Analysis of Vegetation Response to Climate Dynamics and Drought in the Al-Gharraf River Basin Using Remote Sensing Data (1989–2025)

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Abstract: This study analysed the spatial and temporal relationship between climatic drought indices and vegetation indices in the Al-Gharraf River basin for the period 1989–2025, to assess the response of vegetation cover to changes in rainfall. The study relied on a comparison of four selected years to demonstrate variations in drought and moisture conditions, using three main indices: the Six-Month Standardised Precipitation Index (SPI-6), the Normalised Difference Vegetation Index (NDVI), and the Vegetation Condition Index (VCI). The results showed a positive linear correlation between the SPI-3 index and the vegetation indices (NDVI and VCI), confirming the high sensitivity of the ecosystem in the study area to medium-term rainfall fluctuations. The study recorded a strong correlation between the NDVI and VCI indices, reaching 0.81, demonstrating their high efficiency in accurately monitoring environmental stress and assessing plant health. Years with peak rainfall (among the four selected years) showed an immediate vegetative response, manifested as higher values of the vegetation indices, resulting from improved soil moisture and enhanced plant physiological processes, The study thus demonstrates the effectiveness of integrating remote sensing with climatic indices in developing early warning systems for drought, and supports decision-making for agricultural planners and water resource managers in the Al-Gharraf region to address the risks of future climate change...

Keywords Climatic Drought, SPI-6, NDVI, VCI, Change Detection, IDW.

Introduction

In the context of global climate change, the frequency and severity of climatic droughts have become a major threat to agricultural sustainability, particularly in arid and semi-arid regions such as Iraq. The Al-Gharraf River, a vital agricultural artery in the alluvial plain, faces increasing challenges due to fluctuating rainfall and water scarcity. Monitoring these dynamics requires an integrated approach combining climate data with satellite-based vegetation indices. Among the various drought indices, the scientific value of this time series lies in its ability to monitor seasonal trends and the long-term average of rainfall, as it is considered more responsive and accurate in representing prevailing climatic conditions. The SPI-6 is highly effective in assessing rainfall during the driest and wettest seasons; at the end of March, the index provides a comprehensive and reliable graphical representation of rainfall amounts during the rainy season, Furthermore, the SPI-6 serves as a vital analytical tool for linking medium-term rainfall deficits to river flow levels and water storage volumes in reservoirs, making it an effective indicator for predicting the onset of hydrological drought and its impacts on available water resources (WMO-No 1090, Geneva, 2012, p. 8) This study utilises remote sensing techniques and Geographic Information Systems (GIS) to analyse the relationship between the SPI-6 index and plant health indices, namely NDVI and VCI, by comparing four representative years between 1989 and 2025. This research aims to measure the sensitivity of local ecosystems to fluctuations in precipitation. The results provide a scientific basis for developing early warning systems..

and improving water resource management in one of Iraq's most productive agricultural regions The Normalised Difference Vegetation Index (NDVI) is one of the most widely used vegetation indices, employed by researchers worldwide to monitor and assess agricultural drought. As the NDVI is a good indicator of vegetation stress, it has proven effective in all studies related to drought. The radiometric principle underlying the calculation of the NDVI relies on two different energy bands: near-infrared (NIR) and visible red (RED). Since healthy, dense green vegetation strongly reflects near-infrared radiation, it absorbs a significant amount of visible red radiation in the electromagnetic spectrum.

Mathematically, the values of the Normalised Difference Vegetation Index (NDVI) fall within a closed range between (+1 and -1), as this index relies on spectral contrast in the plant's response to estimate the density and vitality of vegetation

Chlorophyll strongly absorbs radiation in the red (Red) range, whilst the cellular structure of leaves strongly reflects radiation in the near-infrared (NIR) range.

Consequently, the mathematical equation for the index yields high positive values approaching (+1) in cases of dense, healthy vegetation, whilst these values decrease or become negative when dealing with non-vegetative surfaces such as bare soil, or water bodies that exhibit a different spectral response. By converting this data into visual outputs, each pixel (Pixel) in the NDVI image represents the greenness or vegetation density of that geographical location, with areas of high vitality appearing in light colours (high values) to distinguish them from dark backgrounds representing areas of low or no vegetation activity (Aziz, 2025) (Al-Khazami, Muhammad Al-Khazami Aziz, 2025, p. 273).

Despite the abundance of studies on vegetation cover in Iraq, there is a scarcity of studies linking spectral indices (NDVI, VCI) and climatic indices (SPI) over long time periods exceeding three decades, specifically in the Al-Gharraf River region. This research, therefore, aims to fill this gap by analysing time series and determining the extent to which local ecosystems respond to extreme climate changes, thereby providing an accurate database for decision-makers in water resource management.

Study area

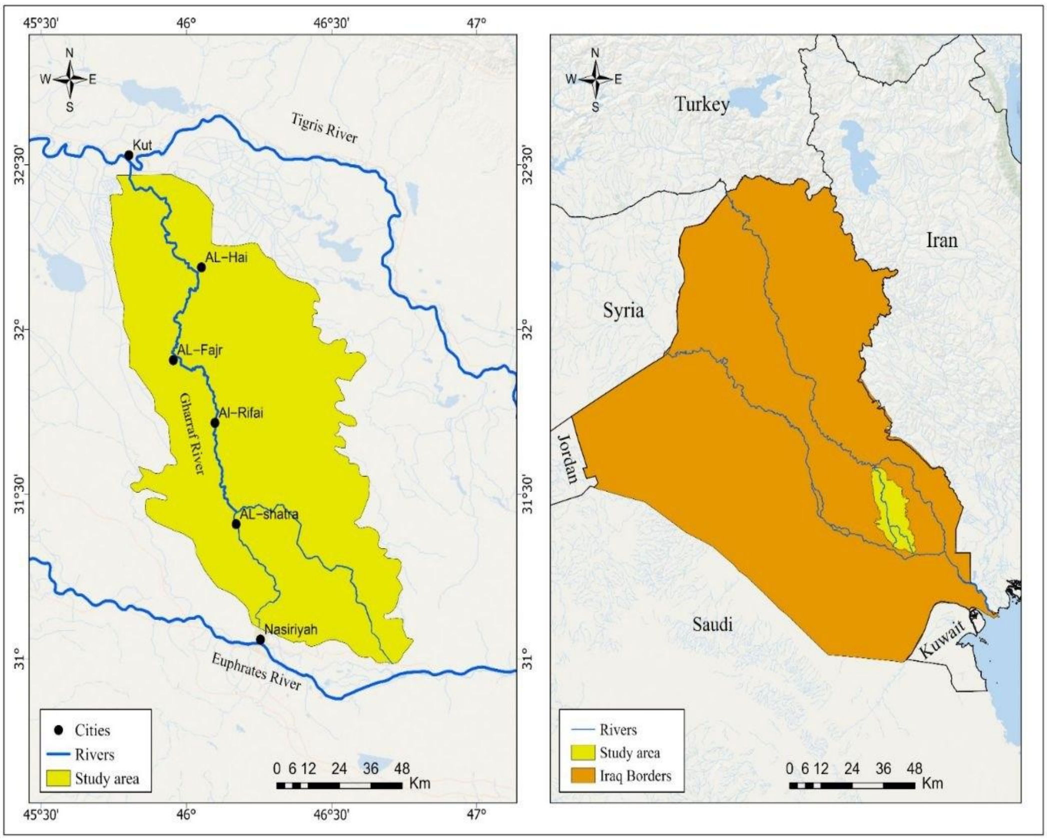
The study area is located within the governorates of Wasit and Dhi Qar, and a very small part of the Maysan governorate, within the Sedimentary Plain region. It extends from the north-west to the south-east, and its area, as calculated using ArcGIS Pro, accounts for 2.06% of Iraq's total area of 435,052 km². Its geographical location is confined between latitudes 2° 31′ – 27° 32′ north and the longitudes 45° 45′ – 43° 46′ east (Map 1).

Table 1: Astronomical coordinates of the stations used in the study

Station	**longitude**	**Circle of latitude**	**Altitude above sea level m**	**Station number**
Al-Kut	49′ 45°	30′ 32°	19	664
Neighborhood	2′ 46°	8′ 32°	17	665
Al-Nasiriyah	14′ 46°	1′ 31°	5	676

Source: Republic of Iraq, Ministry of Transport, General Authority for Meteorology and Seismic Monitoring, Climate Division, Baghdad, 2025.

Map (1) Location of the study area



Source: *Researcher based on Landsat 9 satellite imagery and using ArcGIS Pro software*

The Al-Gharraf River is the oldest and widest of the irrigation canals; it was dug in 2400 BC. The Al-Gharraf branches off from the Tigris River north of the Al-Kut Dam (Al-Kashab, Wafiq Hussein Al-Kashab et al., 1983, p. 180). It was the elevation of the Tigris River valley above that of the Euphrates River valley in this region that encouraged the construction of this river, as it flows on the south-western side of the Tigris River (Al-Hamiri, Abdul-Razzaq Aboud Al-Hamiri, 2013, p. 120). The geographical importance of the Al-Gharraf River lies in its irrigation of the lands between the Tigris and Euphrates rivers; were it not for the Al-Gharraf River, the lands between the two rivers would have become barren.

The Al-Gharraf region generally slopes from the north-east towards the south-west, in line with the general gradient of the Iraqi terrain. This gradient means that the surface slopes from the Tigris River in the north-east of the region towards the Euphrates River in the south-west. This gradient is of great importance for the flow of water in the Al-Gharraf River from the Tigris towards the Euphrates, following the natural slope of the region's surface. Despite the flatness of the region, particularly the succession of drainage networks and natural floods, the land has developed a phenomenon known as micro-relief. This is characterised by the presence of internal basins in the region resulting from repeated flooding, as well as from sediments carried by both ancient and modern streams (Al-Ghazi, Hassan Suadi Najib Al-Ghazi, 2005, p. 24).

The rainfall in the study area largely falls within the characteristics of Mediterranean rainfall, which is a type of transitional rainfall occurring between tropical and temperate latitudes (Al-Mousawi, Ali Sahib Talib Al-Mousawi and Abbas Zaghair Muhsin Al-Mariani, 2018, p. 252). The rainy season runs from October to the end of May, and this is linked to the arrival of Mediterranean low-pressure systems in the study area, followed by the spring months (March, April, May), with rainfall ceasing after May and a dry period setting in from June to the end of September (Al-Jumai, Mustafa Khairallah and Lfta Al-Jumai, 2022, p. 46). Desert herbaceous plants and grasses grow in the study area in early spring and continue into early summer, as do perennial plants, which are the most capable of withstanding drought and high temperatures for most of the year. These are characterised by rapid leaf growth during the rainy season and a well-developed root system, often of short stature. In addition, there are marsh and swamp plants, which are water-loving plants that thrive in marshes and swamps where water is available throughout the year. Reed and papyrus are among the most important of these plants due to their benefits and widespread distribution, reaching heights of 5–7 metres in some areas (Al-Tamimi, Amin Abdul Ali Hussein Ali Al-Tamimi, 2022, p. 59).

Materials and Methods:

This study employs an integrated analytical approach that links climatic variables with spatial plant responses. The materials and methods are summarised as follows:

Data sources: Monthly rainfall time series from meteorological stations (Al-Kut, Al-Hay, Al-Nasiriyah) for the period 1989–2025 were used. As for satellite data, the study relied on imagery from the Landsat satellite series (4, 5, 7, 8, 9) for the month of March to ensure the continuity of the analysis.

Standard Precipitation Index (SPI): The SPI was calculated for six months (Table 3), and its value for March was determined for the three weather stations (Al-Kut, Al-Hay, Al-Nasiriyah) using the Drinc 1.7 programme and monthly rainfall data covering the period 1989–2025, i.e. rainfall before and during the growing season, which influences the nature, condition and activity of vegetation, and thus reflects seasonal drought and wet conditions well (Qasim et al., 2021), To determine drought levels and periods of moisture in the study area, the global classification established by the World Meteorological Organisation (WMO) was adopted, whereby the resulting values are divided into categories ranging from drought to moisture, as shown in Table 2 :

Table (2) Drought Index Values

SPI values	Classification
-2 ≥	Extremely Dry
-1.99 to -1.5	Extremely Dry
-1.49 to -1	Moderately Dry
-0.99 to 0	Moderately Humid
0 to 0.99	Moderately Humid
1 to 1.49	Extremely Humid
1.5 to 1.99	Extremely Humid
2 ≤	Classification

Source: *The researcher's work, based on the World Meteorological Organisation, Standardised Precipitation Index User Guide, WMO-No. 1090, Geneva, 2012, p. .3*

The Standardized Precipitation Index for six months (SPI-6) is used as a tool for statistical comparison; the index value calculated at the end of March represents the sum of actual rainfall recorded for the months of (October, November, December, January, February and March) of the current hydrological year and statistically compared with the total rainfall for the same period (October–March) for all hydrological years in the station's climate record.

Normalised Difference Vegetation Index (NDVI):

NDVI values were extracted using ArcGIS Pro software based on the standard difference between the NIR and Red bands according to the equation:

NDVI = (NIR – Red)/(NIR + Red)

Vegetation Cover Index =NDVI

Near-infrared =NIR

Visible light Infrared =RED

The above equation is used in Landsat satellite data as follows:

Landsat (4,5,7) NDVI = (Band4 -Band3)/ (Band4 + Band3)

Landsat(8,9) NDVI = (Band5-Band4) /(Band5 + Band4)

The values of the Normalised Difference Vegetation Index (NDVI) fall within a fixed range between +1 and -1. This index relies on spectral differences in the plant's response to estimate the density and vitality of vegetation

Chlorophyll strongly absorbs radiation in the red (Red) spectrum, whilst the cellular structure of leaves strongly reflects radiation in the near-infrared (NIR) spectrum.

Consequently, the mathematical equation for the index yields high positive values approaching (+1) in cases of dense, healthy vegetation, whilst these values decrease or become negative when dealing with non-vegetative surfaces such as bare soil, or water bodies that exhibit a different spectral response. By converting this data into visual outputs, each pixel in the NDVI image represents the degree of greenness or vegetation density of that geographical location, with areas of high vitality appearing in light colours (high values) to distinguish them from the dark backgrounds representing areas of low or no vegetation activity (Al-Khazami, Muhammad Al-Khazami Aziz, 2025, p. 273). Four categories of land cover were established based on NDVI values. The first category ranged from -1 to 0.18 and was therefore excluded as it does not represent actual vegetation cover. The other categories were defined as follows: The second category (0.27–0.18) represents low-density vegetation cover; the third category (0.36–0.27) 0.27), representing medium-density vegetation cover, and the fourth category with values higher than (0.36), representing high-density vegetation cover, to calculate the vegetation cover index in the study area for the purpose of monitoring drought.

:3.3Assessment of NDVI vegetation cover change every ten years (decadal): Methods for detecting geographical change, defined as the detection of changes in land cover by comparing satellite imagery taken at different times, are among the important methods in the study and for assessing vegetation change in arid and semi-arid regions. Accordingly, remote sensing technology was employed to detect changes in vegetation cover in the study area by examining the extent of vegetation change and the areas that experienced increases or decreases in vegetation cover, utilising satellite imagery and the NDVI index, which is considered one of the most suitable techniques for detecting vegetation change (Al-Shahri, Reem Mohammed Al-Shahri, n.d., p. 31). A comparison was made between the following years.(2023 ,2013 ,2003 ,1993)

:4-3Vegetation Condition Index (VCI): This index is based on measuring the Normalised Difference Vegetation Index (NDVI) and comparing it with the maximum and minimum values for the same area, to reflect the level of stress or health of the vegetation with high accuracy. VCI values range from zero to one hundred, with low values indicating plant stress or unsuitable environmental conditions, whilst high values indicate good plant health and normal growth. The scientific strength of the VCI lies in its ability to monitor water stress and agricultural drought with high accuracy; it measures not only the quantity of vegetation (as the NDVI does), but also its quality and physiological health relative to the potential of the geographical location. It is an ideal tool for assessing seasonal and annual environmental changes, and for distinguishing the impact of extreme weather conditions from the stable environmental characteristics of the study area. The index values are calculated using software based on the following mathematical relationship (Kogan, Felix N. Kogan, 1990, p. 1405):

$$VCI = \frac{NDVI\ current - NDVI\ min}{NDVI\ max - NDVI\ min} * 100$$

Whereas:

VCI: Represents the Vegetation Condition Index value

NDVI current: Represents the actual (current) value of the Normalised Difference Vegetation Index.

NDVI max: The maximum value of the NDVI recorded during the time series.(2025–1990)

NDVI min: The minimum value of the NDVI recorded during the time series.(2025–1990)

To enable accurate statistical and spatial analysis, the index results in this study were divided into five main categories of equal range (20 degrees per category), reflecting the gradient from severe drought to ideal vegetative recovery.

Using the inverse distance weighting method (Mohammed, Nadia Qasim Mohammed, Ali Mohammed Rajah and Inaam Mohammed Ayd, 2024, p. 550) within the ArcGIS Pro environment to model the spatial variation of drought between stations, based on the principle of spatial correlation, which states that the closer the points, the more similar they are. The concept is primarily based on Tobler's Law (the first law of geography), which states that 'every phenomenon is related to other phenomena, but related phenomena are more closely related than distant ones. The model relies entirely on the distance between units of the phenomenon (Mohammed et al., 2024), , according to a mathematical equation (Njeban, Hassan Suwadi Njeban, 2018, p. 366):

$$z_j = \frac{\sum_i \frac{z_i}{d_{ij}^n}}{\sum_i \frac{1}{d_{ij}^n}}$$

Where:

Zj = the estimated value of the unknown point at location

Zi = the actual value at the known point (station)

= dij the distance between the known point i and the unknown point j to be estimated

n = the power or exponent that determines the extent to which distance affects the weighting; as the value of the exponent increases, the influence of distant points decreases, and that of nearby points increases.

Results and Discussion

Analysis of climatic drought (SPI-6)

Table 3 shows the total rainfall for the entire growing season, which has the greatest impact on agricultural water resources at the stations in the study area, as follows:

The Al-Kut station has shown a trend towards cumulative drought, with the hydrological year (2007–2008) recording a value of (1.59–), classified as severe drought, whilst a series of wet years emerged at the end of the time series (2018–2021) with values ranging from (1.32 and 2.06). Figure 1 shows that the six-month curve at Al-Kut station tends towards greater temporal stability than the three-month index.

Meanwhile, the Al-Hay station recorded a high response to cumulative moisture in the hydrological year (2018–2019) with a value of (2.20), classified as very wet, as for years of water deficit, these peaked in the hydrological year (2017–2018) with a value of (2.02), classified as 'extremely dry'.

From Figure 2, we observe that the Al-Hay station experienced varying degrees of drought, which had an impact on its overall average.

As for the Nasiriyah station, the hydrological year (2013–2014) showed the highest recorded value for moisture, reaching (2.24), which was classified as very wet, whilst the station recorded varying years of drought, with the highest value reaching (1.96) in the hydrological year (2002–2003). Figure 3 clearly indicates that the Nasiriyah station experiences wide fluctuations in the six-month index .

The study area experienced distinct periods of drought during the period (2000–2012), as negative values predominated in Table 3. Furthermore, there was a relative improvement in the latter periods of the study, whilst the Nasiriyah station remained the most vulnerable to climatic extremes (whether increasing or decreasing).

Table (3) :Classification of drought according to SPI values at stations in the study area over six months: (Jan–Feb–Mar–Apr).

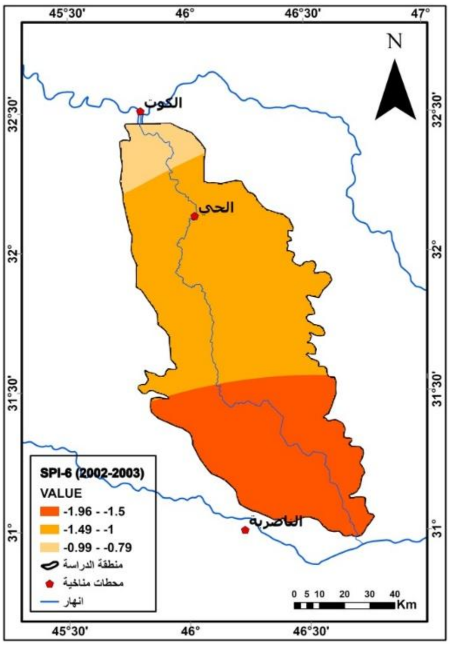
Year	Kut Value	Kut Classification	Hayy Value	Hayy Classification	Nasiriyah Value	Nasiriyah Classification
1989–1990	-0.22	Moderately Dry	-1.02	Moderately Dry	-0.54	Moderately Dry
1990–1991	-1.49	Moderately Dry	0.63	Moderately Wet	0.35	Moderately Wet
1991–1992	0.15	Moderately Wet	0.13	Moderately Wet	0.61	Moderately Wet
1992–1993	0.65	Moderately Wet	0.73	Moderately Wet	0.52	Moderately Wet
1993–1994	0.61	Moderately Wet	-0.19	Moderately Dry	-0.75	Moderately Dry
1994–1995	0.87	Moderately Wet	0.80	Moderately Wet	0.69	Moderately Wet
1995–1996	1.15	Medium Wet	1.41	Medium Wet	1.20	Medium Wet
1996–1997	-0.13	Moderately Dry	-0.95	Moderately Dry	-0.36	Moderately Dry
1997–1998	1.28	Medium Wet	1.42	Medium Wet	1.72	Very Wet
1998–1999	0.22	Moderately Wet	0.06	Moderately Wet	0.43	Moderately Wet
1999–2000	0.37	Moderately Wet	-0.23	Moderately Dry	-0.32	Moderately Dry
2000–2001	0.31	Moderately Wet	-0.35	Moderately Dry	0.15	Moderately Wet
2001–2002	0.31	Moderately Wet	-0.10	Moderately Dry	-0.2	Moderately Dry

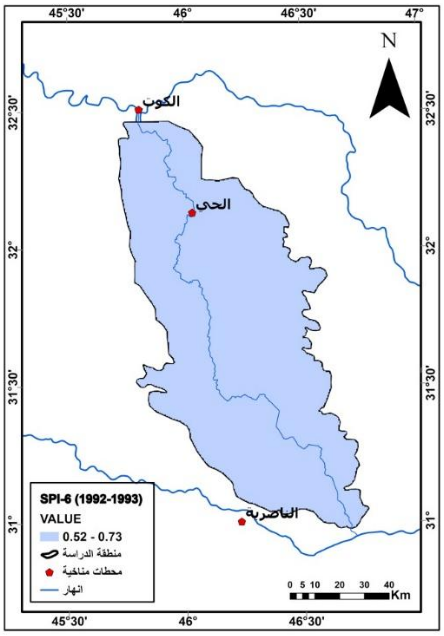
					2	
2002–2003	-0.79	Moderately Dry	-1.13	Medium Dry	-1.96	Severe Dry
2003–2004	-1.34	Medium Dry	-1.60	Severe Dry	-1.32	Medium Dry
2004–2005	-1.16	Medium Dry	0.10	Moderately Wet	0.55	Moderately Wet
2005–2006	-1.37	Medium Dry	0.23	Moderately Wet	0.44	Moderately Wet
2006–2007	-1.35	Medium Dry	0.10	Moderately Wet	1.54	Severe Wet
2007–2008	-1.59	Severe Dry	-0.49	Moderately Dry	-0.69	Moderately Dry
2008–2009	-1.58	Severe Dry	-1.51	Severe Dry	-0.54	Moderately Dry
2009–2010	-1.38	Medium Dry	-0.22	Moderately Dry	-1.35	Medium Dry
2010–2011	0.07	Moderately Wet	0.01	Moderately Wet	-0.78	Moderately Dry
2011–2012	-1.04	Medium Dry	-1.96	Severe Dry	-0.96	Moderately Dry
2012–2013	0.72	Moderately Wet	0.07	Moderately Wet	0.05	Moderately Wet
2013–2014	1.03	Medium Wet	1.14	Medium Wet	2.24	Extremely Wet
2014–2015	0.27	Moderately Wet	0.43	Moderately Wet	-0.43	Moderately Dry
2015–2016	0.97	Moderately Wet	1.31	Medium Wet	0.09	Moderately Wet
2016–2017	-0.04	Moderately Dry	-0.94	Moderately Dry	-1.01	Medium Dry
2017–2018	-0.18	Moderately Dry	-2.02	Extremely Dry	-1.61	Severe Dry
2018–2019	2.06	Extremely Wet	2.20	Extremely Wet	1.75	Severe Wet

2019–2020	1.32	Medium Wet	0.97	Moderately Wet	0.12	Moderately Wet
2020–2021	1.32	Medium Wet	0.13	Moderately Wet	0.49	Moderately Wet
2021–2022	-1.40	Medium Dry	-1.06	Medium Dry	-1.24	Medium Dry
2022–2023	1.16	Medium Wet	1.30	Medium Wet	1.37	Medium Wet
2023–2024	0.23	Moderately Wet	1.01	Medium Wet	0.45	Moderately Wet
2024–2025	-0.03	Moderately Dry	-0.41	Moderately Dry	-0.79	Moderately Dry
Overall Mean	0.84	Moderately Wet	0.00	Moderately Wet	-0.00	Moderately Dry

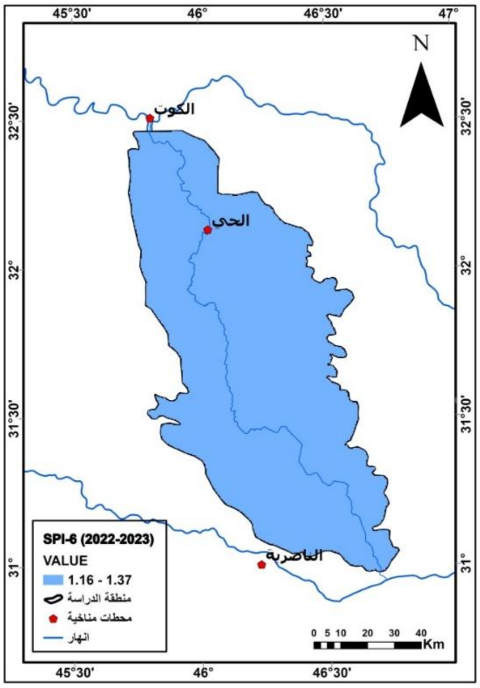
Source: The researcher's work, based on monthly rainfall data using Drinc 1.7 software.

Map (2): SPI Index for the six months 1992–1993 .**Map (3):** SPI Index for the six months 2002–2003

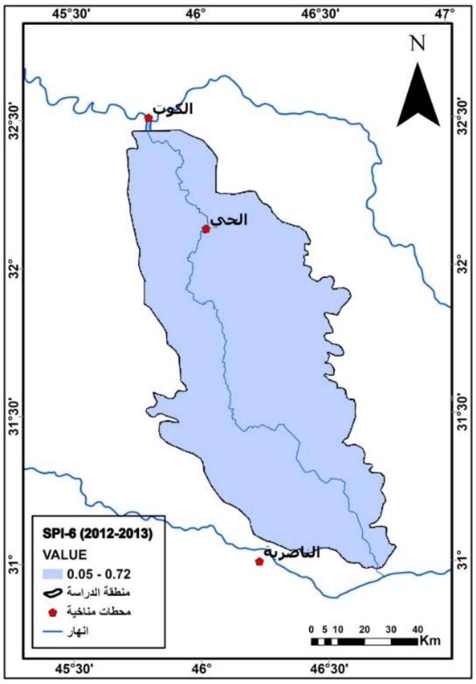




Map (4): SPI Index for the six months of 2022–2023



Map (5): SPI Index for the six months 2012–2013



Analysis of temporal and spatial changes in vegetation cover

The NDVI vegetation index revealed decadal changes in vegetation cover in the study area for the years 1993, 2003, 2013, 2023), as it is one of the most effective spectral indices for monitoring biomass and vegetation changes in arid and semi-arid environments (NASA; USGS.(

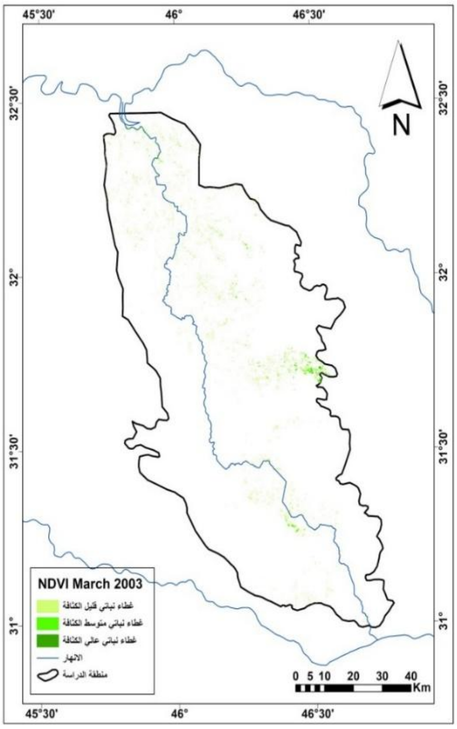
The results for the period 1993–2003 showed a sharp deterioration in vegetation structure, with the area of low-density vegetation decreasing from 725 km² to 91 km², a change of 634 km² (87.44%); Medium-density areas also declined from 437 km² to 16 km², a decrease of 421 km² (96.33%), whilst high-density cover decreased from 426 km² to 1 km², a change of 425 km² and a percentage of 99.76%, bringing the total loss to 1,480 km² and a percentage of 93.20%. This reflects the region's exposure to severe environmental pressures during this period.

In contrast, the period (2003–2013) witnessed a clear recovery phase, as the area of low-density cover increased from (91 km²) to (784 km²), an increase of (693 km²) and a percentage of (761%), areas of medium-density cover increased from 16 km² to 71 km², an increase of 55 km² (343%), whilst high-density cover rose from 1 km² to 3 km², an increase of 2 km² (200%). The total increase was 750 km², representing a 694% rise, indicating a relative improvement in environmental and hydrological conditions.

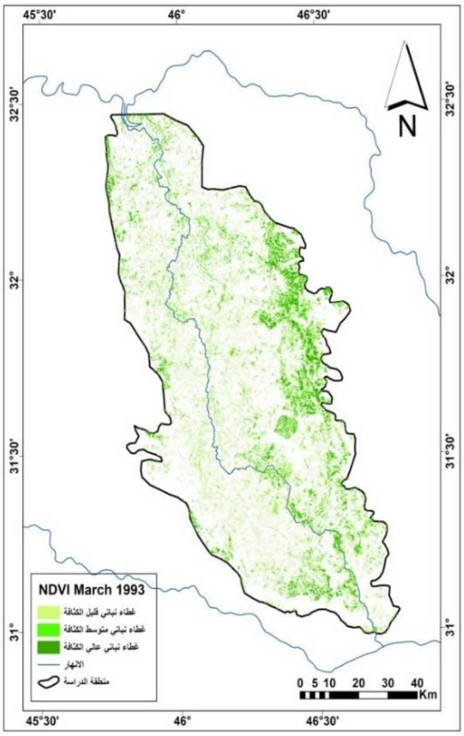
During the period 2013–2023, the region recorded exceptional spatial expansion in vegetation growth, with low-density cover rising from 784 km² to 1,455 km², an increase of 671 km² (85%), whilst medium-density cover jumped from 71 km² to 947 km², an increase of 876 km² (1233%), whilst high-density cover achieved significant growth from 3 km² to 834 km², an increase of 831 km² (27,700%). The total increase amounted to 2,378 km² (277%), reflecting a radical shift in photosynthetic efficiency and biomass in the study area.

Overall, the results illustrate three distinct phases: a phase of sharp decline (1993–2003), followed by a phase of gradual recovery (2003–2013), and then a phase of expansion and marked acceleration in vegetation growth (2013–2023), which confirms the sensitivity of the NDVI index to monitoring long-term environmental changes .

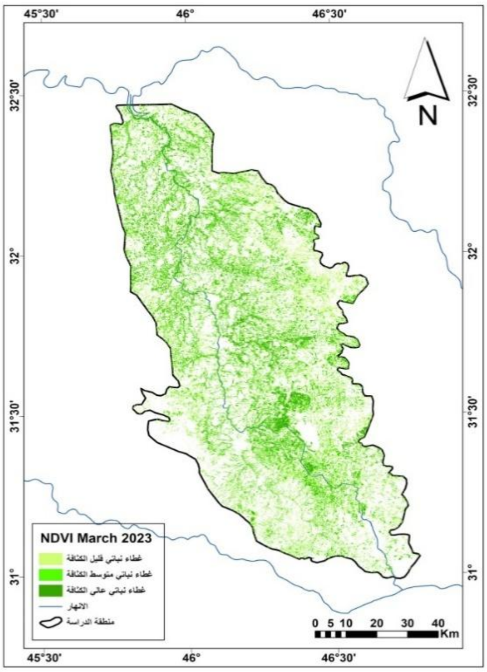
Map (6): NDVI March 1993.



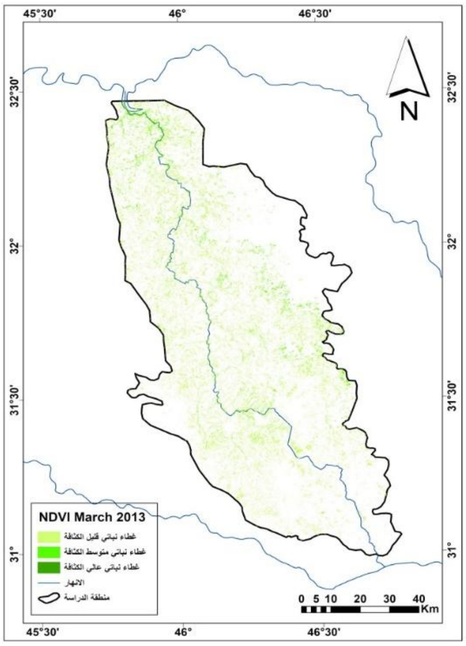
Map (7): NDVI March 2003.



Map (8): NDVI March 2023.



Map (9): NDVI March 2003



Source: The researcher's work, based on observations of the study area using ArcGIS Pro

Vegetation Condition Index (VCI) and drought monitoring

In order to obtain an accurate statistical and spatial analysis, the index results in this study were divided into five main categories of equal range (20 points per category), reflecting the spectrum from severe drought to ideal vegetative recovery, as shown in Table 6:

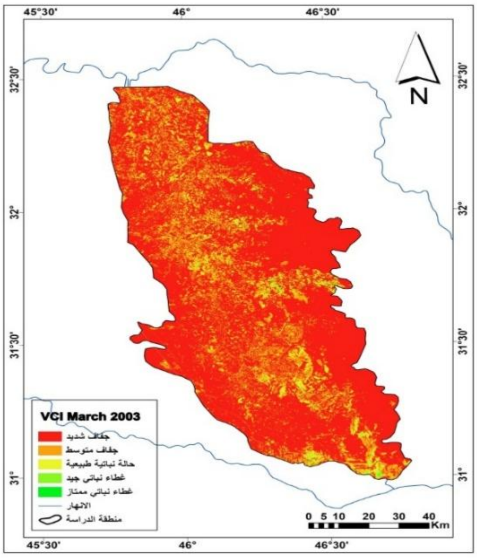
Table 4: Classification of VCI categories and their ecological implications

VCI values	Description	Interpretation:
0-20	Extreme drought	A sharp decline in plant health, often associated with severe drought seasons.
20-40	Moderate drought	The presence of marked plant stress and a decrease in vital activity compared to normal rates.
40-60	Normal vegetation condition	Environmental balance, where vegetation grows within the expected normal range for the region.
60-80	Good vegetation cover	Indicates favorable growth conditions and vegetative recovery exceeding general annual averages.
80-100	Excellent vegetation cover	Represents the peak of vegetative growth, occurring when ideal climatic and water conditions are available.

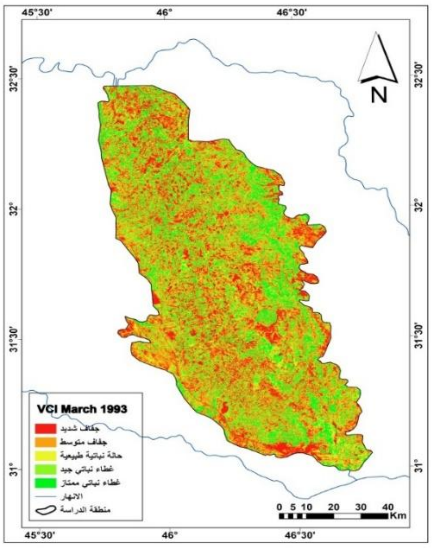
Source*: Plybour, C., Uttaruk, Y., Jeefoo, P., & Laosuwan, N., Spatial Drought Occurrence and Distribution Using Data from Sentinel-2 Satellite and Vegetation Indices, Geographia Technica, Vol. 20, Issue 1, 2025 ،p14.*

VCI maps represent the final output of the digital processing of remote sensing data, accurately reflecting the spatial and temporal variation in vegetation cover within the study area; These maps derive their scientific value from the Vegetation Condition Index (VCI)'s ability to balance current values within the adopted time series (maximum and minimum limits), making them a mirror of the environmental response to climatic variables, as they link plant biotic behaviour to climatic constraints. The notable correlation between the VCI maps and the NDVI maps confirms that the hydrological variable (precipitation) is the primary driver of vegetation health in the study area.

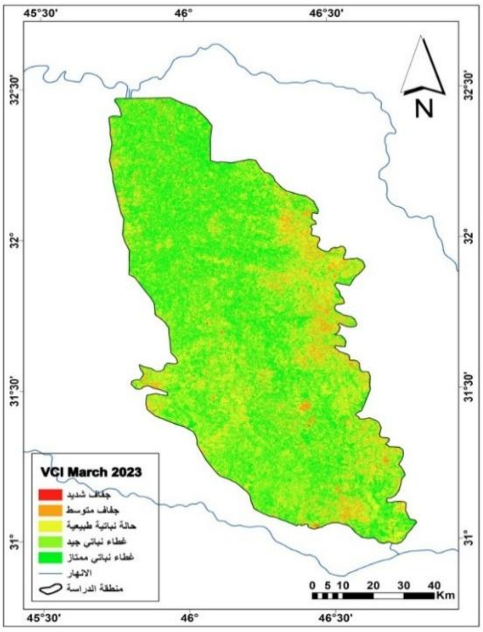
Map (10) : VCI March 1993



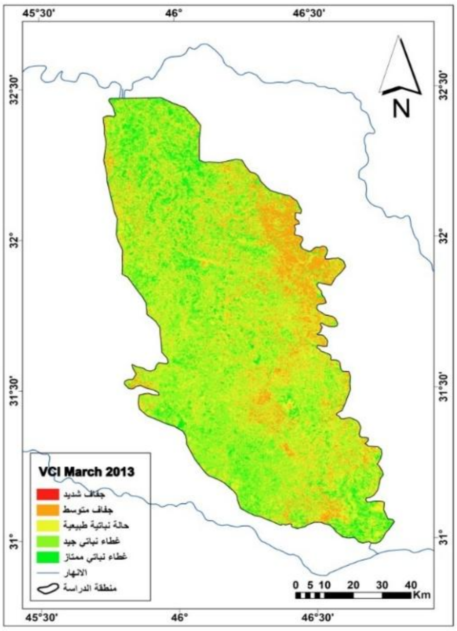
Map (11): VCI March 2003



Map (13) VCI March 2023



Map (12) VCI March 2013



Source: The researcher's work, based on observations of the study area using ArcGIS Pro

The relationship between SPI-6 climatic drought and vegetation cover using the NDV index

The results of the statistical analysis presented in Table 5 and Figure 5 reveal a moderate positive correlation between the Normalised Difference Vegetation Index (NDVI) and the Standardised Precipitation Index (SPI-6) in the Al-Gharraf River basin throughout the study period, with a Pearson correlation coefficient of 0.61. This value is considered a positive statistical indicator reflecting the dynamic response and high sensitivity of vegetation cover to the prevailing hydrological and climatic changes in the region.

The fact that such a strong correlation has been recorded demonstrates the high explanatory power of the independent variable (rainfall variability) in tracking the behaviour of the dependent variable (vegetation density and vitality), as it is evident from the time series data that years of abundant rainfall, particularly the hydrological year (2018–2019) which recorded a peak SPI-6 value of 6.01, were accompanied by a marked surge in NDVI values reaching 3081, This statistical correlation indicates that the ecosystem in the Al-Gharraf River region possesses high resilience to respond rapidly to rainfall inputs, thereby enhancing the efficiency of plant physiological processes.

From a geographical perspective, the choice of the six-month scale (SPI-6) has proven its scientific validity in monitoring this relationship, as it represents a sufficient time span for moisture accumulation in the soil, which is directly reflected in the health status of crops and natural vegetation monitored by remote sensing. Although the region relies primarily on surface irrigation from the Al-Gharraf River, the extracted correlation coefficient (0.61) demonstrates that rainfall remains a decisive and complementary factor, both by supporting rain-fed agriculture and through its role in improving soil quality and reducing the impact of salts, thereby stimulating plant activity comprehensively.

The results of the linear regression analysis in Figure 5 show a strong positive correlation between the Standard Precipitation Index (SPI-6) and the Normalised Difference Vegetation Index (NDVI). According to the coefficient of determination ($R^2 = 0.573$), climate (represented by rainfall) explains approximately 57% of the variations in vegetation density in the study area. Statistically, this result indicates that vegetation cover in the Al-Gharraf Basin is fundamentally and sensitively dependent on short- and medium-term rainfall fluctuations, making the region vulnerable to environmental risks in years of reduced rainfall.

It can be concluded from this analysis that the relationship between the two variables follows a regular causal pattern, enabling the future prediction of vegetation cover and agricultural productivity levels by tracking SPI-6 index values, thereby making it a reliable early warning tool for managing drought risks and their environmental impacts in the study area.

Table 5: The relationship between the Normalised Difference Vegetation Index (NDVI) and the Standard Precipitation Index (SPI-6) in the study area during the period 1989–2025.

Year	**NDVI area km2**	**SPI-6 value**
1989 - 1990	766	-1.78
1990 - 1991	1216	-0.51
1991 - 1992	1112	0.89
1992 - 1993	1588	1.9
1993 - 1994	1376	-0.33
1994 - 1995	2273	2.36
1995 - 1996	2196	3.76
1996 - 1997	1346	-1.44
1997 - 1998	2303	4.42
1998 - 1999	1695	0.71
1999 - 2000	382	-0.18
2000 - 2001	678	0.11
2001 - 2002	626	-0.01
2002 - 2003	108	-3.88

2003 - 2004	183	-4.26
2004 - 2005	1407	-0.51
2005 - 2006	620	-0.7
2006 - 2007	1114	0.29
2007 - 2008	291	-2.77
2008 - 2009	423	-3.63
2009 - 2010	316	-2.95
2010 - 2011	15	-0.7
2011 - 2012	3102	-3.96
2012 - 2013	858	0.84
2013 - 2014	3087	4.41
2014 - 2015	1490	0.27
2015 - 2016	1752	2.37
2016 - 2017	1670	-1.99
2017 - 2018	1537	-3.81
2018 - 2019	3081	6.01
2019 - 2020	3669	2.41
2020 - 2021	3308	1.94
2021 - 2022	1433	-3.7
2022 - 2023	3236	3.83
2023 - 2024	1704	1.69
2024 - 2025	2194	-1.23
Pearson correlation coefficient (0.61)		

Source: The researcher's work using Excel

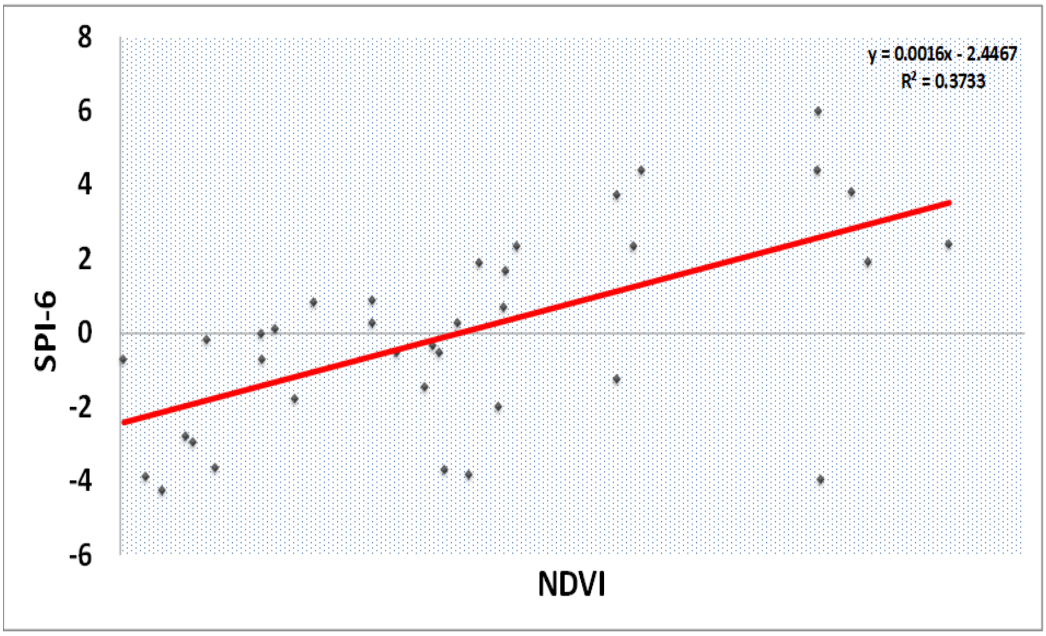


Figure 5: The relationship between the Normalised Difference Vegetation Index (NDVI) and the Standardised Precipitation Index (SPI-6) in the Al-Gharraf River basin during the period 1989–2025.

Source: Researcher's own work based on Table 11

The correlation between vegetation cover areas and the Vegetation Condition Index (VCI) for each decade

The study of the correlation between vegetation cover areas, as represented by the NDVI index, and the Vegetation Condition Index (VCI) is a key focus in drought analysis and the assessment of the ecological response to climate change, as it provides a quantitative and accurate understanding of the nature of the interaction between vegetation density and its health status. The NDVI index reflects the actual state of plant activity, whilst the VCI index reflects the degree to which this activity is affected by prevailing climatic conditions compared to its historical record. Analysis of the correlation between these two indices helps reveal ecosystem stability, determine plant stress levels, assess land degradation risks, and support decision-making in resource management during drought cycles and long-term climate fluctuations.

Consequently, the nature and strength of the statistical relationship between the NDVI and the VCI indices for natural and agricultural areas can be analysed. This analysis also allows for the tracking of temporal trends in environmental changes, linking them across the selected reference years, and interpreting the results considering the climatic and environmental characteristics of the study area.

"The data in Table 24 reveal a sharp and exceptional decline in vegetation cover (NDVI) during 2003, when it recorded its lowest levels (108 km²) compared to other years. This deterioration is attributed to a combination of climatic and hydrological factors, namely a severe drought that struck the Al-Gharraf River region, coinciding with significant fluctuations in water inflows, which led to the drying up of vast areas of agricultural land and natural pastures, This is confirmed by the parallel decline in the Vegetation Cover Index (VCI) to 12.26, indicating a state of severe environmental stress.

Table 6: Correlation between NDVI area and VCI values for the following years ,2003 ,1993) (2023 ,2013

years	NDVI area km²	VCI value
1993	1588	46.52
2003	108	12.26
2013	858	59.24
2023	3236	70.88
Pearson correlation coefficient (0.80)		

Source: Researcher based on the NDVI vegetation index for imagery of the Al-Dur region

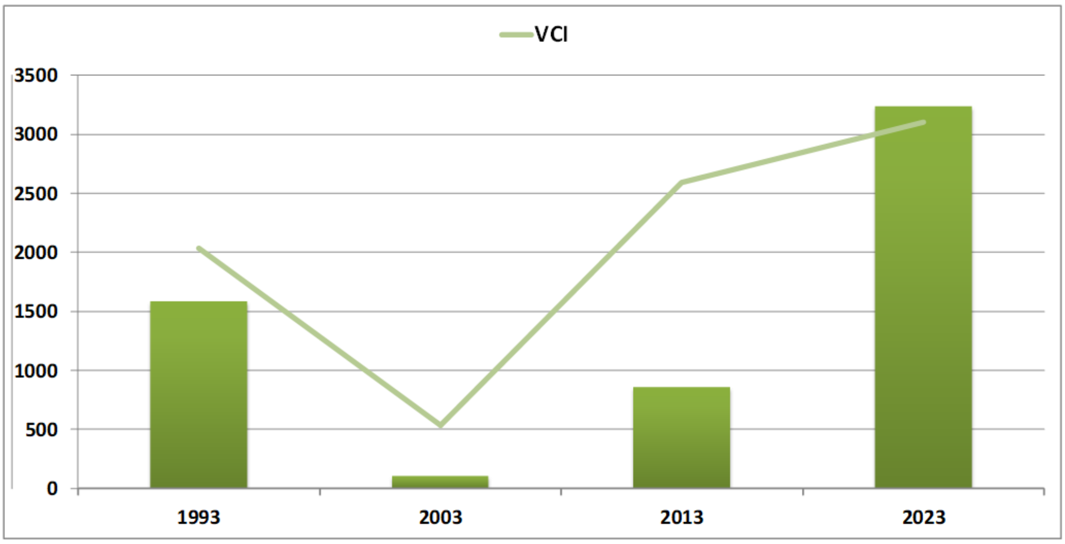


Figure 6: The relationship between the Normalised Difference Vegetation Index (NDVI) and the Vegetation Condition Index (VCI) in the study area for the 1993, 2003, 2013 and 2023. Source: The researcher's own work, based on Table 6

Conclusions

The results of the analysis revealed a positive linear correlation between the Standard Precipitation Index (SPI-6) and the vegetation indices (NDVI and VCI), indicating that changes in rainfall amounts are directly reflected in the condition and biological activity of vegetation in the study area.

The results indicated a strong correlation between the NDVI and VCI indices, amounting to 0.81, confirming their functional complementarity in assessing plant health and monitoring levels of environmental stress.

Years of peak rainfall showed a high plant response, reflected in elevated NDVI and VCI values, indicating the sensitivity of the local ecosystem to climatic fluctuations and its direct dependence on the abundance of water resources.

The positive relationship between climatic drought indices and plant indices can be explained by the fact that increased rainfall improves soil moisture and enhances the roots' ability to absorb water and nutrients, which has a positive effect on plant physiological processes, particularly photosynthesis, and consequently leads to higher values of the (NDVI and VCI). Furthermore, the accumulation of rainfall over longer periods, as in the SPI-6 index, contributes to the stabilisation of soil moisture and a reduction in water stress.

Based on the findings, we recommend the adoption of climate adaptation strategies in the Al-Gharraf River basin and the implementation of remote sensing technologies as an early warning system for drought monitoring. We also emphasise the need to expand green belt and modern irrigation projects to reduce the overall dependence of vegetation cover on fluctuating rainfall, thereby contributing to the enhancement of the region's environmental stability.

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