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ORIGINAL ARTICLE

Characterizing Drought and Its Implications for Water Resources in Western Nepal

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Abstract
Drought events are increasing globally, showing clear connections to climate change and shifts in large-scale atmospheric circulations. In the Himalayan region, rising temperatures, changing precipitation patterns, and glacial melt are disturbing the delicate water balance, heightening vulnerability to drought events. Adequate preparation for future droughts necessitates a thorough comprehension of past drought characteristics and their consequences across different sectors. This study focuses on the Karnali River Basin (KRB) in the central Himalayas of western Nepal, an area significantly impacted by recent drought events. Drought over the past four decades was analyzed in terms of occurrence, severity, and frequency. In addition, the impacts of drought on water resources in the region were also evaluated. Results indicate that droughts have increased in both frequency and intensity, particularly since 2000, significantly affecting water resources. Variations in river flow were directly linked to droughts, the groundwater depletion rate is increasing, and dry spells have extended in some years. These observations not only paint a concern but also provide insight into addressing this pressing climate challenge.

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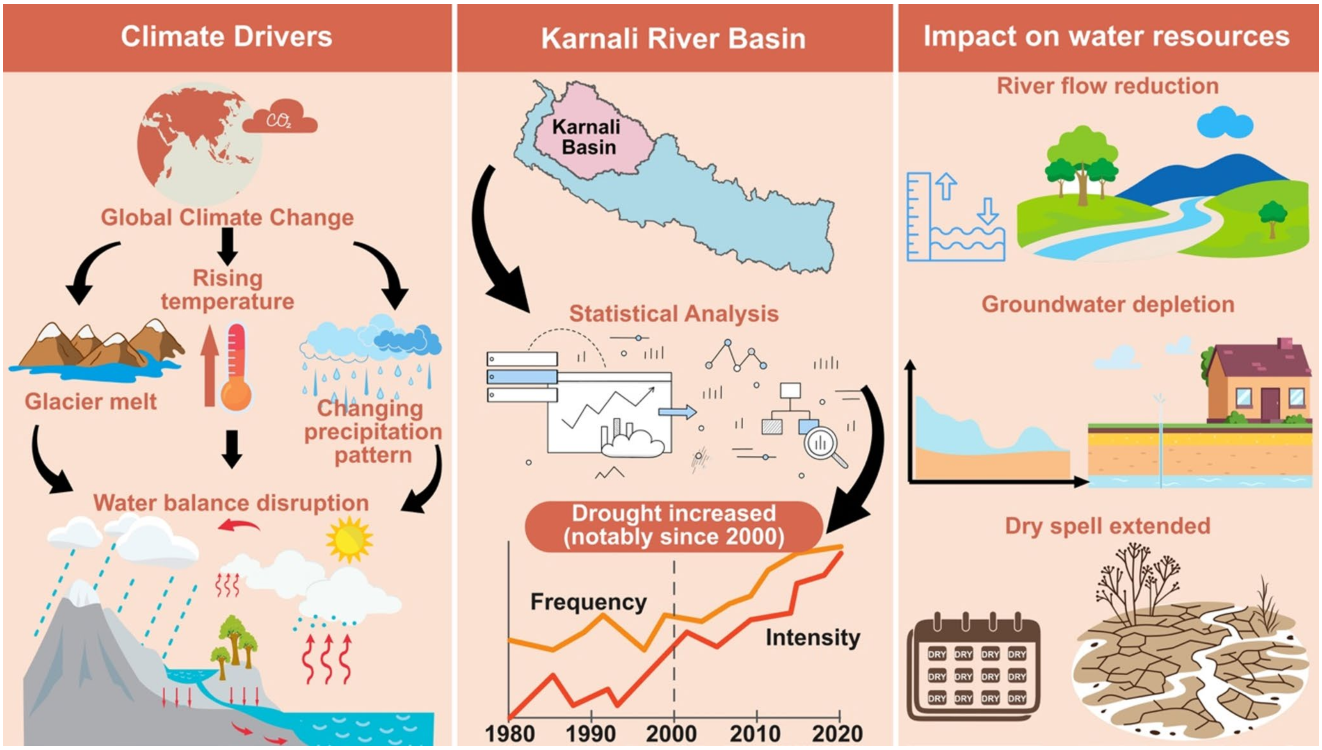
Graphical abstract



This graphical abstract provides a visual summary of the research, highlighting the main findings. It is organized into three linked panels that tell the story from causes to evidence to impacts. The left panel sets the Himalayan context, illustrating how global climate change drives rising temperature, shifting precipitation patterns, and glacial melt together disturbing the region's water balance and increasing drought vulnerability. The middle panel shows the study area, the Karnali River Basin in western Nepal, and depicts the core approach: statistical analysis of multi-decadal records to quantify drought occurrence, severity, and frequency. A trend graphic emphasizes the key result that drought frequency and intensity have increased, notably since around 2000. The right panel present these changes into water-resource consequences to show drought-linked variation in river flow, increasing groundwater depletion, and extended dry spells in some years. By combining clear visuals with minimal text, the figure communicates both the motivation and the practical relevance of the study provides a quick, visually appealing summary of the research, highlighting the main findings of a scientific paper and giving readers a rapid understanding without requiring them to read the entire manuscript.

Highlights

- Assessed 40 years of drought occurrence, severity, and frequency in Nepal's Karnali River Basin (central Himalayas).
- Himalayan warming, shifting precipitation, and glacier melt are heightening drought vulnerability and disrupting basin water balance.
- Droughts increased in frequency and intensity, with a pronounced rise since 2000.
- Drought impacts include reduced river flow, rising groundwater depletion, and longer dry spells in some years.

Keywords Drought · SPI · Water Resources · Western Nepal

1 Introduction

Droughts are extreme climate events characterized by prolonged water deficits that usually commence with reduced precipitation, leading to low soil moisture and altered hydrologic regimes (Tallaksen and Lanen 2004; Wilhite and Glantz 1985). They cause significant losses to ecosystems (e.g., Goulden and Bales 2019), social structures (e.g., Palinkas 2020), and economies (e.g., Martin-Ortega et al. 2012), ultimately affecting livelihoods (e.g., Funk 2011). Some direct losses associated with drought include crop failure (e.g., Santini et al. 2022), reduced water supply for drinking, irrigation, and power generation (Ahn et al. 2016; Pedro-Monzonís et al. 2015), diminished rangeland and forest productivity (e.g., Ciais et al. 2005), increased fire hazard (e.g., Brando et al. 2014), and deterioration of wildlife and aquatic habitats (e.g., Bond et al. 2008). Studies indicate an increase in the frequency, intensity, and duration of droughts globally and regionally (Christian et al. 2021; Dai 2011; Stagge et al. 2017; Yu and Zhai 2020), with climate projections suggesting a future rise in both frequency and severity (Ukkola et al. 2020; Pokhrel et al. 2021; Satoh et al. 2022). Drought impacts are more severe in developing countries due to limited technological capabilities, poor infrastructure, and weak institutional capacities (Elkouk et al. 2022; Miyan 2015; Wilhite et al. 2007).

Prolonged and widespread droughts have been reported in consecutive years in the South Asia (Aadhar and Mishra 2017; Singh et al. 2014) and are anticipated to increase further (Aadhar and Mishra 2021). The increase in frequent droughts post-2000 significantly exacerbates the water crisis in South Asia and beyond (Aadhar and Mishra 2017; Rodell et al. 2009), and Nepal is no exception. In Nepal, drought risk assessment is critical for planning and managing natural resources. Recent studies have reported reduced crop production (Dahal et al. 2015; Ghimire et al. 2010; Wang et al. 2013), increased human mobility and emigration (Chapagain and Gentle 2015), and exacerbated wildfires due to drought in Nepal (Hamal et al. 2022). Western Nepal in particular, is experiencing increasing temperatures and decreasing precipitation, heightening susceptibility to droughts (Dahal et al. 2020). While some studies have analyzed drought conditions in western Nepal (Khatiwada and Pandey 2019; Wang et al. 2013), drought impacts on water resources remain unsatisfactorily addressed.

Drought conditions are commonly quantified using indicators that represent different components of the hydroclimate system, including meteorological, hydrological, groundwater, and integrated water-storage responses. Meteorological drought is widely characterized using standardized indices such as the Standardized Precipitation Index (SPI), which enables consistent comparisons across regions and accumulation timescales (McKee et al. 1993; World Meteorological Organization, 2012). Other indicators are often used to better represent drought propagation through the water cycle, including the Standardized Precipitation Evapotranspiration Index (SPEI), which incorporates atmospheric evaporative demand (Vicente-Serrano et al. 2010), standardized runoff/streamflow indices for hydrological drought (Shukla and Wood 2008), and standardized groundwater indices for groundwater drought (Bloomfield and Marchant 2013). In addition, Gravity Recovery and Climate Experiment (GRACE/GRACE-FO) satellite gravimetry provides terrestrial water storage anomalies that integrate changes in surface and subsurface storage and has been increasingly used for hydrological drought characterization, particularly in data-sparse regions (Humphrey et al. 2023; Thomas et al. 2014; Vishwakarma, 2020).

A comprehensive study of drought implications on various sectors, along with temporal and spatial characteristics, is imperative for developing mitigation and adaptation strategies. This study aims to fill this gap by analyzing drought characteristics using common metrics and its impacts on surface water and groundwater in Western Nepal, as well as long-term climatic, hydrological, and terrestrial water storage datasets. In the Karnali River Basin (KRB) in western Nepal, river flow supports multiple socio-economic and cultural services, including domestic water use, small-scale irrigation, fisheries, tourism, and religious practices among riparian communities, while ongoing and planned hydropower development has the potential to alter the seasonal flow regime and associated water availability (Sharma et al. 2020; Tachamo-Shah et al. 2025). At the basin scale, surface-water resources are also closely linked to irrigation development and food security in western Nepal, making dry-season precipitation deficits and multi-year drought particularly relevant for water security and livelihoods (Pandey et al. 2020a, b; Dahal et al. 2020). Downstream, the Karnali joins the Ghaghara River and contributes to the larger Ganga system, where large populations depend on seasonal river flows for agriculture and rural livelihoods; therefore, drought-related reductions in low flows and shifts in seasonality can have implications beyond the headwaters (Rasul 2015; Gupta et al. 2021). Maintaining adequate dry-season flows is additionally important for riverine ecosystems and fisheries, including habitats for the endangered Ganges River dolphin in the Karnali–Ghaghara corridor, which can be sensitive to reduced depth and competing water withdrawals (Smakhtin et al. 2006; Khanal et al. 2016).In this context, the specific objectives include assessing the frequency and severity of annual and seasonal droughts in western Nepal and examining the relationship between drought episodes and the availability of surface and groundwater. The outcome is to examine drought characteristics and their implications for water resources.

2 Study Area

The Karnali River Basin (KRB), located in western Nepal (Fig. 1), is the largest river basin in Nepal, covering an area of approximately 42,450 km^2. The altitude within the basin ranges from 163 m above sea level in the southern lowland region (Tarai) to over 7,700 m in the high northern Himalayas. Approximately 16% of the basin is used for agricultural purposes, upon which most of the community relies for food

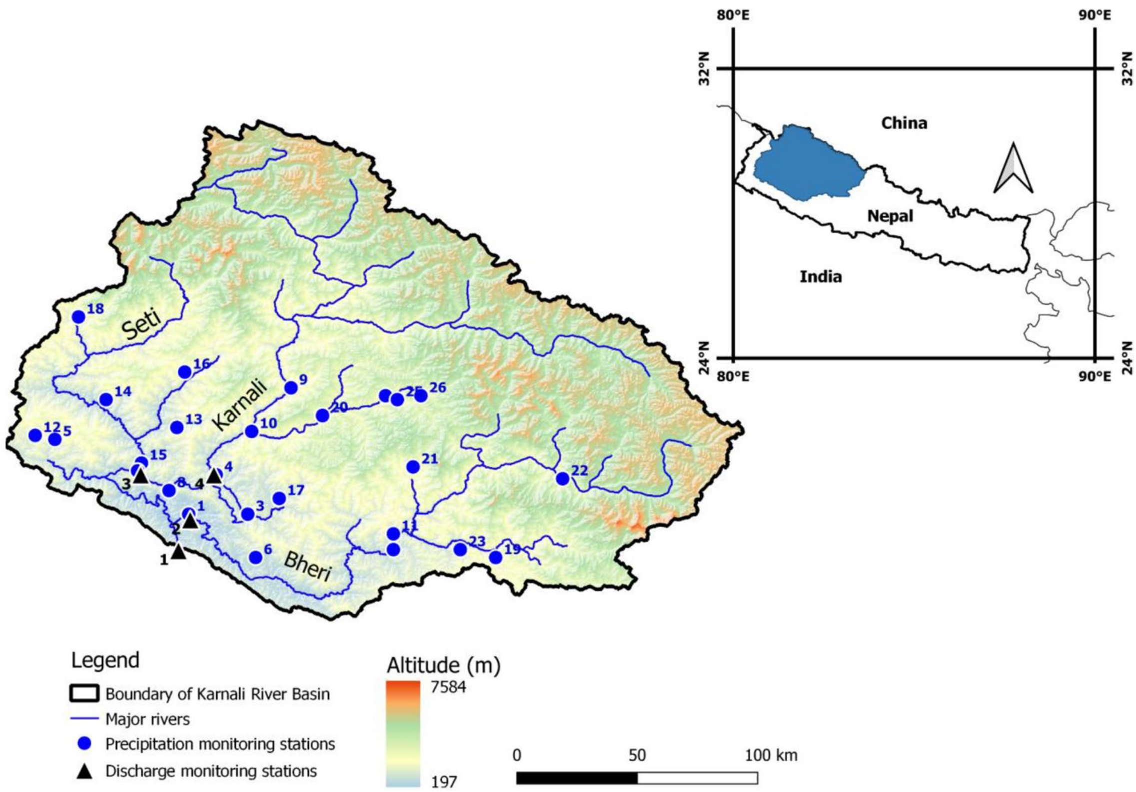


Fig. 1 Altitudinal variation, major rivers, and hydro-climatic stations in Karnali River Basin. The hydro-meteorological stations' indexes are labeled 1 to 26 from low to high altitude locations. The panel on the top right shows the location of the Karnali River Basin (shaded blue) in Nepal

and produce. The climate in KRB is mainly influenced by summer monsoon precipitation, while westerlies prevail in winter (Nayava 1980; Shrestha 2000). During the monsoon season (June through September), the basin receives 55% (at highlands) to 80% (at lower altitudes) of the annual precipitation (Shrestha 2000). The northern part of the basin is relatively dry, receiving less than 300 mm of annual precipitation; however, some pockets in the mountainous areas receive approximately 2,400 mm of annual precipitation.

3 Data and Methods

3.1 Hydro-Meteorological Data

Observed hydro-meteorological data were obtained from the Department of Hydrology and Meteorology (DHM), Government of Nepal. Drought characteristics were analyzed using precipitation data from 26 meteorological stations from 1981 to 2021. Meteorological data were converted into a monthly total and missing monthly data were filled using gridded precipitation data (0.05° spatial resolution) produced by Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE, Yatagai et al. 2012).

The implication of drought on river water was examined for the period 1981–2014 using the daily average river discharge value from 4 gauging stations (see Fig. 1 for the location of hydro-meteorological stations and stations' index). Precipitation records used for SPI calculations span 1981–2021, whereas the available discharge observations for the four river gauges span 1981–2014. River discharge in Nepal is collected by the national hydrometeorological agency and released periodically for public access; however, more recent discharge data were not available for public at the time of analysis. Accordingly, all analyses linking drought conditions to surface-water availability (river discharge) were conducted for the overlapping period 1981–2014, while meteorological drought characterization based on precipitation was performed for 1981–2021.

The station-based precipitation record used for SPI analysis is subject to few limitations that are common in complex mountainous terrain. First, the rain-gauge network is unevenly distributed, with higher station density in accessible valleys and lower elevations and comparatively sparse coverage at high elevations. Because precipitation exhibits strong orographic gradients and high spatial variability in the Himalaya, basin-scale drought characterization may be biased toward better-sampled low-elevation areas, potentially under-representing high-altitude precipitation and snow-dominated zones (Palazzi et al. 2013; Immerzeel et al. 2014). Second, gauge measurements in mountain environments are prone to systematic errors such as wind-induced under catch and underestimation of solid precipitation, which can affect both seasonal totals and inferred drought severity, particularly in winter and at high elevations (Sevruk 1982; Rasmussen et al. 2012). Third, continuous monthly time series are required for SPI calculation; therefore, missing precipitation values were infilled prior to index computation. Infilling can smooth variability and may dampen extremes or alter event counts if data gaps coincide with anomalously wet or dry periods. Accordingly, the results are interpreted primarily in terms of robust basin-scale patterns and multi-year variability rather than exact station-level drought magnitudes, especially for stations with larger proportions of missing data (Stagge et al. 2015).

3.2 Drought Index Calculation

Droughts are multifaceted. Various indices, including the standardized precipitation index (SPI), are used to assess drought severity (McKee et al. 1993; Mishra and Singh 2010). The basic criterion for selecting SPI in this study is that it uses only precipitation as an input, which has been observed for the longest time period and is comparatively of better quality across the study region than other meteorological variables. SPI is the most widely used drought measure/analytical tool, examining meteorological drought severity across different time scales (Guttman 1999). Short accumulation periods like one month or three months (SPI 1, SPI 3) are used better for agricultural practices, while longer periods like twelve months or 24 months (SPI 12, SPI 24) depict drought events affecting water resource management (Guttman 1999; Paulo and Pereira 2008). SPI analysis reveals spatial and temporal features of drought occurrence and severity (Mishra et al. 2007; Sadeghi and Hazbavi 2017; Sigdel and Ikeda 2010). The selection of the SPI standardized Precipitation Index for this study aligns with the research's temporal requirements and data quality imperatives, being computable across a wide range of time scales, from 1 to 72 months, and relying on historically available and comparatively high-quality precipitation data.

Table 1 Standardized Precipitation Index (SPI) thresholds used to classify drought (and wetness) severity in this study

Category	SPI threshold
Moderate drought	$-1.0 \geq SPI > -1.5$
Severe drought	$-1.5 \geq SPI > -2.0$
Extreme drought	$SPI \leq -2.0$
Moderate wet	$1.0 \leq SPI < 1.5$
Very wet	$1.5 \leq SPI < 2.0$
Extremely wet	$SPI \geq 2.0$

SPI calculation is done by fitting the accumulated precipitation to a gamma probability distribution function and converting the probability distribution function to the standard normal distribution (Guttman 1999; McKee et al. 1993). The probability density function of the gamma distribution is defined as

$$f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}}, x > 0$$

where x is monthly precipitation (x>0); α is the **shape** parameter (dimensionless); β is the **scale** parameter (with units of precipitation); and Γ(α) is the gamma function defined as.

$\Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1} e^{-t} dt$. The probability density function g(x) is evaluated for each station and accumulation period using the fitted α and β, which are then transformed into the standard normal distribution to obtain SPI (Hayes et al. 1999). The SPI Generator tool developed by the National Drought Mitigation Center, University of Nebraska-Lincoln (WMO, 2012) was used to generate SPI data.

In this study, drought characteristics were quantified from the SPI time series using annual summary metrics based on a drought threshold. For each year, drought frequency was defined as the number of drought events, where a drought event is a continuous sequence of time with SPI values below the selected threshold. Drought severity was quantified as the magnitude of the drought index relative to the threshold, representing the cumulative deficit associated with drought conditions during the year (computed from SPI values below the threshold). Drought intensity was characterized as the magnitude of the index, representing the typical strength of drought conditions (i.e., the mean deficit magnitude of SPI during drought conditions) for that year. Drought severity was classified using standard SPI thresholds (WMO, 2012) as shown in table below (Table 1).

SPIs were calculated at 2-month, 3-month, 4-month and 12-month timescales. The n-month SPI compares the precipitation over a specific n-month period with the precipitation totals from the same n-month period for all the years included in the historical record. For example, a 3-month SPI at the end of November compares the September-October-November precipitation total in that particular year with the September-October-November precipitation totals of all the years.12-month SPI was used to analyze the implication of drought on water resources.

3.3 Groundwater Storage

Subsurface variables are valuable indicators, too, for drought analysis. Several studies have utilized Terrestrial

Water Storage (TWS) data derived from NASA's Gravity Recovery and Climate Experiment (GRACE) satellite mission to monitor drought impacts on groundwater (Pokhrel et al. 2021; Castle et al. 2014; Li et al. 2012; Li and Rodell 2015; Scanlon et al. 2012; Thomas et al. 2014). TWS anomalies from GRACE satellites indicate significant deficits during drought (Chaudhari et al. 2019; Forootan et al. 2019; Sinha et al. 2019; Zhang et al. 2019).

Groundwater storage variation is an important component for assessing drought impacts on groundwater. Terrestrial water storage (TWS) anomalies inferred from measurements by the Gravity Recovery and Climate Experiment (GRACE) mission were used to estimate basin-scale groundwater storage anomalies in the KRB.

Monthly gridded TWS anomalies were obtained from two mascon solutions: (i) the Center for Space Research (CSR) GRACE RL05 mascon product (Save et al. 2016) and (ii) the Jet Propulsion Laboratory (JPL) mascon product (Watkins et al. 2015). These products provide TWS anomalies (equivalent water height) referenced to a baseline and include standard corrections applied by the processing centers (e.g., removal of atmospheric and oceanic mass variability and application of glacial isostatic adjustment). Basin-mean TWS anomalies were computed as the area-weighted mean over the KRB domain.

Groundwater storage anomalies (GWSA) were derived using a residual mass-balance approach commonly adopted in GRACE-based groundwater studies (Rodell et al. 2009; Scanlon et al. 2012):

$$\mathrm{GWSA} = \mathrm{TWSA\_GRACE} - (\mathrm{SMSA} + \mathrm{SWESA} + \mathrm{SWSA})$$

where SMSA is the soil water storage anomaly, SWESA is the snow water equivalent anomaly, and SWSA is the surface/river water storage anomaly.

The non-groundwater components (SMSA, SWESA, and SWSA) were taken from simulations of the HiGW-MAT model (Pokhrel et al. 2012, 2015). HiGW-MAT is a global land-surface modeling framework that builds on MATSIRO (Minimal Advanced Treatments of Surface Interaction and Runoff), which simulates surface energy and water balance processes, snow accumulation/melt, soil moisture storage, runoff generation, and river routing (Takata et al. 2003). Human water-management processes are incorporated through modules that represent reservoir operation and regulated releases, crop water demand and irrigation, and sectoral water withdrawals (domestic, industrial, and agricultural), with withdrawals satisfied by available surface water and supplemented by groundwater when surface water is insufficient (Pokhrel et al. 2012, 2015). HiGW-MAT further includes a groundwater dynamics and pumping scheme that explicitly simulates groundwater storage and exchanges with the land surface and river system, enabling separation of non-groundwater storage components (soil moisture, snow water equivalent, and surface/river water) used in the GRACE residual approach (Pokhrel et al. 2015). In MIROC-INTEG-LAND applications HiGW-MAT is producing monthly storage components suitable for basin-scale analyses (Yokohata et al. 2020).

The GRACE-based groundwater estimates should be interpreted considering few uncertainties. GRACE-derived terrestrial water storage anomalies represent monthly mass changes at an effective spatial scale of several hundred kilometers; therefore, signals within mountainous river basins can be attenuated and may include leakage from surrounding regions, particularly near strong spatial gradients in water/ice storage (Wahr et al. 1998; Landerer and Swenson 2012). Although mascon solutions reduce striping and improve leakage behavior compared with traditional spherical harmonic products, residual leakage and signal damping can remain and may influence the magnitude of inferred trends (Watkins et al. 2015; Wiese et al. 2016; Save et al. 2016). To reduce sensitivity to mascon choice, groundwater storage anomalies were evaluated using ensemble of both CSR and JPL mascon products; consistent temporal variability across products is emphasized, and the GRACE-based groundwater results are interpreted primarily in terms of basin-scale variability and relative changes rather than exact groundwater volumes. Since groundwater storage was estimated as a residual after subtracting modeled soil moisture, snow water equivalent, and river water storages (HiGW-MAT) from GRACE total water storage; thus, uncertainties in model structure and meteorological forcing can propagate into groundwater estimates (Pokhrel et al. 2015; Felfelani et al. 2017).

4 Results

4.1 Drought Characteristics

The standardized precipitation index (SPI) effectively reflected the variations in drought characteristics in the KRB from 1981 to 2021.

The annual frequency of extreme, severe, and moderate drought occurrences captured by 12-month SPI in KRB over the period 1982–2021 is presented in Fig. 2. The result shows that the drought frequency increased significantly (non-parametric Mann–Kendall trend test at $\alpha = 0.05$, trend magnitude was quantified using Sen's slope estimator), reaching its highest in 2016. An increase in the frequency of drought events after 2000 is readily discernible, with relatively extreme dry episodes occurring in 2005, 2006, 2009, 2010, 2011, and 2016. While extreme drought had a general

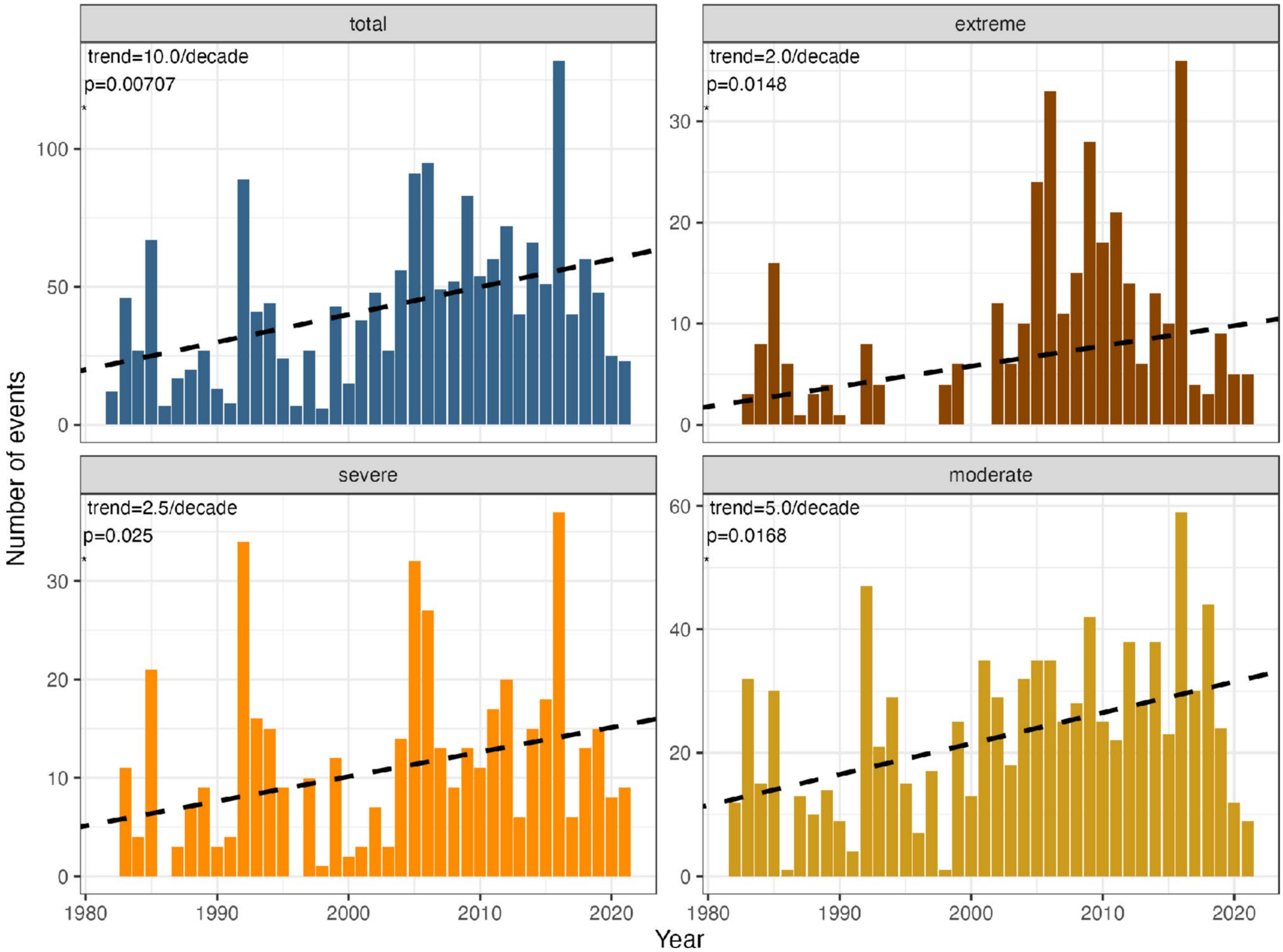


Fig. 2 Frequency of SPI-12 within a year and its trend for the 1982–2021 period

periodicity (e.g., 1985, 1992, 2005, 2006, 2016), which reflects the documented decadal variability of precipitation (Wang and Gillies 2013), results in Fig. 2 indicate a consistent general increase in the frequency of all drought types in the recent decade. Further, severe droughts were found to be more frequent in 1985, 1992, 2005, 2012, 2015, and 2016 with the highest in 2005. In the year 2021 too, Nepal encountered a winter drought that had significant impacts on multiple sectors including agriculture, hydropower production, and air quality (Pokharel et al. 2023; Nepali Times, 2023).

Figure 3 shows the temporal characteristics of drought within KRB during the 1981–2021 period. It is evident from this figure that drought frequently occurred during the study period, as indicated by negative median values of the SPI (e.g., years 1985, 1992, 1994, 1997, 2004–2009, 2012, 2014, 2016, 2018, and 2019). Figure 3 also suggests a decadal variation of drought events in KRB, which features an increase in severity and frequency of extreme drought in recent decades compared to the pre-2000 period.

The highly anomalous SPI values for 1985, 1992, 2005, 2006, 2012, 2016, and 2018 indicate a prolonged dry period or widespread drought across the basin. The presence of both extremely dry and wet conditions in 1984, 2009, 2010, and 2013 indicate drought conditions in parts of the basin or during certain periods of a year. In 2010 and 2011, the boxplot indicates extreme drought and extreme wet conditions, but it is a relatively wet year when the entire area is considered as indicated by the positive SPI median. The median values of SPI for the years 1982, 1984, 1986, 1990, 1991, 1998, 2000, 2010, 2013, and 2020 are positive, indicating wet conditions in the region. The most widespread wet periods occurred in 1982 and 2000. Since 2000, 10 years have been dry, and two years were wet.

Figure 3b depicts 3-month SPI (SPI-3) values, which indicate short-period drought and show different patterns than the SPI-12. Such variability may indicate the dominance of shorter-period drought. Subsequently, the comparison of Fig. 3a and b suggest that the concurrence of prolonged, yet not necessarily more severe drought has increased. There are significant differences, too, in the severity of SPI values

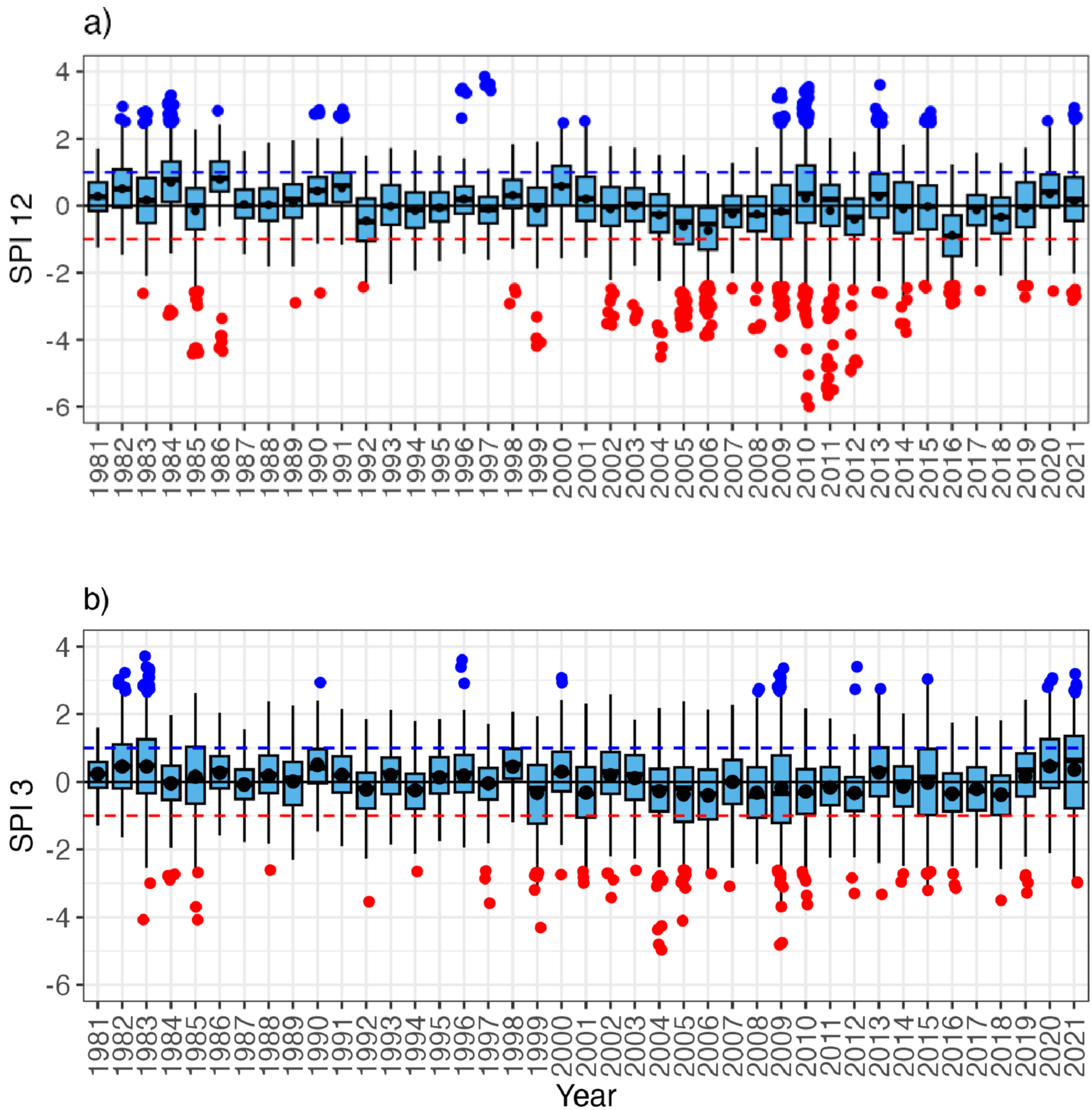


Fig. 3 Boxplots of standardized precipitation index (SPI) values across stations by year: (**a**) 12-month SPI (SPI-12) and (**b**) 3-month SPI (SPI-3). Black dots denote the annual mean SPI. Red dots indicate severe to extreme dry condition, and blue dots indicate very to extreme wet condition

at these two-time scales. This implies that the severity of droughts can vary depending on the time scale over which they are measured, but it is the longer-lasting drought that may have a profound impact on water resources.

Next, drought seasonality is examined. The heat map in Fig. 4 shows the seasonal drought characteristics in the KRB. Results suggest that drought in the past occurred in all seasons. Winter drought (indicated by 3-month SPI in February) occurred periodically in many of the stations from 1982 to 2021, but the basin-wide drought was prominent in the years 1985, 1997, 1999, 2001, 2004, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2016, 2017, 2018 and 2021. It is evident from Fig. 4 that basin-wide winter droughts became more frequent and intense after 2000 (e.g., 13 times in 21 years) suggesting an increase in the frequency and intensity of winter droughts. Pre-monsoon drought (indicated by 3-month SPI in May) occurred on the basin-wide scale in

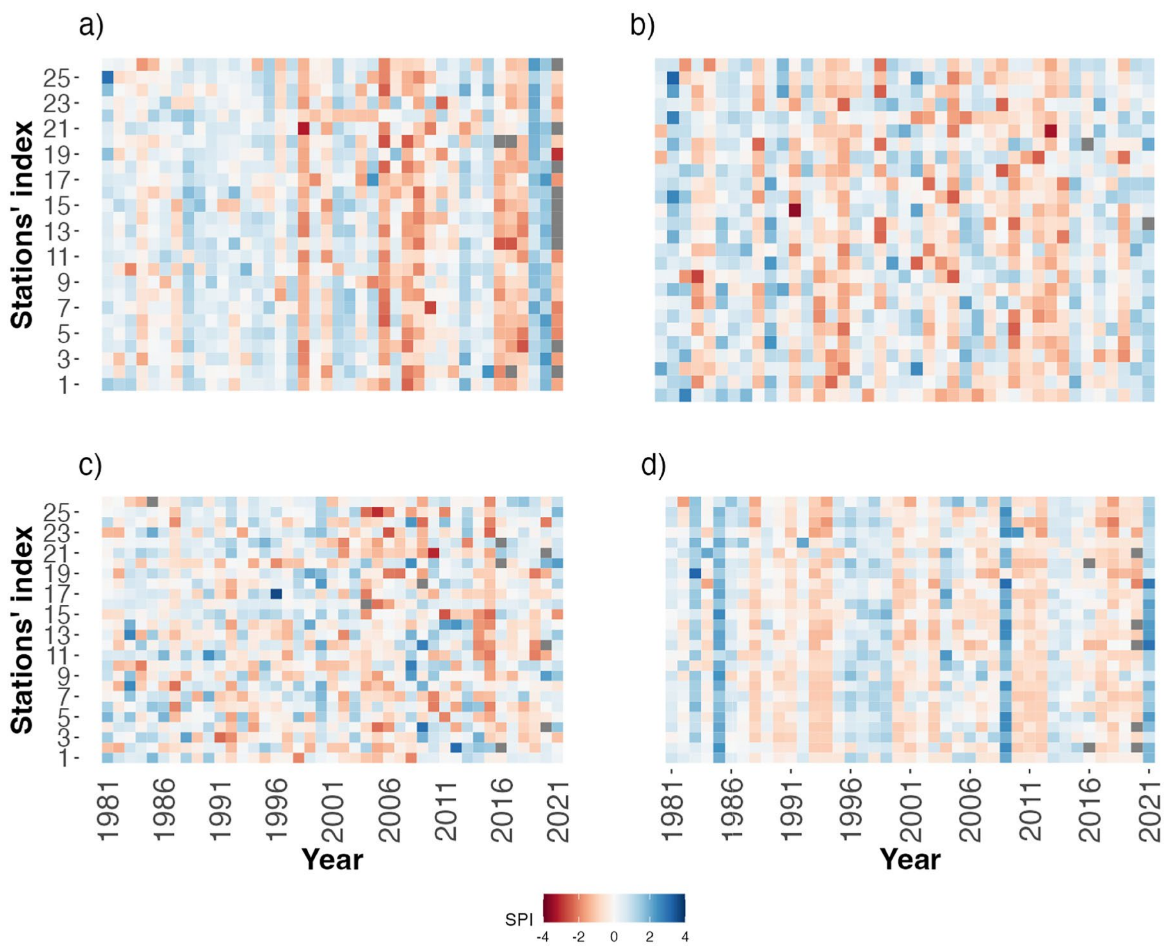


Fig. 4 Seasonal drought heat maps based on SPI: (**a**) winter (SPI-3 in February), (**b**) pre-monsoon (SPI-3 in May), (**c**) monsoon (SPI-4 in September), and (**d**) post-monsoon (SPI-2 in November). Positive SPI (non-drought) is shown in blue shades, and negative SPI (drought) is shown in red shades, with darker colors indicating greater magnitude

1984, 1985, 1989, 1992, 1994 to 1996, 1999, 2003 to 2005, 2008 to 2014, and 2019.

For many years though, the drought has occurred on a basin-wide scale, but the intensity largely varies between stations. The result shows that monsoon drought, i.e., 4-month SPI in September, is experienced in KRB periodically in many stations but is increasingly experienced in more of the stations, such as in 1987, 1992, 2001, 2002, 2004, 2005, and 2015. Monsoon drought occurs in fewer periods on a basin scale than other seasonal droughts but shows large variation between stations in a single year. Post-monsoon drought (indicated by 2-month SPI in November) occurred more frequently but with less intensity than other seasonal droughts in the region. In the case of post-monsoon, drought occurs in 1988, 1990, 1991, 1993, 1994, 1995, 2000, 2001, 2003, 2007, 2008, 2010, 2011, 2012, 2017, 2018, and 2020 on a regional scale, signaling increasing trend.

These results demonstrate a complex pattern marked by two main aspects of change. Firstly, when considering spatial distribution, there are noticeable variations in SPI values between different monitoring stations in any given year. This emphasizes how the impact of drought is specific to localized areas. Secondly, when looking at time, there are fluctuations in SPI values from one year to the next. This suggests that drought occurrences change at predominantly the interannual timescale, showing a dynamic nature. These two aspects of change highlight the intricate nature of understanding and handling drought in KRB. Additionally, the result also clearly indicates the increased variability of drought in recent decades compared to pre-2000, a finding that echoes the increasing teleconnection effect of tropical oceanic variations.

4.2 Drought Implication on Water Resources

The SPI-based analysis characterizes the timing, frequency, and spatial variability of meteorological drought across the KRB. However, drought impacts extend beyond precipitation

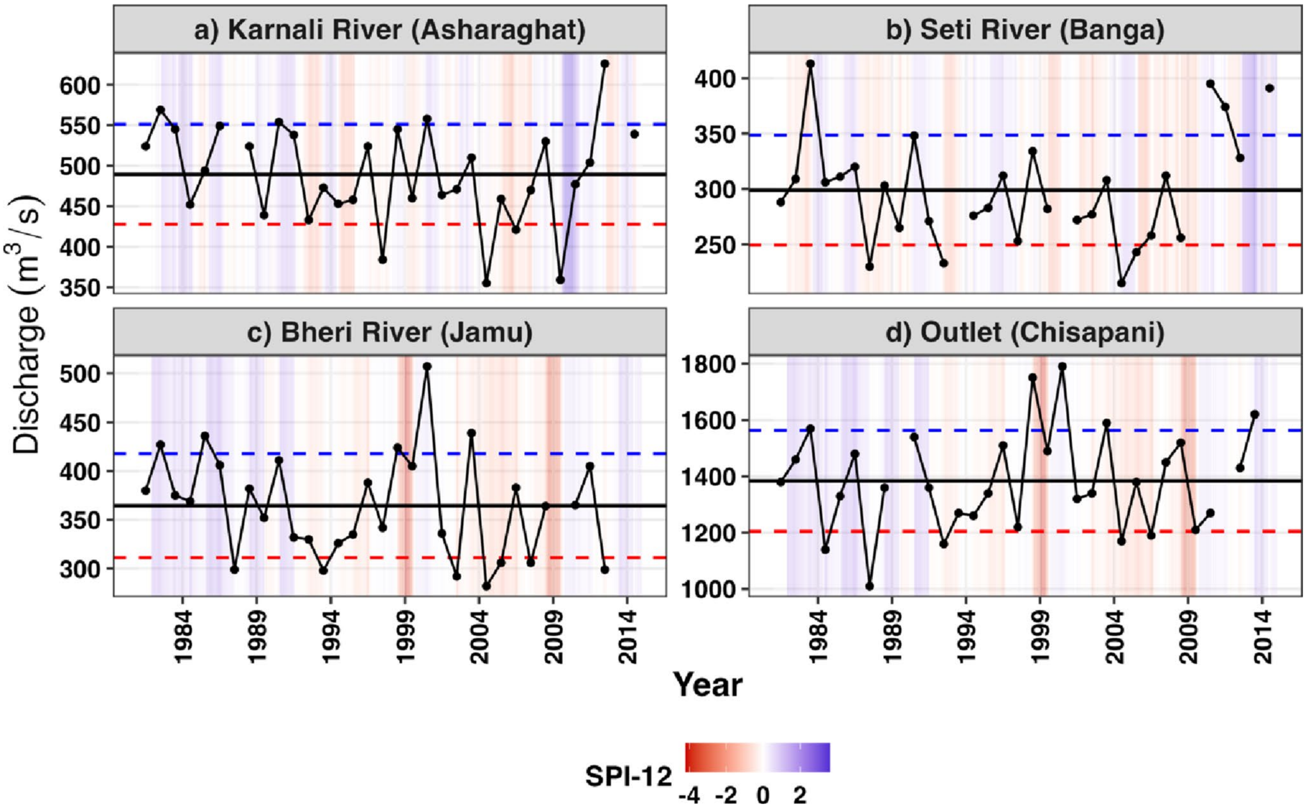


Fig. 5 Mean annual river discharge for (**a**) Karnali River (Asharaghat), (**b**) West Seti River (Banga), (**c**) Bheri River (Jamu), and (**d**) Karnali River (Chisapani), with monthly SPI-12 from the nearest precipitation station shown as background shading (red = dry, blue = wet). Dashed lines indicate ± 1 standard deviation

deficits and are often expressed through changes in surface water availability and subsurface storage. Therefore, the hydrologic responses to drought conditions were examined by evaluating variability in river discharge and terrestrial water storage components, providing a process-based link between meteorological drought signals and basin-scale water availability.

4.2.1 River Discharge

Surface-water availability responses to changing drought patterns were assessed by examining mean annual discharge in the three major tributaries of the KRB (Bheri in the east, Karnali in the middle, and Seti in the west) and at the basin outlet (Chisapani; see Fig. 1 for station locations). Although no statistically significant monotonic trend was detected in mean annual discharge at any of the four gauges (non-parametric Mann–Kendall trend test at $\alpha = 0.05$; Fig. 5), marked interannual variability is evident. Drought years are generally associated with lower annual flows, with pronounced discharge deficits observed during 2004–2007, 2009, 2014, and 2015. To provide a direct visual comparison between meteorological drought and river-flow variability, monthly SPI-12 from the nearest precipitation station to each discharge gauge is shown as background shading in Fig. 5 (red = dry/negative SPI-12; blue = wet/positive SPI-12). Periods of persistently negative SPI-12 broadly coincide with reduced annual discharge, whereas positive SPI-12 is generally associated with higher flows. To quantify the meteorological control on discharge, the Pearson correlation between regional mean SPI-12 and mean annual river discharge was calculated (Table 2). Regional mean SPI-12 is defined as the basin-wide SPI-12 series computed as the average of station-based SPI-12 values across all available stations at each time step. Except for the Karnali River, the absence of a significant long-term trend in discharge suggests damping effects of basin storage and cryospheric contributions (e.g., seasonal snowpack and glacier melt) on annual flows in these glacier-fed river systems.

Table 2 Correlation coefficient between regional mean SPI12 and river discharge at Karnali River (at Asharaghat), Seti River (at Banga), Bheri River (at Jamu), and outlet of KRB (at Chisapani)

S.*N*	Station name	Correlation coefficient	*P* value
1.	Karnali River (at Asharaghat)	0.420	0.016
2.	Seti River (at Banga)	0.343	0.050
3.	Bheri River (at Jamu)	0.463	0.008
4.	Outlet of KRB (at Chisapani)	0.362	0.045

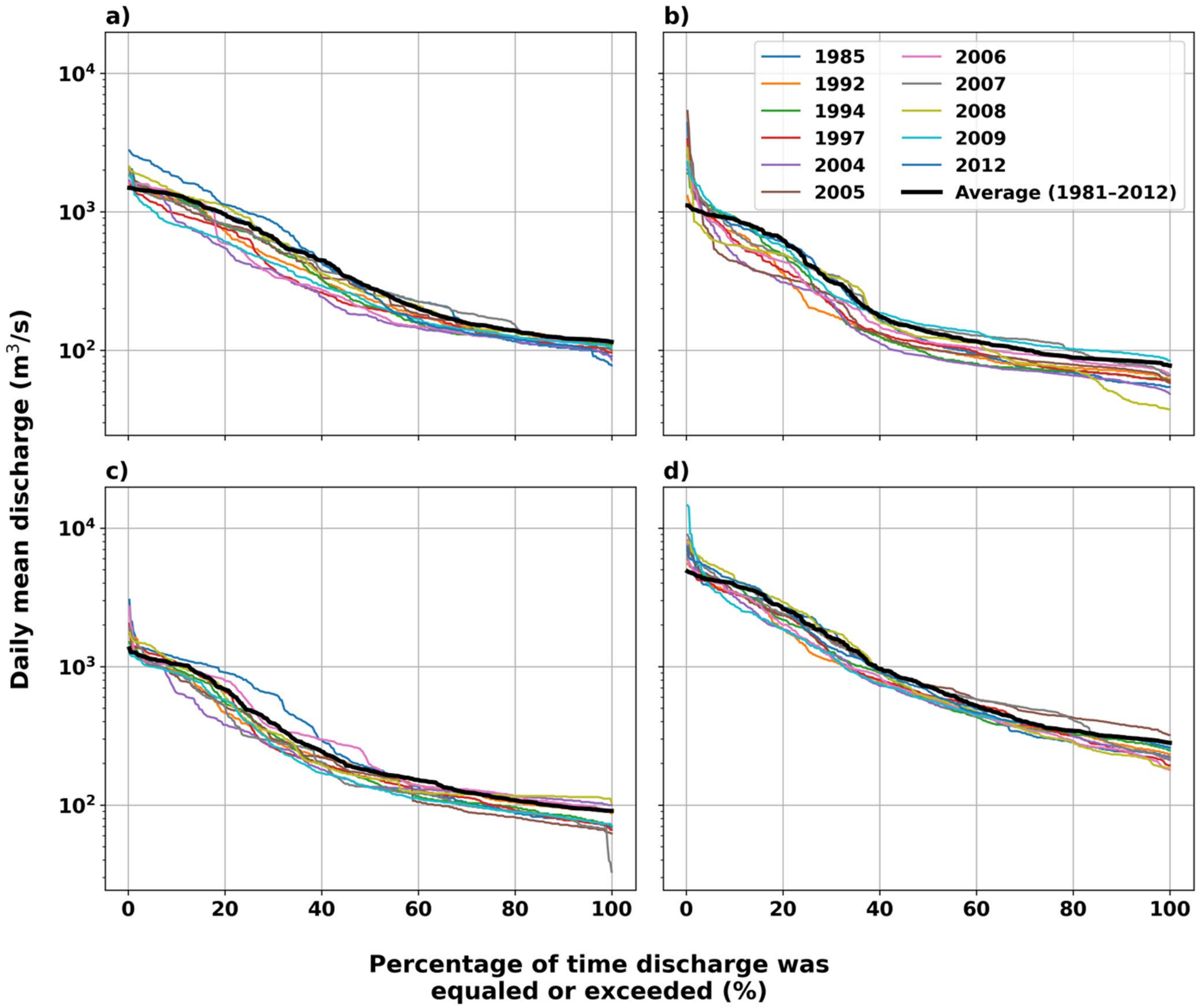


Fig. 6 Flow duration curves for (**A**) Karnali River at Asharaghat, (**B**) Seti River at Banga, (**C**) Bheri River at Jamu, and (**D**) the KRB outlet at Chisapani. The black line shows the mean curve for 1981–2012, and colored lines show individual drought-year curves for the KRB

To further delineate river flow characteristics, flow duration curves (Fig. 6) are plotted to highlight differences in discharge across exceedance probabilities. It is evident from Fig. 6 that droughts significantly impacted river discharge in KRB. At the Asaraghat station, river discharge was substantially lower than the long-term average in most drought years (e.g., 1997, 2004, 2006, and 2009). Similar results can be observed at the other three stations (Fig. 5b-c), with river flows impacted the most in 2004 and 2009, characterized by extreme and widespread basin-wide droughts. Seti river discharges in 1992, 1997, 2004, 2005, and 2008 show the lower values that coincide with the drought year of the region, and the lowest discharge in 2004 may be due to severe widespread drought in 2004. In Bheri, river discharges in 1993, 2002, 2004, 2005, 2007, and 2012 had lower values as the major drought events occurred in the region. In Chisapani, an outlet of the entire KRB, discharges in 1992, 1997, 2004, 2006, and 2009 reduced to lower values, that coincide with drought years. Such correspondence indicates that, as drought characteristics change, the rivers would respond accordingly.

While monsoon rainfall largely controls the annual river flow in the Karnali River Basin, the absence of a significant trend in monsoon drought suggests the absence of a trend in river flow but the low flow in rivers during drought years is primarily attributed to the impact of winter drought, indicating a pronounced impact of seasonal variability on water availability. Interestingly, while monsoon rains contribute substantially to the annual total amount of precipitation and river flow, the absence of monsoon drought does not exhibit a similar trend with groundwater levels (details in the next chapter). This could be attributed to the short and steep nature of most KRB rivers, which facilitate rapid runoff and limit water storage. Consequently, the increased trend of winter drought may have a more pronounced impact on groundwater withdrawal due to reduced replenishment during the monsoon season, highlighting the potential vulnerability of the region to seasonal variations in precipitation and their cascading effects on water resources.

The relationship between basin regional-mean seasonal SPI and seasonal discharge was evaluated to quantify how catchment-scale hydroclimatic conditions control river flow across seasons and to assess whether seasonal wet/dry signals persist into subsequent flows. Seasonal discharge showed clear, season-dependent relationships with regional SPI when SPI was defined using season-specific accumulation windows. Same-season correlations were strongest and most consistent for monsoon and post-monsoon discharge, with positive correlations across all four gauges (Fig. 7). The largest same-season effect sizes occurred at Outlet Chisapani (monsoon: r = 0.73; post-monsoon: r = 0.67), and similarly strong positive relationships were observed at the other stations (e.g., monsoon $r \approx 0.53$–0.58; post-monsoon $r \approx 0.47$–0.57), indicating that wetter basin-wide seasonal conditions are strongly reflected in higher seasonal discharge at the basin scale. Premonsoon discharge also showed positive relationships with regional SPI, with stronger associations at Karnali Asharaghat, Outlet Chisapani, and Seti Banga, while the relationship at Bheri Jamu was weaker (Fig. 7). In contrast, winter discharge showed weak or negative correlations, including a significant negative relationship at Bheri Jamu (r = -0.41), suggesting that winter flows are less directly coupled with contemporaneous meteorological drought/wetness than other seasons.

The seasonal lag analysis further shows how basin-scale drought propagate into later seasonal discharge (Fig. 8). The strongest correlations generally occurred for same-season SPI–discharge pairs, particularly for monsoon and post-monsoon conditions, reinforcing the dominance of immediate seasonal hydroclimatic coupling. In addition, winter SPI (SPI-3 in February) exhibited a clear forward influence on later discharge in several gauges, especially into premonsoon flow (lag = 1), where strong positive correlations were found at Karnali Asharaghat (r = 0.69) and Outlet Chisapani (r = 0.68) (Fig. 8). Winter SPI also showed weaker positive carryover to monsoon flow at some stations and generally weak-to-negative associations with post-monsoon discharge. These patterns indicate that regional drought can affect discharge through both immediate seasonal response and short-term catchment memory, with the strongest delayed signal typically appearing in the following premonsoon season.

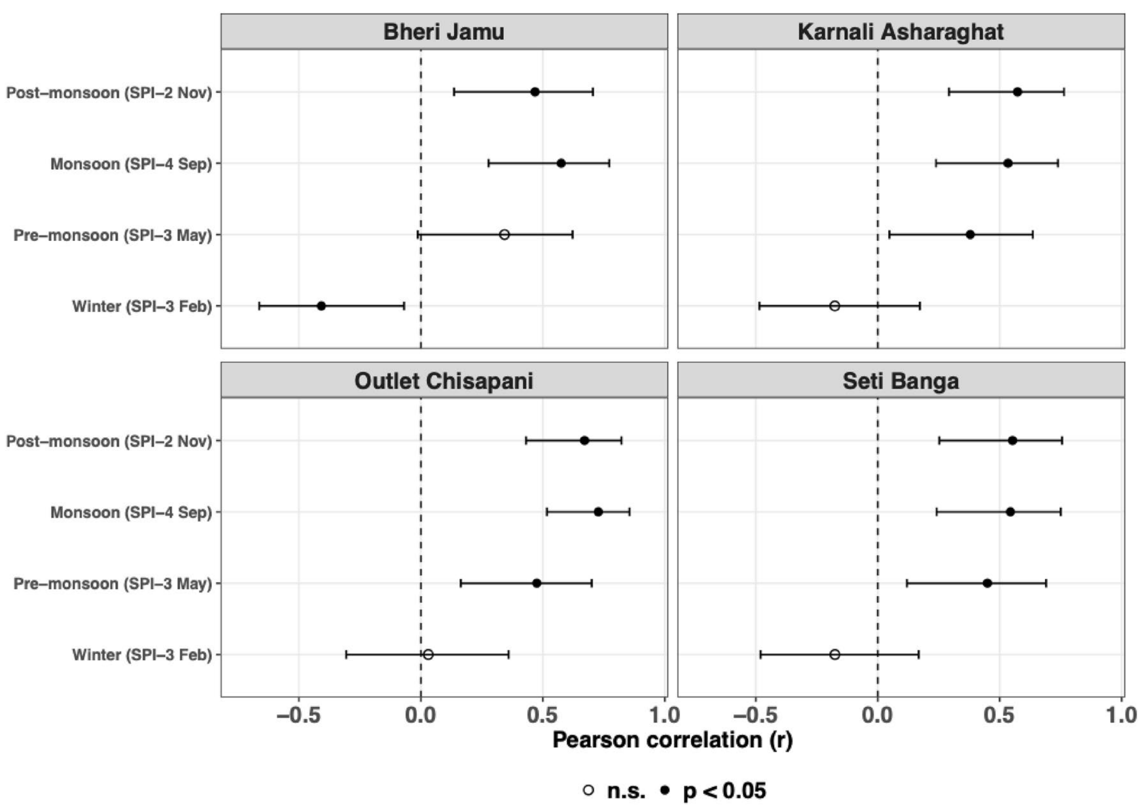


Fig. 7 Same-season Pearson correlations between regional-mean seasonal SPI and seasonal discharge at the four gauges. Points show r and horizontal bars show 95% confidence intervals; filled circles indicate significant at α = 0.05

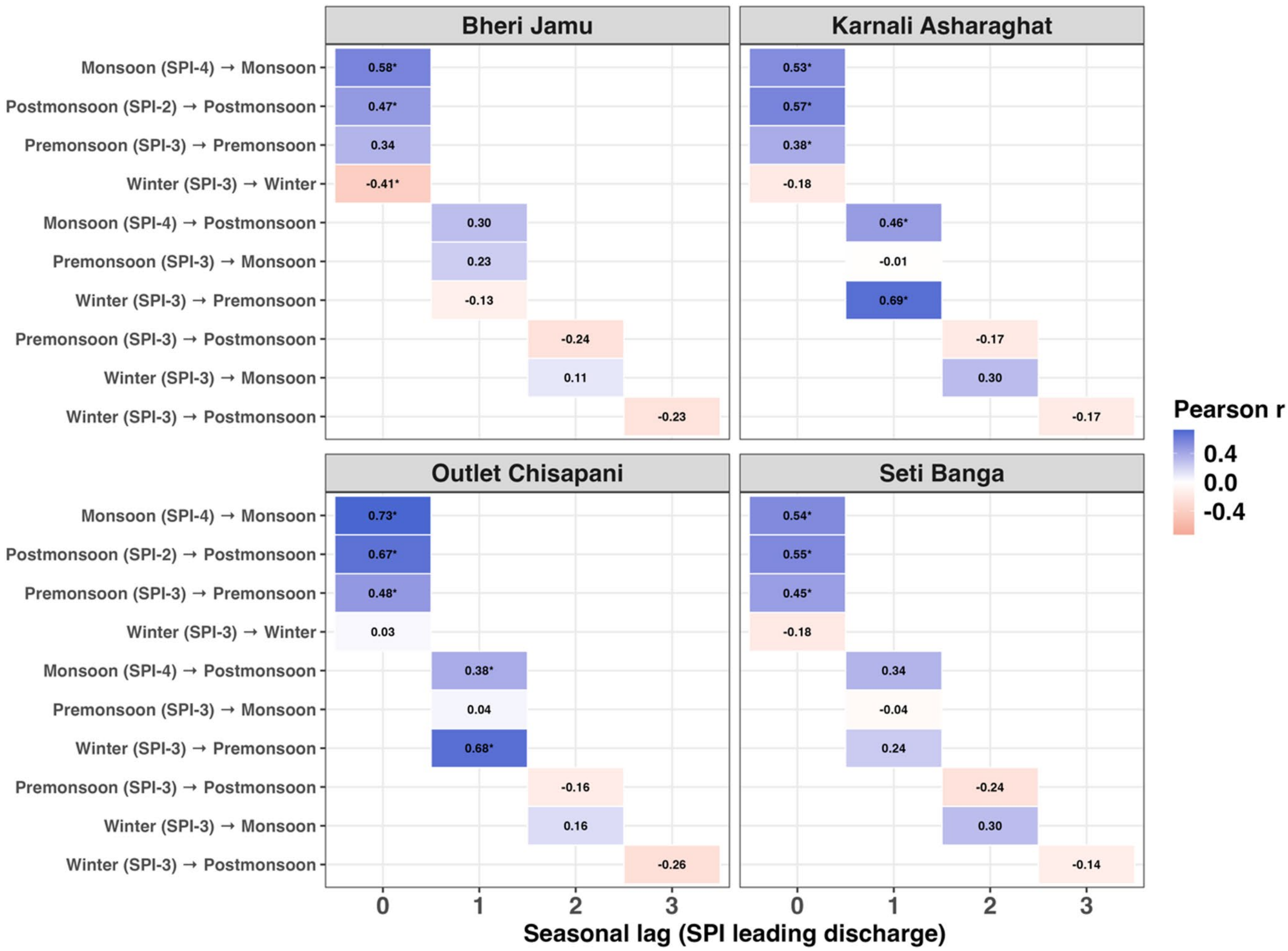


Fig. 8 Seasonal lag Pearson correlations between regional-mean SPI and seasonal discharge (SPI leading discharge) across the four gauges. Heatmaps show correlation coefficients (r) by lag (0–3 seasons); asterisks indicate significant at α = 0.05

4.2.2 Groundwater

Next, the impacts of drought on groundwater storage are analyzed. Figure 9 presents the spatial patterns of the linear trend in GRACE-based TWS anomaly in the study domain and its surrounding regions during the GRACE data availability period of 2002–2016. Results indicate a decline in TWS during the analysis period within and outside of the KRB (significant at α = 0.05); note that results in Fig. 6 are presented for an extended domain because of the relatively large footprint of GRACE data (Pokhrel et al. 2015). Changes in groundwater storage and their linkages to drought are further examined. Temporal variations and trends in groundwater storage (Fig. 10) are analyzed for the region encompassing the KRB (white box in Fig. 9). Based on the results, groundwater declined substantially (-1.21 cm/year, linear trend significant at α = 0.05) and persistently during 2002–2016. Since the other TWS components (such as river water, soil water, and snow water; see Methods and Data section) remained relatively stable or even had increasing trends (Fig. 10), the majority of the decline in TWS was contributed by the decline in groundwater alone.

Further analysis reveals the more significant groundwater deficits due to drought in 2005, 2006, 2007, 2009, 2012, 2013, 2014, and 2016. During the widespread drought periods of 2004–2007, 2012, and 2015–2016 there was a substantial reduction in groundwater storage and very low recharge during the monsoon season. During the extreme western winter drought of 2008–2009, the groundwater level in the winter months was historically low. Since the most widespread drought in the region occurred in 2016, the groundwater plummeted in 2016.

The comparison with drought year in KRB and groundwater storage anomaly also points to groundwater depletion associated with drought phenomenon in western Nepal. It is noted that basin-wide groundwater abstraction in the KRB is likely lower than in the intensively irrigated Terai/Indo-Gangetic Plain; therefore, the persistent decline in GRACE-derived groundwater storage is interpreted primarily as

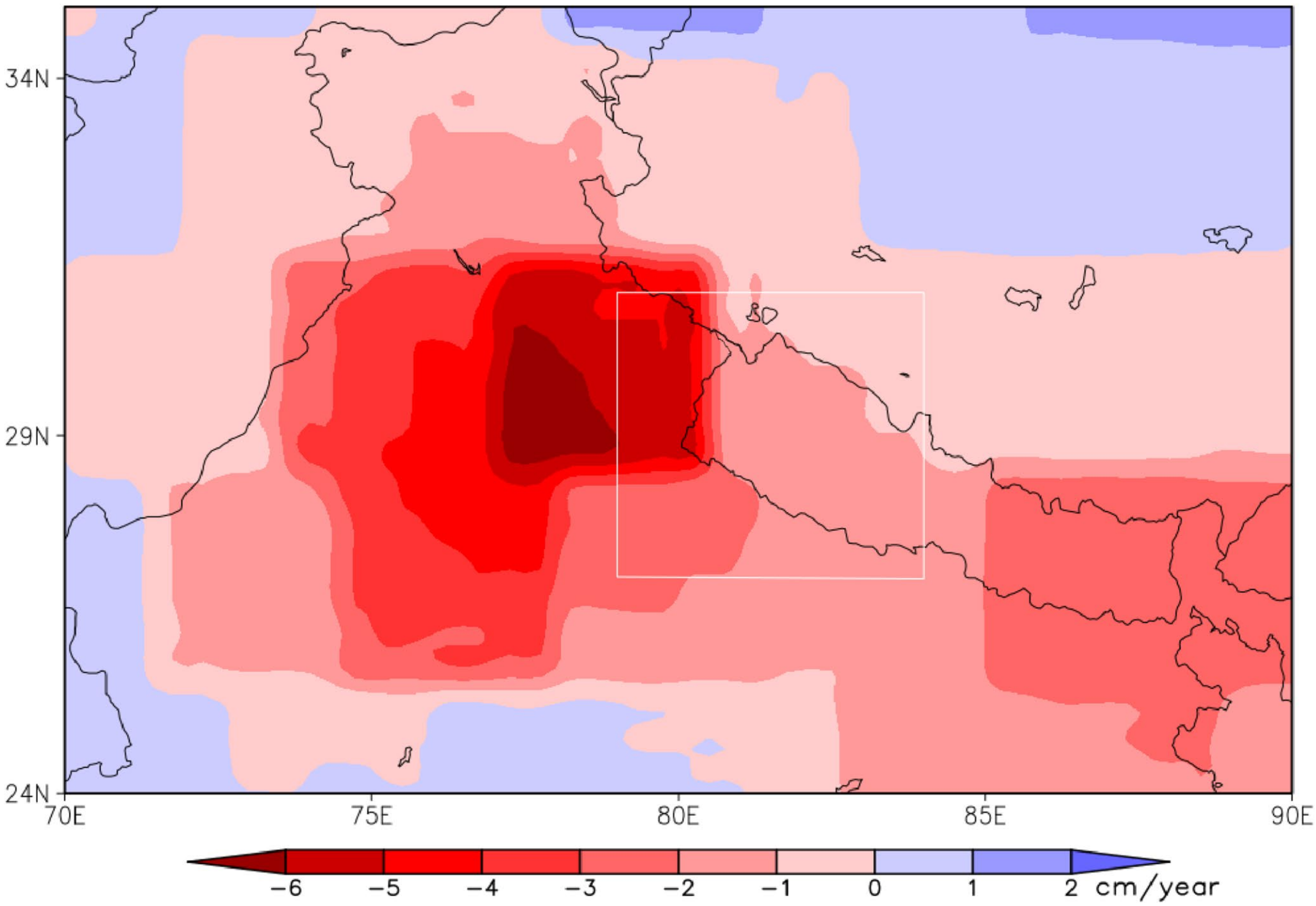


Fig. 9 Spatial trends (2002-2016; cm/year) in GRACE-based TWS in Nepal and the surrounding region

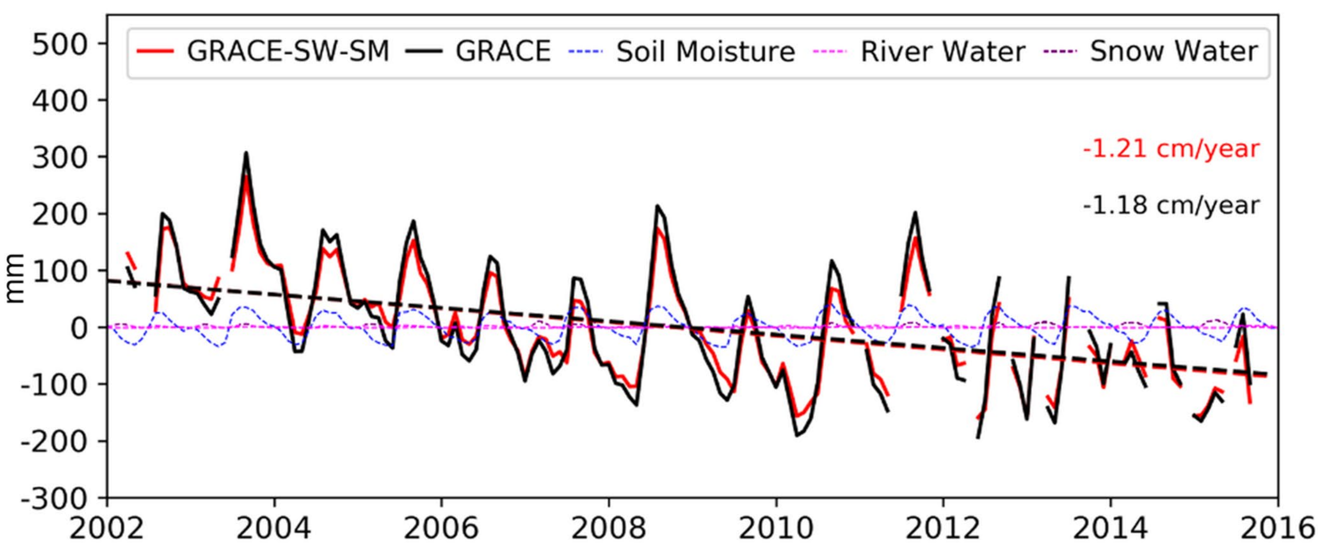


Fig. 10 A linear trend of TWS and groundwater storage (TWS - Surface Water and Soil Moisture) anomalies in the area within the white box in Figure 9

a response to drought-related recharge deficits, although localized abstraction for irrigation and domestic supply cannot be excluded (Department of Water Resources and Irrigation, 2019; Pandey et al. 2020a, b; Bricker et al. 2014; Shah et al. 2006).

Despite the absence of a decreasing trend in river discharge, the annual average discharge was notably lower than the long-term average during most drought years identified by SPI. Significant groundwater deficits during drought years indicate a correlation between SPI-identified droughts and groundwater storage reduction. The findings underscore that drought conditions significantly impact the hydrological cycle, creating a complex interplay between river discharge and groundwater levels. During droughts, reduced precipitation and increased evaporation lead to decreased river flow. Lower river discharge, in turn, can impact groundwater recharge as rivers contribute significantly to replenishing groundwater. When there is prolonged drought, conversely, low groundwater levels can also contribute to reduced river discharge, creating a feedback loop.

5 Discussion

The analysis of SPI indicates more consecutive and worsening drought conditions occurring after 2000, along with a general increasing trend of frequency and severity. Winter drought was more severe in recent decades and strengthened over a longer time scale. The large-scale atmospheric phenomena (Niño 3.4, dipole moment index, arctic oscillation, and its decadal variability) (Sharma et al. 2021; Wang et al. 2013) and anthropogenic influences (anthropogenic aerosols) (Wang et al. 2013) contribute to such drought trends in western Nepal. Winter precipitation over the Himalaya is strongly influenced by mid-latitude circulation through western disturbances (WDs), which are synoptic systems embedded within the subtropical westerly jet (SWJ) (Dimri et al. 2015; Hunt et al. 2018). Multi-annual changes in WD frequency, intensity, and track as well as SWJ position and strength can alter the delivery of winter precipitation across High Mountain Asia, with evidence that the central Himalaya can experience a weakening WD influence and reduced heavy winter precipitation even when neighboring regions exhibit different trends (Cannon et al. 2015). These circulation changes provide a plausible dynamical explanation for the stronger and more persistent winter drought conditions identified in the basin. The amplified groundwater response to winter drought is also physically consistent with high-mountain recharge processes: groundwater in mountainous basins is often replenished by a combination of rainfall infiltration and meltwater inputs, with snowmelt/glacier melt acting as an important and temporally buffered recharge source (Somers and McKenzie 2020; Jeelani et al. 2012). When winter precipitation deficits reduce seasonal snow storage (and/or shift precipitation phase toward rain), the resulting decrease and/or earlier timing of meltwater can reduce the magnitude and duration of infiltration-driven recharge, leading to sustained groundwater storage deficits that can persist beyond a single season. This mechanism is consistent with the observed post-2000 strengthening of winter drought signals and the concurrent decline in groundwater storage, indicating that winter hydroclimatic anomalies can propagate into longer-memory subsurface storage more strongly than short-lived seasonal precipitation variability.

Results show reduced river flow during drought years relative to the study-period average, implying subsequent impacts on ecosystems and livelihoods. Western Nepal is also a region with a higher potential for hydropower development (~ 150 sites identified for hydropower projects) with a total estimated capacity of more than 21,000 MW (Pandey et al. 2020a, b). As the frequency of drought is increasing, it may seriously impact the potential of hydropower and available hydroelectricity in the future. Drought years identified in the SPI analysis coincide with marked reductions in mean annual discharge at the major tributaries and the basin outlet (Fig. 5), which can lower firm energy and increase the risk of generation shortfalls during the dry season when run-of-river plants dominate. Reduced and more variable inflows also complicate reservoir rule curves and sediment management, increasing operational uncertainty and reliability challenges under multi-year drought sequences.

These changes in water resources may also have a significant impact on aquatic biodiversity in the region. Paudel et al. (2020) state that the Ganges River dolphin (*Platanista gangetica*), an important aquatic species of KRB, showed a flow-ecology relationship, and the habitat was heavily reduced when there was low flow in the river. Drought-related low-flow conditions can reduce wetted habitat, increase channel fragmentation, and elevate water temperature, potentially affecting aquatic biota and riverine biodiversity. Therefore, drought may pose a potential threat to aquatic habitats by decreasing the flow of rivers. Moreover, Sharma et al. (2020) studied the livelihood and water flow requirements for the KRB and found that people living in the vicinity of rivers are dependent on rivers for a range of purposes, including irrigation, domestic activities, fishing, and in certain places, drinking. Therefore, these profound impacts of drought could also impact the people downstream of KRB.

This is the first study that focuses on Western in Nepal to assess the relationship of drought events with groundwater resources and the applicability of satellite remote sensing data for monitoring groundwater levels. National irrigation planning in Nepal highlights groundwater development (e.g., shallow tubewells) mainly for the Terai plain, whereas hill and mountain districts are expected to rely largely on springs, rivers, and canals (Department of Water Resources and Irrigation, 2019). Consistent with this, provincial irrigation water-source statistics indicate that Karnali Province is dominated by river water (~63%), with a comparatively smaller contribution from groundwater (~12%) (Pandey et al. 2020a, b). Hydrogeological assessments further suggest that the Middle Hills generally have lower groundwater potential than the Terai, and that more intensive groundwater use is concentrated in a few intermontane valleys (e.g., Dang and Kathmandu) rather than being widespread across mountain terrain (Bricker et al. 2014). Accordingly, GRACE-inferred groundwater decline is discussed as being primarily climate-driven at the basin scale, while recognizing that localized abstraction may contribute in specific valley bottoms and population centers. This result infers that SPI can indicate the groundwater reduction, as well.

Though precipitation is the main determining factor for meteorological drought conditions, rising trends in temperature in recent decades may have caused positive trends of evapotranspiration which may also have resulted in higher drought-prone conditions in different sectors. Observed temperature records show an increasing trend at the rate of 0.029 per year (significant at α = 0.01, Mann-Kendall Test) in KRB (Fig. 11). This indicates that drought severity could be even greater than indicated by SPI alone.

The meteorological aridity index (AI) also confirms (Fig 12) the decreased moisture balance in KRB in drought years. Aridity index (AI) was computed as the ratio of precipitation (P) to potential evapotranspiration (PET), AI=P/PET. Annual and winter mean AI were calculated for 1981–2021 using AgERA5 data (Copernicus Climate Change Service 2019). PET is estimated using Hargreaves equation, which is a temperature-based method to approximate how much water could evaporate and transpire if water were not limiting. Lower AI values indicate drier conditions (higher atmospheric water demand relative to precipitation), whereas higher AI values indicate more humid conditions.

In the Himalayan region, the timing of seasonal snowmelt exerts a strong control on water resources by regulating both direct runoff to rivers and delayed recharge to groundwater systems that sustain dry-season flow. The annual melting of accumulated winter snowfall is a critical phase of the hydrologic cycle in high-altitude and mountainous basins, with major implications for streamflow seasonality, groundwater recharge, and downstream water availability (Barnhart et al. 2016). Regional assessments indicate that snow

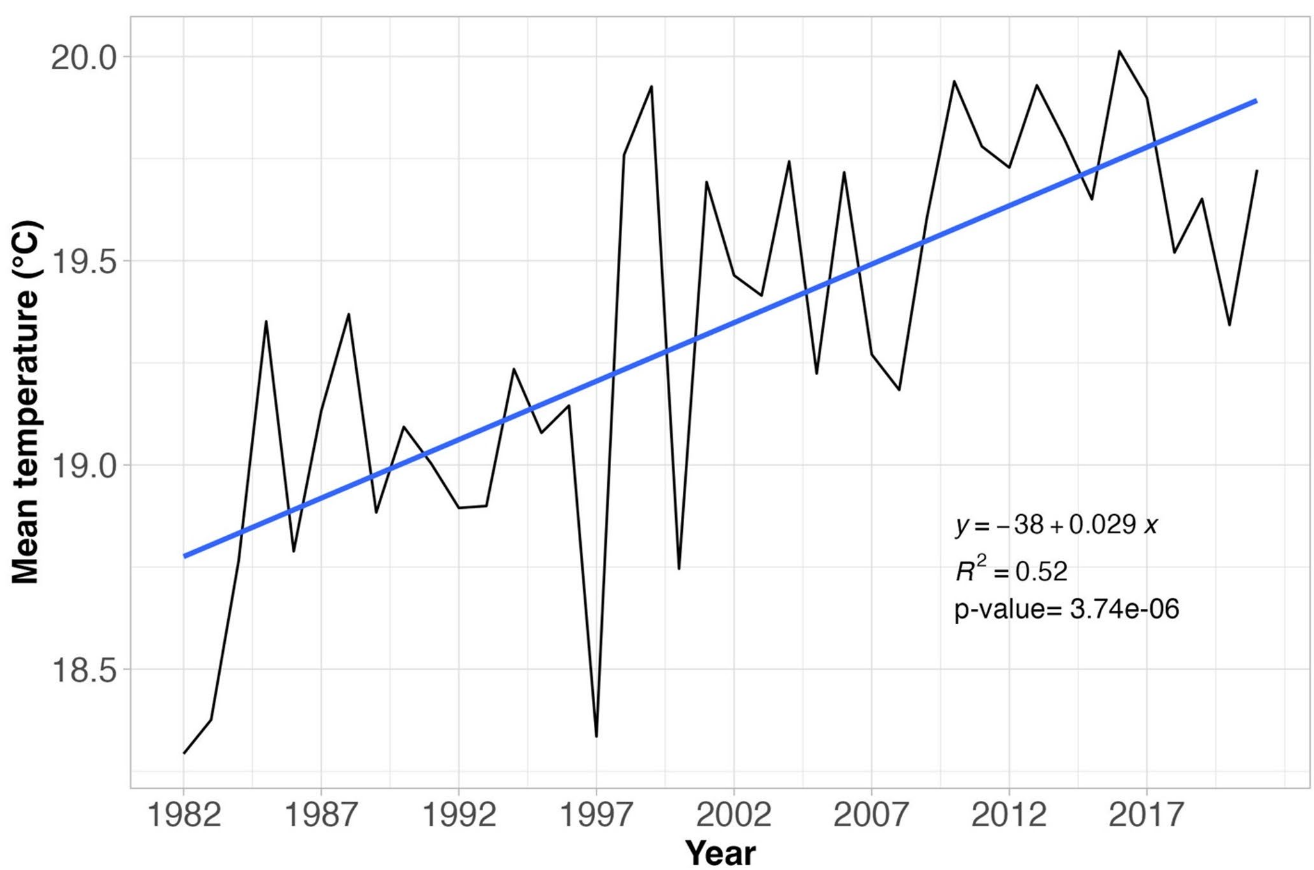


Fig. 11 Annual mean temperature and linear trend in KRB (1982-2021)

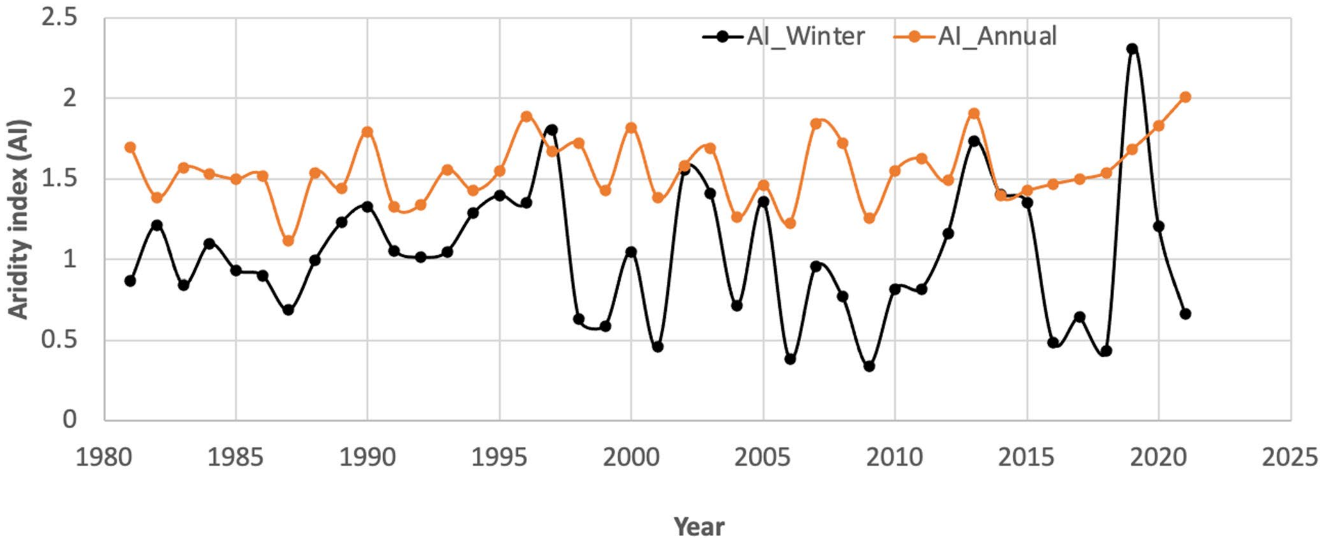


Fig. 12 Annual and winter mean aridity index (AI) in KRB (1981-2021). AgERA5 precipitation and Hargreaves potential evapotranspiration data were used to calculate the aridity index. Refer (Copernicus Climate Change Service, 2019) for details of the data used

and glacier melt are key components of Himalayan–Karakoram river flow, although their relative contribution varies substantially by basin and season, making shifts in melt timing especially important for downstream users (Azam et al. 2021). In addition to its surface-water contribution, snowmelt is an important source of groundwater recharge in the Himalaya; isotope- and hydrograph-based studies in the western Himalaya and Upper Indus show that meltwater forms a major share of recharge, while groundwater contributes persistently to river discharge, particularly in downstream reaches (Maurya et al. 2018; Lone et al. 2021; Somers and McKenzie 2020). This groundwater pathway buffers and redistributes meltwater through time, as demonstrated by evidence from Himalayan basins showing that transient groundwater storage can delay runoff release by weeks and substantially alter annual discharge volumes, and by estimates from the northern Himalaya (Yarlung Zangbo) indicating large groundwater recharge and baseflow contributions to river flow (Andermann et al. 2012; Yao et al. 2021). Because this seasonal snow resource is rapidly changing under a warming climate and is also sensitive to regional drought conditions, shifts toward earlier snowmelt can advance spring hydrographs and recharge pulses, potentially increasing mismatches between water supply and later-season irrigation and ecosystem demands where storage is limited (Srivastava et al. 2024).

The spatial and temporal variability of the first snow-free day in the KRB was analyzed to provide a spatially explicit indicator of changing snow dynamics. Seasonal snow cover was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) daily snow-cover product (MOD10A1), which is based on the Normalized Difference Snow Index (NDSI) (Hall et al. 2002). The slope of the first snow-free day was generated by first deriving, for each pixel and each year (2000–2021), the first snow-free day of year (DOY) from daily MODIS MOD10A1 snow-cover data as the earliest day when snow cover equaled zero. The analysis was limited to non-water, seasonal-snow pixels using a mask based on MOD44W and a reference-year snow-persistence filter to exclude water and persistent snow/ice areas. A pixel-wise linear regression of annual first snow-free DOY against year was then applied, and the regression slope (days/year) was extracted to represent the temporal trend in snow disappearance timing. Figure 13a presents the spatial distribution of regression slopes (days/year) as a descriptive trend indicator, while statistical significance is evaluated and reported for the basin-mean annual first snow-free day time series (Fig. 13b). The calculations were performed in Google Earth Engine. For details of the data and methods, refer to Armstrong et al. (2024). Results are presented in Fig. 11a and b. Figure 13a shows that many areas in the KRB have a negative slope for the first snow-free day, indicating that snow is melting earlier in recent years. In Fig. 13a, negative slope values indicate earlier snow-free dates over time, while positive values indicate later snow-free dates. The first snow-free day is used here as an independent snow-dynamics indicator to interpret potential hydrologic pathways linking drought conditions, seasonal storage, and water availability. Figure 13b shows that, although no statistically significant linear trend is detected in basin-mean snow-free timing ($\alpha = 0.05$), earlier snow-free dates occur in several drought years identified by the SPI analysis (red bands in the figure). Without a substantially wet year following a drought, terrestrial water storage may not fully rebound.

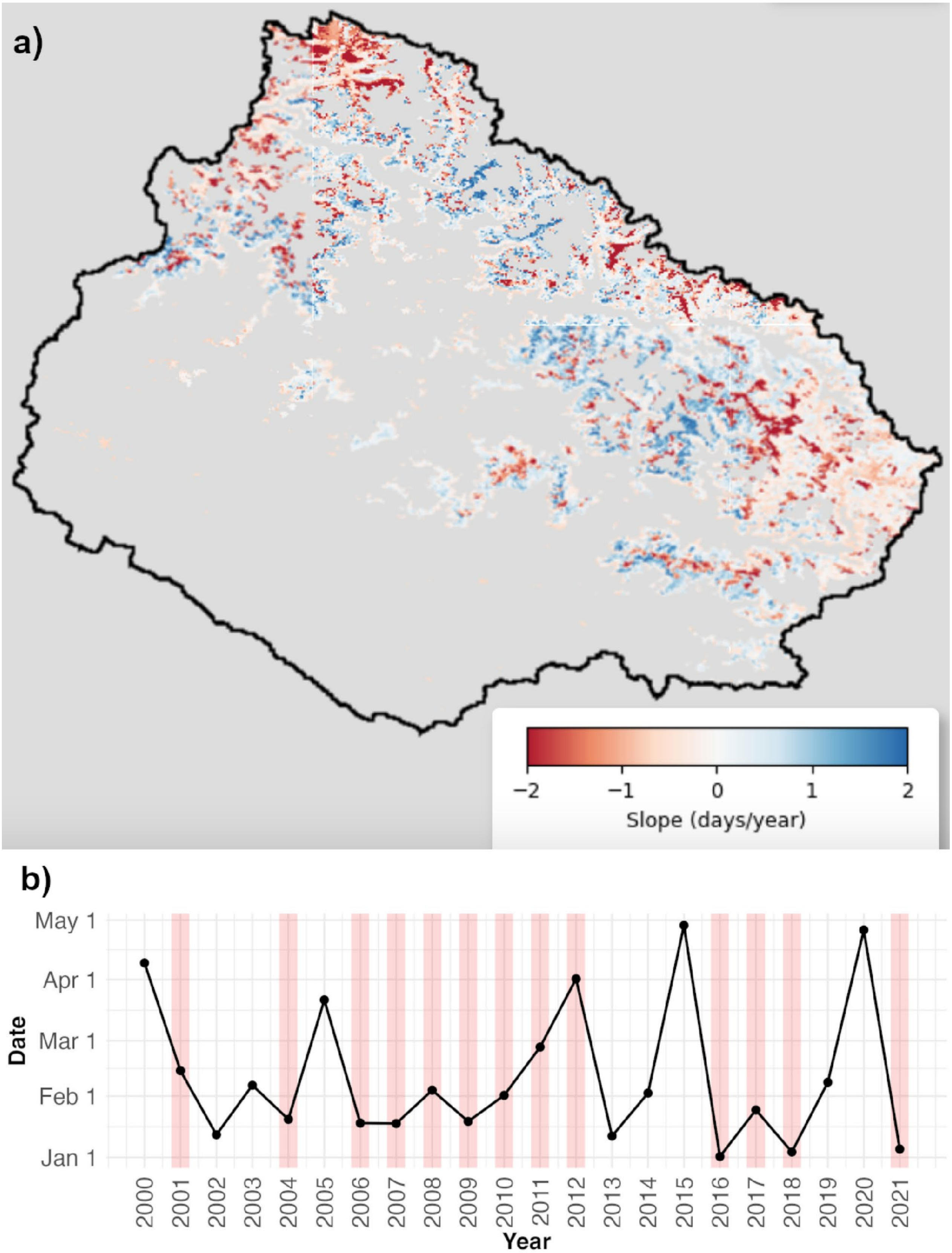


Fig. 13 **a**) Map showing the slope of the first snow-free day of year (DOY) from 2000 to 2021. Colors grade from red to blue as the slope in DOY increases. Gray indicates water bodies, glaciers/persistent snow, or areas with no change. **b**) Time series of the annual basin-mean first snow-free day. Red bands indicate winter drought years in the KRB

Although several drought years coincide with basin-mean snow-free dates, the snowmelt analysis is used as a complementary indicator of changing seasonal water-storage dynamics. A formal SPI–snowmelt correlation analysis is recommended for future work to know the physical relationship between drought and snow dynamics.

6 Conclusion

This study provides a basin-scale characterization of drought conditions in the Karnali River Basin using multi-timescale SPI and evaluates associated responses in river discharge and ground water storage. Results indicate a strengthening of drought conditions in the post-2000 period, with drought years corresponding to pronounced reductions in river discharge across the major tributaries and the basin outlet. GRACE-based analysis further suggests that subsurface water storage exhibits persistent declines during extended drought periods, indicating limited buffering capacity during multi-year precipitation deficits. Snow-cover timing results indicate earlier snow-free conditions in several drought years, consistent with reduced seasonal water storage and potential impacts on dry-season water availability. These findings imply increasing risks for hydropower reliability, irrigation water security, and riverine ecosystems, highlighting the need for policy actions that strengthen basin monitoring and management capacity. Recommended priorities include expanding and maintaining hydrometeorological and groundwater monitoring networks (including groundwater level and abstraction reporting), applying drought information and forecasting, and improving irrigation efficiency and conjunctive surface–groundwater planning in drought-prone lowland areas. Future research should evaluate multi-indicator drought frameworks that incorporate evaporative demand, quantify linkages between snowmelt timing and discharge/groundwater anomalies, and develop decision-support tools that integrate seasonal drought forecasts for water allocation, hydropower operations, and ecosystem protection.

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Declarations

Conflict of interest The authors declare that they have no known competing interests for this publication.

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