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ORIGINAL ARTICLE

Does climate change induce desertification in Gujarat?

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Abstract

Land degradation refers to the decline in economic and biological productivity of land caused by climatic variability and human activities, leading to disrupted ecosystem functions. Gujarat, located in the dry and semi-arid region of India, is particularly vulnerable to these processes due to its dependence on monsoon precipitation, which is characterized by significant variability. This study examines rainfall data from the India Meteorological Department for the period 2000 to 2020 and satellite-derived Normalized Difference Vegetation Index (NDVI) values for 2001, 2011, and 2021 to assess spatial and temporal trends in desertification across selected districts. The analysis indicates an overall increasing trend in monsoonal rainfall during the two decades, but this increase is unevenly distributed, with certain districts experiencing more pronounced variability. Remote sensing data reveal a complex pattern of vegetation dynamics. Districts like Porbandar and Bharuch show improvements in NDVI values, suggesting enhanced vegetation cover and potential recovery from land degradation. Conversely, Vadodara exhibits declining NDVI trends, highlighting escalating risks of desertification, likely driven by intensified anthropogenic pressures such as industrialization and deforestation. This research highlights the critical interplay between climatic factors and land use changes in shaping regional ecological health. The findings underscore the need for proactive and region-specific land management strategies to mitigate desertification. With the help of reliance on robust satellite-based monitoring and high-resolution climatic data, this study provides a replicable framework for understanding and combating land degradation in similar vulnerable districts.

Keywords Drought · Land degradation · Desertification · NDVI · Remote sensing

Introduction

Land degradation is a global environmental issue which encompasses the decline in land productivity and ecosystem functionality, caused by natural and anthropogenic factors. In semi-arid and arid districts, such as Gujarat in western India where, land degradation poses significant challenges due to erratic rainfall, soil erosion, and anthropogenic disturbances including deforestation, overgrazing, and unsustainable agricultural practices (Kundu et al. 2017). The interaction of these factors exacerbates desertification, a subset of land degradation marked by the persistent reduction in land's capacity to sustain soil microbiome (Prăvălie 2021). Land degradation is driven by soil erosion, climatic variability, and human activities, including deforestation and overgrazing. Mishra and Desai (2005) highlighted drought as a recurring climatic phenomenon that significantly impacts vegetation and soil health, especially in districts like Gujarat that experience frequent drought events. Swain et al. (2020) reported that rising greenhouse gas concentrations exacerbate climatic variability, intensifying droughts and extreme weather events. The study across the Eurasian steppe from 2000 to 2022 by using Finer Resolution Observation and Monitoring of Global Land Cover (FROM-GLC) Plus platform and the UNCCD land degradation monitoring framework which indicates a net increase in grassland areas, primarily transforming from cropland, forest, and bare land, although grassland degradation was lower than the overall land degradation level. The study identifies urbanization,

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cropland changes, and moisture distribution as significant drivers of land degradation, emphasizing the spatial aggregation of degradation near urban centres and grassland regions adjacent to deserts. The findings provide valuable insights for policymakers to develop conservation strategies and promote sustainable land management (Du et al. 2024). A study in semi-arid Region of Anantapur District, Southern India by utilizing geospatial modelling techniques with Landsat satellite images from 1990, 2000, 2010, and 2018 reveal that over 28 years, 31.93% of the land experienced degradation, with 17.34% classified as severely degraded and 14.59% as desertified and water bodies decreased by 57%, while agricultural lands shrank by 16%. The study attributes degradation to wind erosion, vegetation loss, soil salinization, and changing agricultural practices. This study uses Desertification Status Maps (DSM) for visualization and quantification (Kumar et al. 2020). However, the validation using Area Under the Curve (AUC) analysis demonstrated high accuracy and confirmed the reliability of the methodology. This study highlights the effectiveness of MLA-based approaches in identifying degradation patterns over the region and showed Digital Land Degradation (DLD) map a valuable tool for land management and environmental conservation, offering actionable insights for targeted interventions and promoting sustainable land use practices (Badapalli et al. 2025). Jain et al. (2010) emphasizes the importance of vegetation indices such as NDVI in monitoring and assessing vegetation dynamics under varying climatic conditions. NDVI is particularly effective in semi-arid districts where vegetation response to rainfall is immediate but varies spatially. Farrar et al. (1994) and Li and Tao (2002) noted that NDVI trends are strongly correlated with rainfall variability, albeit with a temporal lag due to delayed vegetation recovery post-precipitation. Their findings align with those of Kumar et al. (2020), who documented increasing trends in rainfall extremes across Gujarat, particularly during the monsoon season. These extremes often lead to erratic vegetation recovery and heightened desertification risks. Remote sensing and GIS-based studies, such as those by Sur et al. (2018), have demonstrated the utility of satellite imagery in tracking land degradation patterns. These tools have proven particularly useful in Gujarat, where climatic variability is significant. Kundu et al. (2017) applied NDVI alongside rain-use efficiency to assess desertification in Rajasthan and Gujarat, illustrating how climatic and anthropogenic factors jointly drive land degradation.

Therefore, by integrating climate data and remote sensing techniques, this research seeks to identify areas most affected by desertification of coastal and inland districts of Gujarat by systematically analysing rainfall trends from 2000 to 2020 and their relationship with NDVI-derived vegetation changes. The findings contribute to a deeper understanding of how climatic and anthropogenic factors influence desertification. The study provides a comprehensive analysis of rainfall and NDVI for analysis of desertification in coastal and inland districts of Gujarat.

Study area

Desertification and land degradation have been extensively studied in semi-arid and arid districts worldwide. Gujarat is located along the Tropic of Cancer, on India's (Fig. 1a) western coast between latitudes and lies in the subtropical climatic zone (Fig. 1b). This state is geographically sharing boundaries with Rajasthan in the northeast, Madhya Pradesh in the east, and Maharashtra in the south and south-eastern directions while a large part is coastal boundary. Its coastline is 1600 km long (Prizomwala et al. 2021). Its northern border creates Pakistan's international border. The state receives major proportion of annual rainfall during the southwest monsoon season (June–September), but this rainfall is spatially and temporally inconsistent which makes some regions vulnerable to droughts and water scarcity (Vyas et al. 2015). This climatic challenge alongwith human-induced factors, have led to significant shifts in land use patterns and vegetation dynamics over recent decades. Studies highlight that desertification risks in Gujarat are aggravated by the combined effects of climate change and anthropogenic activities, making it a critical area for focused research (Kelkar and Bhadwal 2007).

This study focuses on four districts of Gujarat—Bharuch, Porbandar, Jamnagar and Vadodara—each representing unique climatic and anthropogenic challenges contributing to land degradation. Bharuch (Fig. 1c; 21° 41′41″ N latitude and 72° 58′49″ E longitude) is known for its industrial significance and proximity to the Narmada River which has a contrasting landscape of industrial zones and agricultural areas. While the river provides crucial water resources, unplanned industrialization and urban sprawl have exacerbated soil erosion, groundwater depletion, and vegetation loss, contributing to escalating desertification risks. Porbandar (Fig. 1d; 21° 38′30″ N latitude and 69° 37′45″ E longitude) is located on the western coast and have rich coastal ecosystem but this district faces significant challenges from saline water intrusion and soil salinization due to erratic rainfall patterns and rising sea levels (Siddha & Sahu 2020). These factors, compounded by limited vegetation cover, make Porbandar highly vulnerable to desertification. Vadodara (Fig. 1e; 22° 18′26″ N latitude and 73° 10′52″ E longitude) is situated in central Gujarat and represents a rapidly urbanizing districts with extensive deforestation and land-use changes. This region is facing declining NDVI trends in this region indicate severe vegetation loss which is driven by infrastructure expansion, overgrazing, and unsustainable farming practices. Vadodara's susceptibility to prolonged droughts further

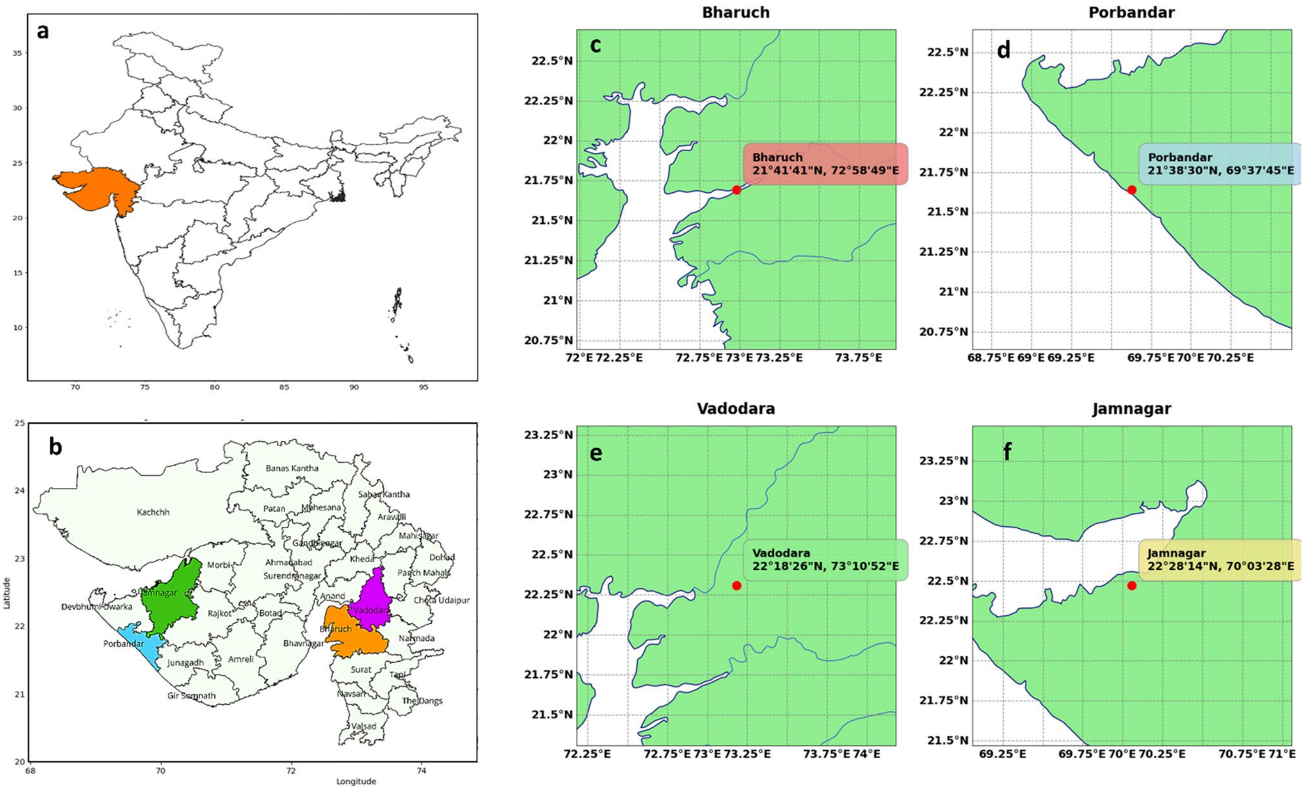

Fig.1 Visualizing study area map; **a**. Coloured part showing Gujarat state, **b**. showing the four districts in coloured area and **c**.,**d**.,**e**. and f is for Bharuch, Porbandar, Vadodara and Jamnagar respectively

amplifies its desertification challenges (Jodhani et al. 2024). Jamnagar (Fig. 1f; 22° 28′14″ N latitude and 70° 03′27″ E) is located in the arid Saurashtra region; Jamnagar faces extreme climatic variability and frequent droughts. The district's dependence on monsoon rainfall for agriculture and its industrial activities make it a critical region for studying the impacts of climatic variability on land degradation. Overexploitation of natural resources and limited adaptive measures have intensified the risk of desertification in Jamnagar.

Data and methodology

This study utilized two primary datasets: climatic data and satellite imagery. Daily gridded rainfall data (0.25×0.25) from the India Meteorological Department (IMD) for the period 2001 to 2021 were collected (Bhatla et al. 2019). These data were aggregated into monthly and seasonal rainfall totals to analyse spatial and temporal variability. The focus was on the monsoon months (June–September), which accounts for the majority of annual rainfall in Gujarat. The Standardized Precipitation Index (SPI) was calculated to assess drought severity and its temporal evolution across the study districts (Verma et al. 2022). Figure 2 representing the methodology carried in this study.

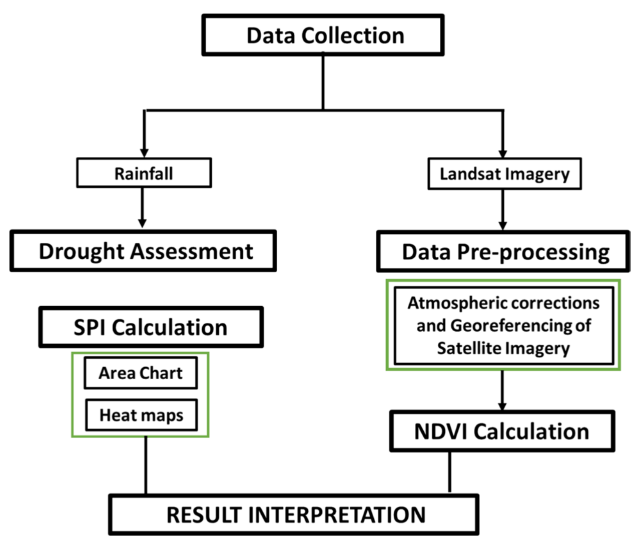

Fig. 2 Flow diagram representing step followed in the study

The SPI, a widely recognized drought indicator calculated using monthly precipitation data. The SPI analysis is performed using the Spyder IDE, which is part of the Anaconda distribution for Python. Matplotlib and scipy library have been imported for data visualization and probability distribution respectively, to the monthly rainfall data. Visualization of SPI transitions over time using Matplotlib provide distinct color coding to differentiate between wet and dry conditions. The analysis utilized three distinct visualization approaches: area charts illustrating SPI transitions over time, monthly heatmaps displaying SPI intensity across years, and individual year-wise trend analysis. The SPI values are categorised in reference with McKee et al. 1993; Lloyd-Hughes and Saunders 2002 but for convenience here, the values are re-categorized into specific ranges, with values above 2.0 indicating extremely wet conditions, 0 to 2.0 for moderately wet conditions, 0 to −2.0 for moderate drought, −2.0 to −4.0 for severe drought, and below −4.0 for extreme drought conditions (Table 1).

Multi-temporal Landsat satellite imagery was used for NDVI analysis using QGIS software. Landsat 7 Enhanced Thematic Mapper Plus (ETM +) and Landsat 8 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS) data, with a spatial resolution of 30 m, were acquired for the years 2001, 2011, and 2021 from the United States Geological Survey (USGS) Earth Explorer platform (Shahfahad et al. 2021). The imagery was pre-processed to correct for atmospheric distortions and georeferenced to ensure spatial accuracy.

Table 1 Classification of SPI values and event occurrences (McKee et al. 1993; Lloyd-Hughes and Saunders 2002)

Class	Events	SPI Values
1	Extreme Drought	$SPI \le -2$
2	Severe Drought	$-2 < SPI \le -1.5$
3	Moderate Drought	$-1.5 < SPI \le -1$
4	Near Normal	$-1 < SPI < 1$
5	Moderately Wet	$1 \le SPI < 1.5$
6	Severely Wet	$1.5 \le SPI < 2$
7	Extremely Wet	$SPI \ge 2$
Re-classified Range	Events	SPI Values
1	Extreme Drought	$SPI \le -4$
2	Severe Drought	$-4 < SPI \le -2$
3	Moderately Wet	$-2 \le SPI < 0$
4	Severely Wet	$0 \le SPI < 2$
5	Extremely Wet	$SPI \ge 2$

$$NDVI = \frac{(Band\ 5 - Band\ 4)}{(Band\ 5 + Band\ 4)} \tag{1}$$

$$NDVI = \frac{(Band\ 4 - Band\ 3)}{(Band\ 4 + Band\ 3)} \tag{2}$$

For Landsat 8, Band 5 (NIR) and Band 4 (RED) were used (Eq. 1), while for Landsat 7, Band 4 (NIR) and Band 3 (RED) (Eq. 2) were employed. The NDVI values were classified into categories representing vegetation health, ranging from degraded (negative values) to dense vegetation (values close to + 1). The Normalized Difference Vegetation Index (NDVI) has emerged as a reliable metric for monitoring vegetation health and assessing land degradation. The Normalized Difference Vegetation Index (NDVI) has emerged as a reliable metric for monitoring vegetation health and assessing land degradation (Pettorelli 2013). NDVI utilizes satellite-derived spectral reflectance data to quantify vegetation cover and its temporal changes. It serves as an effective tool for understanding the impacts of climatic variability, such as fluctuations in precipitation, on vegetation dynamics and land degradation processes. Remote sensing coupled with Geographic Information Systems (GIS), offers an efficient method to map and monitor desertification processes at spatial and temporal scales (Albalawi and Kumar 2013). GIS tools were employed to map NDVI values and identify spatial patterns of vegetation change. Table 2. shows NDVI threshold values of different cover types which is considered as reference in this study. Temporal changes in NDVI were analysed to detect areas experiencing significant land degradation or recovery. Rainfall and NDVI data were combined to explore correlations between precipitation variability and vegetation dynamics.

Results

Rainfall analysis in contribution of desertification

According to analysis of rainfall across four different districts of Gujarat between the years 2001 and 2021, there was a growing pattern in rainfall over state throughout the monsoon months of June, July, August, and September. SPI analysis is done on yearly, monthly and seasonal basis.

Table 2 NDVI threshold values of different cover types

Cover Type	NDVI Value Threshold	Reference
Water	−0.046	(Berhanu & Bisrat, 2020, Dalezios et al. 2001)
Bare Soil	0.25	(Ding, et al. 2007, Thorat et al., 2015)
Sparse vegetation	0.35	(Thorat et al. 2015)
Moderate vegetation	0.5	(Berhanu & Bisrat, 2020 , Dalezios et al. 2001)
Dense vegetation	1	(Dalezios et al. 2001)

Figure 3 shows significant fluctuations between wet (blue) and drought (red) which represents several extreme drought events where the SPI drops below −4 in Bharuch. Wet periods appear to be less extreme, typically not exceeding SPI of +4 in most years. The droughts appear to be more frequent in recent years (2016–2020) and the duration of drought periods seems to be increasing. There are multiple instances of severe drought (SPI < −2) which can accelerate desertification.

The SPI heatmap (Fig. 4) for the Bharuch region reveals complex temporal and seasonal patterns of precipitation variability from 2001 to 2021. The monsoon period, spanning June through September, consistently exhibits wet conditions as indicated by blue shades, with peak rainfall typically occurring in July–August. This represents the most reliable wet period across all years, though the intensity varies while maintaining positive SPI values. In contrast, the winter period from November to February predominantly shows drought conditions, represented by red and pink shades, with particularly severe droughts observed in 2002–2003 and 2016–2017. These winter droughts appear to be intensifying in recent year which raises concern about environmental instability (Hanson and Weltzin 2000). The pre-monsoon period (March–May) displays a mixed pattern but generally trends towards drier conditions, with May serving as a transition period from dry to wet conditions. Several severe drought years stand out in the dataset, notably 2003 with an extended severe drought through the early months, 2016–2017 with an intense drought period, and 2002 showing significant drought conditions except during the monsoon. Conversely, years like 2019, 2004, and 2008–2009 experienced notably wetter conditions, particularly during the monsoon periods. These critical patterns emerge in the drought characteristics, with winter droughts becoming more frequent and intense, and early-year droughts (January-May) showing increasing frequency. The post-monsoon drought recovery appears to be becoming less effective over time (Bandyopadhyay 2023).

The SPI area chart for Porbandar (Fig. 5) from 2001 to 2020 reveals significant patterns of wet and drought periods that provide insights into the region's precipitation trends and potential desertification risks. The data shows recurring intense drought periods, indicated by the red areas, with SPI values frequently dropping to extreme levels between −6 to −8. Particularly severe drought episodes are visible around 2004, 2008, 2012, and notably intense ones in 2016 and 2020. This pattern suggests a consistent cycle of severe moisture stress in the Porbandar region. The wet periods, shown in blue areas, generally maintain SPI values between 2 and 4. However, there's an observable pattern where these wet periods appear relatively shorter in duration compared to the drought periods. The intensity of wet periods remains fairly consistent throughout the timeline, though their distribution is somewhat irregular. The overall temporal analysis indicates a concerning pattern where drought periods are not only frequent but also intense and prolonged. This is particularly significant for Porbandar, being a coastal region in Gujarat, as such prolonged drought periods could contribute to increased soil salinity and land degradation. The transitions between wet and drought periods are quite sharp, suggesting rapid changes in precipitation patterns that could affect the region's agricultural productivity and natural vegetation recovery. These patterns suggest that Porbandar faces significant challenges regarding water security and potential desertification, particularly given the frequency and intensity of drought periods. The data indicates that while the

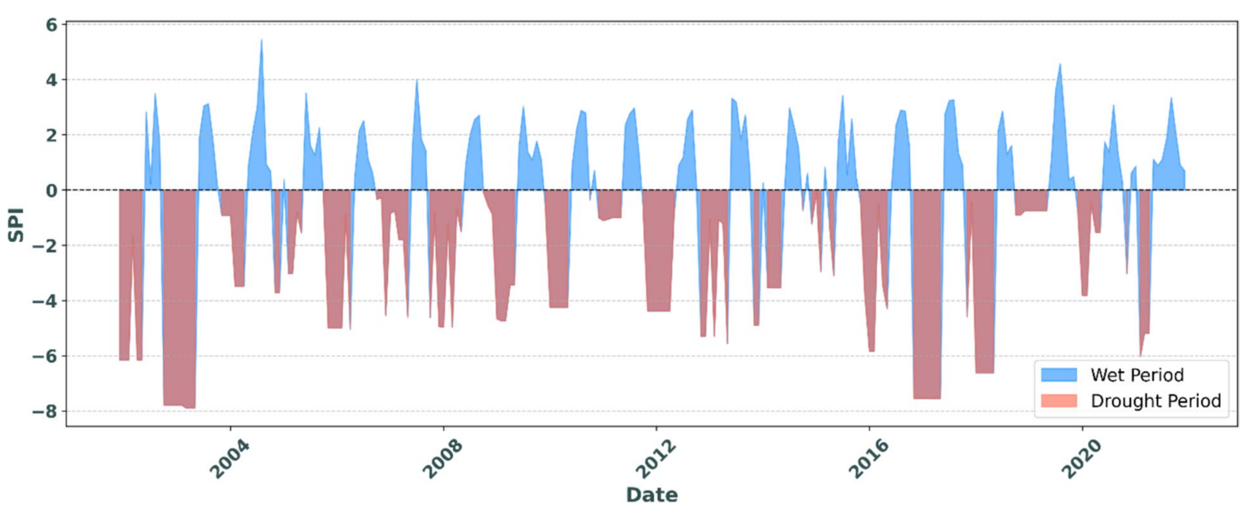

Fig. 3 Showing transition over time of SPI on area chart over Bharuch

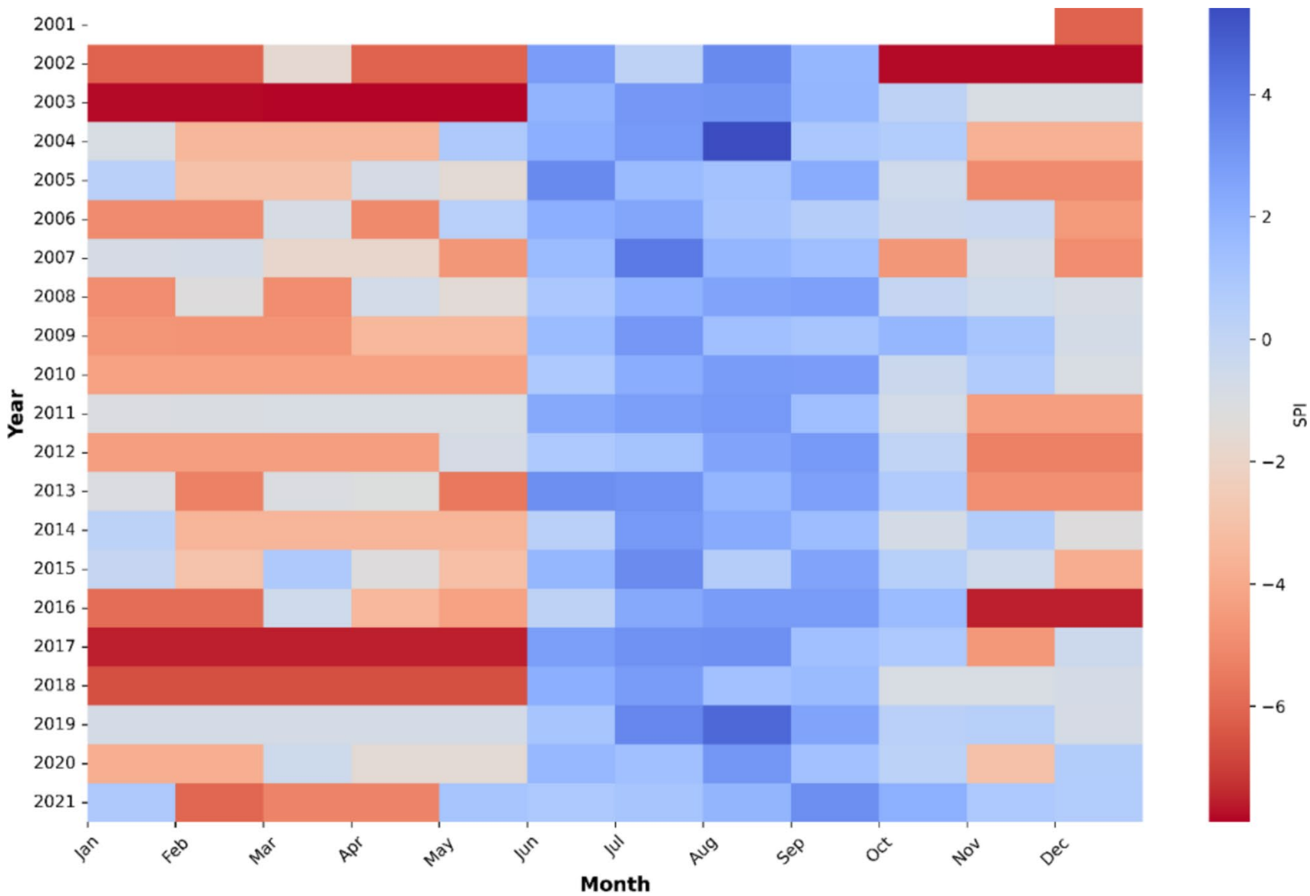

Fig. 4 Heat-map visualizing monthly trends across year over Bharuch

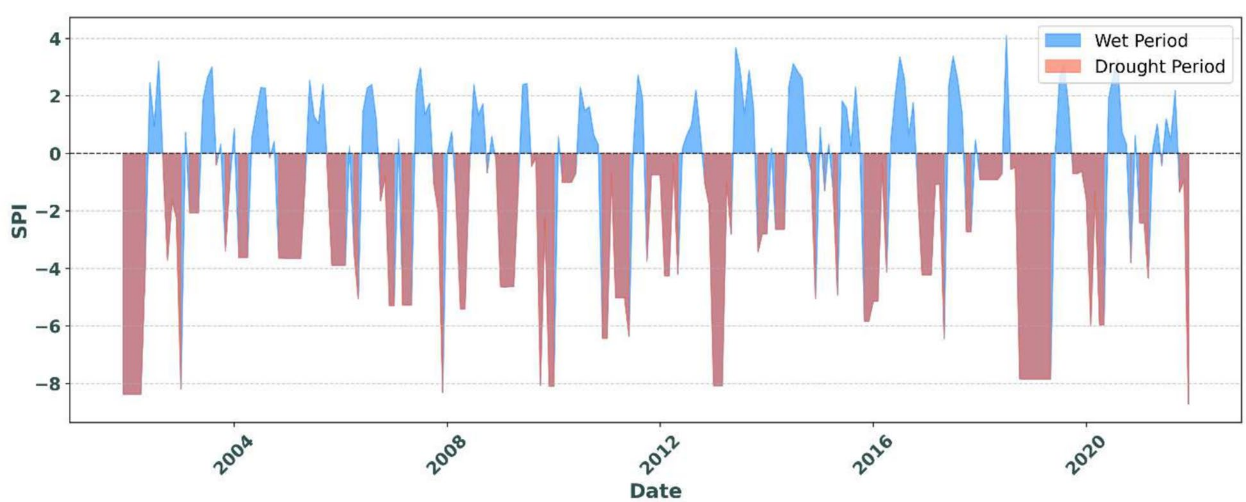

Fig. 5 Showing transition over time of SPI on area chart over Porbandar

region does experience periodic wet spells, they might not be sufficient to fully offset the impact of the more severe and prolonged drought periods.

The SPI heatmap for Porbandar (Fig. 6) (2001–2021) reveals distinctive precipitation patterns characteristic of this coastal region of Gujarat. The data shows a clear seasonal

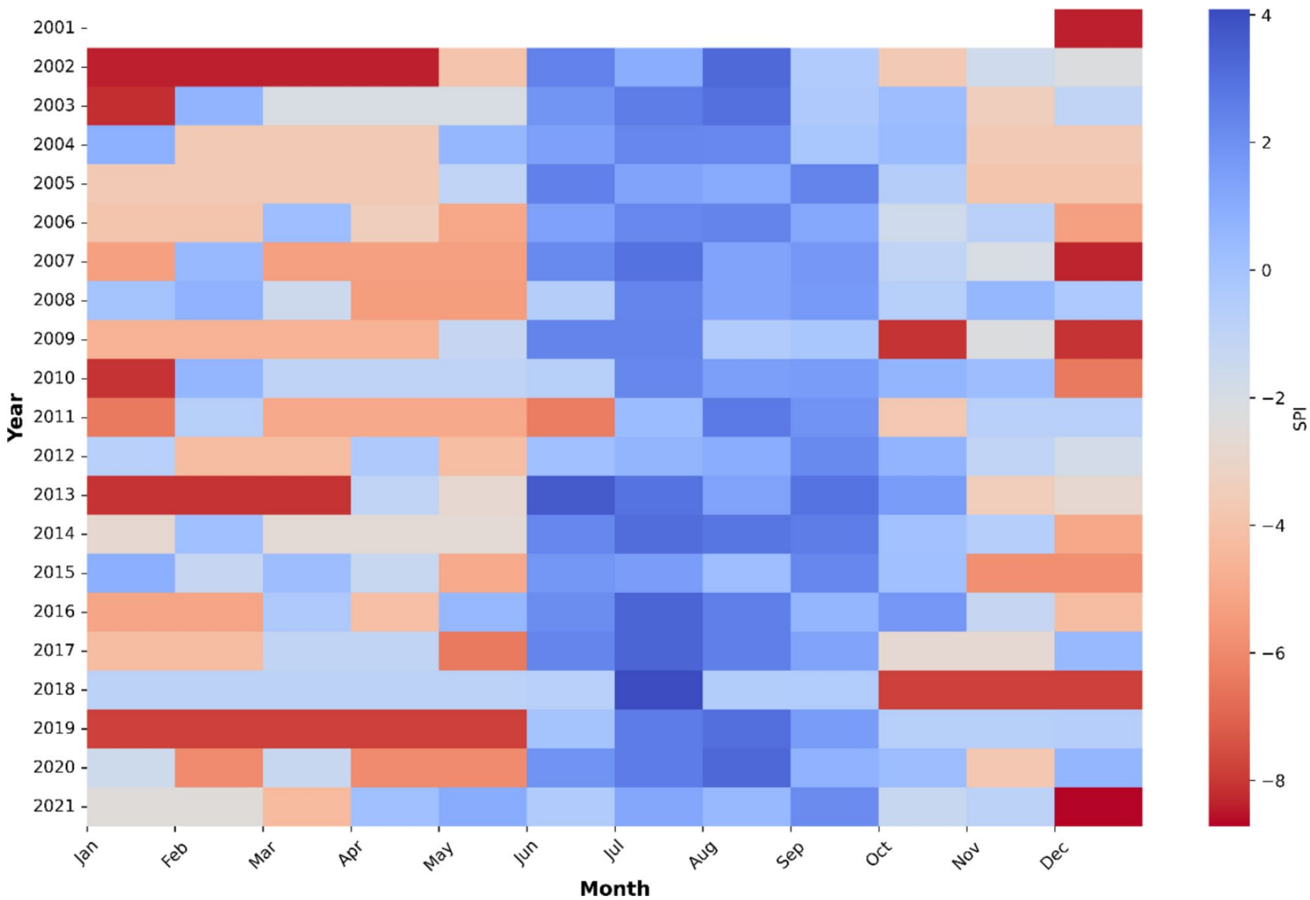

Fig. 6 Heat-map visualizing monthly trends across year over Porbandar

pattern with notable extremes and transitions throughout the study period. The monsoon season (June–September) consistently displays positive SPI values, represented by blue shades, indicating reliable wet conditions during these months. The intensity of monsoon precipitation varies across years, with particularly strong monsoon periods evident in years like 2013, 2017, and 2020, where darker blue shades indicate SPI values exceeding 2. The pre-monsoon period (January-May) shows a concerning trend of drought conditions, represented by red shades. Severe drought conditions (SPI values below −6, shown in dark red) are particularly notable in 2002, 2003, 2013, and 2019, with extended periods of drought spanning multiple months. These prolonged dry periods pose significant challenges for water resource management and agricultural activities in the region. A striking feature of Porbandar's precipitation pattern is the post-monsoon period (October-December), which shows high variability. The year 2018 experienced an unusually severe and extended drought during these months, indicated by the continuous dark red band. Similarly, 2007 and 2021 show intense drought conditions specifically in December, suggesting an increasing tendency toward year-end water stress. Recent years (2018–2021) demonstrate more extreme fluctuations between wet and dry periods, with sharper transitions becoming more common. This intensification of extremes is particularly evident in 2019, which experienced severe drought conditions in the first half of the year followed by a relatively strong monsoon. The data suggests that while the monsoon remains a dependable source of precipitation, the region is experiencing more pronounced variability in its precipitation patterns, with drought periods becoming more intense and prolonged. The temporal evolution of these patterns indicates a potential shift toward more extreme weather events, which has significant implications for water security, agricultural planning, and potential desertification processes in the Porbandar region. The increased frequency and intensity of drought periods, particularly in recent years, suggest a need for enhanced water management strategies and drought mitigation measures.

The SPI area chart for Vadodara (Fig. 7) spanning from 2001 to 2021 reveals important patterns about the region's precipitation and drought conditions that are relevant to understanding potential desertification risks. The drought periods, shown in red, demonstrate moderate to severe

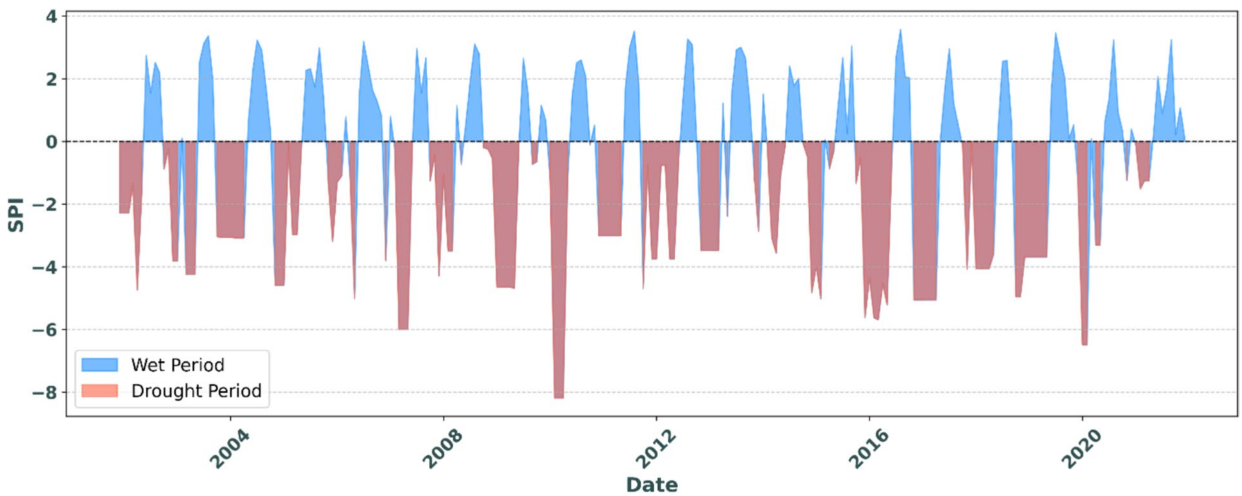

Fig. 7 Showing transition over time of SPI on area chart on Vadodara

intensity with SPI values typically ranging from −2 to −6, with a notably extreme drought event around 2012 reaching an SPI of approximately −8. The drought episodes appear to be more moderate compared to some other districts of Gujarat, though they remain significant enough to impact the local environment and agriculture. The wet periods, indicated in blue, show relatively consistent patterns with SPI values generally between 2 and 3, occasionally reaching 4. These wet periods appear to be more evenly distributed throughout the timeline compared to other districts, suggesting a somewhat more stable precipitation pattern. The frequency and duration of wet periods indicate that Vadodara experiences regular moisture replenishment cycles. The temporal analysis reveals a relatively balanced pattern between wet and drought periods, though there's a slight trend toward more frequent moderate drought episodes in recent years (2016–2020). The transitions between wet and dry periods are less abrupt compared to other districts, suggesting a more gradual shift in precipitation patterns. This characteristic might provide better opportunities for ecological adaptation and natural resource management. Despite the presence of regular wet periods, the recurring drought episodes, particularly the severe event in 2012 and the increased frequency of moderate droughts in recent years, indicate that Vadodara faces ongoing challenges in maintaining its water balance. This pattern suggests a moderate risk of desertification, though perhaps less severe than in some other districts of Gujarat, partly due to the more consistent distribution of wet periods and generally moderate nature of drought episodes.

The SPI heatmap for Vadodara (Fig. 8) (2001–2021) reveals distinct precipitation patterns and drought cycles characteristic of this central Gujarat region. The most prominent feature is the consistent monsoon pattern (June–September), shown in blue shades, indicating reliable wet conditions. The monsoon intensity varies across years, with notably strong periods evident in 2003, 2004, and 2013, where darker blue shades indicate SPI values exceeding 2. A particularly severe drought event is visible in 2010 during the pre-monsoon months (February-April), shown by the dark red colour indicates SPI values below −8. This represents one of the most extreme drought periods in the dataset. The pre-monsoon period generally shows a tendency toward drought conditions, though the severity varies considerably across years. The data reveals an interesting pattern of increasing drought frequency in recent years (2015–2020), particularly during the pre-monsoon months. This trend is evident in the more frequent appearance of red and pink shades during these periods, suggesting a potential shift toward drier conditions in the first half of the year. However, 2021 shows a departure from this trend with more moderate conditions throughout the year. Post-monsoon periods (October-December) show considerable variability, with some years experiencing moderate drought conditions (shown in light red) while others maintain neutral or slightly wet conditions (shown in light blue). There's a noticeable trend of increased variability in these months in recent years, suggesting less predictable post-monsoon precipitation patterns. The temporal evolution of these patterns suggests that while Vadodara's monsoon remains relatively stable, the region is experiencing more extreme variations in its non-monsoon periods. This increased variability, particularly in pre-monsoon months, poses significant challenges for water resource management and agricultural planning. The data also indicates a potential intensification of the seasonal contrast, with sharper transitions between wet and dry periods becoming more common in recent years.

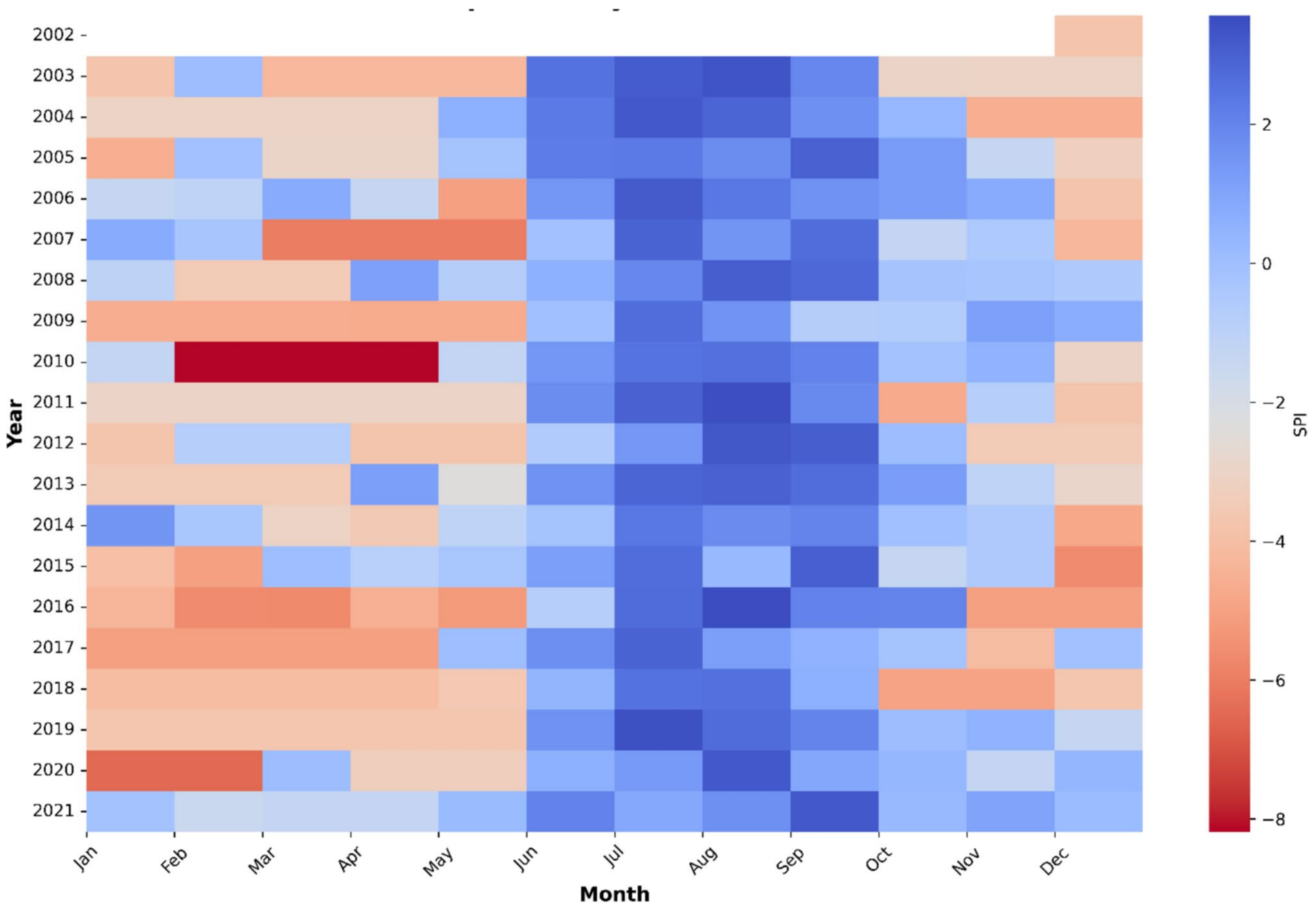

Fig. 8 Heat-map visualizing monthly trends across year over Vadodara

The SPI area chart for Jamnagar (Fig. 9) reveals concerning patterns related to desertification over the analyzed period from 2001 to 2021. The data shows significant drought periods, marked in red, with SPI values frequently plunging to severe levels between −6 to −8. These intense drought episodes were particularly notable around 2004,

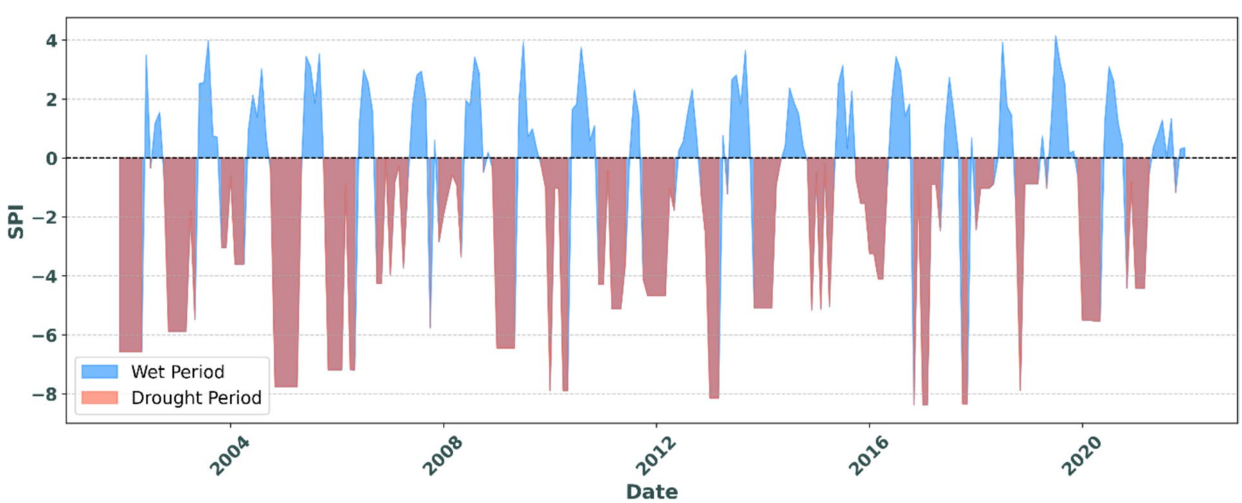

Fig. 9 Showing transition over time of SPI on area chart over Jamnagar

2008, 2012, 2016, and 2020, indicating a recurring pattern of severe moisture stress in the region. The wet periods, shown in blue, typically demonstrate SPI values ranging between 2 and 4, but their intensity appears to be gradually diminishing over time. This trend is particularly worrisome as it suggests a reduced capacity for environmental recovery between drought episodes. The irregularity in the distribution of wet periods, combined with their decreasing intensity, points to a potentially compromised water balance in the region. From a desertification perspective, the recurring intense drought periods with SPI values consistently dropping below −2 indicate significant and persistent moisture stress on the landscape. This pattern suggests a high risk of progressive land degradation, as the relatively shorter and less intense wet periods may not provide sufficient moisture replenishment to counteract the impacts of prolonged droughts. The cyclical pattern of drought-wet transitions shows a slight but concerning trend toward intensification of drought conditions over the 16-year period, with recovery periods becoming less pronounced. These observed patterns collectively indicate active desertification risk factors in Jamnagar, primarily driven by frequent intense drought episodes, insufficient recovery periods, and consistent moisture deficit cycles. The data suggests that without intervention, the region may face increasing challenges related to water scarcity and land degradation, potentially accelerating the desertification process.

The SPI heatmap for Jamnagar (Fig. 10) from 2001 to 2021 reveals distinct precipitation patterns and drought cycles that characterize this region of Gujarat. The monsoon period, spanning from June to September, consistently shows positive SPI values (indicated by blue shades), representing the most reliable wet period throughout the years. However, the intensity of these wet periods varies significantly, with particularly strong monsoons evident in years like 2009, 2013, and 2017, where the darker blue shades indicate SPI values exceeding 2. The pre-monsoon period (January to May) exhibits a concerning pattern of drought conditions, shown by the predominant red and pink shades. Severe drought conditions (SPI values below −6, shown in dark red) are particularly notable in 2005, 2010, 2013, and 2017, especially during the February–March period. This pattern suggests a recurring cycle of extreme water stress during the first half of the year.

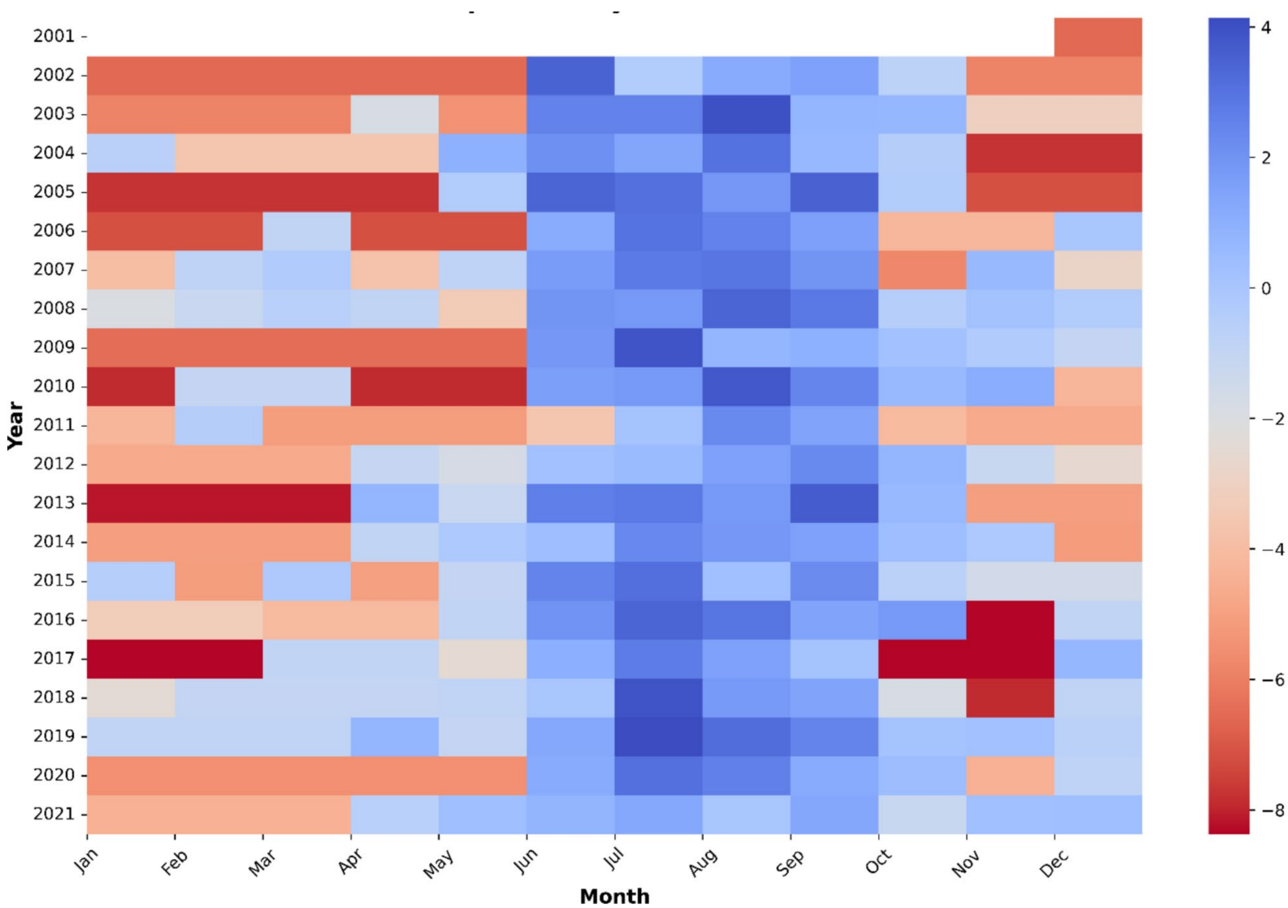

Fig. 10 Heat-map visualizing monthly trends across year over Jamnagar

The post-monsoon period (October to December) shows considerable variability across years. Some years, like 2004 and 2005, experienced severe drought conditions during these months (indicated by dark red), while others maintained neutral or slightly wet conditions (shown by light blue or white shades). There's a noticeable trend of increasing drought severity during this period in recent years, particularly evident in 2016–2017. A significant observation is the intensification of the contrast between wet and dry seasons over the study period. The transitions between extreme drought conditions and wet periods have become more abrupt in recent years, particularly from 2015 onwards. This pattern is especially concerning for Jamnagar because this sharp transitions can have severe implications for agriculture, water resource management, and potential desertification processes. The data suggests that while the monsoon remains a reliable source of precipitation, the region is experiencing more extreme variations in its precipitation patterns, with longer and more severe dry periods becoming more common. The most recent years (2019–2021) show a slight moderation in these extremes, but the overall pattern of pronounced seasonality remains, with clear distinctions between the monsoon and non-monsoon periods. This temporal pattern underscores the need for robust water management strategies in Jamnagar, particularly during the increasingly challenging pre-monsoon months.

Analysis of NDVI in contribution of desertification

The analysis of NDVI distribution patterns across four major districts of Gujarat—Porbandar, Bharuch, Jamnagar, and Vadodara—reveals significant temporal changes in vegetation cover and land use dynamics over the twenty-year study period (2001–2021). As shown in Fig. 11 (a, b, c), this district demonstrated progressive improvement in vegetation coverage throughout the study period. In 2001, the district was characterized by dominant mid-range NDVI values (1,604.23 km^{2}in the 0 category) with relatively low maximum NDVI coverage (701.44 km^2). The situation improved significantly by 2011, with enhanced distribution across positive NDVI values and increased maximum NDVI area (861.48 km^2). By 2021, the district showed remarkable progress with substantial maximum NDVI coverage (1,188.28 km^2) and better balance between moderate and high vegetation areas, indicating successful implementation of vegetation enhancement and conservation strategies (Table 3).

As shown in Fig. 12 (a, b, c), it is confirmed clearly that the 2001 NDVI values are significantly lower than 2011, 2021 NDVI values, from the Table 4, the area covered by the NDVI value −1 is decreased from 2001 to 2021. The activity is increased like plantation, home gardening increased so the area covered by the NDVI value −0.5 to 0.5 is increased. The NDVI distribution showed a relatively stable pattern with notable fluctuations in this district. The year 2001 exhibited a balanced distribution with

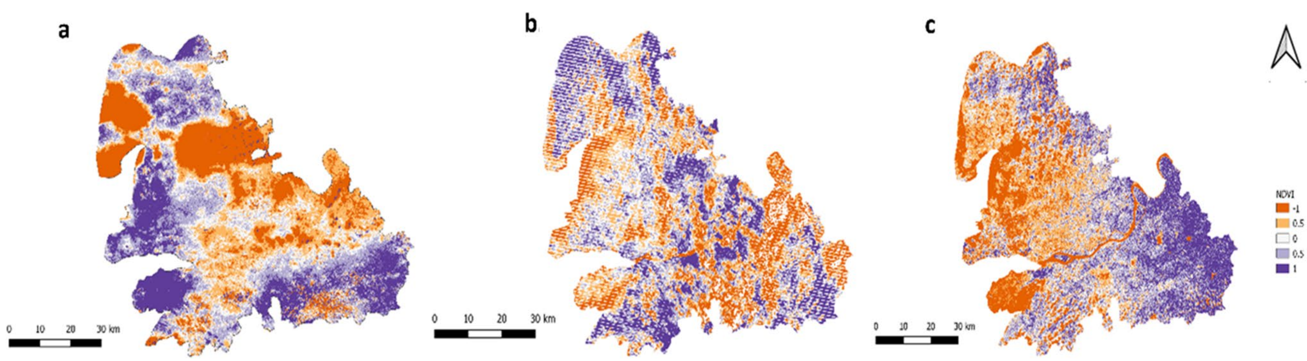

Fig. 11 NDVI of Bharuch; **a**. 2001, **b**. 2011, **c**. 2021

Table 3 Area covered by the NDVI values over Bharuch

2001(LANDSAT image)			2011(LANDSAT image)			2021(LANDSAT image)		
NDVI value	Pixel count	Area(km^2)	NDVI value	Pixel count	Area(km^2)	NDVI value	Pixel count	Area(km^2)
−1	1157806	1042.03	−1	873450	786.11	−1	1014368	913.03
−0.5	1125438	1,012.89	−0.5	790098	711.09	−0.5	1169168	1,052.25
0	1782476	1,604.23	0	1187523	1,068.77	0	1159015	1,043.11
0.5	822944	740.65	0.5	940605	846.54	0.5	1006166	905.55
1	779377	701.44	1	957202	861.48	1	1320306	1,188.28

significant water bodies and bare soil areas (509.28 km^2) alongside substantial maximum NDVI coverage (483.92 km^2). By 2011, there was a marked reduction in negative NDVI areas to 398.86 km^2, indicating a decrease in water bodies or bare soil, although this was accompanied by a slight decrease in maximum NDVI areas (453.52 km^2). The 2021 shows a recovery in vegetation health, with improved maximum NDVI coverage (481.08 km^2) and a better balance across vegetation classes, suggesting successful adaptation to changing environmental conditions.

Vadodara (Fig. 13) district experienced the most dramatic transitions in land use and vegetation cover. Starting with substantial maximum NDVI areas (901.67 km^2) in 2001, the district underwent significant changes by 2011, showing a sharp increase in zero NDVI areas (1,661,099,400 m^2) and a substantial decrease in maximum NDVI coverage (185.36 km^2). By 2021, the transformation was even more pronounced, with maximum NDVI areas reduced to mere 5.36 km^2 and dominance of moderate NDVI values, strongly indicating rapid urbanization and land use conversion (Table 5).

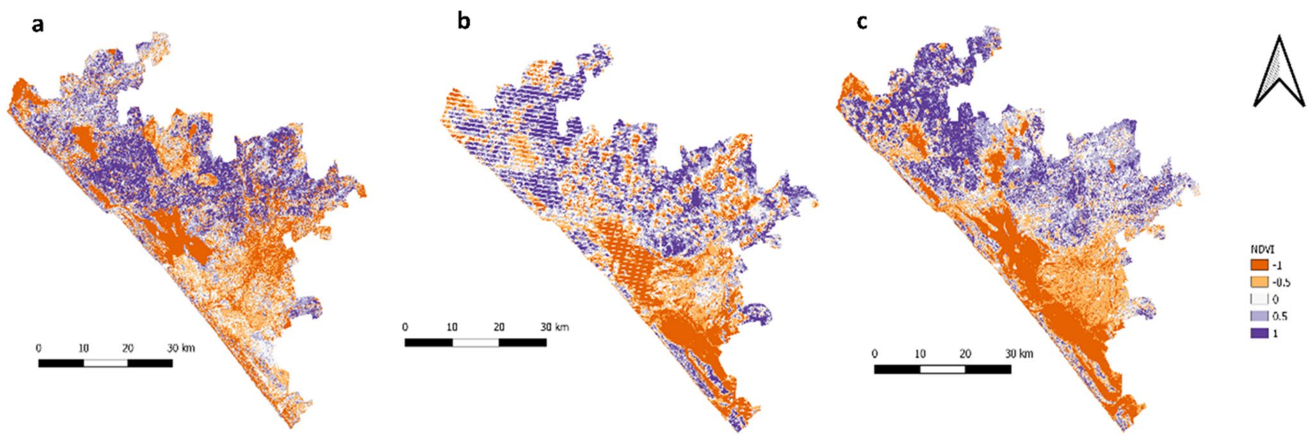

Fig. 12 NDVI of Porbandar; **a**. 2001, **b**. 2011, **c**. 2021

Table 4 Area covered by the NDVI values over Porbandar

2001(LANDSAT image)			2011(LANDSAT image)			2021(LANDSAT image)		
NDVI value	Pixel count	Area(km2)	NDVI value	Pixel count	Area(km2)	NDVI value	Pixel count	Area(km2)
−1	565864	509.28	−1	443177	398.86	−1	484058	435.65
−0.5	440816	396.73	−0.5	450929	405.84	−0.5	536801	483.12
0	527463	474.72	0	440067	396.06	0	510714	459.64
0.5	501399	451.26	0.5	431581	388.42	0.5	507287	456.56
1	537693	483.92	1	503910	453.52	1	534538	481.08

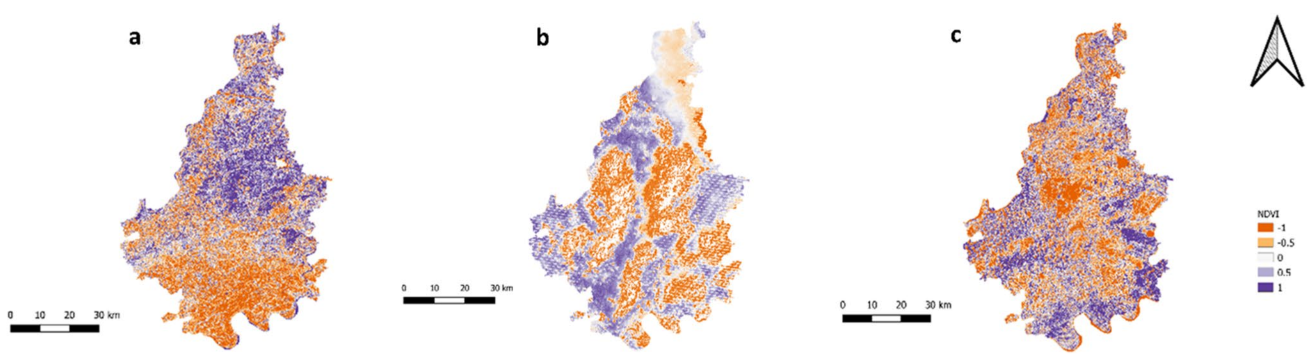

Fig. 13 NDVI of Vadodara **a**. 2001, **b**. 2011, **c**. 2021

Jamnagar (Fig. 14) district exhibited the most dynamic vegetation changes among all studied districts. The 2001 data showed extensive negative NDVI areas (1,278.93 km^2) with uniform distribution across positive values. A dramatic transformation occurred by 2011, characterized by a significant reduction in negative NDVI areas and a massive increase in moderate vegetation (2,617.47 km^{2}at 0.5 NDVI). The 2021 data reveal a recovery in maximum NDVI areas (1,487.83 km^2) with more balanced distribution, suggesting dynamic vegetation responses to changing climate and land use patterns (Table 6).

The comparative analysis of minimum and maximum NDVI trends (Table 7) reveals distinct patterns across districts. Minimum NDVI values showed overall improvement, with Bharuch showing the most significant improvement (−0.59 to −0.12), followed by Vadodara (−0.45 to −0.04) and Porbandar (−0.40 to −0.11). Jamnagar showed a fluctuating pattern (−0.30 to −0.21). Maximum NDVI trends indicate improvement across all districts by 2021, with Jamnagar achieving the highest value (0.64), while Vadodara showed remarkable recovery from its 2001 low (0.18 to 0.60).

The study indicates significant transformations in precipitation patterns and vegetation dynamics across the coastal and inland districts of Gujarat from 2001 to 2021 with overall increasing trend in monsoonal rainfall but unevenly distributed across all these districts. Bharuch exhibits the most variable precipitation patterns and improving vegetation coverage with significant increase in maximum

Table 5 Area covered by the NDVI values over Vadodara

2001(LANDSAT image)			2011(LANDSAT image)			2021(LANDSAT image)		
NDVI value	Pixel count	Area(km^2)	NDVI value	Pixel count	Area(km^2)	NDVI value	Pixel count	Area(km^2)
−1	947827	853.04	−1	955690	860.12	−1	64249	
−0.5	858655	772.79	−0.5	2564	2.31	−0.5	543760	489.38
0	949354	854.42	0	1845666	1,661.10	0	2221794	1,999.61
0.5	745214	670.69	0.5	876409	788.77	0.5	1667969	1,501.17
1	1001850	901.67	1	205959	185.36	1	5958	5.36

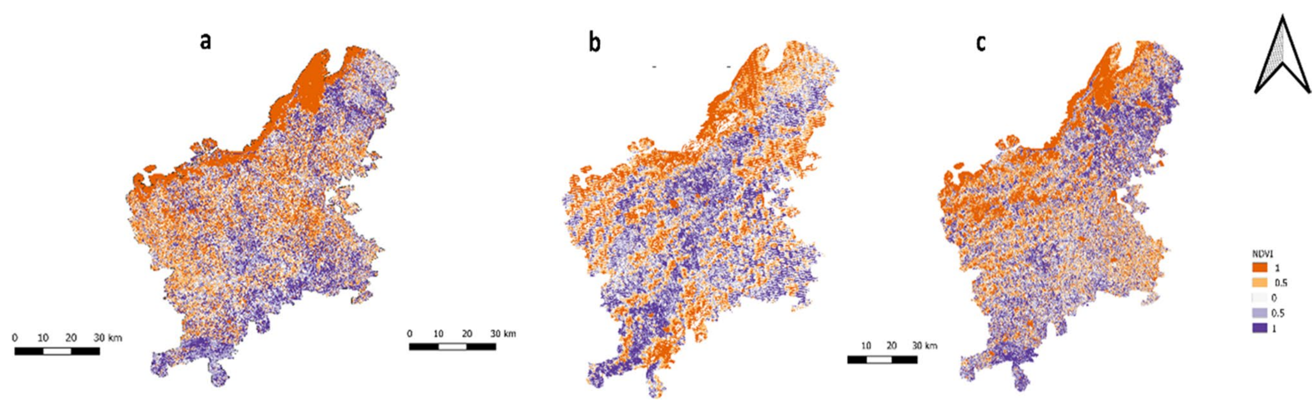

Fig. 14 NDVI of Jamnagar; **a**. 2001, **b**. 2011, **c**. 2021

Table 6 Area covered by the NDVI values over Jamnagar

2001(LANDSAT image)			2011(LANDSAT image)			2021(LANDSAT image)		
NDVI value	Pixel count	Area (km^2)	NDVI value	Pixel count	Area (km^2)	NDVI value	Pixel count	Area (km^2)
−1	1421034	1278.93	−1	540617	486.56	−1	1339598	1205.64
−0.5	1524923	1372.43	−0.5	117516	105.76	−0.5	1470261	1323.23
0	1319635	1187.67	0	2092089	1882.88	0	1396428	1256.79
0.5	1529998	1377.00	0.5	2908304	2617.47	0.5	1478219	1330.40
1	1542181	1387.96	1	760610	684.55	1	1653141	1487.83

Table 7 Compare the minimum and maximum NDVI values over all district

Year	2001(LANDSAT image)		2011(LANDSAT image)		2021(LANDSAT image)	
Station Name	Minimum NDVI	Maximum NDVI	Minimum NDVI	Maximum NDVI	Minimum NDVI	Maximum NDVI
Porbandar	−0.40	0.43	−0.36	0.52	−0.11	0.60
Bharuch	−0.59	0.52	−0.34	0.46	−0.12	0.63
Vadodara	−0.45	0.18	−0.35	0.49	−0.04	0.60
Jamnagar	−0.30	0.50	−0.37	0.51	−0.21	0.64

NDVI values, while Jamnagar (Fig. 14) shows strong seasonal contrasts characterized by intense summer droughts and dynamic vegetation changes, with a notable recovery in maximum NDVI areas by 2021. While, Vadodara (Fig. 13) experienced declining NDVI trends and highlights escalating risks of desertification due to urbanization and land use changes. The SPI area charts indicate Porbandar (Fig. 5) and Jamnagar (Fig. 9) have frequented severe drought episodes and heightened risk of desertification.

Discussion

Rainfall in Gujarat exhibits significant spatial and temporal variability, leading to periods of drought that stress vegetation and soil health. The frequent alternation between wet and dry periods in Bharuch has led to soil degradation and extended drought periods (shown in red) which reduces vegetation cover, increase soil erosion, lowers groundwater levels and makes the soil more vulnerable to wind erosion. The intensity of droughts in this region suggests a high potential for land degradation, as indicated by SPI values which frequently spikes to severe levels between −6 to −8 during critical drought years (Ye et al. 2011). The rainfall distribution shows that while monsoon reliability remains stable, its intensity varies significantly, and there's an increasing contrast between wet and dry seasons. Some years exhibit abrupt transitions from extreme dry to wet conditions, which can have significant implications for soil stability and vegetation health. These patterns have serious implications for desertification in the region. The extended winter droughts stress vegetation during critical growth periods, while intense wet-dry cycles can lead to soil structure degradation (Zhang et al. 2019). The increasing frequency of extreme events accelerates land degradation processes, with the analysis indicating that the duration of dry periods has increased across all districts (Gupta et al. 2021). Particularly, vulnerable periods include the pre-monsoon months (March–May), which show increased vulnerability with SPI values indicating moderate to severe drought conditions, and the post-monsoon transition are more abrupt. The winter months demonstrate heightened desertification risk, suggesting a need for targeted land management strategies during these critical growth periods (Kumar et al. 2020). This analysis indicates a concerning trend toward more extreme and variable precipitation patterns, which could accelerate desertification processes in the region if not properly managed (Mall et al. 2011).

The rainfall analysis reveals compelling patterns and trends across the studied districts, with each area displaying distinct characteristics in their precipitation and drought cycles. Bharuch demonstrates the most variable precipitation patterns with frequent extreme events, while Jamnagar exhibits strong seasonal contrasts characterized by intense summer droughts. Porbandar shows increased vulnerability to post-monsoon droughts, and Vadodara maintains relatively stable monsoon patterns but displays an increasing frequency of pre-monsoon droughts. A notable temporal trend across all districts indicates an intensification of extreme events post-2015, with pre-monsoon drought periods becoming more frequent and severe. However, the maximum NDVI values across all districts show improvement by 2021, with Jamnagar achieving the highest value of 0.64, while Vadodara showed remarkable recovery from its 2001 low of 0.18 to 0.60. While monsoon reliability remains consistent, its intensity varies significantly, and post-monsoon recovery patterns show declining effectiveness. The drought characteristics reveal increasing duration of dry periods across all districts, particularly intensifying during pre-monsoon phases, with rapid transitions between extreme wet and dry conditions becoming more common (Yadav 2022). These findings indicate complex interactions between climate variables, particularly monsoon rainfall, and vegetation patterns. Intense rainfall events can cause soil erosion, particularly in areas with poor vegetation cover with this erratic rainfall patterns which negatively impact groundwater recharge. Heavy rains wash away topsoil, crucial for agricultural productivity and ecosystem health. The study highlights that the alternation between wet and dry periods contributes to soil degradation, making land more vulnerable to erosion. The increasing frequency of extreme events accelerates these land degradation processes. The increasing monsoon rainfall trend correlates with improving maximum NDVI values, although the response varies significantly among districts. This variability suggests the influence of local factors such as urbanization, land use policies, and conservation efforts. The most striking example is Vadodara's transformation which indicates significant urban expansion, while Bharuch's improvement demonstrates successful vegetation conservation strategies.

Conclusion

The analysis of SPI patterns across four districts of Gujarat from 2001–2021 reveals significant transformations in precipitation patterns and drought characteristics, with important implications for regional climate resilience. The comparative analysis of drought characteristics across the coastal districts (Jamnagar and Porbandar) and inland districts (Bharuch and Vadodara) reveals significant differences that have important implications for regional climate resilience strategies. Coastal districts face unique challenges due to their proximity to the sea, which influences precipitation patterns and drought characteristics. For instance, Jamnagar and Porbandar experience increased salinity and soil degradation due to saline water intrusion, exacerbated by erratic rainfall and rising sea levels (Bandyopadhyay 2023). The SPI analysis indicates that these coastal regions are particularly vulnerable to prolonged and intense drought periods, necessitating targeted water management strategies that address both immediate impacts and long-term sustainability. While, inland districts like Bharuch and Vadodara exhibit different drought characteristics, with more pronounced seasonal contrasts and a higher frequency of extreme events. The variability in precipitation patterns in these regions is influenced by urbanization and land use changes, which can exacerbate drought impacts. The study identifies increasing frequency and intensity of extreme events, more pronounced seasonal contrasts, and greater unpredictability in non-monsoon periods. These findings emphasize the critical need for region-specific drought management strategies, strengthened water conservation measures, and improved agricultural planning and adaptation (Bandyopadhyay et al. 2020). This research suggests the importance of long-term monitoring of these trends, development of early warning systems for extreme events, implementation of region-specific mitigation strategies, and integration of these findings into policy planning (Prabhakar and Shaw 2008). The observed changes in precipitation patterns and increasing drought vulnerability across Gujarat's different districts necessitate immediate attention and strategic intervention for sustainable water resource management. These results emphasize the need for district-specific approaches to vegetation management and conservation (Sahoo & Moharaj 2024). Future urban development must be balanced with green space preservation, particularly in rapidly urbanizing districts like Vadodara. The establishment of green corridors and implementation of urban growth boundaries could help maintain ecological connectivity (Joshi 2017). This analysis sets the foundation for future research directions, including detailed investigation of land use change drivers and assessment of vegetation response to extreme rainfall events which would be crucial for developing effective environmental management strategies in Gujarat's diverse landscape.

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Author contribution R. Bhatla and R.K. Mall has developed the research idea, framed the manuscript and has subsequently supervised the work and modified the paper. Richa, Priyanka and Sanjay Bist have done the data collection, analysis, plotting and wrote the manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

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