Quantifying land degradation and desertification in semi-arid regions through environmental monitoring and assessment (A case study of the Imiter area, Toudgha River catchment, Morocco)

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Abstract

This study focuses on the spatiotemporal drought analysis in the driest region of southeastern Morocco, specifically the Imiter region within the eastern Anti Atlas region. The region has witnessed various climate change events in recent years, necessitating a comprehensive investigation of the relationship between climate and environmental conditions. To achieve this, Landsat 7, 8 and 9 satellite data were utilized for drought analysis. Additionally, satellite-based drought indices including the Normalized Difference Vegetation Index (NDVI) and Vegetation Condition Index (VCI), were employed to assess the extent of drought evolution. Over a period of two decades (from 1998 to 2022), 24 annual spatial maps were generated for each index to identify the most affected areas.

The analysis of NDVI and VCI from 1998 to 2011 revealed significant year-to-year variability, attributed to various factors such as declining piezometric levels, deforestation and mining activities. These findings contribute to a better understanding of drought dynamics in the study area and highlight the importance of monitoring environmental conditions for effective drought management and mitigation strategies.

Keywords: Drought analysis, Spatiotemporal variability, Semi-arid region, Imiter region, NDVI and VCI indices, Eastern Anti-Atlas, Morocco.

Introduction

The terrestrial ecosystems have been greatly impacted by global climate change since the industrial revolution[40], leading to a growing trend of ecological degradation in source areas caused by both climate change and unsustainable resource exploitation[10]. Vegetation plays a vital role in maintaining environmental balance and responding to climate change with strong connections between vegetation and ecoclimatic variables. However, traditional methods like field observations are rarely used to study the effects of climate change on ecosystems. In recent years, the utilization of satellite imagery has emerged as a viable approach for monitoring environmental phenomena[8].

The presence of vegetation cover is of utmost importance in maintaining the delicate balance of ecosystems. It serves critical functions such as soil protection, erosion prevention and mitigating the impact of rainfall by enhancing soil infiltration capacity and reducing surface runoff. The significance of vegetation cover in these processes has been emphasized by studies conducted by Maimouni et al[25] and Vasquez et al[39]. Moreover, vegetation cover plays a crucial role in biodiversity conservation and acts as a natural defense against natural hazards like landslides and floods, as highlighted by[28]. Therefore, the preservation and promotion of vegetation cover are crucial, particularly in arid and semi-arid regions, where the need for soil protection and erosion control is particularly urgent[25].

Given the increasing demand for food production to meet the growing global food needs, achieving higher crop yields and resilient agriculture is essential[24]. Changes in crop production resulting from climate change have attracted the attention of various stakeholders concerned with mitigating the impacts of natural disasters and extreme events, implementing corrective measures and ensuring food security[19]. Drought is a severe phenomenon with global implications, impacting crop production and raising concerns regarding food and water security worldwide[34]. It is a recurrent event occurring in various climatic zones[27], leading to soil moisture deficits and reduced runoff, particularly affecting rain-fed agricultural systems and water resources[29].

Droughts can be categorized based on their duration and impact on water cycle components into socioeconomic droughts, meteorological droughts, agricultural droughts and hydrological droughts[41]. Considered one of the most devastating natural disasters globally[35], drought is characterized by abnormally low precipitation causing changes in vegetation[6]. Remote sensing technology provides an effective means to monitor large-scale vegetation changes[35], with the Normalized Difference Vegetation Index (NDVI) serving as a valuable tool not only to assess spatial changes in vegetation but also to examine vegetation responses to climate change over time[11].

Land degradation has gained global attention as a pressing environmental problem in recent years, drawing the interest of researchers, planners and policymakers alike. It encompasses the decline in land productivity due to the deterioration of its physical, chemical and biological properties, either temporarily or permanently. This degradation has adverse impacts on agricultural production,

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ecosystem functioning, overall quality of life and human livelihoods. The rise of technological advancements has facilitated population growth while also enabling human activities that contribute to the process of desertification[31].

In numerous studies, the Normalized Difference Vegetation Index (NDVI) has been employed as a remote sensing tool to monitor vegetation dynamics and to explore the spatio-temporal patterns of vegetation cover. These investigations have revealed the significant influence of climate factors such as temperature and precipitation as well as human activities including deforestation/reforestation and topographic parameters like elevation and slope on the dynamics of vegetation cover[2].

Researchers[13,25] have conducted studies to examine the relationship between vegetation coverage and climate factors using NDVI time series data, highlighting the strong dependence of vegetation dynamics on precipitation, particularly in arid and semi-arid regions. Human activities, on the other hand, can either enhance or diminish NDVI, depending on the nature of the interaction. Unsustainable practices such as irrational farming, excessive grazing, deforestation and urbanization have the potential to significantly reduce vegetation coverage[14]. However, carefully planned activities such as afforestation and reforestation can have a positive impact on vegetation cover [32].

The Landsat satellites have played a crucial role in providing valuable land surface observations from space for over four decades. The introduction of Landsat-8 in 2013 equipped with the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) have further advanced this legacy[31]. However, the use of multi-temporal optical wavelength satellite data collected under varying conditions and by different sensors can be affected by issues such as reflectance inconsistencies caused by various factors. These factors include atmospheric and cloud contamination, variations in sun-surface-sensor geometry, sensor degradation and calibration changes, differences in spectral band pass and spatial resolution and data processing concerns[9].

The Anti-Atlas region of Morocco is currently experiencing a severe and prolonged drought, presenting significant challenges to local communities and ecosystems. The drought's impact on the region's agriculture, water availability and overall socio-economic conditions is a cause for concern. Water scarcity has led to decreased agricultural productivity, increased soil erosion and diminished vegetation cover. Livelihoods dependent on agriculture and livestock have been severely affected, exacerbating poverty and food insecurity[7].

This study focuses on analyzing the vegetation dynamics in the Imiter sub-watershed and investigating the influence of the semi-arid climate on vegetation cover. Earth observation data processing techniques are utilized to accomplish this objective. Specifically, the study aims to demonstrate the efficacy of software tools such as ArcGIS in computing and mapping the normalized difference vegetation index (NDVI).

Additionally, it seeks to illustrate the spatiotemporal dynamics of NDVI and vegetation condition Index (VCI) from 1998 to 2022 by employing Landsat TM, ETM+ and OLI imagery. Through the analysis of NDVI data over this time frame, the study provides valuable insights into the changes observed in vegetation cover within the Imiter region and their correlation with climatic factors. The outcomes of this research can inform the development of sustainable land management strategies and helps to mitigate the adverse effects of climate change on vegetation cover in the region.

Study area

Geological and geographical setting: The village of Imiter is situated within the Toudgha river catchment which is located in the eastern part of the Anti-Atlas region in Morocco. The Anti-Atlas region is a mountainous area known for its rugged terrain and arid to semi-arid climate. Imiter village specifically lies within the Imiter sub-watershed, characterized by its semi-arid climate conditions. The region experiences hot and dry summers, with limited precipitation throughout the year. The Toudgha river, flowing through the catchment, serves as a vital water resource for the local communities and agricultural activities in the area. The geographical setting of Imiter village and its location within the Toudgha river catchment make it susceptible to the challenges and impacts of water scarcity and the effects of climate change on vegetation and overall environmental conditions.

Situated approximately 300km southeast of Marrakech, the Imiter sub-watershed is located on the north-eastern flank of the Jbel Saghro mountain range which extends in an east-west direction. It is positioned about 26km southwest of Tinghir town [15] (Fig.1). The Jbel Saghro, along with the Jbel Ougnat, forms the eastern boundary of the Anti-Atlas region. Geologically, the Imiter area is situated within a depression known as the Precambrian buttonhole of Imiter. This depression is part of the northern edge of the West African craton which includes other buttonholes like Krdous, Bou Azze and Seroua[38].

The Imiter silver deposit is found within the low-grade meta-sedimentary terrains of the Middle Neoproterozoic, located at the base of the Upper Neoproterozoic volcanic-sedimentary and volcanic formations[15]. The middle neoproterozoic is predominantly composed of a series of sandstone-pelitic layers interspersed with granite apices[15].

Hydrogeological setting: The study area is located within the larger Rheris watershed (Fig. 2) which is characterized by Paleozoic formations consisting of sandstones, quartzites, shales and Mesozoic limestone dominantly. The region is bordered to the North and Northwest by the High Atlas and to the Southwest by the Anti-Atlas terrain while plateaus are located in the central part, particularly in the Ipre-African trough[18] (Fig. 2). The Rheris watershed has a dense hydrographic network with a total length of extracted waterways of approximately 4,931 km distributed over an area of 12,702 km², resulting in an average drainage density of 0.4 m/m² (Fig. 2)[4].

The region is characterized by a hot and dry arid climate with cool winters due to altitude. Generally, temperatures vary from 16°C to 39°C on an average. Rainfall is low and concentrated mostly in the winter and fall seasons (Fig. 3) and it may even snow occasionally in Tinghir. Towards the end of summer, frequent winds and thunderstorms can occasionally disrupt transportation for several hours[1].

Vegetation cover: In the Rheris watershed, the climate is predominantly Saharan. Vegetation cover is very sparse with the exception of a few palm groves located around waterholes and along the main rivers, in the form of narrow oases (Fig. 4a). The agricultural sector in this region is the main source of income for the population and plays a very important role in people's work and the development of the local economy. Cereal, vegetable and fodder crops are a valuable supplement in a region where tree cultivation is predominant (mainly date palms and olive trees accompanied by a few fruit trees)[1]. The palm groves represent an area whose balance, subject to fluctuations in water resources, remains fragile. These areas are irrigated by wells, khettaras and surface water (Fig. 4b)[5].

Material and Methods

The methodology used in this study involves the analysis of vegetation dynamics in the Imiter area using Earth Observation data. The aim of the study is to identify the impact of climate change on vegetation dynamics with specific objectives that include demonstrating the potential of ArcQGis software in mapping the normalized difference vegetation index (NDVI) and showing the spatiotemporal dynamics of the NDVI index and vegetation condition index (VCI) from 1998 to 2022 using Landsat TM, ETM and OLI images.

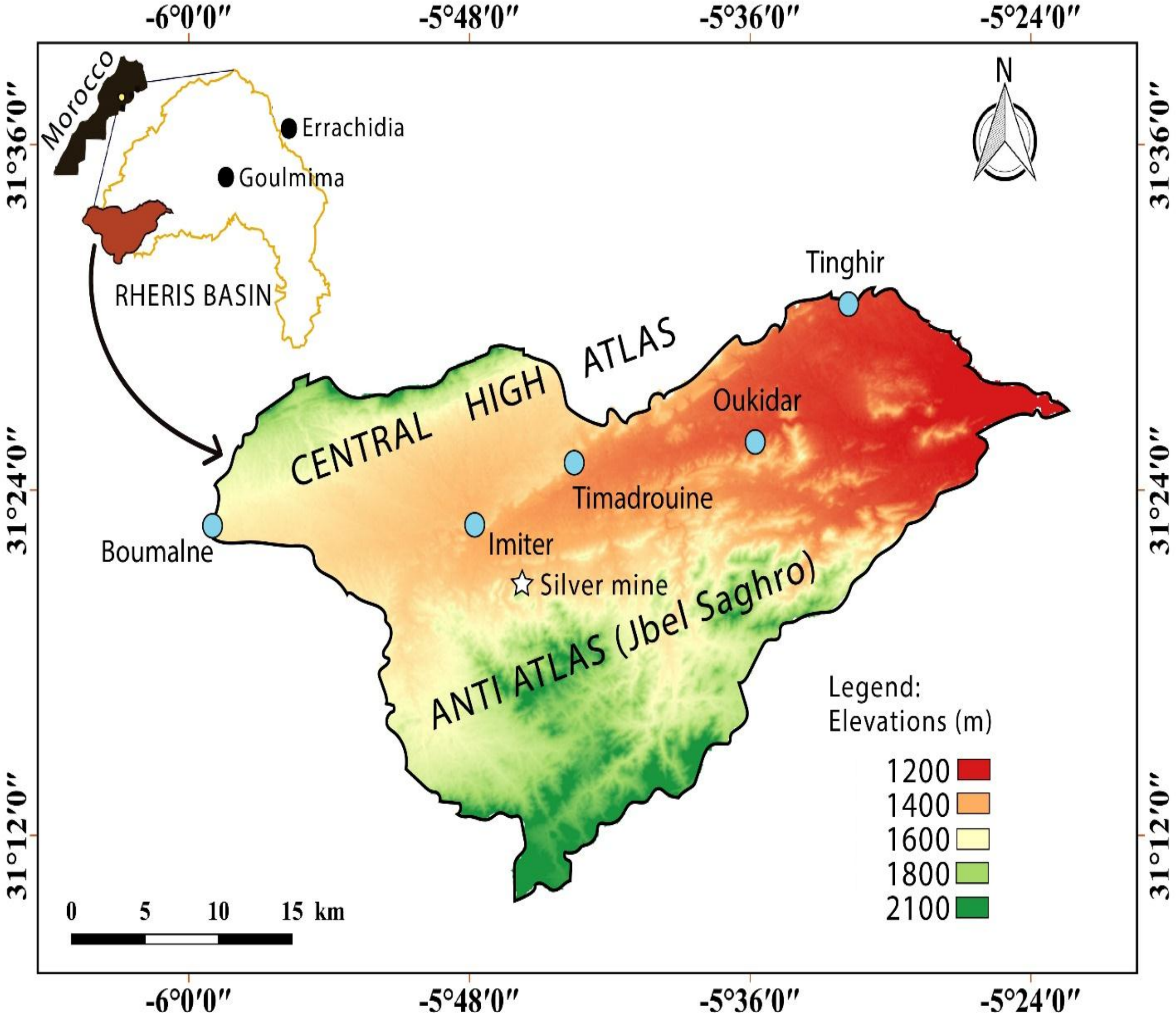

Figure 1: Geographic setting of the chosen area under the Rheris basin

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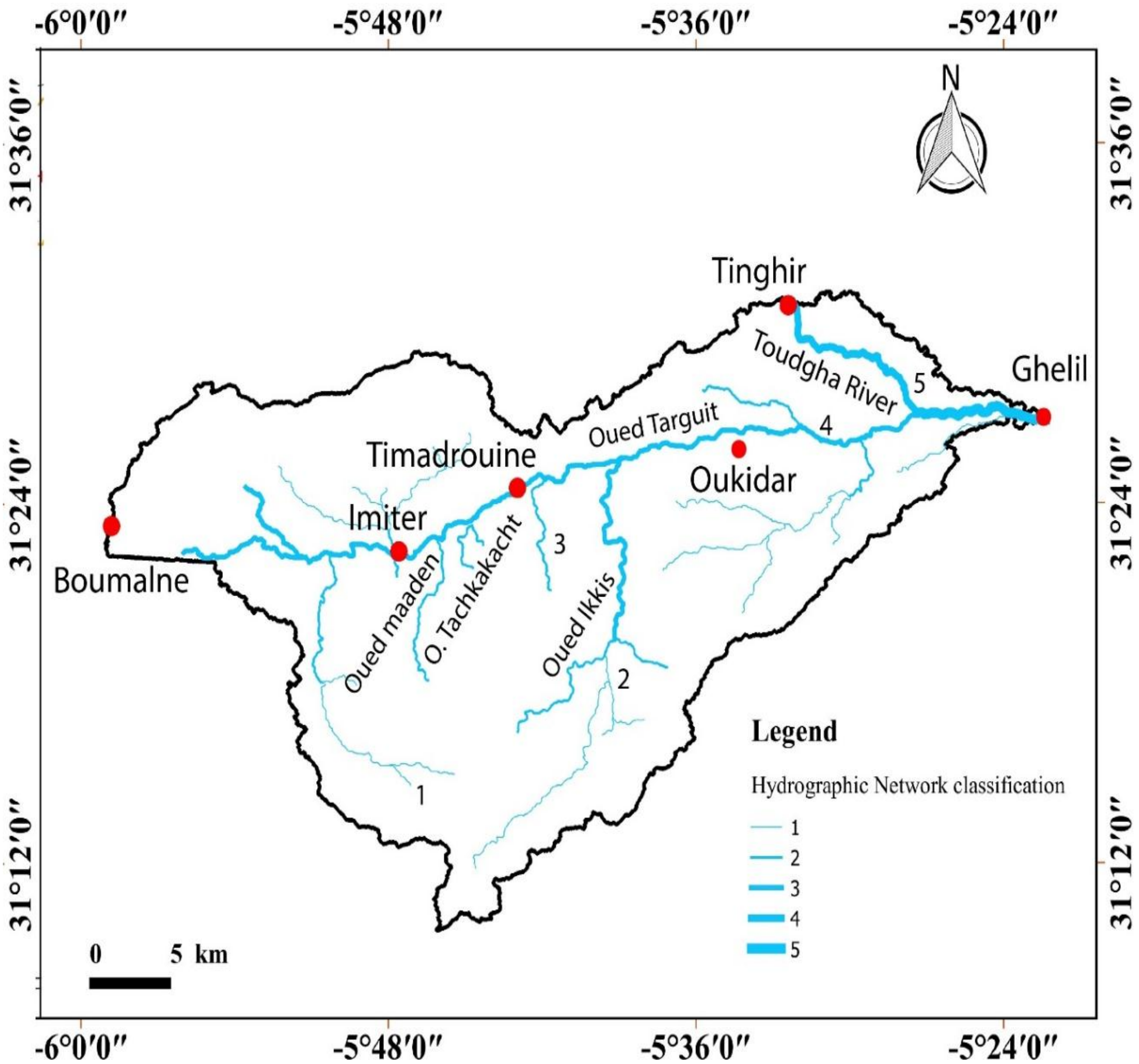

Figure 2: Hydrographic system network of the study area

Climate setting:

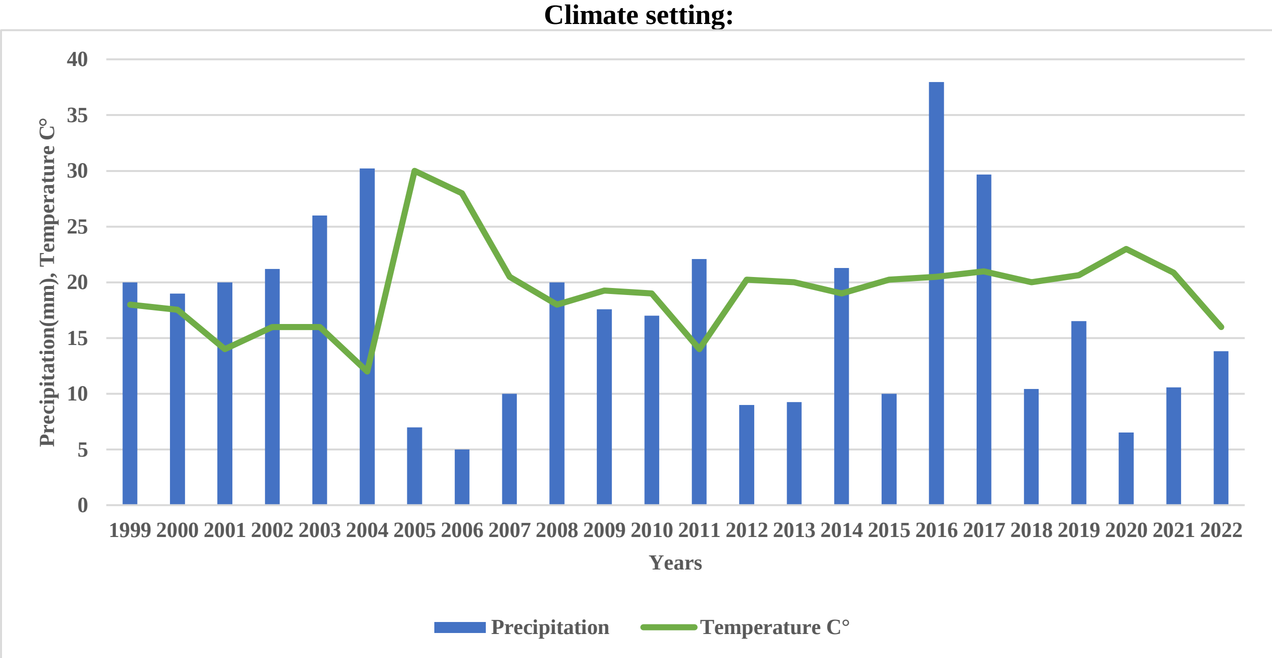

Figure 3: Average annual precipitation and temperature of the Imiter area (1999–2022)[1]

Figure 4: a. Crop filed around Toudgha River, b. groundwater retention basin, c. Toudgha River and d. Imiter tributary

To carry out the comparative analysis of the NDVI and VCI, three scenes from four different satellites, namely Landsat (5,7,8 and 9) were used and 24 annual spatial maps were created. For a relevant comparison, it is important that the images are taken under the same observation conditions such as time, % cloud cover, sunshine, among others (Fig. 5).

The NDVI is a commonly used vegetation index and is calculated using the formula NDVI = (NIR–R)/(NIR+R), as proposed by Rouse et al[33]. This formula involves the red and near-red bands of each scene and while the numbers of spectral reflectances may differ for different satellites, the wavelengths are almost identical for the red and near-red bands.

The vegetation condition index (VCI) is a metric used to assess the current state of vegetation by comparing the current normalized difference vegetation index (NDVI) with the range of values observed during the same period in previous years. The VCI is expressed as a percentage and provides an indication of where the current value falls between the minimum and maximum values recorded in previous years. Lower and higher VCI values indicate unfavorable and favorable vegetation conditions respectively. The VCI ranges from 0 (representing extremely unfavorable conditions) to 100 (indicating optimal conditions as in table 1).

The VCI is a metric used to assess vegetation moisture conditions and monitor agricultural drought. It was introduced by Kogan et al[23] and has proven to be effective in detecting drought, measuring its severity, duration, occurrence and impact on vegetation. This parameter provides reliable information on both short-term and long-term drought situations[21].

The VCI is calculated using the following equation:

VCI = (NDVI - NDVImin) / (NDVImax - NDVImin) * 100
where NDVI represents the Normalized Difference Vegetation Index for the specific period under study, NDVImin refers to the minimum NDVI observed during the study period which is calculated based on historical data and NDVImax represents the maximum NDVI observed during the study period, also calculated from historical data.

Table 1
Classification Schemes for Drought Monitoring using[23].

Value %	Drought severtity
<10%	Extreme Drought
10 - 20%	Severe Drought
20 - 30%	Moderate Drought
30 - 40%	No Drought
>40%	Wet

The VCI formula allows for the quantification of vegetation moisture conditions and facilitates the assessment of drought impact on vegetation. It provides valuable information for drought monitoring and management in agriculture.

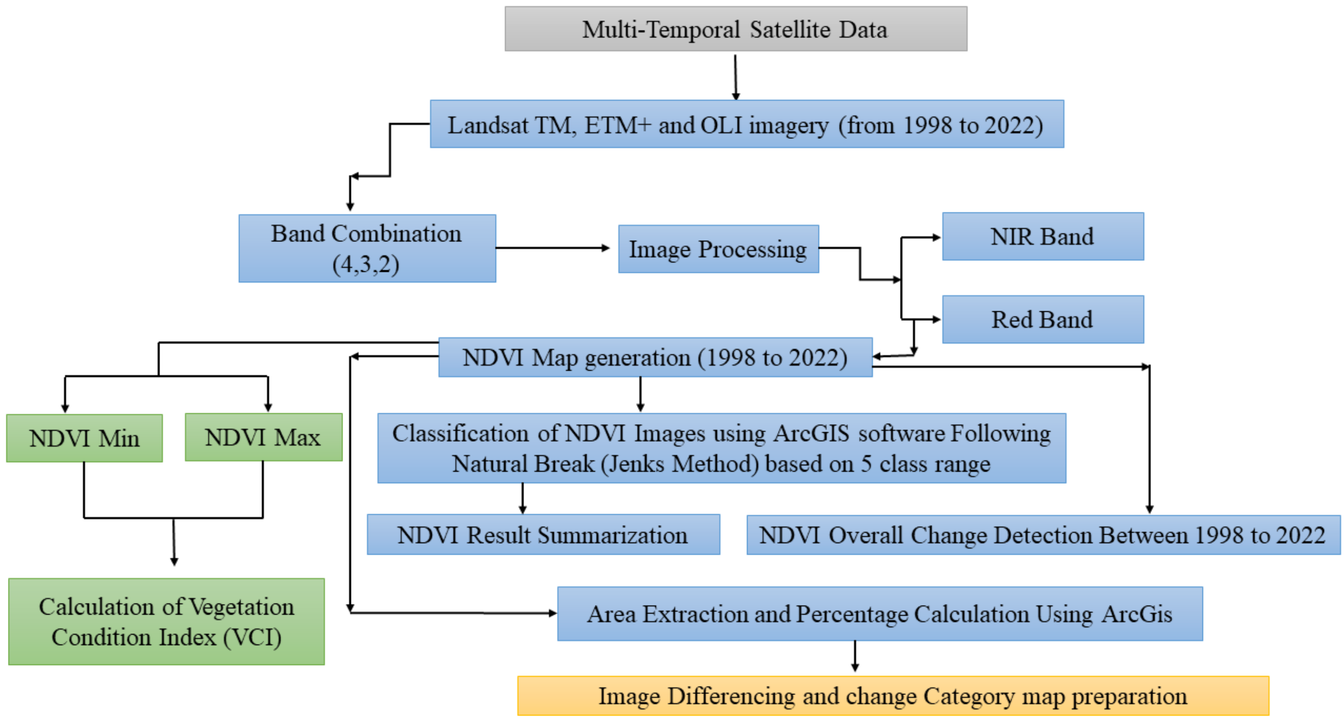

Figure 5: Methodology

The methodological workflow of NDVI mapping includes several working steps such as atmosphere image correction using the "Top of Atmosphere reflectance" algorithm and clipping the study area.

This study utilized Landsat satellite images from 1999 to 2023, The images were obtained from the United States Geological Survey (USGS) website, Earth Explorer (http://earthexplorer.usgs.gov/). Specifically, Landsat 8 Operational Land Imager (OLI) images were used which have a spatial resolution of 30 meters.

For the purpose of land cover classification in the region of interest, band 4 and band 5 of the Landsat 8 images were utilized. The band descriptions of Landsat 8 images are provided as follows:

Band 4: This band is known as the red band and is sensitive to red light (0.64 - 0.67 µm). It captures the reflectance of vegetation, land cover and other features.
Band 5: This band is known as the near-infrared band (NIR) and is sensitive to near-infrared light (0.85 - 0.88 µm). It primarily captures the reflectance of vegetation which can be useful for vegetation monitoring and analysis.

Results and Discussion

Normalized difference vegetation index (NDVI): Analysis of NDVI maps from 1998 to 2022 reveals interesting trends and patterns in vegetation growth during the study period (Fig. 8). The results show a significant increase in NDVI in some areas, especially in the northeastern part of the sub-watershed where we still find intense vegetation in the range of 0.20–0.50 (Fig. 6). This is mainly due to the constant stream of Oued Toudgha (Fig. 4c) and the extension of the groundwater table. The southeastern zone also has a relatively high proportion of vegetation. This increase can be attributed to factors such as improved agricultural management practices, increased rainfall and land use change (Fig. 4) These favorable conditions likely contributed to increased water availability and more favorable environmental conditions for vegetation growth.

However, it is important to note that some regions have also observed a decrease in NDVI. This indicates vegetation degradation in the northwestern part of the study area. These declines may be due to factors such as deforestation, drought, mining activities and other environmental stresses. Understanding the causes of this decline is important for implementing appropriate land and natural resource management strategies and mitigating negative impacts on vegetation. Identifying these trends and their possible causes can provide valuable information for decision-making in land and natural resource management.

It is important to note that the results of this study are based on satellite data and therefore have certain limitations. Factors such as spatial resolution and sensor accuracy can affect the results obtained[12]. Therefore, we recommend interpreting these results with caution and supplementing them with other data sources and field information to better understand the environmental situation in the study area. Finally, it should be noted that vegetation was relatively high in 2002 and 2010, mainly due to heavy rainfall. These specific climatic events may have a significant impact on vegetation growth and should be considered when interpreting results for that specific period (Fig. 3).

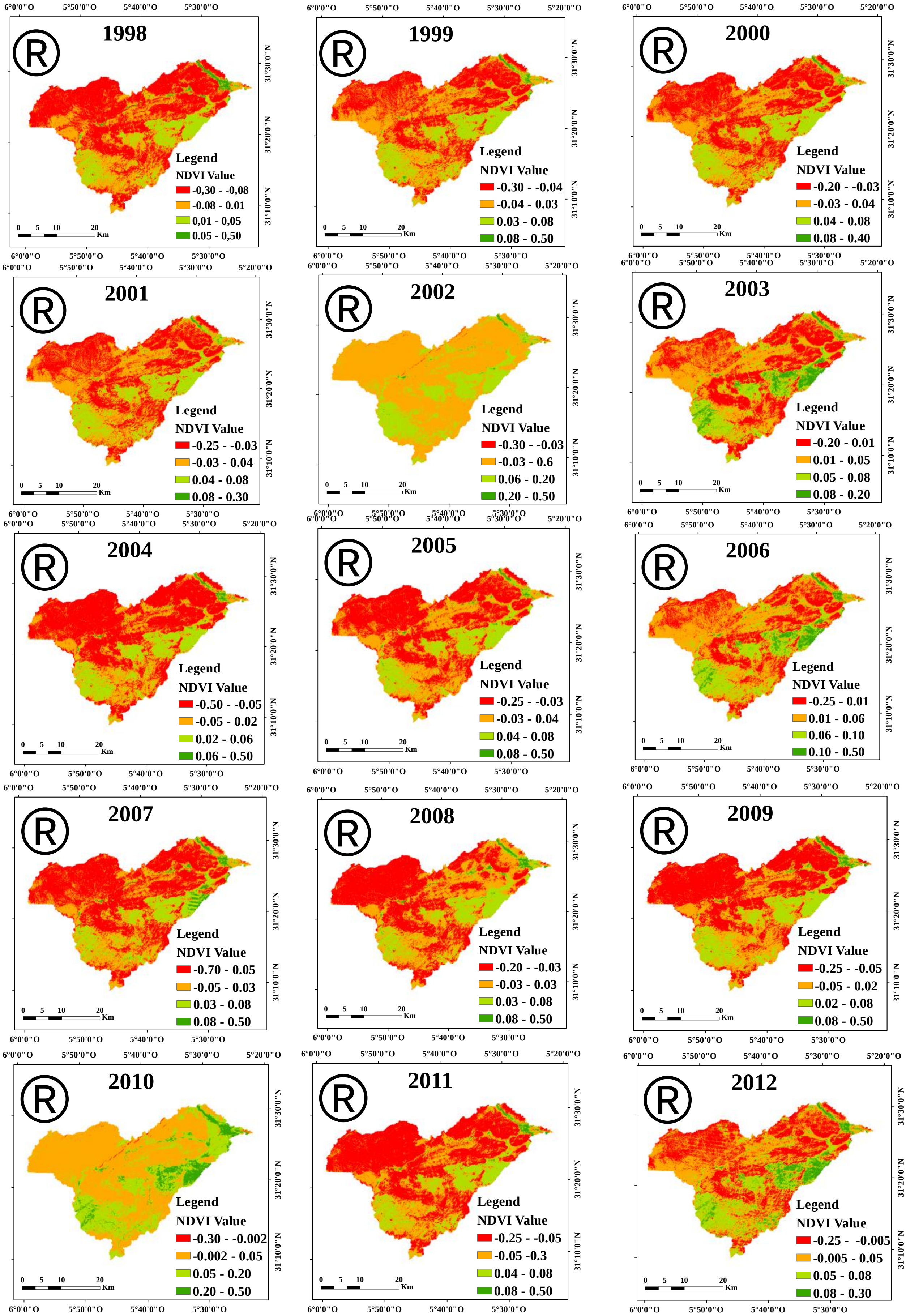

Figure 6: NDVI maps of the study area (1998-2012)

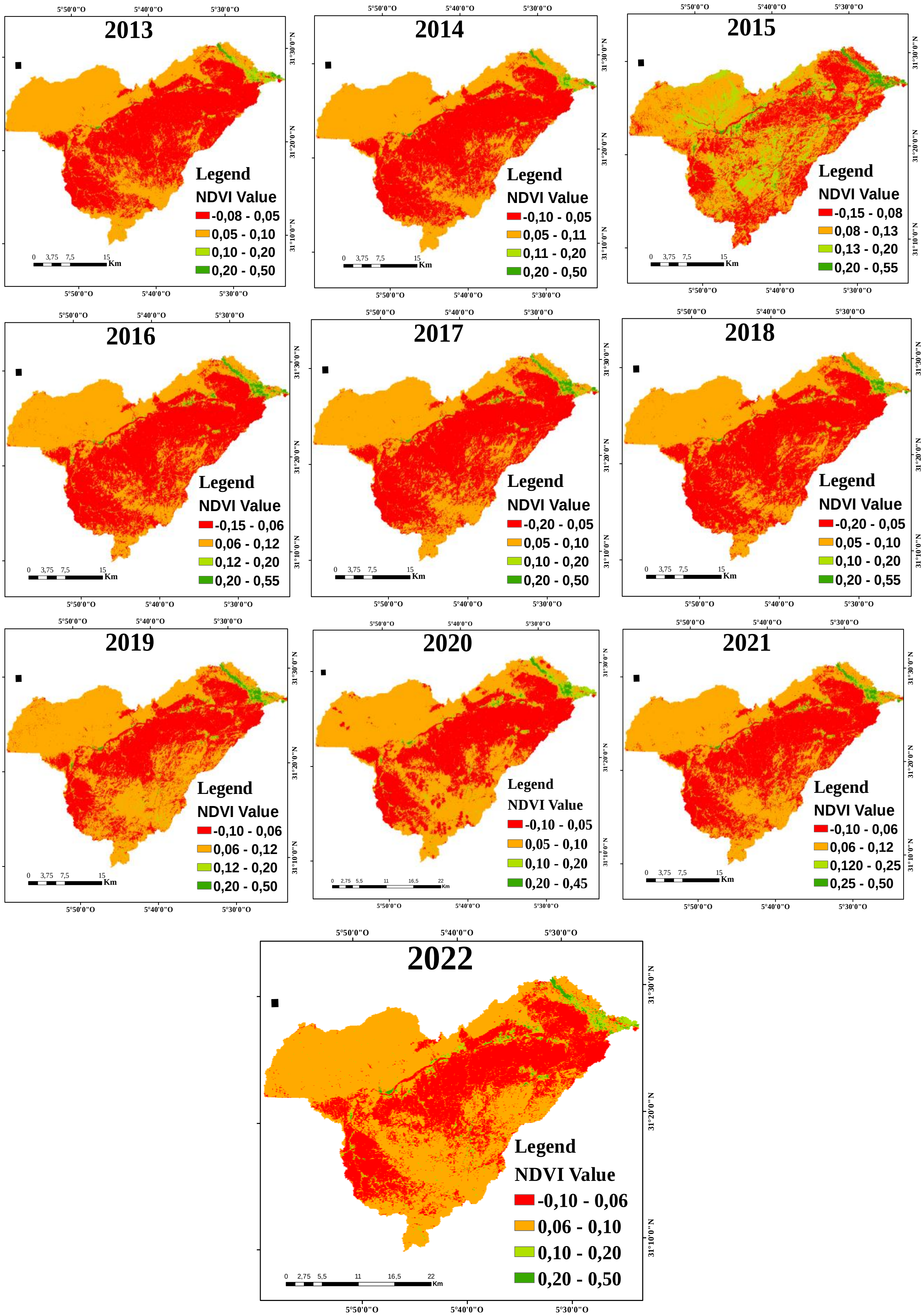

Figure 7: NDVI maps of the study area (2013-2022)

Since 2013, a clear change in vegetation in the area has been observed (Fig. 7). Vegetation has virtually disappeared. This dramatic change is largely due to the harsh climatic conditions, especially considering that the region is located in a semi-arid to arid zone (Fig. 3). Predominantly, due to the decrease in precipitation in recent years, the absence of reforestation and plantation policies, the decrease in groundwater levels due to intense exploitation by the local population for drinking and agricultural purposes, result in the region's gradual drought.

From a scientific point of view, it is important to emphasize the important role that environmental factors such as climate play in maintaining vegetation. In this region, vegetation degradation is progressing due to the difficult climatic conditions of limited rainfall[8]. A lack of regular and sufficient rainfall reduces soil moisture, making it difficult for plants and trees to survive. In addition, repeated droughts have exacerbated water shortages, further reducing the water resources needed to grow crops.

Vegetation Condition Index (VCI): The VCI results from 1998 to 2011 showing a significant change with the VCI fluctuating significantly from year to year. 1998, 2004, 2009 and 2010 were relatively wet, indicating favorable conditions for vegetation. In contrast, 1999, 2000, 2001, 2002, 2003 and 2011 were characterized by low humidity and slight drought. Of these, 2007 and 2006 were most affected by drought due to lack of rainfall. Humidity has dropped significantly over the last two years, adversely affecting plant health and growth. These changes in vegetation condition index can be studied to understand the environmental and climatic factors that influenced these changes.

Based on the meteorological data of precipitation and temperature, a close relationship between these variables and VCI can be observed. Years with high precipitation rates and lower temperatures indicate favorable conditions, resulting in higher VCI values (Fig. 3 and 9). In contrast years characterized by low precipitation and high temperatures indicate unfavorable conditions, resulting in lower VCI values.

In summary, our analysis of the VCI from 1998 to 2011 shows significant year-to-year variability with periods of relatively high humidity and periods of mild drought. 2007 and 2006 were most affected by drought, probably due to lack of rainfall (Fig. 3). The extreme drought rate increased from 30% in 1998 to 60% in 2011, while the wet rate decreased from 20% to 2.6% over the same period. This shows a clear change from 1998 to 2011. Moreover, in 2005 and 2006, the extreme drought rate was even higher reaching 70% (Fig. 10).

These results highlight an alarming trend of increasing drought conditions and decreasing humidity during the study period. The increasing rate of extreme drought points to the prevalence of prolonged and severe drought that can adversely affect vegetation, agriculture and water resources. Lower moisture content means less available moisture in the atmosphere, exacerbating aridity in the region. Low humidity increases evaporation rates, further reduces soil moisture and can impede plant growth.

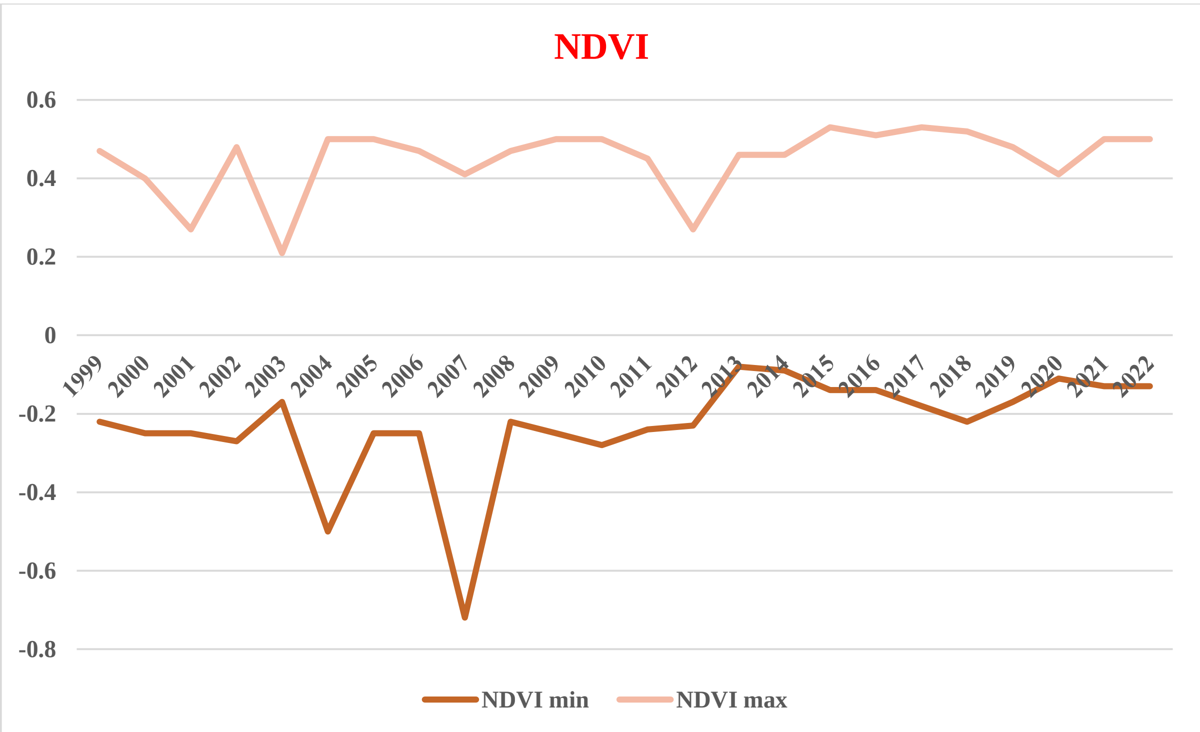

Figure 8: Variation of NDVI Min and Max from 1999 to 2022

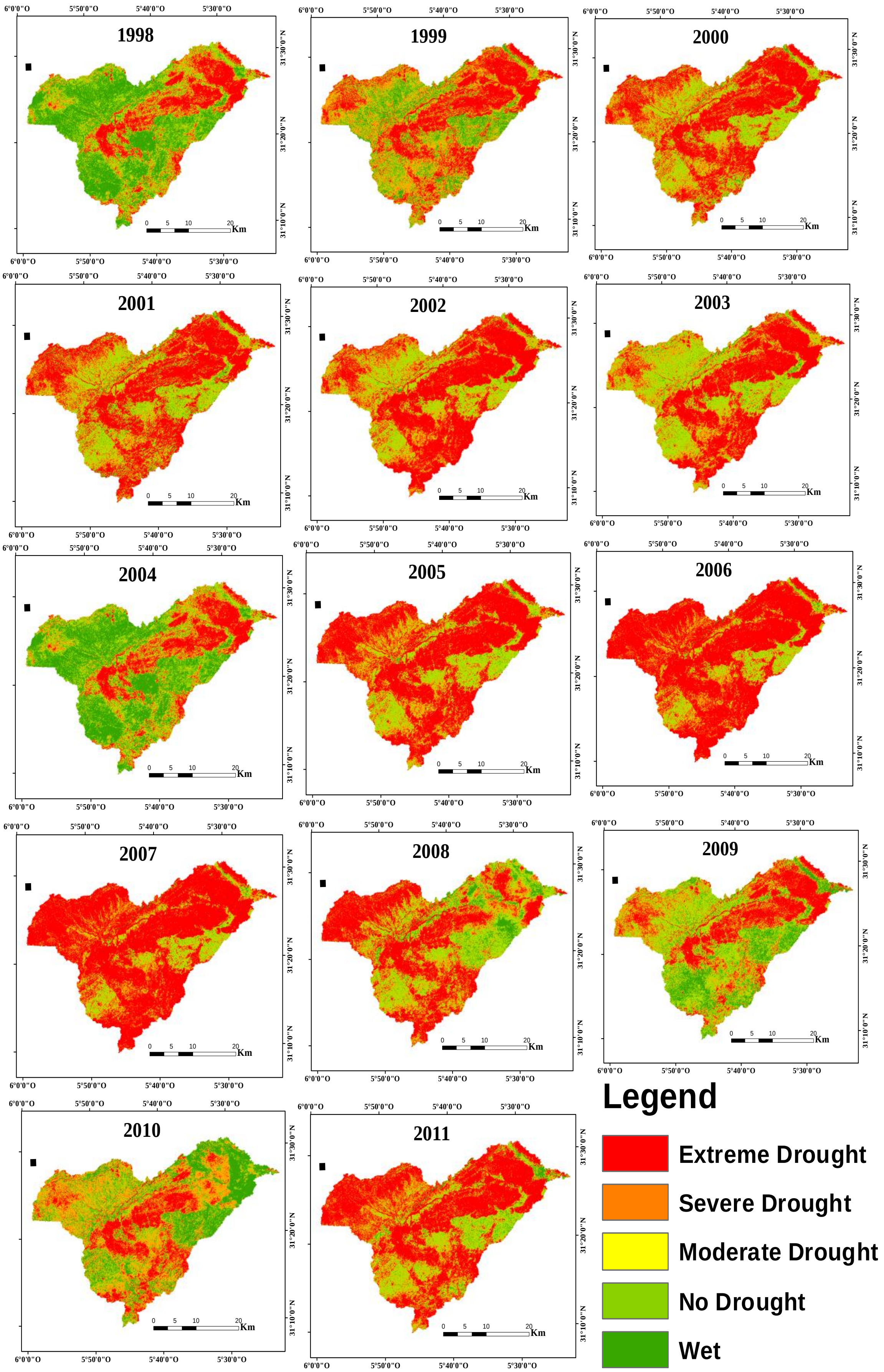

Figure 9: VCI maps of the study area (1998-2011)

Changes in observed extreme drought rates and humidity may have been influenced by several factors including climate patterns, rainfall patterns and land management practices. To comprehensively understand the drivers of such change, it is important to address these factors in scientific research.

Understanding the underlying mechanisms will help develop effective mitigation strategies to combat the adverse effects of drought and promote sustainable management of water resources. This may include implementing water-saving measures, improving irrigation techniques, introducing drought-tolerant crop varieties and improving land restoration practices. Since 2012, significant changes have taken place including a gradual rise in humidity (Fig. 11). Humidity rose from 3% in 2012 to 50% in 2022. This increase indicates that the region's water environment has improved and water availability has increased (Fig. 12).

At the same time, the incidence of extreme drought has decreased significantly from 50% in 2012 to just 5% in 2022 (Fig.12). This significant reduction indicates a reduction in long-term severe droughts which are having a positive impact on vegetation, agriculture and water resources. Several factors may have influenced the increase in humidity and the reduction in extreme drought rates. These include more favorable rainfall patterns, improved water resource management, water conservation efforts, sustainable agricultural practices and adaptation measures to climate change.

The study area is characterized by harsh climatic conditions including low precipitation and high temperatures (Fig.3). Vegetation coverage is sparse and the rivers remain dry throughout the year (Fig. 13b).

In the Imiter region, there is an extensive and important groundwater table. However, due to significant water extraction by the local population for various purposes, the piezometric level of the groundwater has been declining year after year.

In addition to these conditions, the presence of silver and mercury mining activity in Imiter exacerbates the situation. The expansion of the mine's surface area is increasing annually, resulting in significant water consumption for processing purposes. Furthermore, the pollution associated with mining activities in the area leads to a decline in vegetation cover (Fig. 13a).

Additionally, the absence of a plantation and reforestation policy in the region further compounds the challenges. Without a systematic approach to planting and establishing forests, there is a lack of effort to restore and enhance vegetation cover in the area.

Several studies have investigated the use of NDVI in assessing vegetation dynamics and ecosystem health. Amri et al[3] focused on analyzing NDVI time series data to identify trends and patterns in vegetation growth in a semi-arid region. The researchers explored the influences of factors such as precipitation, land use changes and human activities on vegetation dynamics.

Study by Jabal et al[16] investigated the impact of climate change on agricultural land and crop production in the Dukandam (DDW) basin in northern Iraq. The researchers used MODIS data and his NDVI to analyze long-term changes in agricultural land from 2000 to 2020.

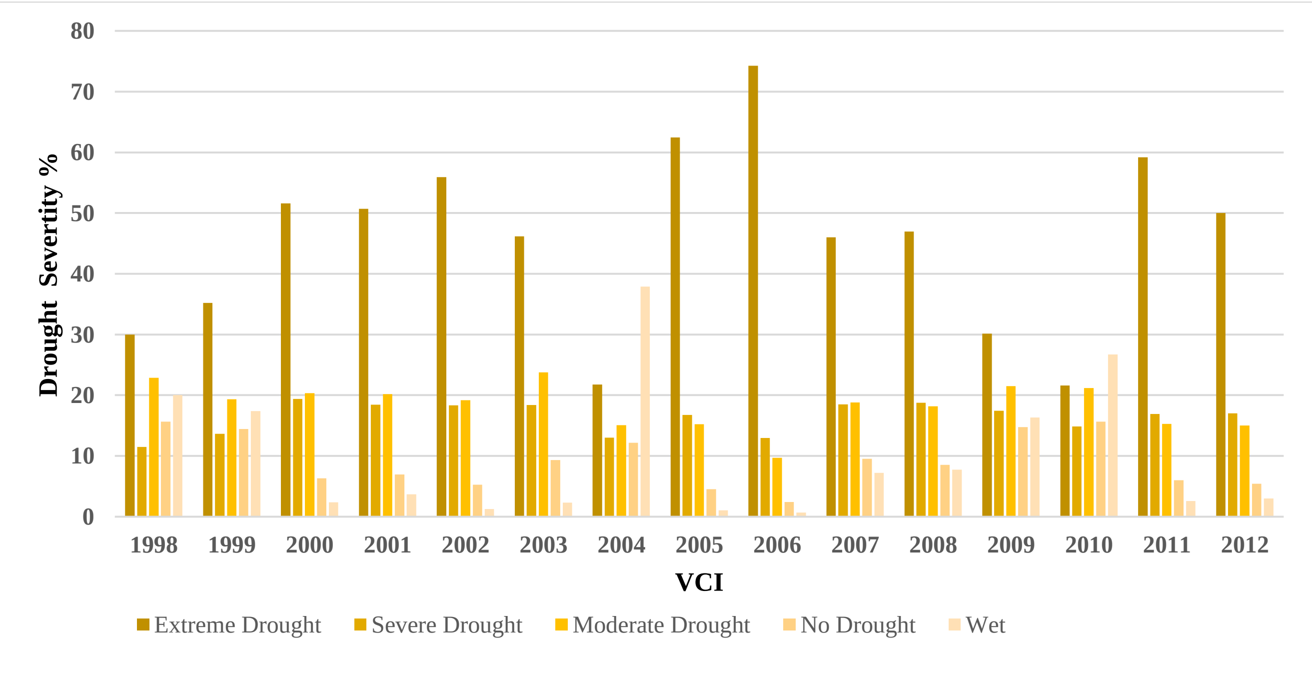

Figure 10: Drought Severtity from 1998 to 2011

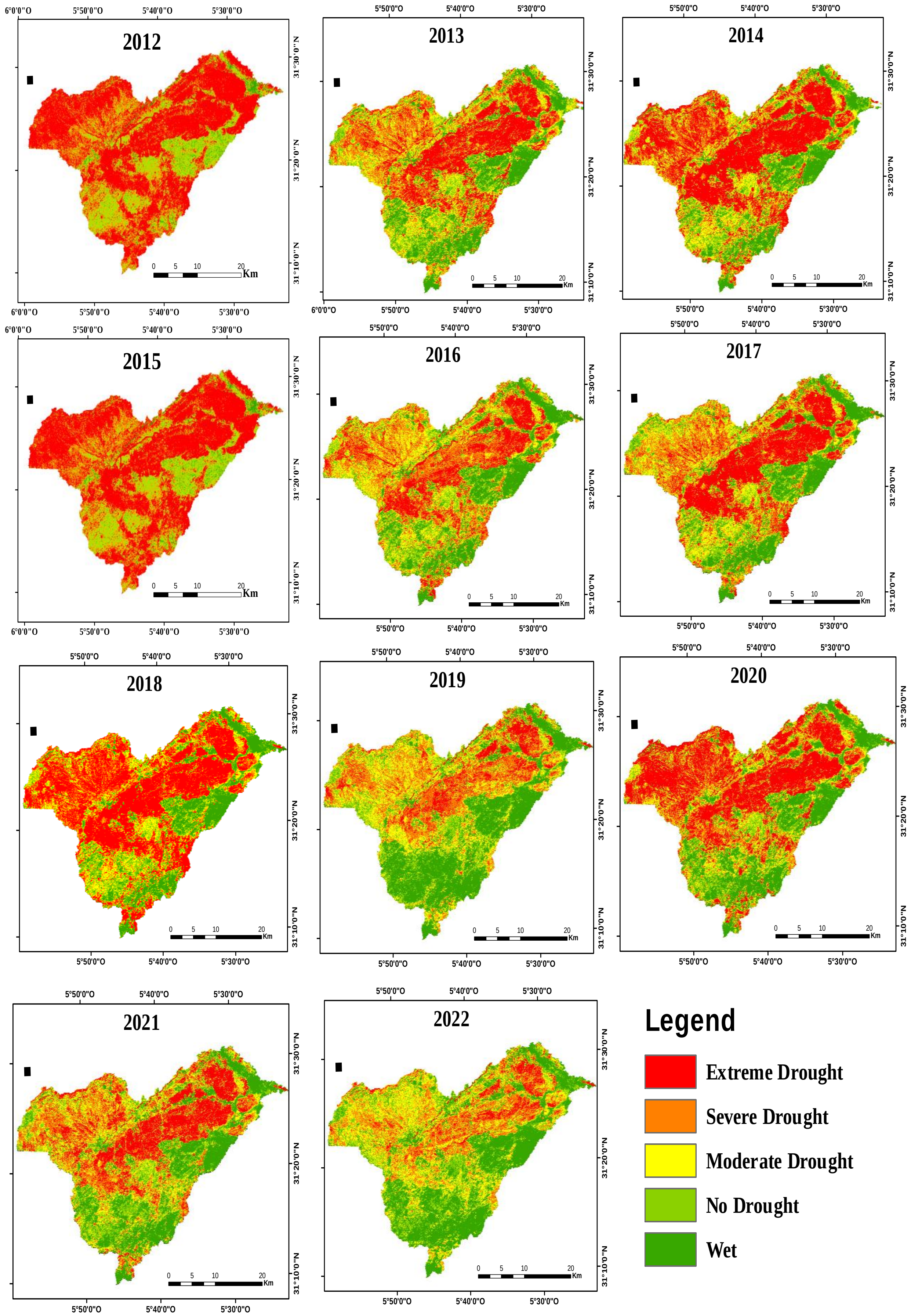

Figure 11: VCI maps of the study area (2013-2022)

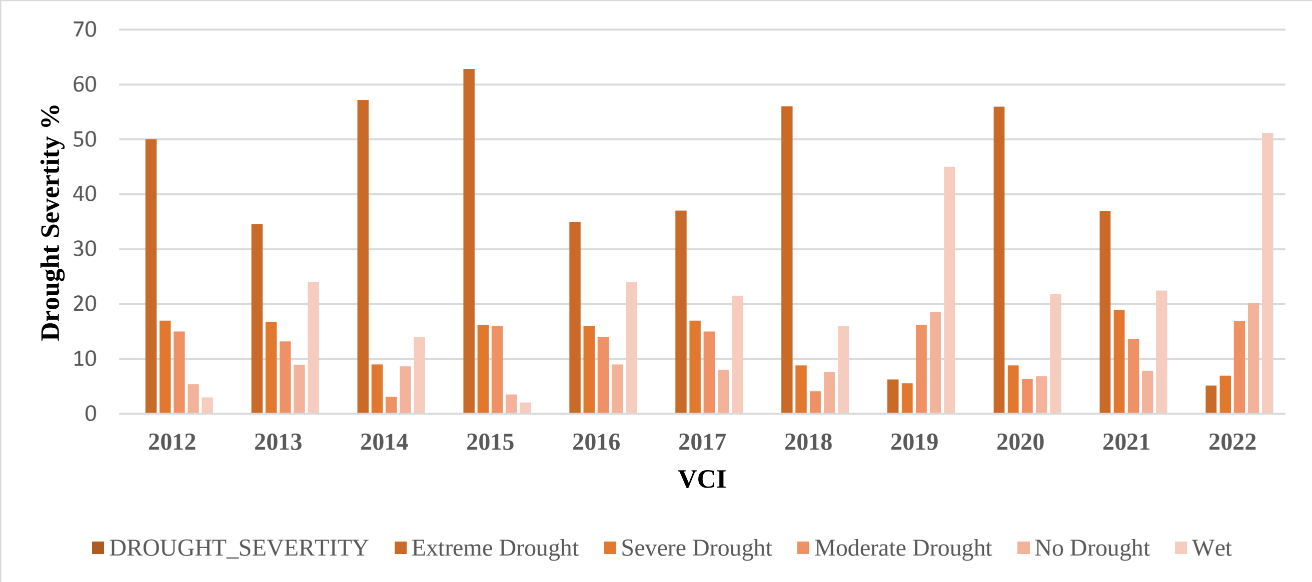

Figure 12: Drought Severtity from 2012 to 2022

Figure 13: Pictures of the study area, a; the Imiter silver and mercury mine showing the impact of its activities on the vegetation cover. b; Imiter tributary and vegetation cover

The results showed an increasing trend in crop production resulting from the use of groundwater, surface water sources and greenhouse cultivation. Winter crops such as wheat and barley were more affected by annual rainfall (59–63%) while summer crops such as rice, maize and sunflower were less affected by temperature (20–40%). These results highlight the importance of understanding the impacts of climate change on crop production and promoting sustainable agricultural practices in response to these changes.

The studies mentioned have significantly contributed to the field of vegetation monitoring and drought assessment using the VCI. Tucker[37] examined the use of linear combinations of red and infrared reflectance for monitoring vegetation. The results show that these combinations can quantify vegetation density and vigor providing valuable information for environmental monitoring.

The study by Jiang et al[17] analyzes the vegetation indices NDVI (Normalized Difference Vegetation Index) and SDVI (Scaled Difference Vegetation Index) to estimate vegetation fraction. The results show that these indices can be used to assess vegetation density and provide information on plant health.

Another study by Kogan[22] focused on the global monitoring of droughts using VCI and satellite data, emphasizing its effectiveness in detecting and monitoring drought periods worldwide.

There are several possible solutions to reduce the impact on vegetation cover. First, sustainable land management practices such as afforestation and agroforestry promote vegetation growth and help restore degraded areas. Furthermore, promoting water conservation and efficient irrigation techniques can ensure adequate water supply for vegetation, especially in water-scarce areas.

Adopting climate-friendly agricultural practices such as crop diversification and conservation agriculture, can improve resilience to climate change and optimize resource use.

Additionally, increasing awareness and education about the importance of maintaining and restoring vegetation cover can encourage active involvement of local communities in conservation efforts. Cooperation between Governments, organizations and local communities is essential to effectively implement these solutions and build a sustainable future for vegetation and ecosystem health.

Conclusion

NDVI and VCI are crucial tools for assessing drought severity and their impact on vegetation. NDVI provides insights into vegetation health and vigor while VCI specifically evaluates the condition of vegetation in relation to water availability. By utilizing these indices, researchers and land managers can effectively monitor and quantify the severity of drought and its implications for vegetation cover. This information is essential for implementing appropriate mitigation strategies and promoting sustainable land and water resource management in drought-affected regions.

This study demonstrates the importance of monitoring and evaluating the geological environment for understanding the processes of land degradation and desertification in semi-arid regions. This case study was conducted in the Imiter Watershed in the Anti-Atlas region, using Landsat 7, 8 and 9 satellite imagery and utilizing VCI and NDVI approaches to assess vegetation status and dynamics over time. The results highlight the importance of these indicators in detecting and quantifying changes in vegetation cover and assessing the extent of land degradation and desertification. Analysis of NDVI maps from 1998 to 2022 reveals interesting trends and patterns in vegetative growth.

Large increases in his NDVI in certain areas, especially in the northeastern part of the basin with concentrated vegetation and in the southeastern part with a pronounced proportion of vegetation, suggest positive changes in ecosystems. These results suggest possible factors such as improved agricultural practices, increased precipitation and land use changes that contributed to the observed vegetation growth. The analysis of VCI from 1998 to 2011 reveals significant year-to-year variability, with periods of both favorable and adverse vegetation conditions. The years 2007 and 2006 were particularly affected by drought, while 1998, 2004, 2009 and 2010 exhibited relatively wet conditions.

These findings highlight the influence of environmental and climatic factors on vegetation health and growth. Moreover, since 2012, there has been a gradual increase in humidity and a significant decrease in the occurrence of extreme drought, indicating an improvement in the water environment and increased water availability in the region. This study provides valuable insight into the spatial and temporal patterns of these processes, enabling informed decision-making and the implementation of appropriate land management strategies. The integration of remote sensing techniques and vegetation indices provides powerful tools for continuous monitoring and assessment, contributing to the conservation and sustainable management of semi-arid areas and helping to combat land degradation and desertification.

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