986.4 km^2 (19.2%), developed land accounted for 35,346.2 km^2 (17.4%), shallow water bodies covered 38,755.6 km^2 (19.1%), and permanent water bodies, including glaciers, extended over 22,216.2 km^2 (10.16%). The relatively lower extent of surface water bodies can be attributed to reduced annual rainfall during this period. Figures 9a and 10 illustrate the land cover changes based on MNDWI for the year 2005.

Table 3. Temporal variations in land use and land cover categories (2005–2020)

Categories	*2005*		*2010*		*2015*		*2020*	
	Sq.km	*%*	*Sq.km*	*%*	*Sq.km*	*%*	*Sq.km*	*%*
Fellow land	69684.8	34.3	83568.2	41.2	64032.5	31.9	70155.6	34.6
Vegetation Land	38986.4	19.2	39826.0	19.2	38791	19.6	36257.9	17.8
Developed Land	35346.2	17.4	32073.3	15.1	29305.4	14.6	36113.1	17.8
Shallow Water Bodies	38755.6	19.1	30796.6	15.1	37822.8	18.9	38851.8	19.9
Permanent water bodies/Glacier	22216.2	10.1	19211.2	9.4	30299.3	14.9	18816.4	9.8

The estimated land cover distribution in the Upper Indus Basin (UIB) for 2010 was as follows: fallow land expanded to 83,568.2 km^2 (41.2%), vegetation land covered 39,826.0 km^2 (19.2%), developed land accounted for 32,073.3 km^2 (15.1%), shallow water bodies occupied 30,796.6 km^2 (15.1%), and permanent water bodies, including glaciers, extended over 19,211.2 km^2 (9.4%). Compared to 2005, a significant increase in fallow land and vegetation land was observed, while permanent water bodies, including glaciers, exhibited a decline. This reduction in surface water extent is likely attributed to decreasing annual rainfall, which declined from 852.4 mm in 2005 to 807.6 mm in 2010. Figures 9b and 10 illustrate the land cover changes based on MNDWI for the year 2010.

In 2015, the MNDWI-derived land cover classification for the Upper Indus Basin (UIB) was generated using Landsat satellite imagery, with spatial analysis performed in the ArcGIS environment (Table 3). The land cover distribution for 2015 was as follows: fallow land covered 64,032.5 km^2 (31.9%), vegetation land occupied 38,791.0 km^2 (19.6%), developed land accounted for 29,305.4 km^2 (14.6%), shallow water bodies extended over 37,822.8 km^2 (18.9%), and permanent water bodies, including glaciers, covered 30,299.3 km^2 (14.9%). Compared to 2010, a notable decrease in fallow land and vegetation land was observed, while permanent water bodies, including glaciers, increased significantly. The expansion of surface water extent may be attributed to the changes in precipitation patterns and glacial melt contributions. Precipitation and glacial melt drive land cover changes in UIB, expanding permanent water bodies (Krakauer, et al., 2019). Figures 9c and 10 illustrate the land cover changes based on MNDWI for the year 2015.

In 2020, the MNDWI-derived land cover classification for the Upper Indus Basin (UIB) revealed significant shifts in land cover patterns compared to the previous years. Based on satellite imagery analysis (Table 3), fallow land covered 70,155.6 km^2 (34.6%), Vegetation land occupied 36,257.9 km^2 (17.8%), developed land accounted for 36,113.1 km^2 (17.8%), shallow water bodies extended over 38,851.8 km^2 (19.9%), and permanent water bodies, including glaciers, covered 18,816.4 km^2 (9.8%). Compared to 2015, there was an increase in fallow land and decrease in vegetation land, indicating possible shifts in land management and climate conditions influencing vegetation growth. However, permanent water bodies, including glaciers, exhibited a notable decrease, likely due to glacial retreat and changes in hydrological dynamics. The variations in shallow water bodies suggest seasonal hydrological fluctuations, potentially influenced by precipitation trends and surface runoff. Figures 9d and 10 illustrate these spatial and temporal land cover changes in UIB for the year 2020.

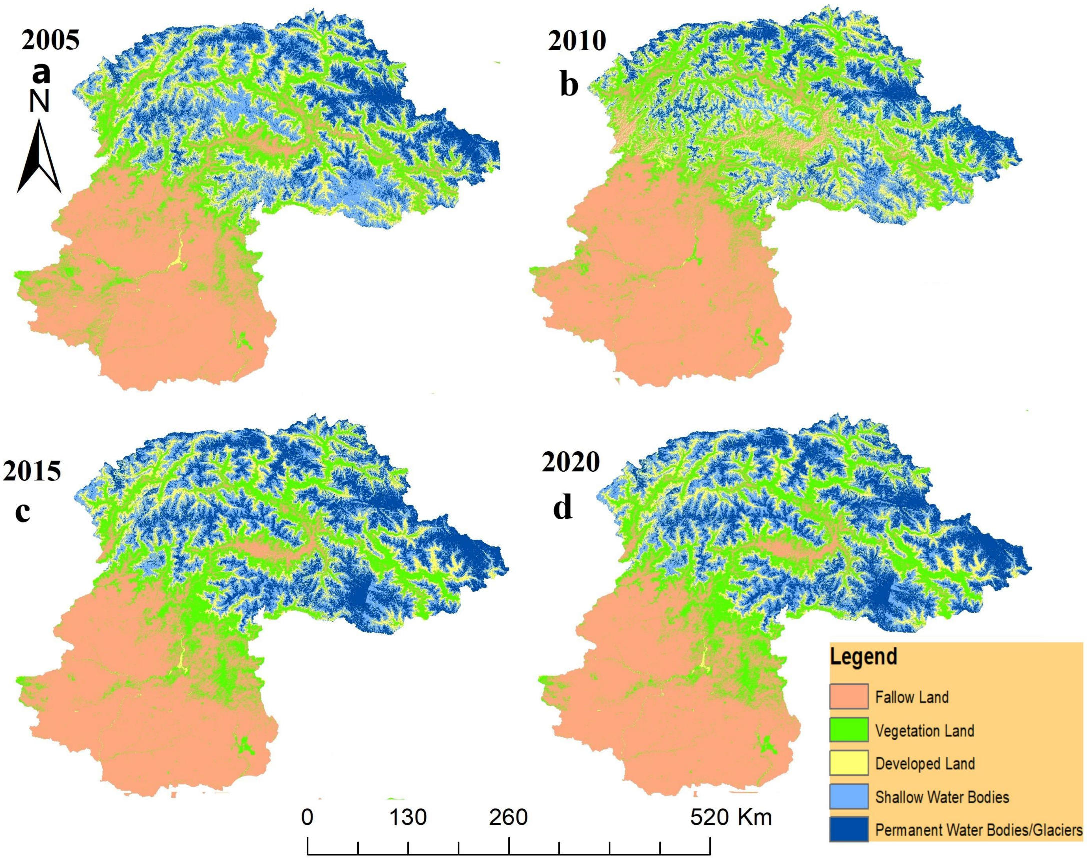

Fig. 9 Spatial Analysis of Land Use and Land Cover (LULC) Changes from 2005 to 2020

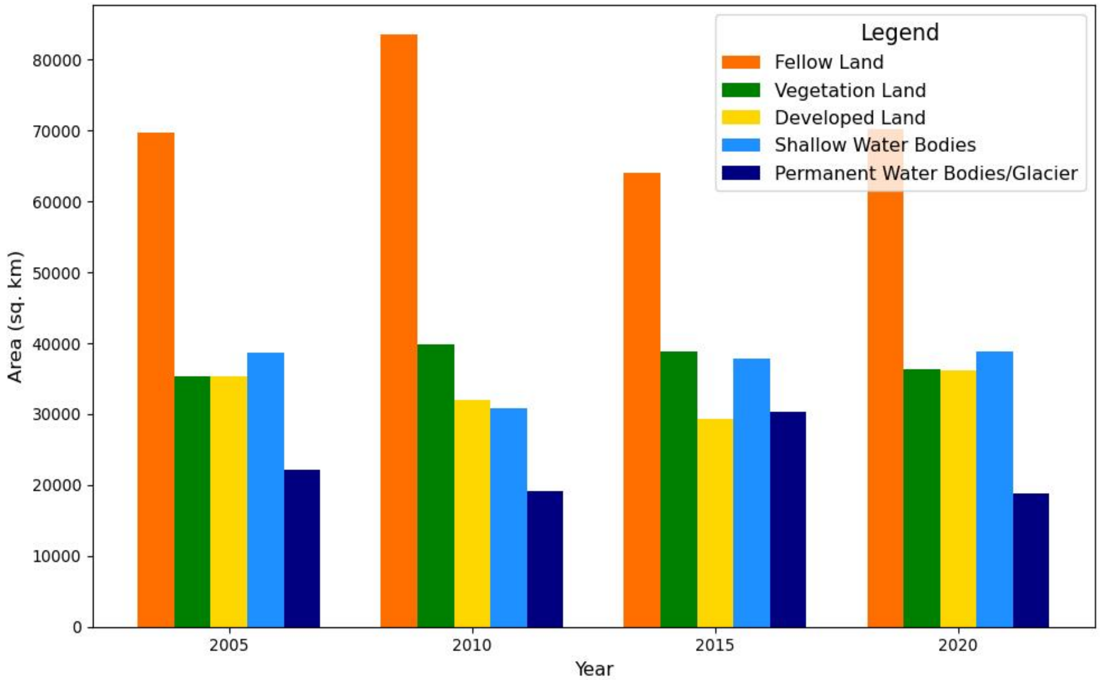

Fig. 10 Temporal changes in different classes of Land Use and Land Cover

The analysis of land cover changes from 2005 to 2020, based on the Modified Normalized Difference Water Index (MNDWI), revealed significant transformations in the Upper Indus Basin (UIB) as shown in Table 4. The most notable change is the decline in permanent water bodies and glaciers, which decreased by approximately 3399.8 km^2 (2%). This reduction is likely due to climate change-driven glacial retreat and reduced snow cover in high-altitude regions. Additionally, vegetation land has shrunk by 2728.4 km^2 (1.34%), suggesting a shift towards either vegetated or urbanized areas. Conversely, fallow land has increased by 470.7 km^2 (0.2%), and developed land has expanded by 766.9 km^2 (0.3%), indicating possible land-use changes, reforestation efforts, or improved climatic conditions. The extent of shallow water bodies has a minor increase of 96.1 km^2 (0.047%). The graphical representation further highlights these shifts, particularly the reduction in glacial cover and arid land, emphasizing the ongoing impact of climate variability in (Figure 11). These findings underscore the need for continuous remote sensing-based monitoring to assess long-term hydrological trends and develop effective water resource management strategies in the UIB.

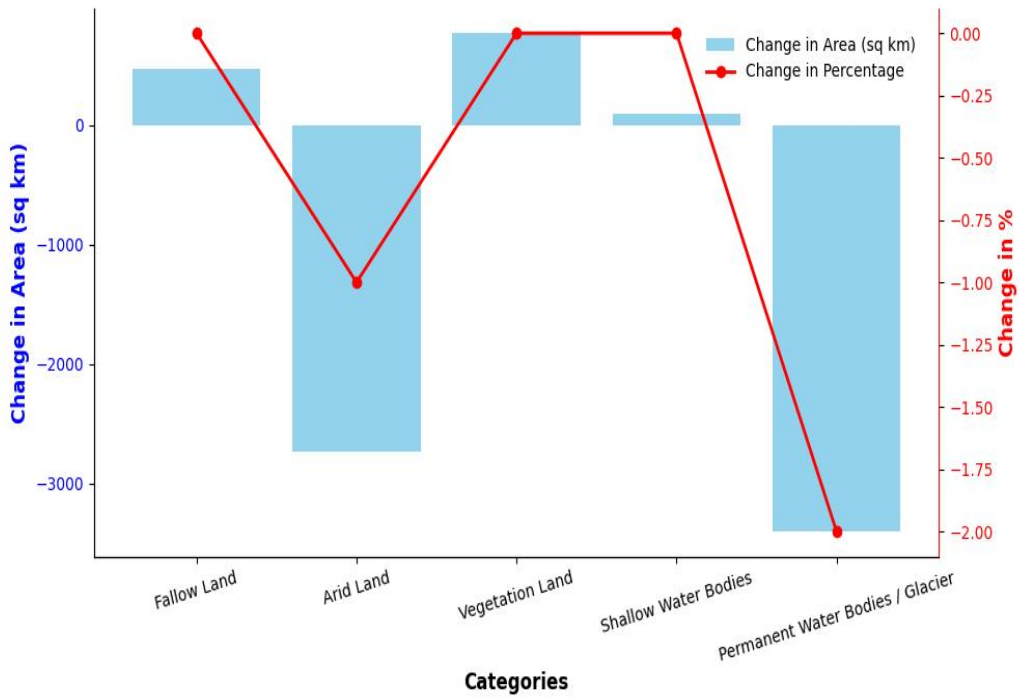

Fig. 11 Resultant landcover changes of MNDWI from 2005 to 2020.

Table 4. Land Cover Change in the Upper Indus Basin from 2005 to 2020

Categories	*Changes (km²)*
Fellow land	470.77
Vegetation Land	-2728.49
Developed Land	766.93
Shallow Water Bodies	96.15
Permanent water bodies/Glacier	-3399.81

4. Discussion

The results of this study indicated significant changes in land cover across the Upper Indus Basin (UIB) from 2005 to 2020, as assessed using the MNDWI. A notable decline in permanent water bodies and an expansion of arid land highlighted the pressing challenges posed by climate variability and human-induced environmental changes. The accuracy of MNDWI in distinguishing water bodies from other land cover types was reaffirmed, demonstrating its effectiveness in hydrological and environmental monitoring. The observed decline in permanent water bodies can be attributed to multiple factors, including glacial retreat, reduced precipitation, and increased water extraction for agricultural and domestic use. The expansion of arid land suggests a combination of decreased water availability and land degradation, possibly exacerbated by deforestation and unsustainable land management practices.

The analysis of land cover changes in the Upper Indus Basin (UIB) from 2000 to 2020, derived from the Modified Normalized Difference Water Index (MNDWI), aligns with recent studies highlighting significant environmental transformations in the region. For instance, research by Rehman et al. (2022) observed that land-use and land-cover (LULC) changes have contributed to variations in land surface temperature (LST) within the UIB, with built-up areas and vegetation increasing by 2.1% and 11%, respectively, over the past three decades, accompanied by a decline in barren land by 8.5%. Similarly, a study by Khan et al. (2025) assessed the impact of LULC changes on environmental parameters in Khyber Pakhtunkhwa, Pakistan, noting that these changes have led to higher LST, lower Normalized Difference Vegetation Index (NDVI), and lower MNDWI values, indicating reduced water availability and increased heat stress (Younis & Ammar, 2018). Furthermore, research focusing on the UIB has quantified the impact of LULC changes on hydrology, revealing that natural wetlands, including permanent water bodies, have experienced significant reductions, which could affect the region's hydrological balance (Dharpure et al., 2025).

The accurate mapping of water resources using MNDWI can inform water conservation policies, hydrological modeling, and disaster risk management strategies. Despite the robustness of our analysis, certain limitations must be acknowledged. The reliance on remote sensing data introduces uncertainties related to atmospheric distortions, sensor limitations, and seasonal variations in water body reflectance. Additionally, the study does not incorporate ground-based validation, which could improve classification accuracy. The classification of mixed land cover types, particularly in transitional zones, may also pose challenges in interpretation. Efforts were made to minimize bias by employing standardized pre-processing techniques and robust classification algorithms. The use of multi-temporal satellite imagery ensured consistency in data acquisition, reducing seasonal and inter-annual variations. However, future studies should incorporate in-situ measurements and integrate machine learning techniques to enhance classification reliability. Cross-validation with other remote sensing indices and hydrological datasets would further strengthen the validity of the findings.

5. Conclusion

This study proposed an effective framework for the water resource management, by using different geospatial techniques like remote sensing in the Upper Indus Basin (UIB). From the results, the conclusion can be summarized as follows:

The Upper Indus Basin (UIB) is a crucial freshwater source for millions in South Asia, yet its water resources face significant challenges due to climate change, population growth, and increasing water demand. Effective monitoring, mapping, and management of these resources are essential for sustainable utilization. This study employed the Modified Normalized Difference Water Index (MNDWI) to assess water resource dynamics in the UIB over a 15-year period. Results indicated that MNDWI is highly effective in distinguishing water bodies from other land cover types, with minimal error. The study identified notable land cover changes, including an increase in barren land by 470.7 km^2 and a decline in water bodies by 3399.8 km^2 from 2005 to 2020 (Figure 9), highlighting the impact of environmental and anthropogenic factors on water availability. The findings provide a valuable basis for water resource managers and researchers to implement evidence-based water conservation strategies. In order to translate the above findings into concrete policy measures, we recommend (i) Precision Irrigation: Encourage water-saving techniques like High Efficiency Irrigation System (HEIS), and canal lining, especially in regions where vegetation is expanding to minimize water loss and maximize crop yields (ii) Glacier Protection and Monitoring: In order to assess retreat patterns and better manage snow melting, set up long-term glacier monitoring programs with early warning systems (iii) Land Use Regulation: To protect recharge zones and reduce land degradation, enforce zoning laws to stop the conversion of arid and fallow regions into urban areas, and (iv) Reforestation and Soil Conservation: To improve infiltration and groundwater recharge and prevent soil erosion on steep slopes, extensive afforestation and reforestation campaigns are recommended.

Author Contributions

Hafiz Waseem Sajjad: Conceptualization; data curation; formal analysis; investigation; methodology; software; writing – original draft. Muhammad Laraib: Conceptualization; formal analysis; methodology; writing – review and editing. Abdul Raheem: Conceptualization; formal analysis; methodology; resources; supervision; writing – review and editing. Obaid Khalid: Data curation; formal analysis; writing – review and editing. Abu Bakar Arshed: Data curation; formal analysis; supervision; writing – review and editing. Kamran Mustafa: Data curation; formal analysis; supervision; writing – review and editing.

Conflict Of Interest

The authors collectively state that they do not possess any conflicts of interest.

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