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RESEARCH ARTICLE

Integrating Cloud-Based Geospatial Analysis for Understanding Spatio-Temporal Drought Dynamics and Microclimate Variability in Rajasthan: Implications for Urban Development Planning

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Abstract

This study examines the spatio-temporal dynamics of drought and microclimate variability in Rajasthan, India, from 2010 to 2022 using the Standardized Drought Composite Index (SDCI). The SDCI integrates the Temperature Condition Index (TCI), Precipitation Condition Index (PCI), and Vegetation Condition Index (VCI) to assess drought severity. Remote sensing data from MODIS and CHIRPS were processed using Google Earth Engine (GEE) for large-scale, continuous drought monitoring. The results reveal significant drought conditions in 2014, 2015, 2020, 2021, and 2022, with southeastern districts like Kota, Bundi, and Baran experiencing SDCI values below 0.2, indicating severe drought. Arid regions, including Jaisalmer, Barmer, and Bikaner, consistently exhibited extreme drought (SDCI < 0.1) due to low annual precipitation (less than 250 mm). In contrast, semi-humid regions like Udaipur and Ajmer showed variable drought intensities linked to localized climatic factors. Temperature-related vegetation stress was particularly high during pre-monsoon periods, affecting agricultural productivity. The spatial analysis highlights significant regional disparities in drought severity, emphasizing the need for tailored, location-specific drought management strategies. Incorporating green infrastructure, such as urban forests and permeable pavements, is recommended to mitigate the impacts of drought and desertification. This study underscores the utility of cloud-based geospatial tools for drought monitoring and resource planning, providing critical insights for sustainable urban and agricultural development. Future research could refine the SDCI methodology and integrate socio-economic factors to enhance drought resilience.

Keywords Drought · Standardized Drought Composite Index (SDCI) · Geospatial analysis · Google Earth Engine (GEE) · Climate variability · Remote sensing

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Introduction

Climate change and global warming have been two main concerns in recent decades, significantly impacting global weather patterns and increasing the risk of droughts (Azamathulla et al., 2018). As global temperatures rise, changes in precipitation patterns become more pronounced, with some regions experiencing severe dryness while others may face increased rainfall. These alterations disrupt natural water cycles, leading to more frequent and severe droughts. Recent estimates indicate that at least 45 countries are at heightened drought risk, putting millions of people and their livelihoods at stake (Pellicone et al., 2019). The 2022 Intergovernmental Panel on Climate Change (IPCC) report (Intergovernmental Panel on Climate Change (IPCC), 2023) highlighted the severe impacts of climate change across various ecosystems. Terrestrial, freshwater, coastal, and open ocean marine ecosystems have all suffered considerable harm, with biodiversity loss, habitat degradation, and species distribution shifting being some of the most critical issues. This ecological disruption further exacerbates the vulnerability of human populations dependent on these ecosystems for food, water, and other resources (Khaniya et al., 2021).

Recent urban development trends have exacerbated the challenges posed by climate change, particularly in the context of droughts and desertification. As cities expand, natural landscapes are replaced with impervious surfaces, disrupting the natural water cycle and reducing the amount of water that infiltrates the ground (Gramaglia et al., 2024). This urban sprawl often leads to increased surface runoff and decreased groundwater recharge, intensifying water scarcity in urban areas.

Green infrastructure, which includes green roofs, urban forests, and permeable pavements, plays a crucial role in mitigating these adverse effects. By promoting natural water infiltration and reducing surface runoff, green infrastructure helps maintain local water cycles and replenishes groundwater. This is particularly important in regions susceptible to drought, as maintaining groundwater levels can help buffer against the impacts of prolonged dry periods. Furthermore, the lack of vegetation in urban areas can lead to higher temperatures, known as the urban heat island effect, which can exacerbate water evaporation rates and further strain water resources. By integrating green spaces into urban planning, cities can cool their environments, support biodiversity, and improve overall resilience to climate-induced stresses (Olgun et al., 2024). However, the rapid pace of urbanization and inadequate planning and implementation of green infrastructure can lead to conditions that favor desertification. As natural landscapes are increasingly converted to urban areas without sufficient green infrastructure, soil erosion, and land degradation risk increases. This can set off a feedback loop where reduced vegetation cover leads to further soil degradation, making it increasingly challenging to support plant life, thus accelerating the process of desertification.

Drought is a recurring phenomenon characterized by prolonged periods of lower-than-normal precipitation, resulting in reduced stream flow, lower lake and reservoir levels, and decreased groundwater levels (Haider & Adnan, 2014). These hydrological impacts manifest in various forms, such as agricultural droughts that impair crop production, hydrological droughts that reduce water availability for drinking and irrigation, and socio-economic droughts that affect the overall economy and quality of life (Haile et al., 2020). The impacts of drought are extensive, affecting transportation systems by lowering river and canal water levels, thereby hindering navigation and increasing transportation costs. Soil quality deteriorates due to reduced moisture, leading to decreased agricultural productivity and increased susceptibility to erosion (Gavrilov et al., 2019). Ecosystems suffer as plants and animals face water stress, leading to diminished biodiversity and altered ecological balances. Energy generation, mainly hydroelectric power, is compromised due to lower water availability. Global export and trade are also impacted as key agricultural regions face reduced yields, leading to higher prices and scarcity of certain commodities. Drought's indirect and cascading effects can influence employment rates as agricultural and related industries experience downturns. Food security is threatened as crop failures and reduced livestock productivity lead to shortages and increased prices. International trade patterns can shift as countries adapt to these new challenges, sometimes resulting in geopolitical tensions over water resources (Mishra & Rai, 2016; Yazdanpanah et al., 2014).

Remote sensing (RS) products provide meteorological data and monitor changes in surface variables such as plant health and water availability, offering extensive contextual data for drought monitoring (Alahacoon & Edirisinghe, 2022; Omia et al., 2023; Vreugdenhil et al., 2022). RS and Geographic Information Systems (GIS) have made it easier to observe the world with sensors and track changes over time. The primary advantage of RS and GIS techniques is their ability to deliver continuous data over large areas in both space and time, significantly addressing data scarcity issues in arid regions like Rajasthan.

With the advancement of RS and GIS techniques, several remote-sensing-based drought indices have been proposed and evaluated, including the Normalized Difference Vegetation Index (NDVI) (Huang et al., 2021), the Temperature Condition Index (TCI) (Li et al., 2024), the Vegetation Condition Index (VCI) (Yin et al., 2024), and the Vegetation Health Index (VHI) (Zeng et al., 2023). TCI, VCI, and VHI are classified as vegetation indices as they describe the vegetation condition in specific areas, categorize it into different drought classes, and are commonly used for drought monitoring. VCI is widely used to detect changes in vegetation from significantly worse to favorable conditions. TCI identifies vegetative stress caused by high temperatures and heavy moisture. VHI, a combination of TCI and VCI, comprehensively assesses vegetation health (Gorelick et al., 2017).

Despite significant advancements in remote sensing and drought monitoring techniques, existing studies on drought dynamics in Rajasthan often emphasize isolated indices or have limited temporal coverage. Few studies integrate multiple drought indices using cloud-computing platforms like Google Earth Engine (GEE) for large-scale, continuous drought monitoring over extended periods. Additionally, research that thoroughly evaluates spatial variations in drought severity across diverse climatic zones within Rajasthan remains limited. This study addresses these gaps by employing a composite drought index (SDCI) that integrates the Temperature Condition Index (TCI), Precipitation Condition Index (PCI), and Vegetation Condition Index (VCI). By leveraging GEE's automated analysis capabilities, the study spans from 2010 to 2022, offering a robust framework for spatiotemporal drought assessment. The research explores how spatial and temporal drought patterns vary across different climatic regions of Rajasthan during the study period. It investigates which districts are most vulnerable to drought severity and examines the influence of climatic and anthropogenic factors on drought dynamics. Additionally, it evaluates how geospatial technologies, particularly cloud-based platforms like GEE, can enhance drought monitoring and inform targeted mitigation strategies in arid and semi-arid regions. This comprehensive approach provides valuable insights for policymakers to develop effective, location-specific drought management and adaptation strategies.

Given the extensive impacts of drought, effective monitoring and analysis are crucial for mitigation and adaptation strategies. Traditional methods of drought assessment often rely on ground-based measurements and historical data, which can be limited in scope and resolution. In contrast, modern technologies offer more comprehensive and timely insights (Qin et al., 2015). This study uses advanced geospatial technologies, specifically the Google Earth Engine (GEE), to conduct a spatiotemporal drought analysis in Rajasthan, India. GEE is a cloud-based platform that enables large-scale geospatial data analysis, providing access to vast datasets and powerful computational capabilities. Using satellite imagery and climate data, we can derive various drought indices to monitor and assess drought conditions over time (Du et al., 2013). Rajasthan, known for its arid and semi-arid climate, is particularly vulnerable to drought due to its dependence on monsoon rains and limited water resources. The state's agriculture, economy, and social structure are heavily influenced by water availability, making it an ideal case study for understanding drought dynamics and microclimate variability. This study aims to assess the current drought in Rajasthan and develop tools and methodologies that can be applied to other regions facing similar challenges. By integrating remote sensing data with advanced analytical techniques, we hope to provide a robust framework for drought monitoring and management, aiding policymakers and stakeholders in making informed decisions to mitigate the adverse effects of drought.

Materials and Methods

Study Area

Rajasthan, a state in India, is known for its beautiful landscapes and diverse ecology, nestled within the Thar Desert and representing a microcosm of global environmental challenges (refer to Fig. 1). With a population exceeding 77 million, Rajasthan's economy spans agriculture to tourism, closely tied to its natural resources such as land and water. However, rapid urbanization, unsustainable land use, and climate variability have strained its ecosystems, intensifying issues like soil erosion, water shortages, biodiversity decline, desertification, and forest cover loss. Covering approximately 342,239 square kilometers, Rajasthan is the largest state in India by land area, constituting about 10.4% of the country's total geographical area (refer to Fig. 1). It shares an international border with Pakistan to the west and northwest and is bordered by Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, and Gujarat. Geographically, Rajasthan features diverse landscapes, including the arid Thar Desert, rocky terrains, hilly regions of the Vindhya and Aravalli ranges, and fertile plains, resulting in climatic conditions ranging from extreme aridity to semi-arid and subtropical humid zones.

Data Collection

In this research, three remotely sensed derived indices—Vegetation Condition Index (VCI), Temperature Condition Index (TCI), and Precipitation Condition Index (PCI)—are used to assess drought conditions in Rajasthan from 2010 to 2022. These indicators are computed using the Google Earth Engine (GEE) platform. This service facilitates the retrieval of satellite imagery and remote sensing derived products, such as Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST), and Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data and processes them in the cloud. Temperature and vegetation parameters are acquired from

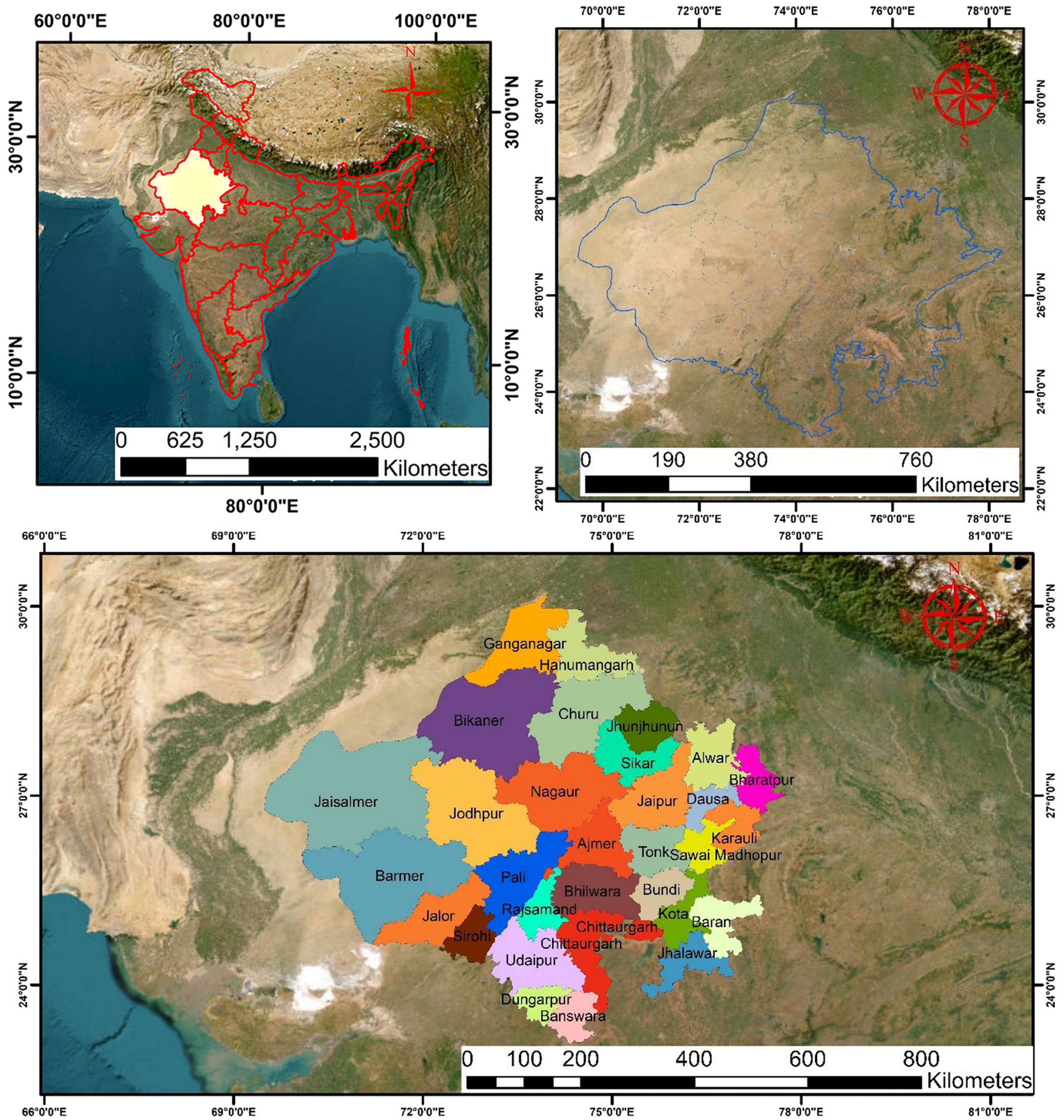


Fig. 1 Location of the study area

the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on the Terra satellite, while precipitation data are derived from CHIRPS. The datasets and sensors used are detailed in the subsequent sections. The results, presented in maps and charts, are imported into ArcGIS Pro v2.9 and Excel for map production, reclassification, and the final presentation. Additionally, the outcomes are available in the GEE applications, though customized graphs and figures can be created outside these apps.

Vegetation Condition Index (VCI)

The National Oceanic and Atmospheric Administration (NOAA) has designed an AVHRR-based Vegetation

Condition Index (VCI) that is highly useful for agricultural drought monitoring (Rojas, 2021). VCI compares the current NDVI to the range of values observed in the same period in previous years (Copernicus Global Land Service, https://land.copernicus.eu/global/products/vci, accessed on 21 February 2023) and can detect vegetation growth over a time interval. VCI is derived using Eq. (1) and can provide information about the intensity and extent of drought:

$$VCI = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \tag{1}$$

NDVI, $NDVI_{max}$ and $NDVI_{min}$ are the average monthly NDVI and the corresponding multi-year absolute maximum and minimum for the same month as NDVI, respectively. NDVI is obtained using MOD13Q1, a product of the MODIS sensor generated every 16 days at a 250 m resolution. Lower and higher values of VCI indicate poor and good vegetation state conditions, respectively (Chen et al., 2024; Nyongesa et al., 2023; Senhorelo et al., 2023). Since VCI does not apply to water bodies, areas where permanent water bodies cover at least 60% are masked from the map. The water bodies are detected using the MCD12Q1 product, Version 6.1, derived from supervised MODIS Terra and Aqua reflectance data classifications.

Temperature Condition Index (TCI)

The Temperature Condition Index (TCI) determines temperature-related vegetation stress and stress due to excessive moisture. This indicator has a formula similar to that of VCI. To calculate TCI, the MOD11A2 products of the MODIS sensor are used, which provide land surface temperature (LST) every eight days with a 1000 m spatial resolution. TCI is then obtained using Eq. (2) (Kogan, 1995).

$$TCI = \frac{T_{\max} - T}{T_{\max} - T_{\min}} \tag{2}$$

where T_{max} and T_{min} are the average monthly temperature derived from LST and its multi-year maximum and minimum for the same month, respectively, TCI varies from 0, indicating extremely unfavorable temperature conditions, to 1, indicating optimal temperature conditions.

Precipitation Condition Index (PCI)

Since one of the primary causes of aridity in any region is a lack of rainfall, it is essential to explicitly quantify the amount of rainfall in addition to the defined indicators. This research uses the Precipitation Condition Index (PCI) to evaluate precipitation patterns and detect precipitation deficits arising from climate signals (Karavitis et al., 2014). The PCI is calculated using data from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), a global dataset that combines satellite imagery with in-situ station data to provide a comprehensive view of rainfall distribution. The CHIRPS dataset offers high-resolution data that spans over three decades, enabling the analysis of long-term precipitation trends and anomalies. This robust dataset is instrumental in assessing the variability and changes in precipitation, which are critical for understanding the aridity conditions in the study region. The expression for calculating the PCI is as follows (Salameh, 2024).

$$PCI = \sum_{i=1}^{n} \frac{(p_i - p)^2}{np} \tag{3}$$

where P_i represents the monthly precipitation values, P denotes the long-term mean monthly precipitation, n is the number of months in the period of interest.

By applying the PCI, researchers can quantify the extent of precipitation deficits and surpluses, providing a clearer picture of the climatic conditions contributing to aridity. This information is crucial for developing strategies to mitigate the impacts of reduced rainfall and for better water resource management in arid regions.

Methodology

The methodology employed in this study begins with classifying Rajasthan’s territory into homogeneous climate zones using the De Martonne index, essential for accurately computing the SDCI combined index integrating the Temperature Condition Index (TCI), Vegetation Condition Index (VCI), and Precipitation Condition Index (PCI). This approach ensures the generation of coherent and region-specific values for TCI, VCI, and PCI, considering Rajasthan's diverse climatic and geographical characteristics. Remote sensing imagery, including MODIS sensor and CHIRPS data, forms the basis of data acquisition. Processing is automated through the Google Earth Engine (GEE) platform, harnessing its robust cloud computing capabilities for efficient and periodic monitoring of Rajasthan's territory. This framework provides timely insights into drought dynamics and microclimate variability, aiding decision-makers in the region's water resource management, agricultural planning, and environmental conservation efforts.

Climate Classification

The climate of Rajasthan, characterized by its diverse meteorological patterns over extended periods, necessitates a comprehensive analysis incorporating long-term data such as temperature, rainfall, humidity, radiation, and wind dynamics (MODIS and CHIRPS). To ensure consistent computation of drought indices, the territory is initially classified into homogeneous climate zones using the De Martonne aridity index (IDM) as outlined in Eq. (4) (Mishra et al., 2021). This classification is pivotal for accurately assessing drought conditions and microclimate variability across Rajasthan, leveraging cloud-based geospatial analysis facilitated by the Google Earth Engine (GEE) platform. This approach enhances understanding spatio-temporal drought dynamics and supports informed decision-making in sustainable water management, agriculture, and environmental conservation strategies tailored to Rajasthan's unique climatic contexts (Ismail & Go, 2021).

The De Martonne aridity index (IDM) is significant in research that integrates cloud-based geospatial analysis to comprehend spatiotemporal drought dynamics and microclimate variability in Rajasthan. The IDM is computed using the formula.

$$IDM = \frac{P}{\left(T_a + 10\right)} \tag{4}$$

P represents the annual rainfall amount obtained from CHIRPS data, and T_a signifies the mean yearly air temperature derived from the MODIS satellite's MOD11A2 product. This method utilizes a 12-year time series from January 2010 to December 2022, with data retrieval facilitated through the Google Earth Engine platform. Applying the De Martonne index (refer to Table 1), the study discerns specific climate types across Rajasthan, enabling the classification and comprehension of regional climatic variations crucial for evaluating drought conditions and microclimate dynamics. This comprehensive analysis provides valuable insights into the region's intricate patterns of drought and microclimate dynamics.

Scaled Drought Combined Indicator (SDCI)

This research uses cloud-based geospatial analysis to understand Rajasthan's drought dynamics and microclimate variability. Our approach uses the De Martonne aridity index to classify different climate types based on long-term precipitation and temperature data. Instead of analyzing drought across the entire region of Rajasthan, we are evaluating each climatic region separately. This allows us to assess changes in the Vegetation Condition Index (VCI), Temperature Condition Index (TCI) (Zhang et al., 2022), and Precipitation Condition Index (PCI) (Zhang et al., 2022) individually, providing a more detailed understanding of the conditions. These indices are then combined into the scaled drought condition index (SDCI), which gives us a comprehensive indicator to monitor drought severity and its implications for agriculture, weather, and hydrology. Unlike traditional methods, the SDCI allows for flexibility in monitoring drought across diverse climatic zones by adjusting the weighting of precipitation. The approach also assigns equal empirical weights to PCI, TCI, and VCI in Mediterranean, semi-arid, and arid zones, and these classifications are illustrated in Table 2 within the study's framework.

For semi-humid climate:

$$SDCI = \frac{1}{2}PCI + \frac{1}{4}TCI + \frac{1}{4}VCI \tag{5}$$

For arid, semi-arid, and Mediterranean climates:

$$SDCI = \frac{1}{3}PCI + \frac{1}{3}TCI + \frac{1}{3}VCI \tag{6}$$

Results

Drought Analysis over Rajasthan

In a recent study, researchers used cloud-based geospatial analysis to understand spatio-temporal drought dynamics and microclimate variability in Rajasthan, India. The study begins with an overview of Rajasthan's climate classification using the De Martonne index. Subsequently, the researchers analyze drought's spatial and temporal distribution across Rajasthan from January 2010 to December 2022 using the scaled drought condition index (SDCI). Their analysis reveals how unfavorable temperature extremes, such as very high or very low temperatures combined with low precipitation, contribute to lower values of vegetation condition index (VCI) and SDCI, highlighting prevalent drought conditions. The study also includes selected graphs illustrating significant changes

Table 1 The De Martonne aridity index classification

Type of climate	Values of IDM
Arid	IDM < 10
Semi-arid	10 ≤ IDM < 20
Mediterranean	20 ≤ IDM < 24
Semi-humid	24 ≤ IDM < 28

Table 2 Drought classification based on SDCI

Classification	SDCI index
Extreme drought	0 ≤ SDCI < 0.1
Severe drought	0.1 ≤ SDCI < 0.2
Moderate drought	0.2 ≤ SDCI < 0.3
Light drought	0.3 ≤ SDCI < 0.4
No drought	SDCI ≥ 0.4

and provides detailed discussions in subsequent sections. These insights are vital for comprehensively assessing and managing drought impacts in Rajasthan's diverse climatic settings.

Climate Classification of Rajasthan

The climate classification for Rajasthan is depicted in Fig. 2 using the De Martonne index (IDM) calculated over a specific study period. The IDM serves to quantify the relationship between precipitation and temperature, providing crucial insights into the aridity levels experienced in the region. Rajasthan encompasses diverse climatic zones. The arid zones, characterized by IDM values below 10, include Barmer, Bikaner, Churu, Hanumangarh, Jaisalmer, Jalore, Jhunjhunu, Jodhpur, Nagaur, Pali, Sikar, Sirohi, and Sri Ganganagar. These areas face severe water scarcity due to minimal rainfall compared to potential evapotranspiration, presenting significant challenges for agriculture and water management. The semi-arid zones, with IDM values ranging from 10 to 20, encompass Ajmer, Alwar, Banswara, Baran, Bharatpur, Bhilwara, Bundi, Chittorgarh, Dausa, Dholpur, Dungarpur, Jaipur, Jhalawar, Karauli, Kota, Pratapgarh, Rajsamand, Sawai Madhopur, Tonk, and Udaipur. These regions experience moderate to sporadic rainfall, which supports a mix of rainfed agriculture and semi-arid vegetation. The variations in precipitation and temperature patterns across these climatic zones significantly influence agriculture, water resource management, and ecological sustainability in Rajasthan. Developing tailored strategies that consider the specific climatic characteristics of each zone is essential for mitigating drought risks, improving agricultural productivity, and fostering sustainable regional development.

Arid Climate

The results of this study revealed significant temporal variations in drought severity, with notable drought years including 2010, 2012, and 2015, as well as better conditions in 2013 and 2016. Spatial analysis indicated more severe drought conditions in western Rajasthan, particularly in the Thar Desert region, compared to the eastern areas. Seasonal analysis identified pre-monsoon (March–May) and post-monsoon (October–December) periods as critical for drought development, with pre-monsoon periods often experiencing higher severity. Classifying homogeneous climate zones showed that arid and semi-arid zones were more vulnerable to droughts. A strong correlation between drought indices and agricultural productivity was established, highlighting significant declines in crop yields during severe drought years. Figure 3 presents the results from the analysis of SDCI, PCI, VIC, and TCI indices for arid climate.

The SDCI values for the 12 years indicate that moderate to severe dryness is a predominant weather condition in the

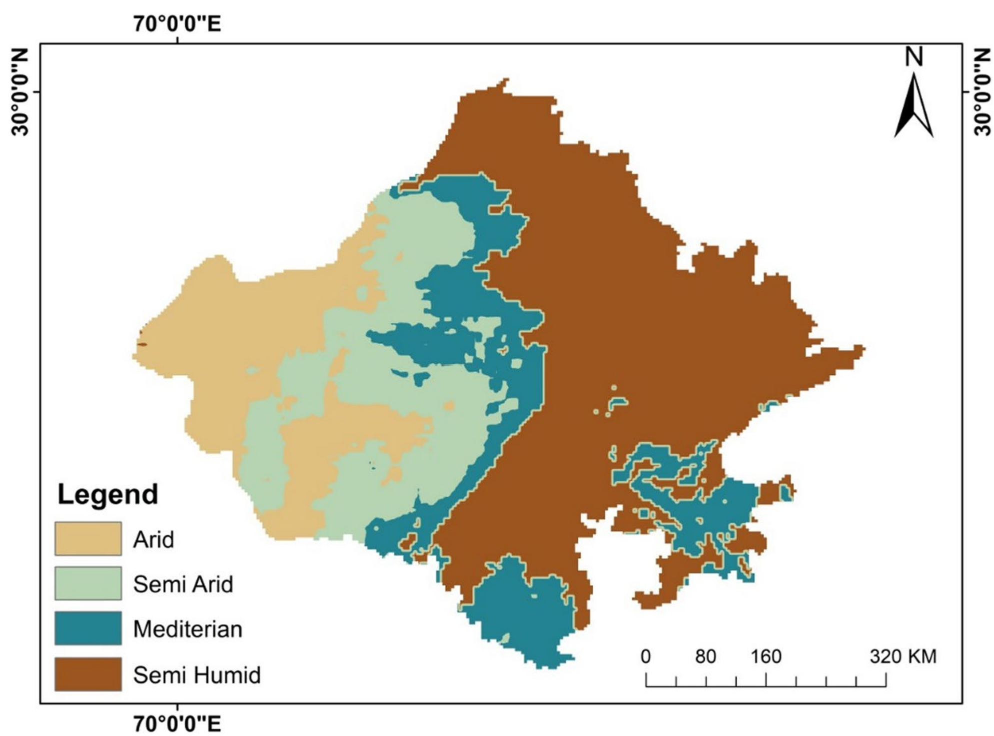
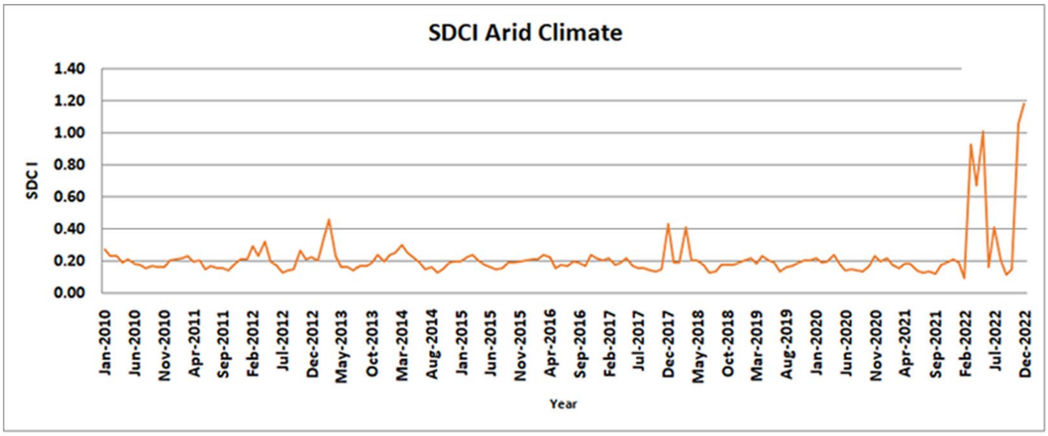
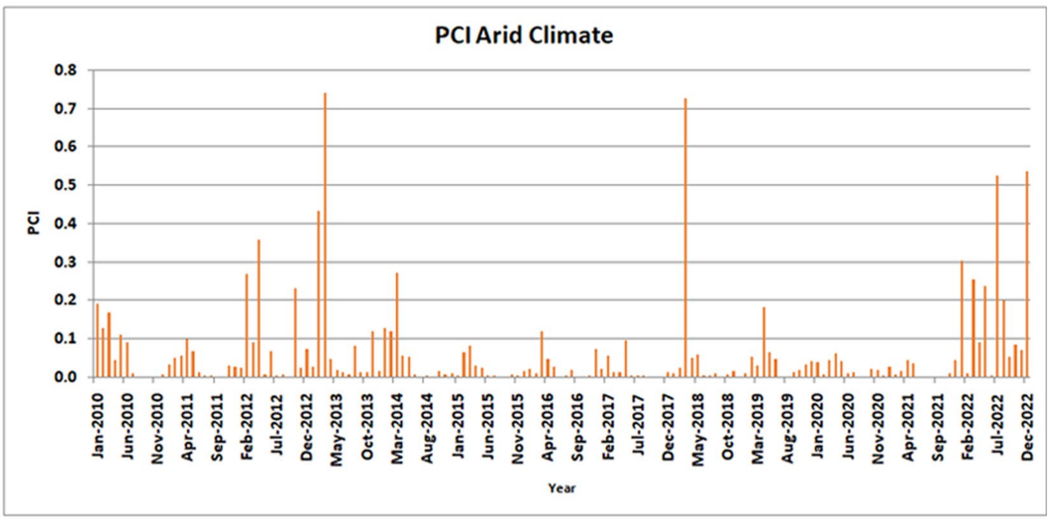


Fig. 2 Climate classes of Rajasthan



(a)



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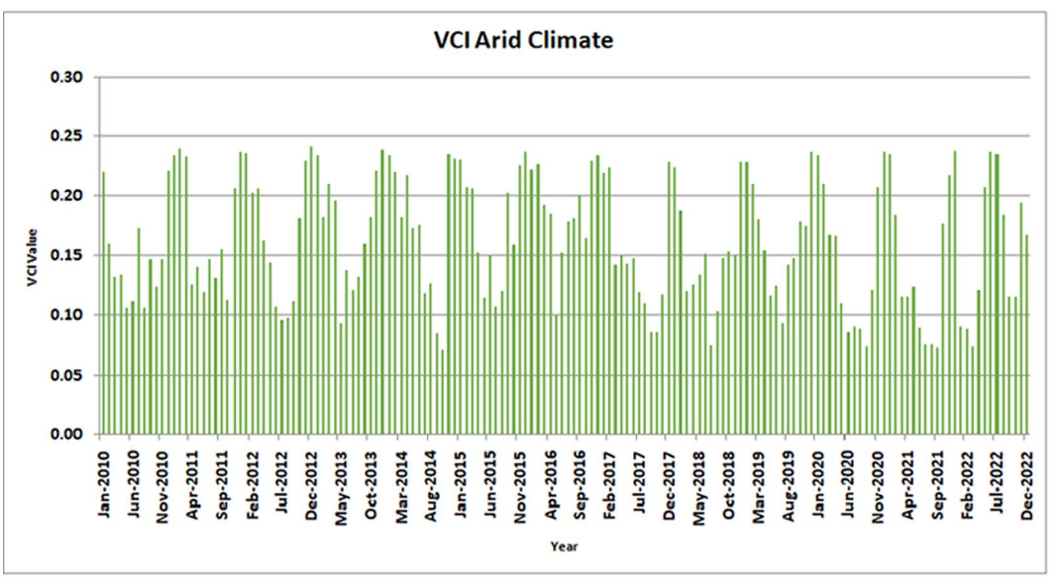
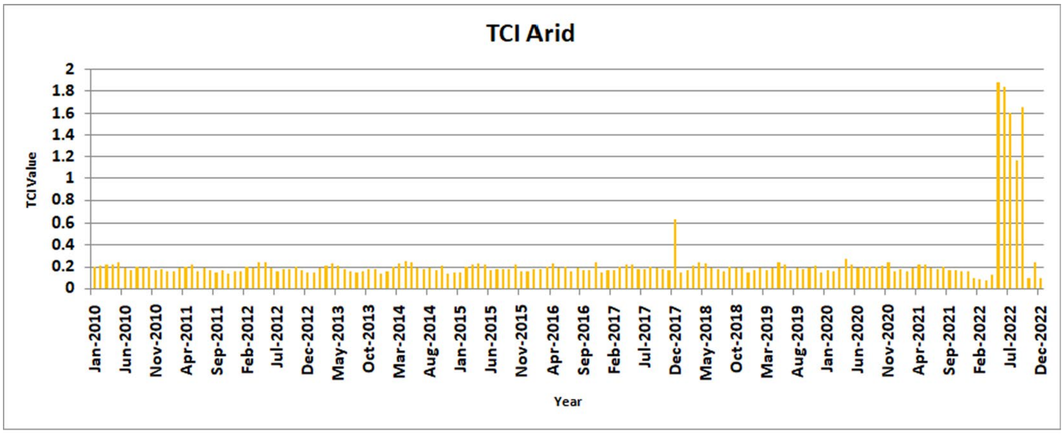


(c)

Fig. 3 Trends in arid climate from January 2010 to December 2022: **a** For SDCI, **b** For PCI, **c** For VCI, **d** For TCI



(d)

Fig. 3 (continued)

arid regions of Rajasthan, as illustrated in Fig. 3a. This persistent dryness, except for notable periods in March 2013, December 2017, and March 2018, reflects the undesirable weather conditions characterized by low precipitation and high vegetation stress, as indicated by the TCI, PCI, and VCI indices. Additionally, based on the De Martonne classification, the arid regions of Rajasthan exhibit these challenging conditions, highlighting the critical need for targeted drought management and microclimate adaptation strategies. Integrating cloud-based geospatial analysis provided a robust framework for real-time assessment and decision-making.

The Precipitation Condition Index (PCI) from January 2010 to December 2022 in Rajasthan's arid region exhibited dynamic temporal patterns linked closely to climatic variability. From January 2010 to December 2012, PCI values generally reflected favorable precipitation conditions, fluctuating seasonally with rainfall patterns. However, from January 2013 to December 2015, PCI experienced notable declines, coinciding with prolonged droughts that severely impacted water availability. Subsequent years, especially from January 2016 to December 2018, showed variable recovery trends in PCI amidst fluctuating precipitation levels. PCI values exhibited mixed trends from January 2019 to December 2022, responding to erratic precipitation and temperature shifts.

The observed PCI fluctuations underscore the region's susceptibility to climatic extremes, particularly droughts, which profoundly affect water resources. The period from 2013 to 2015 highlighted the critical role of precipitation in maintaining ecological balance in arid environments. Post-2015 recovery phases underscored the region's resilience to adapt to climatic variations, although effectiveness varied across different years and regions within Rajasthan. The alignment of PCI fluctuations with changes in the Standardized Drought Condition Index (SDCI) further emphasizes the strong correlation between precipitation conditions and drought severity. Integrating PCI and SDCI assessments proves valuable for comprehensive drought monitoring and adaptive management strategies in arid regions, such as Rajasthan, and is essential for enhancing resilience and sustainability in water resource management under changing climatic conditions. The temporal trends of the Precipitation Condition Index (PCI) from 2010 to 2022 are depicted in Fig. 3b, illustrating fluctuations that reflect the region's sensitivity to climatic variability and drought impacts.

Analysis of Vegetation Condition Index (VCI) trends from January 2010 to December 2022 Fig. 3c revealed significant temporal variability in vegetation health in the arid region of Rajasthan. VCI values fluctuated widely over the study period, reflecting sensitivity to climatic conditions such as rainfall and drought events. 2010–2012 generally exhibited moderate to high VCI values, indicative of favorable vegetation conditions following adequate rainfall. However, 2013 to 2015 saw pronounced declines in VCI, signaling vegetation stress during prolonged droughts. Subsequent years showed partial recovery, with VCI values from 2016 to 2018 fluctuating but generally recovering to moderate levels. The latter part of the study period, from 2019 to 2022, displayed mixed trends, with VCI values varying in response to seasonal rainfall patterns. Looking forward, projections for the next six years (2023–2028) suggest potential challenges due to predicted shifts in precipitation patterns and increasing variability in climate conditions. These findings underscore the dynamic nature of vegetation responses to climatic variability and highlight the importance of adaptive management strategies to enhance resilience and sustainable land use practices in arid regions.

The Temporal Climate Index (TCI) data from January 2010 to December 2022 for the arid region of Rajasthan reveal significant variability in climatic conditions over the study period. From January 2010 to December 2015, TCI values generally remained low, indicating prolonged periods of dry and unfavorable climatic conditions. This period corresponds to severe drought years, as reflected in the TCI data, with notable dips in values during certain months, such as May 2010, September 2012, and November 2014, suggesting acute climatic stress affecting the region's agricultural and ecological systems. From January 2016 onwards, the TCI shows a mixed pattern of recovery and variability. Some years exhibit moderate to high TCI values, indicating relatively better climatic conditions and recovery phases following drought periods. For instance, notable peaks in TCI values occurred in March 2016, April 2018, and September 2019, reflecting periods of improved climatic conditions conducive to agriculture and environmental stability. However, the data also highlight continuing challenges, with fluctuations in TCI values post-2016 underscoring ongoing climatic variability and occasional stress periods despite recovery trends. Figure 3d illustrates the temporal variation in TCI from 2010 to 2022, emphasizing the arid region's dynamic nature of climatic conditions. This graphical representation visually captures the peaks and troughs in TCI values, clearly depicting climatic variability and its impact on regional water resources and agricultural productivity. About the Standardized Drought Condition Index (SDCI), the fluctuations observed in TCI closely align with changes in drought severity, as reflected in supplementary data (not shown). This alignment underscores the interplay between precipitation deficits, temperature variations, and overall climatic stress, highlighting the interconnectedness of TCI and SDCI in assessing and monitoring drought impacts in arid regions like Rajasthan. Effective drought management strategies, informed by integrated TCI and SDCI assessments, are crucial for mitigating agricultural losses, sustaining water availability, and enhancing resilience to future climatic uncertainties.

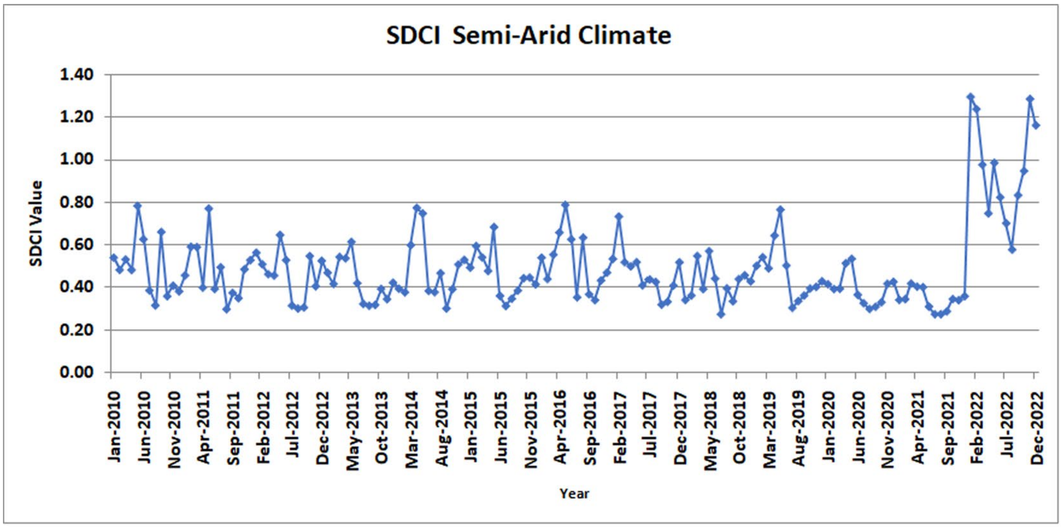
Semi-Arid Climate

SDCI values in a semi-arid area, as depicted in Fig. 4a from 2010 to 2022, exhibit dynamic fluctuations indicative of the region's susceptibility to varying drought conditions. Over this period, the data illustrate a range of drought intensities from mild to moderate, with periodic occurrences of more severe drought events. Particularly noteworthy are the summer months, which consistently show heightened drought stress, often followed by periods of relief during the fall with increased rainfall and moderate weather conditions, benefiting vegetation and soil health. The analysis reveals several notable periods of extreme and severe drought, including significant episodes in July 2018 and July to September 2021. These instances underscore the severe impacts of prolonged droughts on the ecosystem, highlighting the critical need for adaptive management strategies to mitigate drought effects and enhance resilience in semi-arid environments.

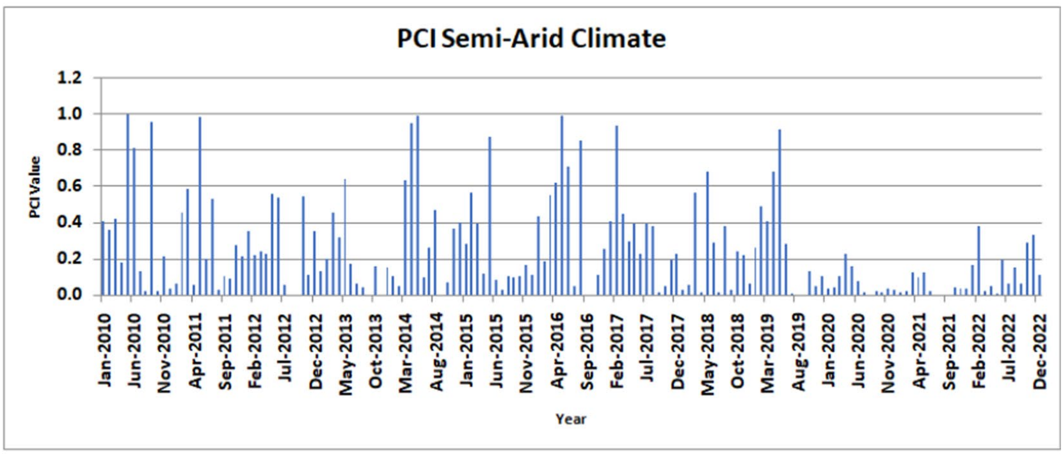
The Precipitation Concentration Index (PCI) data from January 2010 to December 2022 is in the semi-arid region. Figure 4b have revealed significant variations in rainfall distribution, which have directly affected drought conditions as indicated by the Standardized Drought Condition Index (SDCI). The higher PCI values during concentrated rainfall periods in mid-2010, mid-2015, and mid-2020 are associated with lower SDCI values, indicating less severe drought conditions. Conversely, lower PCI values in early 2018 and early 2022 have corresponded to higher SDCI values, suggesting more intense drought episodes. This connection emphasizes the vital impact of rainfall distribution on drought severity. It underscores the necessity for effective water resource management and adaptive measures to alleviate the effects of drought in semi-arid environments.

Significant seasonal and annual variations were observed in analyzing Vegetation Condition Index (VCI) data from January 2010 to December 2022 Fig. 4c for the Semi-Arid region. VCI values fluctuate seasonally, reflecting vegetation response to varying climatic conditions, with specific years showing distinct trends of higher or lower VCI values, indicative of better or poorer vegetation health, respectively. Extreme VCI values during particular months and years suggest occurrences of severe weather events like droughts or excessive rainfall. The relationship between VCI and the Standardized Drought Condition Index (SDCI) highlights VCI's role in assessing drought severity, which is crucial for understanding impacts on agriculture and ecosystems. By comparing VCI trends with historical rainfall patterns and other indices, correlations were drawn to validate vegetation health assessments and inform adaptive management strategies in semi-arid regions vulnerable to droughts. Visual representation in Fig. 4c illustrates these trends, aiding in the interpretation of long-term vegetation dynamics and their implications for sustainable land management practices.

The Transformed Soil Moisture Index (TCI) data from January 2010 to December 2022 in the Semi-Humid region exhibit seasonal variability and annual trends (refer to Fig. 4d). TCI values fluctuate across months, indicating variations in soil moisture content influenced by seasonal rainfall patterns. Higher TCI values during monsoon months like July to September suggest increased soil moisture, which is critical for agricultural productivity. Conversely, lower TCI values in dry months such as April and May indicate drier soil conditions. Figure 4d illustrates these fluctuations, showing peaks during monsoon periods and troughs during dry seasons. The relationship between TCI and the Standardized Drought Condition Index (SDCI) reveals TCI's role in assessing drought severity; periods with consistently low TCI values often correlate with higher SDCI scores, indicative of drought conditions. Understanding these dynamics is



(a)



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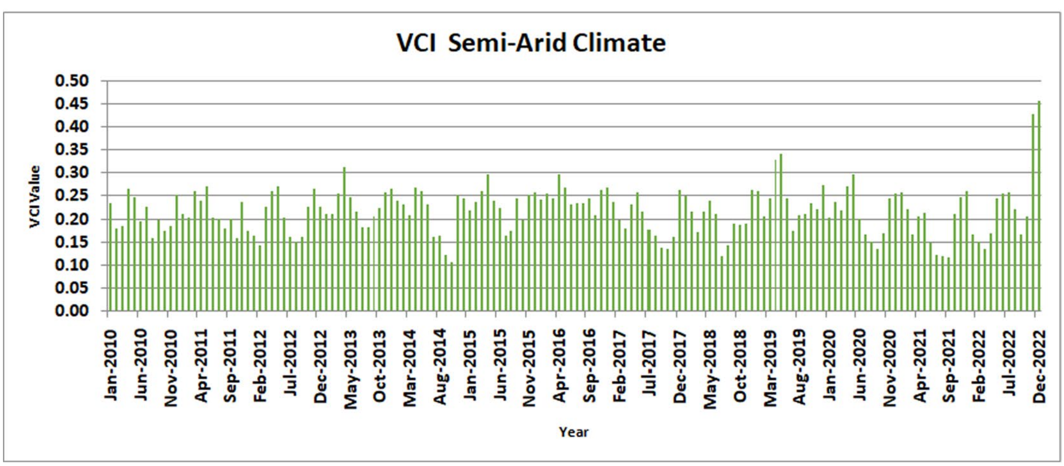
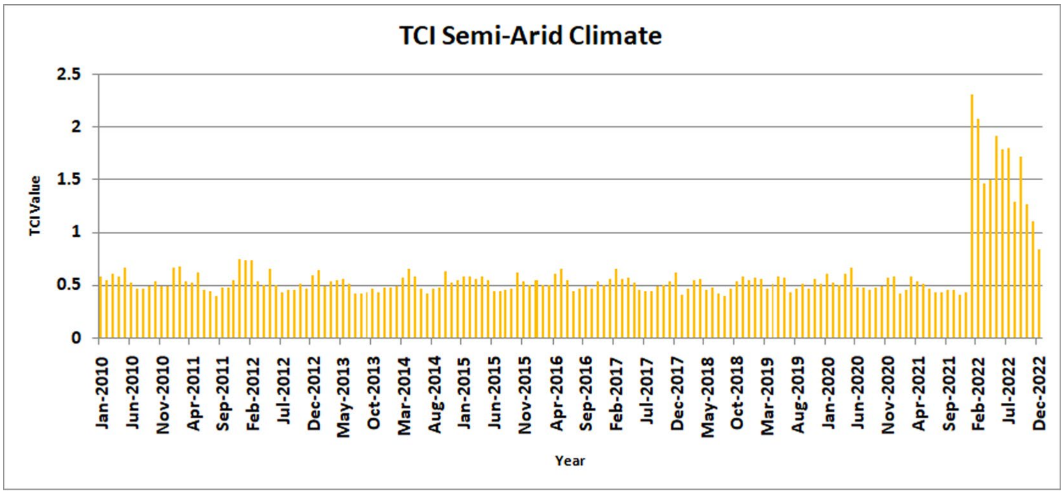


(c)

Fig. 4 Trends in semi-arid climate from January 2010 to December 2022: **a** For SDCI, **b** For PCI, **c** For VCI, **d** For TCI



(d)

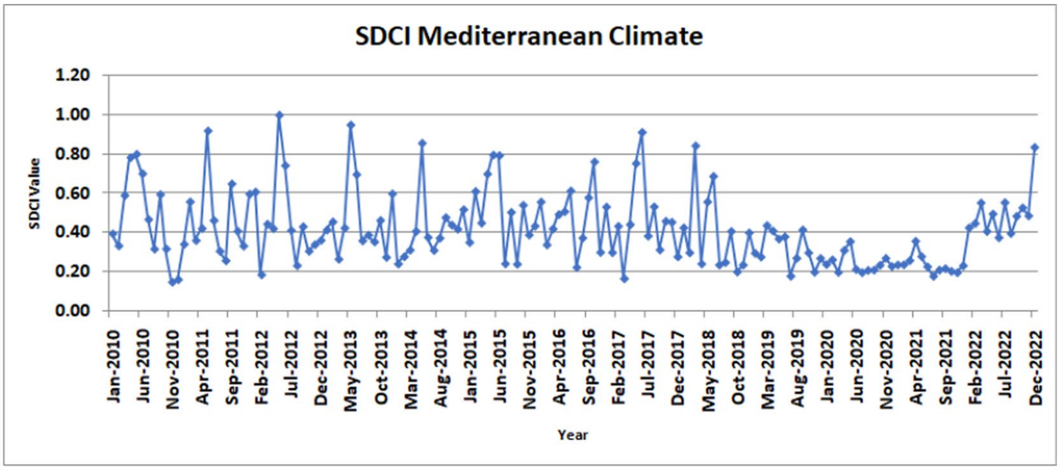
Fig. 4 (continued)

crucial for water resource management and agricultural planning in semi-humid regions vulnerable to drought impacts.

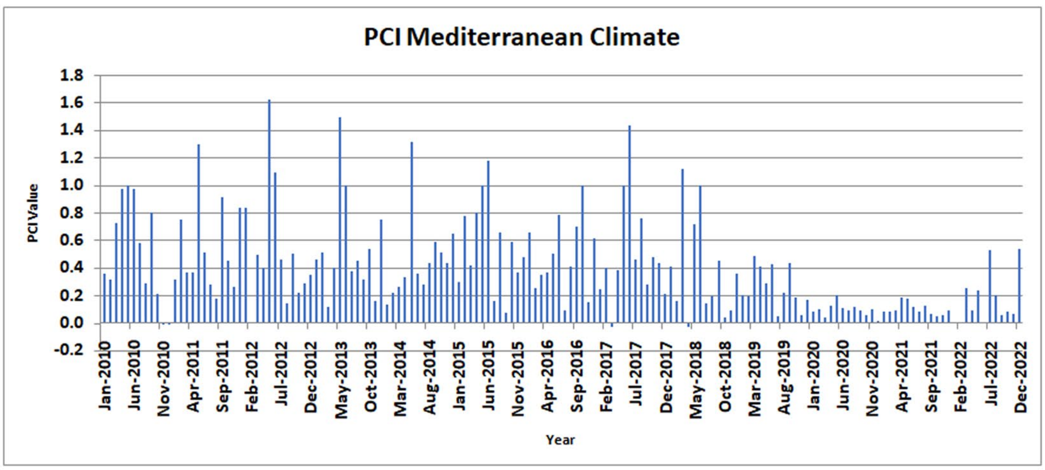
Mediterranean Climate

The Seasonal Drought Severity Index (SDCI) data from January 2010 to March 2023 for the Mediterranean climate region reflect significant variations and trends in drought severity over time (refer to Fig. 5a). Initially, from January 2010 to December 2012, SDCI values generally exhibit moderate fluctuations with occasional peaks, suggesting intermittent drought conditions interspersed with relatively regular periods. Notably, from April 2010 to September 2010, there is a sustained increase in SDCI values, indicating a prolonged dry spell likely impacting agricultural and environmental conditions. This pattern recurs in subsequent years, such as from June to September 2011, where SDCI peaks suggest severe droughts, possibly influenced by climatic oscillations or regional weather anomalies. From 2013 onwards, there is a discernible shift in SDCI dynamics, characterized by more frequent and intense drought episodes, notably in the summer months (June–August). These periods often exhibit consistently high SDCI values, indicative of severe and prolonged drought conditions that likely exacerbate agricultural stress and water resource management challenges. For instance, from June to August 2015 and June to July 2017, SDCI values reached peaks, aligning with historically dry periods that can strain the region's water availability and agricultural productivity. The relationship between SDCI and drought impacts underscores their socio-economic implications, particularly in Mediterranean climates reliant on stable farm production and water resources. High SDCI values coincide with reduced water availability, impacting crop yields and increasing dependency on irrigation practices. Furthermore, the ecological consequences of prolonged droughts are evident in vegetation stress and land degradation, influencing biodiversity and ecosystem resilience. Analyzing Fig. 5a, which likely depicts the temporal distribution of SDCI values and their corresponding drought severity categories, reveals seasonal trends and interannual variability. Peaks in SDCI during specific months highlight critical periods of water stress, which are crucial for understanding vulnerability and resilience in the face of climate change. The variability observed underscores the importance of adaptive strategies in agriculture, such as crop diversification and improved water management practices, to mitigate drought impacts. In conclusion, the SDCI data analysis for the Mediterranean climate region illustrates the complex interplay between climate variability, drought severity, and socio-economic impacts. The insights gained are essential for informing policy interventions and adaptive strategies to enhance resilience and sustainable development in drought-prone regions. Future research could focus on refining predictive models using advanced statistical techniques and integrating socio-economic indicators to effectively strengthen drought preparedness and response frameworks.

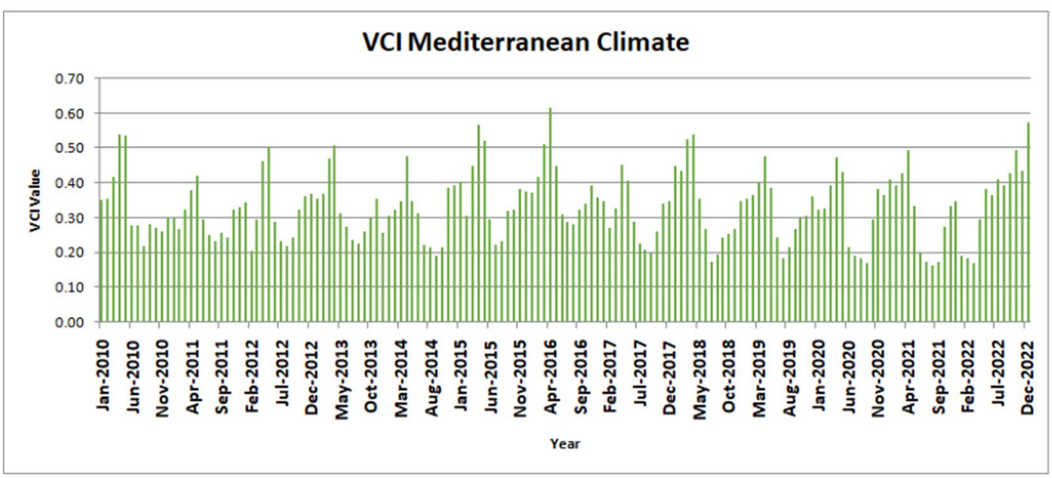
Analyzing the PCI (Percent of Normalized Difference Vegetation Index (NDVI) Composite Index) data from January 2010 to December 2022 for the Mediterranean Climate region provides a comprehensive insight into vegetation dynamics and their correlation with climatic conditions and drought resilience. The PCI values exhibit notable seasonal variations, peaking during cooler, wetter months (November–April) and declining sharply during the hot, dry summer period (June–August) (refer to Fig. 5b). This pattern reflects vegetation's response to moisture availability, which



(a)

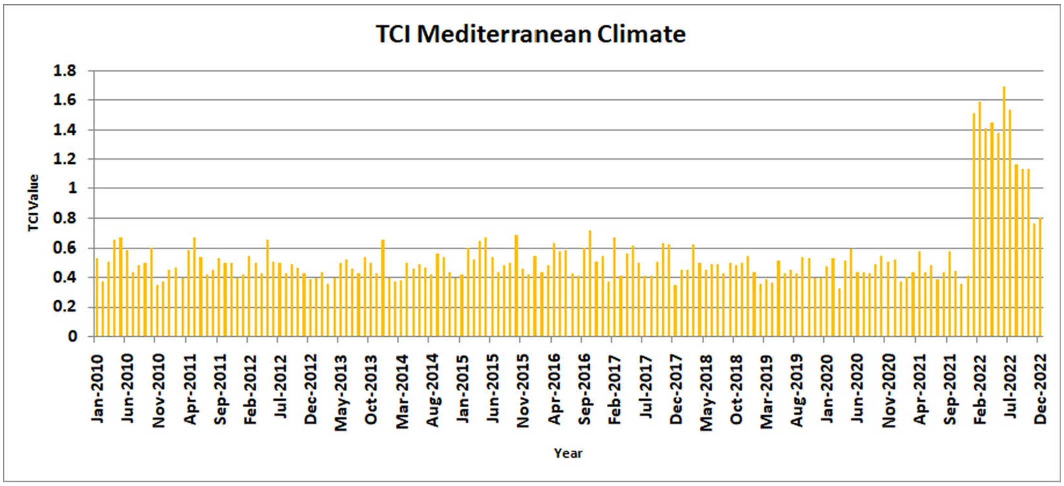


(b)



(c)

Fig. 5 Trends in Mediterranean climate from January 2010 to December 2022: **a** For SDCI, **b** For PCI, **c** For VCI, **d** For TCI



(d)

Fig. 5 (continued)

is crucial for sustaining health and productivity. Across the years, fluctuations in PCI values underscore the region's susceptibility to climatic variability, with years like 2010 and 2013 showcasing higher average PCI values indicative of favorable conditions, whereas drier periods such as 2017 and 2020 reveal lower PCI values, signaling heightened water stress and reduced vegetation vigor. These trends align closely with the region's climatic cycles, where winter rainfall rejuvenates vegetation while summer droughts constrain growth. The PCI's relationship with the Standardized Precipitation Evapotranspiration Index (SPEI) further elucidates its role in drought assessment, where high PCI values correspond to lower SPEI values, indicating less severe drought impacts, and vice versa. Figure 5b likely illustrates these dynamics visually, capturing the temporal variability and long-term trends in PCI across seasons and years. Such visual representations are crucial for policymakers and environmental managers, facilitating informed decisions regarding water resource management, agricultural planning, and ecosystem conservation in the Mediterranean region. By integrating PCI insights with SPEI and other climate indices, stakeholders can proactively mitigate drought risks, enhance agricultural resilience, and safeguard ecosystem health amid evolving climate conditions, ensuring sustainable development and resource use in this ecologically sensitive area.

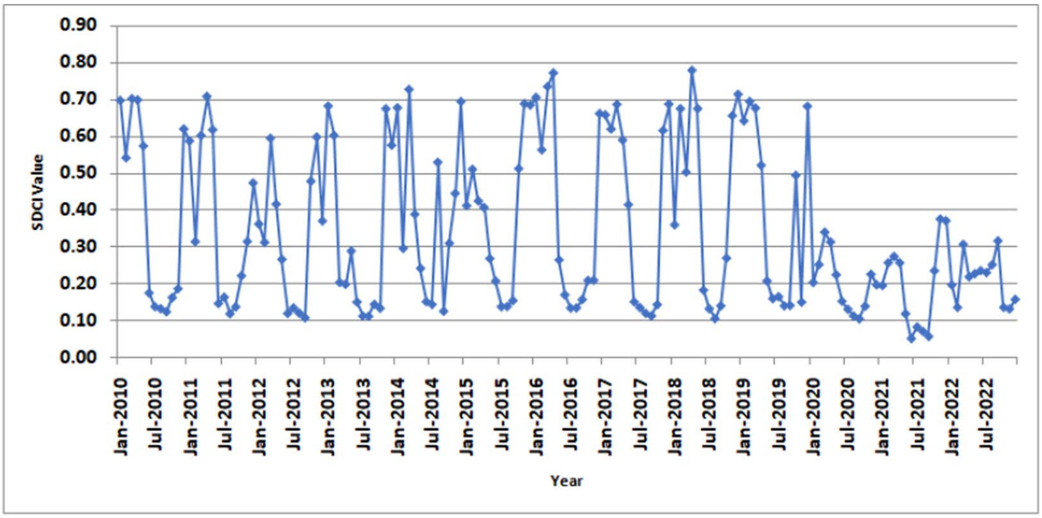
The Vegetation Condition Index (VCI) data for the Mediterranean Climate region from January 2010 to December 2023 reveals significant variability and trends in vegetation health over the years (refer to Fig. 5c). VCI, a key indicator derived from satellite data, reflects vegetation's greenness or health status, crucial for understanding ecosystem dynamics and agricultural productivity. Initially, from January 2010 to December 2012, VCI values exhibit moderate fluctuations, with peaks observed in March and April coinciding with spring growth, and dips during dry summer months like July and August. This pattern indicates seasonal variations typical of Mediterranean climates, where vegetation responds strongly to winter rains and summer droughts. From January 2013 to December 2015, VCI trends show increased variability, possibly influenced by climatic anomalies or human activities impacting vegetation resilience. From January 2016 onwards, VCI values generally depict a recovering trend, with periodic spikes in March and April, suggesting improved vegetation health, possibly due to better precipitation distribution or adaptive agricultural practices. However, intermittent dips in VCI during mid-year months like July and August indicate recurring susceptibility to dry spells, underscoring the region's vulnerability to climate variability. The highest recorded VCI peaks in May 2012, May 2015, and April 2016 coincide with exceptional vegetation vigor, likely influenced by favorable climate conditions promoting robust growth. Analyzing the relation between VCI and the Standardized Drought Condition Index (SDCI) reveals complementary insights into drought impacts on vegetation health. For instance, periods of low VCI align with elevated SDCI values, indicating severe drought stress adversely affecting vegetation. Conversely, periods of high VCI correspond with lower SDCI values, signifying improved vegetation health during relatively wetter conditions. This inverse relationship underscores the utility of VCI as an early warning tool for drought impacts on agricultural productivity and ecosystem stability in Mediterranean climates. Furthermore, comparing VCI trends with historical drought records and agricultural productivity data could enhance our understanding of long-term ecosystem resilience and adaptation strategies. Integrating such analyses with regional climate models and land-use dynamics would provide a comprehensive framework for sustainable land management and policy formulation to mitigate climate risks and enhance agricultural resilience. In conclusion, the VCI dataset for the Mediterranean Climate region highlights nuanced seasonal patterns and long-term trends crucial for informed decision-making in climate adaptation and sustainable development efforts.

The Total Vegetation Condition Index (TCI) dataset for the Mediterranean Climate region from January 2010 to December 2022 illustrates significant variability in vegetation health over the years, crucial for understanding ecosystem dynamics and climate impacts (refer to Fig. 5d). Initially, from January 2010 to December 2012, TCI values fluctuated moderately, peaking in the spring months (March–May) and declining during the dry summer (June–August). This pattern reflects typical Mediterranean climate dynamics, where vegetation responds positively to winter rains and faces stress during prolonged dry spells. Notably, from January 2013 to December 2015, TCI trends indicate increased variability, potentially influenced by climatic anomalies affecting vegetation resilience. From January 2016 onwards, TCI generally shows a recovering trend, with peaks observed in spring (March–May), indicating improved vegetation vigor, possibly due to better rainfall distribution or adaptive land management practices. However, periodic dips in TCI during summer months (July and August) suggest ongoing vulnerability to seasonal drought impacts, highlighting the region's sensitivity to climate variability. The highest TCI peaks in May 2012, May 2015, and April 2016 coincide with periods of optimal vegetation health, likely influenced by favorable climate conditions supporting robust growth. Analyzing the relationship between TCI and the Standardized Drought Condition Index (SDCI) provides insights into drought impacts on vegetation. Periods of low TCI correspond with elevated SDCI values, indicating severe drought stress detrimental to vegetation health. Conversely, periods of high TCI align with lower SDCI values, suggesting improved vegetation conditions during less severe drought periods or favorable climatic conditions. This inverse correlation underscores TCI's utility as an indicator for monitoring vegetation resilience and assessing drought impacts on agricultural productivity and ecosystem stability in Mediterranean climates. Figure 5d depicts the temporal variability of TCI across the Mediterranean Climate region from January 2010 to December 2022. The graph highlights seasonal fluctuations and long-term trends in vegetation health, emphasizing peak values during spring months and declines during summer droughts. This visual representation underscores the seasonal dynamics and interannual variability crucial for understanding ecosystem responses to climate fluctuations. In conclusion, the TCI dataset for the Mediterranean Climate region provides valuable insights into vegetation dynamics, climate resilience, and drought impacts over the past decade. Integrating these findings with regional climate models and land-use dynamics can enhance sustainable land management strategies and policy interventions to mitigate climate risks and promote ecosystem resilience in Mediterranean environments.

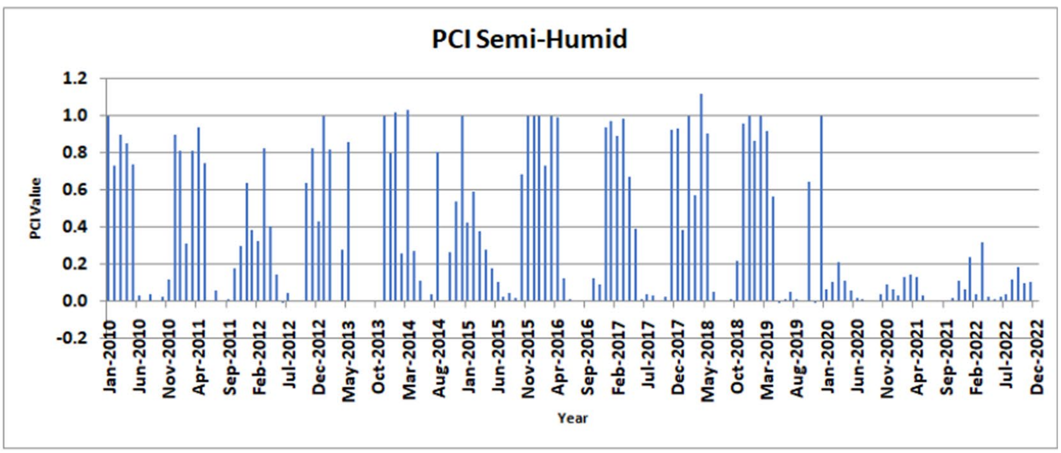
Semi-humid Climate

Analyzing the Standardized Drought Climate Index (SDCI) data for the Semi-humid Climate region from 2010 to 2022 reveals significant insights into drought dynamics and their implications (refer to Fig. 6a). The SDCI, derived from temperature and precipitation data, is a crucial metric for assessing drought severity relative to long-term averages. Over this period, trends in SDCI values exhibit notable variability and trends, reflecting the region's susceptibility to climate extremes. Beginning with 2010, the data indicate relatively moderate SDCI values, suggesting normal to slightly dry periods. However, as the years progress, there is a noticeable shift towards more pronounced fluctuations, with intermittent spikes in SDCI values indicating periods of heightened drought severity. Notably, 2015 and 2019 stand out with sustained periods of elevated SDCI values, signifying prolonged drought episodes that likely significantly stress the region's agricultural productivity and water resources. Conversely, years like 2013 and 2018 display more neutral or negative SDCI values, indicative of wetter conditions or temporary relief from drought impacts. Spatially, Fig. 6a illustrates the distribution of SDCI across the Semi-humid Climate zone, highlighting localized variations in drought severity over time. Such spatial insights are crucial for understanding the uneven impact of drought on different areas within the region, influencing water management strategies and agricultural planning. The relationship between SDCI values and drought impacts underscores the index's utility in informing resilience strategies, emphasizing the need for adaptive measures to mitigate drought's socio-economic and environmental consequences. Overall, the analysis of SDCI data from 2010 to 2022 in the Semi-humid Climate region illuminates the complex interplay of climate variability and drought dynamics, providing a foundation for targeted interventions and policy frameworks to enhance climate resilience and sustainable development in vulnerable regions.

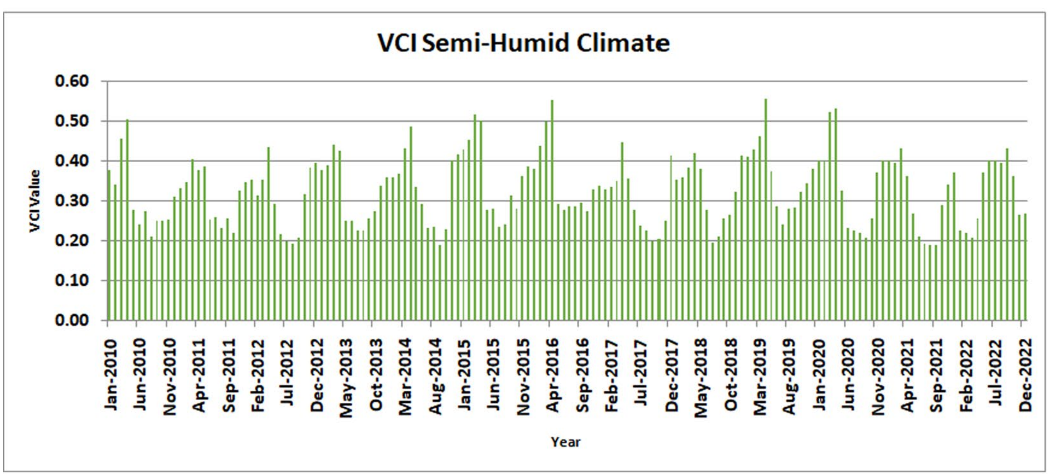
The Precipitation Condition Index (PCI) data for the Semi-humid Climate region from January 2010 to September 2022. Figure 6b shows variability in drought conditions over time. Generally, PCI values fluctuate seasonally, with higher values indicating better conditions for agriculture and lower values suggesting increased drought risk. For instance, from 2010 to early 2013, PCI values were relatively stable, reflecting moderate conditions. However, from mid-2013 to 2015, PCI decreased significantly, indicating prolonged



(a)

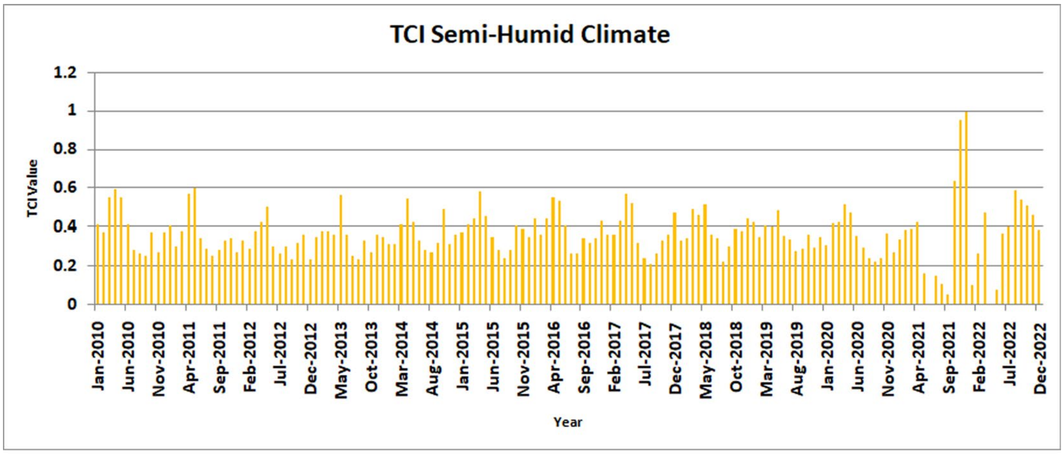


(b)



(c)

Fig. 6 Trends in semi-humid climate from January 2010 to December 2022: **a** For SDCI, **b** For PCI, **c** For VCI, **d** For TCI



(d)

Fig. 6 (continued)

drought conditions, particularly severe in early 2014 and 2015. This period likely impacted agricultural productivity and water availability in the region. Post-2015, PCI values recovered somewhat but remained variable, highlighting ongoing climatic fluctuations and the region's vulnerability to drought events. Overall, the PCI data illustrate the dynamic nature of drought in the semi-humid climate region, emphasizing the need for adaptive water management strategies and resilient agricultural practices to climate variability.

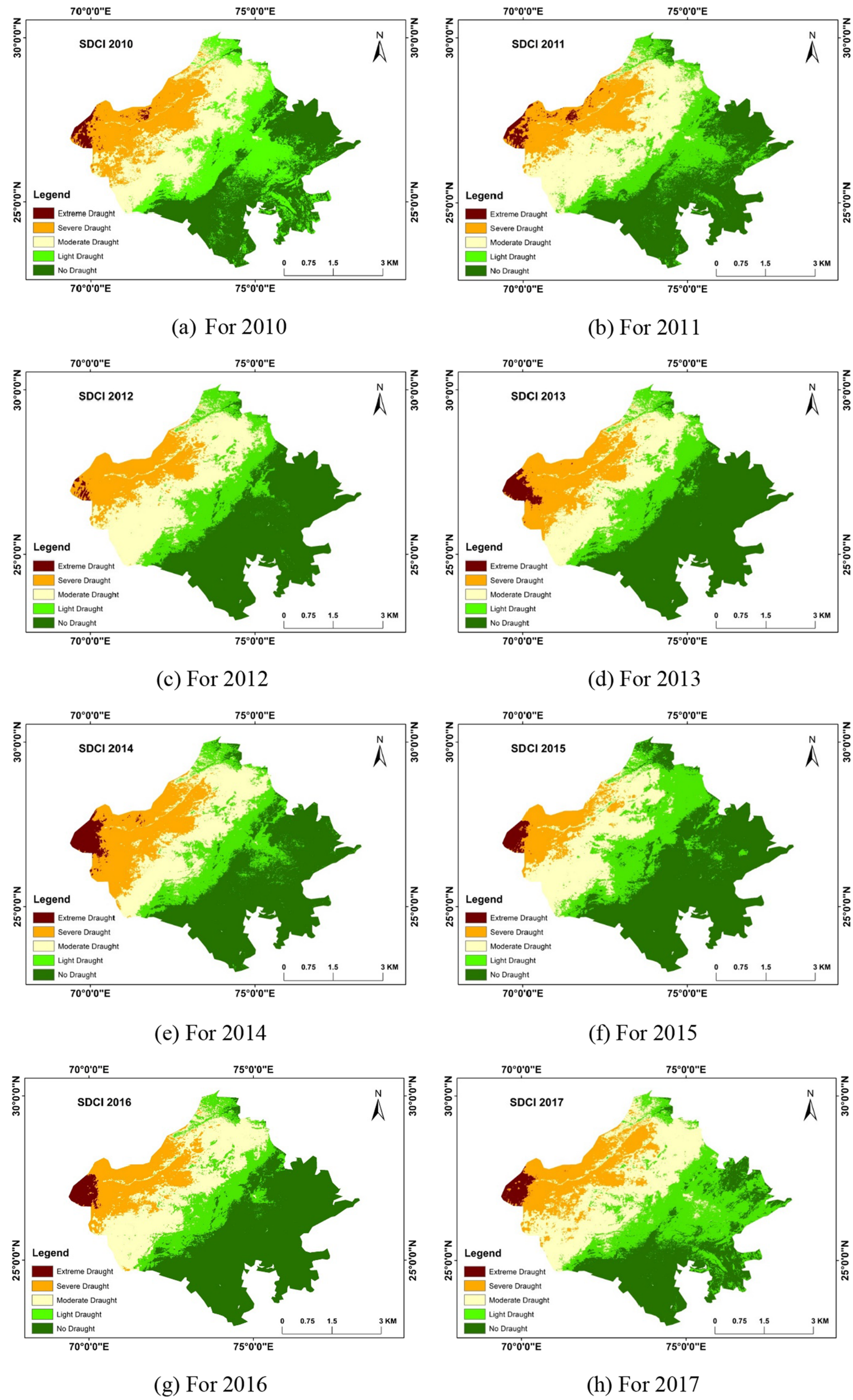
We discovered significant insights into vegetation health and its relationship with drought conditions after carefully analyzing the Semi-humid Climate region's Vegetation Condition Index (VCI) data from January 2010 to December 2023 (refer to Fig. 6c). The VCI values fluctuate throughout the years, reflecting the seasonal and yearly variations in vegetation greenness. From January 2010 to December 2013, VCI values generally indicate moderate to good vegetation condition, with occasional declines suggesting periods of stress possibly due to insufficient rainfall or other environmental factors. Peaks in VCI, such as in May 2011 and May 2012, correspond to periods of solid vegetation growth, likely influenced by favorable precipitation levels. Conversely, low VCI values during drought indicate vegetation stress due to reduced water availability. From 2014 to 2017, the VCI data trended towards lower values, particularly from October 2014 to May 2015 and September 2016 to December 2017, indicating prolonged drought impacts on vegetation health. These periods coincide with less favorable climatic conditions, potentially exacerbating agricultural challenges and environmental stressors in the Semi-humid Climate region. The recovery phases, notably from February 2016 to May 2016 and April 2017 to May 2018, demonstrate improved vegetation following enhanced rainfall and drought mitigation. Examining Fig. 6c alongside VCI data provides visual context to these observations. The graph illustrates how VCI trends align with broader climatic patterns and regional drought occurrences. Peaks and valleys in the VCI data correspond closely with shifts in climatic conditions, underscoring the index’s sensitivity to environmental factors impacting vegetation growth. The relationship between VCI and drought is evident through prolonged periods of low VCI values coinciding with drought phases, highlighting the index's utility in monitoring drought impacts on vegetation health over time. Furthermore, the analysis emphasizes the need for adaptive management strategies in agriculture and natural resource management to mitigate the effects of climate variability and drought. Integrating remote sensing-based indices like VCI can enable proactive measures by providing timely information on vegetation health dynamics, aiding in early warning systems and decision-making processes. Continuous monitoring and analysis of VCI trends are vital for assessing ecosystems' long-term resilience and vulnerability to climate change and variability in the Semi-humid Climate region. The VCI dataset for the Semi-humid Climate region highlights the complex interplay between vegetation dynamics, climate variability, and drought impacts. A comprehensive data analysis offers valuable insights for policymakers, researchers, and stakeholders in environmental conservation, agriculture, and water resource management. It underscores the importance of proactive strategies to enhance resilience and sustainability in vulnerable regions, emphasizing the practical implications of the research.

Analyzing the Temperature Condition Index (TCI) for the Semi-humid Climate region from January 2010 to December 2022 provides critical insights into the temperature-related stress on vegetation and its correlation with drought conditions (refer to Fig. 6d). The TCI values, which range from 0 to 1, with higher values indicating better vegetation health, vary significantly over the years, reflecting changes in temperature conditions. In Fig. 6d, the TCI data demonstrate a complex pattern of temperature stress on vegetation, with noticeable fluctuations corresponding to seasonal changes and long-term climatic trends. For instance, the period from January 2010 to December 2013 shows moderate TCI values, with some seasonal peaks in May and troughs in August, indicating periods of relative temperature favorability and stress, respectively. From January 2010 to May 2010, the TCI values remain moderate, indicating relatively stable temperature conditions. However, a decline in TCI values from June to September 2010 suggests increased temperature stress during the peak summer months, likely exacerbating drought conditions. This pattern is recurrent in subsequent years, where TCI values dip during summer, highlighting the detrimental impact of high temperatures on vegetation health. For example, the period from January 2011 to May 2011 shows higher TCI values, indicating better temperature conditions, which correspond to improved vegetation health, as depicted in Fig. 6d. However, the summer months of 2011 again show a decline in TCI values, reflecting increased temperature stress. In 2014 and 2015, TCI values exhibit more variability, with significant drops in the summer months (June to September), indicating severe temperature stress. This period aligns with documented drought conditions, further emphasizing the impact of high temperatures on vegetation health. The relationship between TCI and drought is evident as lower TCI values correspond to periods of drought, highlighting the role of temperature in exacerbating drought conditions. For instance, the low TCI values in July and August 2015 correlate with severe drought conditions, as depicted in Fig. 6d, indicating the compounded stress on vegetation due to high temperatures and water scarcity. The years 2016 to 2018 show a mix of moderate to high TCI values, with occasional dips during the summer months. For example, the TCI values in July and August 2017 are shallow, indicating high-temperature stress during drought. This pattern continues into 2019 and 2020, where TCI values exhibit seasonal peaks and troughs corresponding to temperature fluctuations. Notably, the TCI values in 2021 and 2022 show significant anomalies, with extremely low values in the summer, reflecting severe temperature stress during drought conditions. For instance, the TCI values in June and July 2021 are particularly low, indicating extreme temperature stress during a severe drought period. Overall, the TCI data for the Semi-humid Climate region underscore the critical role of temperature in influencing vegetation health and its relationship with drought conditions. The recurring pattern of low TCI values during the summer months highlights the increased temperature stress on vegetation, which, when coupled with drought, can severely impact vegetation health. The analysis of TCI trends, in conjunction with Fig. 6d, provides valuable insights into the temporal dynamics of temperature stress and its implications for drought management and vegetation health monitoring. Proactive measures, such as improving irrigation practices and adopting temperature-resilient crop varieties, are essential for mitigating the adverse effects of temperature stress and enhancing the resilience of vegetation in the Semi-humid Climate region.

Spatial Analysis of Drought in Rajasthan

In addition to temporal analysis, the same method allows for exploring drought from the spatial point of view over the area of interest. The considered indices TCI, PCI, and VCI (excluding water bodies) were calculated for Rajasthan each year from 2010 to 2022 and then combined to produce the SDCI indicator using the empirical weights through the GEE platform. SDCI was then classified into five classes, from extreme drought to no drought condition. Comparing the time series of drought maps of SDCI allows us to investigate the changes in aridity conditions over Rajasthan. When observing Fig. 7a and b, for instance, which show maps of SDCI for 2010 and 2020, it is possible to notice that the state has undergone drought conditions, especially in the western and north-western districts like Jaisalmer, Barmer, and Bikaner. The maps produced by SDCI show a dry condition in 2020. A report published in the Global Drought Observatory (GDO) in May 2021 also confirms the initiation of a severe drought over the state in early 2020 and an extreme drought in the northeast, followed by an extreme depletion of water resources and high vegetation stress over the same year. This aridity is still proceeding and has caused significant losses in the agricultural sector.

The study of SDCI in other years also illustrates extreme dryness in 2019 in the central, northeastern, and northwestern districts, including Jaipur, Sikar, and Jodhpur. From 2010 to 2013, except for the areas near the Aravalli Range, the state was under moderate to extreme drought conditions, which partially recovered over the following years. The proposed applications enable the spatial analysis of drought according to SDCI over time. For example, the area of interest (AOI) includes districts like Udaipur, Chittorgarh, and Ajmer, which mostly have semi-humid to very humid climate classes according to the De Martonne climate classification. Figure 7c–m shows the time series of SDCI maps for the Area of Interest, which allows us to see the potential of this type of spatial analysis. It is possible to notice that the spatial distribution of the SDCI classes varies over time. In particular, it is possible to see a similar behavior of the SDCI distribution for the years 2010 and 2011 and from 2016 to 2019, characterized by no drought in the northeast and light to moderate drought for the remaining part of the AOI. Contrastingly, moderate drought prevails



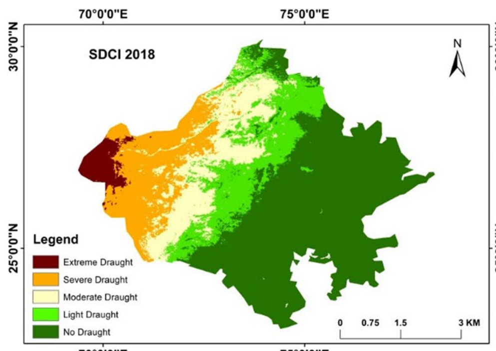
(a) For 2010 (b) For 2011

(c) For 2012 (d) For 2013

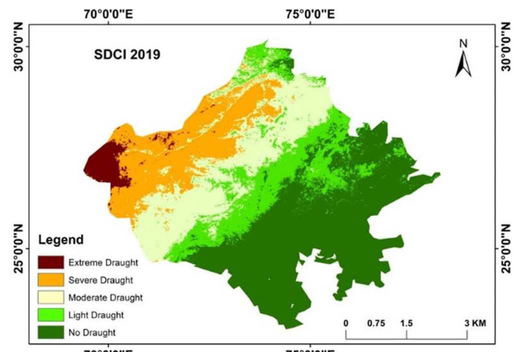
(e) For 2014 (f) For 2015

(g) For 2016 (h) For 2017

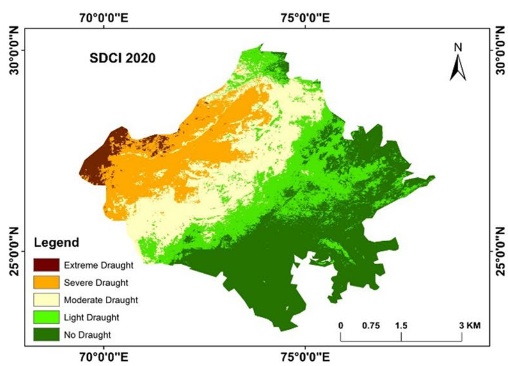
Fig. 7 Spatial analysis of SDCI from 2010 to 2022



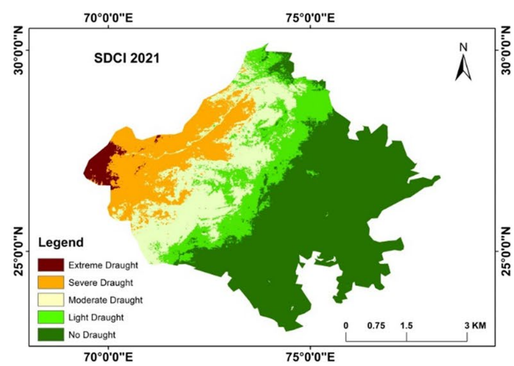
(i) For 2018



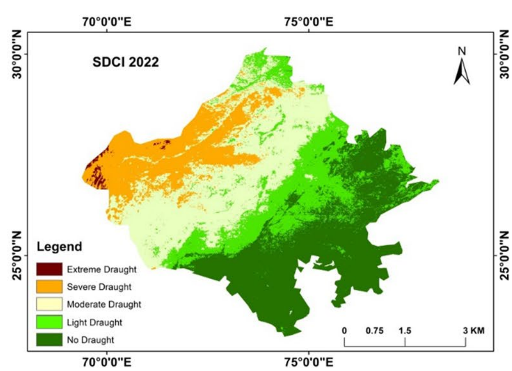
(j) For 2019



(k) For 2020



(l) For 2021



(m) For 2022

Fig. 7 (continued)

in 2014, 2015, 2020, 2021, and 2022, with severe drought appearing in the southeastern zone, affecting cropland areas. This type of visualization allows decision-makers to visualize the change in the distribution of drought over space and time, measure the territory's recovery capability, and plan interventions. In the context of Rajasthan, the semi-humid climate regions have experienced significant variability in the TCI from 2010 to 2022, as shown in the provided data. The TCI values for semi-humid regions typically range between 0.2 and 0.66, with occasional peaks reaching as high as 2.31 in January 2022. These values reflect the varying temperature conditions and their impact on vegetation health. The data indicates that the semi-humid regions have faced periodic drought conditions, particularly during the summer months (June–September), where TCI values often drop below 0.5, and indicating stress on vegetation due to higher temperatures. Although generally more humid, the months of March, April, and May also show variability in TCI, suggesting fluctuations in climatic conditions that could impact agricultural productivity.

Our research underscores the importance of the SDCI indicator in monitoring and assessing drought dynamics over time and space. By combining TCI, PCI, and VCI, the SDCI provides a comprehensive view of drought conditions across Rajasthan. The time series analysis of SDCI maps from 2010 to 2022 reveals the region’s varying degrees of drought, with severe conditions in 2014, 2015, 2020, 2021, and 2022. These years significantly impacted cropland areas, particularly in the southeastern zones. The spatial analysis of drought using SDCI is a powerful tool for identifying regions most affected by drought and those that show resilience. This research is significant in guiding targeted interventions, efficient resource allocation, and strategies for mitigating the impacts of drought on agriculture and water resources.

Discussion

Analyzing drought conditions in Rajasthan using the Standardized Drought Composite Index (SDCI) offers valuable insights into the region's drought dynamics from 2010 to 2022. By integrating the Temperature Condition Index (TCI), Precipitation Condition Index (PCI), and Vegetation Condition Index (VCI) on the Google Earth Engine (GEE) platform, this study has provided a comprehensive understanding of the varying degrees of aridity across the state. The findings reveal that Rajasthan experienced significant drought conditions, particularly in 2014, 2015, 2020, 2021, and 2022, with severe impacts in the southeastern districts such as Kota, Bundi, and Baran. Implementing green infrastructure in urban areas presents a promising strategy for mitigating the adverse impacts of drought and desertification, as highlighted by the recurrent drought conditions observed in Rajasthan. Green infrastructure, including green roofs, urban forests, rain gardens, and permeable pavements, is crucial in enhancing urban resilience to climatic extremes. By promoting natural water infiltration and reducing surface runoff, these green solutions help maintain groundwater levels and reduce the strain on municipal water resources during drought. This is particularly significant in regions like Rajasthan, where water scarcity is persistent and efficient water management is critical for sustaining agricultural productivity and urban living conditions. The analysis underscores the recurrent nature of droughts in Rajasthan, calling for ongoing monitoring and adaptive management strategies to mitigate the impacts on agriculture and water resources. Spatial analysis indicates that drought conditions are not uniformly distributed across Rajasthan, with the western and northwestern districts being particularly prone to extreme drought conditions. Moreover, integrating green infrastructure can help mitigate the urban heat island effect, which exacerbates water evaporation rates and further strains water resources. The cooling effect of urban greenery improves the microclimate and reduces the demand for water in urban landscapes. This is especially relevant for the semi-humid regions in southeastern Rajasthan, where the variability in drought intensity can be partially managed by incorporating green infrastructure into urban planning. The spatial analysis indicating varying degrees of aridity across Rajasthan underscores the need for targeted interventions, and green infrastructure provides a scalable and adaptable solution to address these localized climatic challenges. In contrast, the semi-humid regions in the state's southeastern part have shown significant variability in drought intensity, reflecting the complex interplay of climatic factors affecting these regions. The study also highlights the importance of closely monitoring climatic variables to predict and manage the impacts of drought on crop yields. As highlighted by the findings, the recurrent nature of droughts in Rajasthan calls for innovative and sustainable approaches to water management. Green infrastructure offers a dual benefit by enhancing water retention in urban areas and supporting biodiversity, contributing to soil health and reducing the risk of desertification. The western and northwestern districts of Rajasthan, which are particularly prone to extreme drought conditions, can significantly benefit from green infrastructure to enhance water conservation efforts and improve the resilience of local communities to climatic stresses. Visualizing and analyzing the spatial distribution of drought conditions over time can provide valuable insights for decision-makers, allowing them to prioritize interventions and allocate resources more efficiently (Kalisa et al., 2021). The methodology employed in this study can be further refined and expanded to enhance the accuracy of drought predictions and explore the integration of socio-economic factors to assess the broader impacts of drought on communities and livelihoods. In conclusion, this cloud-based geospatial analysis using the SDCI offers a robust framework for monitoring and evaluating drought conditions in Rajasthan, providing valuable information for effective decision-making and targeted interventions to mitigate the adverse effects of drought on agriculture and water resources in the region.

Conclusions

From 2010 to 2022, we looked at droughts in Rajasthan. The study used the Standardized Drought Composite Index (SDCI) to see how droughts changed over time and in different places. We found that Rajasthan often had severe droughts. In 2014, 2015, 2020, 2021, and 2022, terrible droughts in parts of the southeast, like Kota, Bundi, and Baran. In conclusion, the study's findings on Rajasthan's recurrent and severe drought conditions from 2010 to 2022 highlight the urgent need for adaptive management strategies. Increasing the green infrastructure in urban areas emerges as a vital component of these strategies, offering a sustainable solution to mitigate the impacts of drought and desertification. Green infrastructure can be pivotal in sustaining agricultural productivity and water resources in drought-prone regions like Rajasthan by enhancing water retention, reducing surface runoff, and improving the urban microclimate. The Global Drought Observatory (GDO) also reported that droughts often hurt farming and water in the area. Droughts are more likely in some places like Jaisalmer, Barmer, and Bikaner because it's dry and doesn't rain much. But in the southeast areas like Udaipur, Chittorgarh, and Ajmer, sometimes there are droughts, and sometimes there aren't. This is because of the different weather there. When the Temperature Condition Index (TCI) changes, it affects how well plants grow and how much food we can make. This clarifies that we must plan for droughts and change how we farm. Our study underscores the importance of proactive planning and innovative tools like the Standardized Drought Composite Index (SDCI) for monitoring and managing drought conditions. Integrating green infrastructure into these plans can significantly enhance their efficacy, providing a robust framework for addressing the multifaceted challenges of droughts. As researchers and policymakers continue to explore and refine strategies for drought mitigation, the role of green infrastructure should be recognized and prioritized as a critical element in building resilient and sustainable urban environments. We used Google Earth Engine (GEE) to watch for droughts over extensive areas for a long time. The maps we made with the SDCI help leaders see where droughts might happen and plan to save water, use better farming, and grow crops that can handle droughts better. Our study can help other researchers, too. They could use different things in the SDCI and look at other places like ours. This can help everyone understand droughts better and help other places that have the same weather as us. So, we need to plan now for bad droughts. If we use good tools and watch for droughts, we can stop them from hurting farming and help the environment. The adoption of green infrastructure not only supports effective water management but also promotes ecological resilience and sustainability. The insights gained from the spatial distribution of drought conditions underscore the potential for green infrastructure to provide targeted interventions that address the specific climatic challenges faced by different regions of Rajasthan. By prioritizing the implementation of green infrastructure, decision-makers can enhance the effectiveness of drought mitigation efforts, reduce the vulnerability of urban and rural communities, and contribute to long-term environmental sustainability.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

Ethical Approval This study adhered to ethical guidelines concerning data usage and sharing. The data were obtained from publicly available and reputable sources, including MODIS and CHIRPS satellite imagery and open-access environmental monitoring data. All sources were appropriately cited, and their use complied with licensing agreements and data-sharing policies. No personal or sensitive data were involved, and all analyses were conducted for academic research. The findings are presented responsibly to avoid misinterpretation or misuse, contributing to transparent, sustainable, and ethical geospatial research practices.

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