Studia Quaternaria, vol. 42 (2025): 61–73
DOI: 10.24425/sq.2025.154327

ASSESSING CLIMATE CHANGE IMPACTS ON VEGETATION AND WATER DYNAMICS IN SEMI-ARID WATERSHEDS USING REMOTE SENSING TECHNIQUES

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Abstract:
This study aims to assess the impact of climate change on vegetation and water resources in the Safsaf watershed of northeastern Algeria. We analyzed Landsat satellite imagery from 2012 to 2022 to compute the Normalized Difference Vegetation Index (NDVI) and employed MODIS and CHIRPS data through Google Earth Engine (GEE) to explore the relationships between NDVI, Land Surface Temperature (LST), and precipitation. Our analysis revealed a significant decline in water surfaces and vegetation cover, which correlates with increased human activities and rapid urbanization due to population growth. Pearson's correlation analysis indicated a moderate negative relationship between NDVI and LST, alongside a weak negative correlation between the Normalized Difference Water Index (NDWI) and precipitation. These findings highlight the urgent need for integrated environmental management strategies to mitigate climate change impacts and prevent further degradation of the Safsaf watershed, emphasizing the importance of incorporating ecological and hydrological considerations into future planning efforts.

Key words: Normalized Difference Water Index, vegetation cover, hydric stress, environmental management, remote sensing.

Manuscript received 25 June 2025, accepted 4 August 2025

INTRODUCTION

Climate change is one of the most pressing global challenges of the 21st century, posing significant threats to ecosystems, human livelihoods, and overall environmental stability. The Intergovernmental Panel on Climate Change (IPCC) identifies anthropogenic activities (such as urbanization, deforestation, and industrial processes) as primary drivers of rising global temperatures and intensified climate change (Gayar and Hamed, 2018). These activities have resulted in increased greenhouse gas emissions, exacerbating air and water pollution and triggering a series of detrimental environmental effects. A significant consequence is the disruption of ecological balances, particularly regarding vegetation cover, which plays a vital role in sequestering carbon dioxide and mitigating climate change (Bouri *et al.*, 2008; Ben Brahim *et al.*, 2012; Ayed *et al.*, 2017; Hajji *et al.*, 2021; Ncibi *et al.*, 2022; Guha *et al.*, 2022; Al-Hussein *et al.*, 2023; Hamed *et al.*, 2023, 2024).

Despite existing research, there is a critical gap in our understanding of the specific impacts of climate change on vegetation health and water dynamics in the Safsaf watershed. Current climate processes are known to contribute to land degradation, especially in semi-arid regions (Yang *et al.*, 2024). Global warming is expected to alter both the seasonality and magnitude of precipitation patterns (Hiraga *et al.*, 2025), while climate change will likely modify land surface water balances by increasing atmospheric evaporative demand. As air temperatures rise and vapor pressure deficits increase, evaporation demands are projected to intensify over the coming decades (Vicente-Serrano *et al.*, 2015). These climatic shifts are anticipated to lead to more frequent and severe droughts, exacerbating existing land degradation and potentially initiating new degradation processes in semi-arid environments. The interaction between increased evaporative demand, altered precipitation patterns, and resultant water stress on vegetation underscores the urgency of understanding these dynamics. Semi-arid regions, such as the Safsaf watershed, depend heavily on fragile ecosystems, making them particularly vulnerable to the compounding effects of climate change, which may result in irreversible damage and biodiversity loss. Addressing these challenges is essential for developing effective land management strategies and fostering resilience against adverse climate impacts.

To monitor vegetation health and assess the multifaceted impacts of climate change, remote sensing tools such as the Normalized Difference Vegetation Index (NDVI) are invaluable. Developed by Rouse *et al.* in 1974, NDVI utilizes satellite data from red and near-infrared spectral bands to quantify vegetation greenness and physiological health. Higher NDVI values indicate increased photosynthetic activity and healthier vegetation canopies (Guha and Govil, 2020). Additionally, Land Surface Temperature (LST) provides crucial insights into biogeochemical processes and ecological conditions, revealing variations in land texture and thermal properties (Guha, 2021). The Normalized Difference Water Index (NDWI) is also essential for monitoring surface water dynamics and detecting land cover changes, thereby elucidating the hydrological effects of climate variability.

The relationship between climate change, vegetation health, and water dynamics is complex and varies by region, influenced by spatial and temporal fluctuations in environmental conditions. This study aims to assess the vegetation health of the Safsaf watershed using NDVI, alongside surface water dynamics measured by NDWI in relation to LST and precipitation patterns. By utilizing Landsat data from 2012 to 2022, our research seeks to identify spatial and temporal changes in the Safsaf region and explore the relationships among NDVI, LST, and NDWI with precipitation.

While this study provides critical insights, it is important to acknowledge limitations such as data availability, methodological constraints, and potential scale-dependent interpretations. Ultimately, our findings aim to inform targeted management strategies that enhance the resilience of the Safsaf watershed against the adverse effects of climate change, contributing to the broader scientific discourse on climate impacts in semi-arid regions.

STUDY AREA

The Safsaf watershed is situated within the Skikda province of northeastern Algeria, defined by the geographic coordinates of longitudes 6.691679° to 7.084795° and latitudes 36.881228° to 36.455868° (Fig. 1). Encompassing a total area of approximately 1,012 square kilometers, this region exhibits a distinctive Mediterranean climate characterized by two prominent seasons: a relatively cool, wet season and a warmer, dry season. Average annual temperatures in the Safsaf watershed typically range from 16°C to 18.4°C, while annual precipitation fluctuates between 577 mm and 873 mm (Maou *et al.*, 2025).

Geologically, the Safsaf watershed is part of the Maghrebides mountain range, which features a highly intricate structural framework formed by the superposition of various geological units. This complexity contributes to the

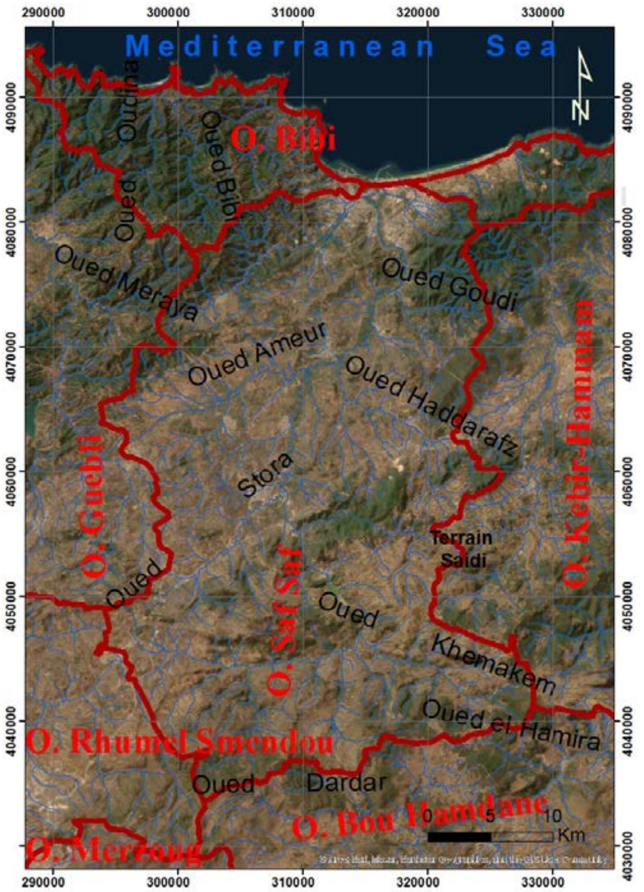

Fig. 1. Geographic location of the study area.

region's diverse topography and ecological characteristics. The watershed is primarily drained by the Safsaf River, which extends for 53 km and plays a crucial role in the hydrology of the area.

Additionally, the region includes an extensive irrigation perimeter that covers approximately 5,654 hectares, providing vital resources for agricultural activities. The vegetation within the Safsaf watershed is marked by significant variation, primarily consisting of shrubs and grasslands, interspersed with areas of sparse vegetation (Samia *et al.*, 2013). This diversity is influenced by both climatic factors and land management practices, underscoring the ecological significance of the watershed in the face of ongoing climate change. Understanding the hydrological and ecological dynamics of the Safsaf watershed is vital for developing sustainable management strategies to mitigate the impacts of climate variability.

MATERIALS AND METHODS

Data source

This research utilizes several key datasets obtained from Google Earth Engine (GEE) (https://code.earthengine.google.com), focusing on the years 2012, 2014, 2016, 2018, 2020 and 2022. The primary satellite imagery sources are Landsat and MODIS, both provided by the United States Geological Survey (USGS).

Landsat Satellite Data

We employed data from Landsat 7 (ETM+) and Landsat 8 (OLI/TIRS), specifically the Surface Reflectance (Collection 2, Level 2, Tier 1) products. These datasets are essential for analyzing the Normalized Difference Vegetation Index (NDVI), which helps detect vegetative changes in the study area across the selected years. Landsat satellites provide a spatial resolution of 30 meters and a temporal resolution of 16 days, enabling detailed insights into land cover dynamics over time.

MODIS Satellite Data

For NDVI and Normalized Difference Water Index (NDWI) calculations, we used the MODIS MOD09GA.061 Terra/Aqua Surface Reflectance dataset (https://doi.org/10.5067/MODIS/MOD09GA.061). This dataset includes seven reflective bands crucial for vegetation and water index calculations. Additionally, Land Surface Temperature (LST) data were sourced from the MODIS MOD11A1.061 dataset, which contains two thermal bands. Both MODIS datasets offer a spatial resolution of 1 km and daily temporal resolution, providing comprehensive global coverage.

Meteorological Data

Precipitation data were obtained from the Climate Hazard Center Infrared Precipitation with Stations (CHIRPS) dataset, developed by the University of California, Santa Barbara (UCSB/CHG). This dataset has a geographic resolution of 0.05°, approximately equivalent to 5.3 km, and features daily temporal resolution.

The integration of MODIS and CHIRPS data facilitates Pearson's correlation analyses, allowing us to examine relationships between NDVI and LST, as well as the compatibility of NDWI with precipitation data. All datasets were processed using ArcMap 10.8, establishing a robust analytical framework for our study on climate change impacts in the semi-arid region.

Methodology

Figure 2 presents the framework of this study, outlining the steps undertaken to achieve the research objectives.

Processing of Landsat Data

To calculate the NDVI, we utilized the GEE code editor. The mean annual NDVI for the study area was computed using the Near-Infrared (NIR) and Red bands: band 5 and

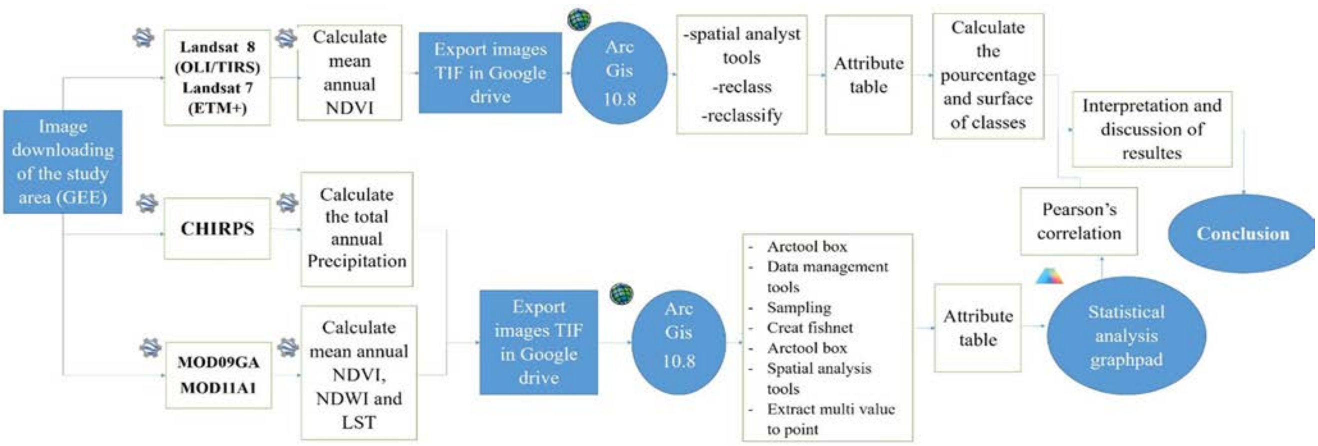

Fig. 2. The methodological framework of the study.

Table 1. NDVI range and classification.

Sl. No	Class	NDVI Range
1	water	-0.028–0.015
2	built-up	0.015–0.14
3	barren land	0.14–0.18
4	shrub and grassland	0.18–0.27
5	sparse vegetation	0.27–0.36
6	dense vegetation	0.36–0.74

band 4 for Landsat 8, and band 4 and band 3 for Landsat 7. The NDVI was calculated using the following equation (Gelata *et al.*, 2023):

NDVI = (NIR – RED) / (NIR + RED) (Eq. 1)

Upon acquiring the NDVI results, we exported them in TIF format for further processing. Using ArcMap 10.8, we reclassified the images according to the classification scheme outlined in Table 1 (Chandramohan *et al.*, 2024). We then extracted the attribute table containing the number of pixels for each class, allowing us to compute the percentage (%) and area (km^2) for each class across the different years.

Processing of MODIS and CHIRPS Data

The GEE code editor was also used to extract average annual NDVI and NDWI from the MOD09GA dataset, employing the following equation (McFeeters, 1996):

NDWI = (Green – NIR) / (Green + NIR) (Eq. 2)

For NDVI calculations, we utilized band 1 (sur_refl_b01) and band 2 (sur_refl_b02). For NDWI, we employed band 4 (sur_refl_b04) and band 2 (sur_refl_b02). Additionally, we computed the mean annual Land Surface Temperature (LST) from the MOD11A1 dataset. LST values were converted from Kelvin to Celsius using the following equation (Imtiaz *et al.*, 2024):

$$LST_{Celsius} = (LST_{kelvin} * 0.02) – 273.15 \quad \text{(Eq. 3)}$$

Using the CHIRPS dataset, we extracted annual precipitation for the study area. The results were exported in TIF format and processed in ArcMap 10.8. We created a fishnet to facilitate the extraction of multi-values to point locations, enabling the retrieval of NDVI, NDWI, LST, and precipitation values at corresponding points within the fishnet.

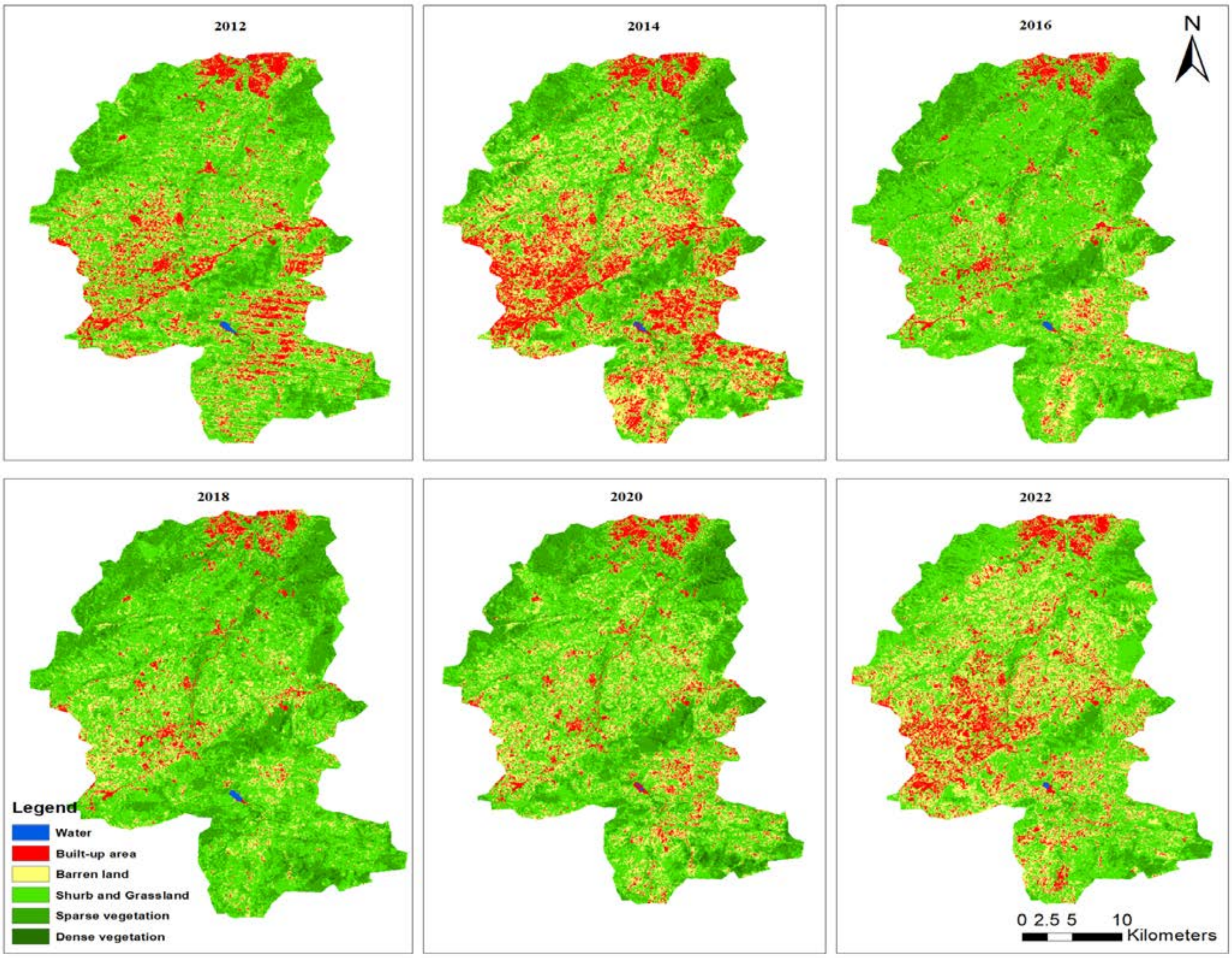

Fig. 3. Vegetation land cover in Safsaf watershed from 2012 to 2022.

Table 2. Area and percentage of vegetation land cover classes of SafSaf watershed from 2012 to 2022.

	Water (0.028; 0.015)		Built-up area (0.0015; 0.14)		Barren Land (0.14; 0.18)		Shrub and grassland (0.18; 0.27)		Sparse vegetation (0.27; 0.36)		Dense vegetation (0.36; 0.74)	
Year	Area (km²)	(%)	Area (km²)	(%)	Area (km²)	(%)	Area (km²)	(%)	Area (km²)	(%)	Area (km²)	(%)
2012	1.16	0.11	146.01	14.43	203.1	20.07	516.7	51.06	143.99	14.23	1.04	0.10
2014	0.76	0.07	202.81	20.04	274.72	27.15	367.16	36.28	159.01	15.75	7.55	0.75
2016	0.78	0.08	68.43	6.76	150.24	14.85	565.91	55.92	218.87	21.63	7.76	0.77
2018	0.99	0.10	54.78	5.41	132.25	13.07	535.64	52.93	275.35	27.21	12.99	1.28
2020	0.34	0.03	81.06	8.01	200.78	19.84	480.83	47.51	232.37	22.96	16.63	1.64
2022	0.44	0.04	147.84	14.16	292.56	28.91	482.58	47.69	87.96	8.69	0.62	0.06

We calculated Pearson's correlation using GraphPad Prism, assessing the relationships among NDVI, NDWI, LST, and precipitation. This comprehensive analysis is essential for understanding the impacts of climate change in the semi-arid region under investigation.

RESULTS

Land cover variation

The classification of vegetation land cover derived from NDVI calculations using Landsat imagery (Fig. 3) provides a direct overview of the spatial distribution of different vegetation classes from 2012 to 2022. Analysis of the NDVI maps and corresponding area estimates for each class (Table 2) reveals notable changes in water surface area throughout the study period. In 2012, the water surface area was measured at 1.16 km², which declined to 0.76 km² by 2014. This experienced a slight increase to 0.78 km² in 2016, followed by a more substantial rise to 0.99 km² in 2018. However, the water surface area saw a significant reduction to 0.34 km² in 2020, before marginally increasing again to 0.44 km² in 2022.

For barren land, the recorded area was 203.1 km² in 2012, which increased to 274.72 km² in 2014. This trend was not sustained, as the area decreased to 150.24 km² in 2016 and further declined to 132.25 km² in 2018. A rebound was observed in 2020, with the area expanding to 200.78 km², and then reaching 292.56 km² by 2022.

The extent of shrub and grassland exhibited relatively minor fluctuations over the years, with areas measuring 516.7 km² in 2012, decreasing to 367.16 km² in 2014 and then rising to 565.91 km² in 2016. The area fell to 535.64 km² in 2018, further to 480.83 km² in 2020, and finally stabilizing at 482.58 km² in 2022.

Sparse vegetation areas showed a progressive increase

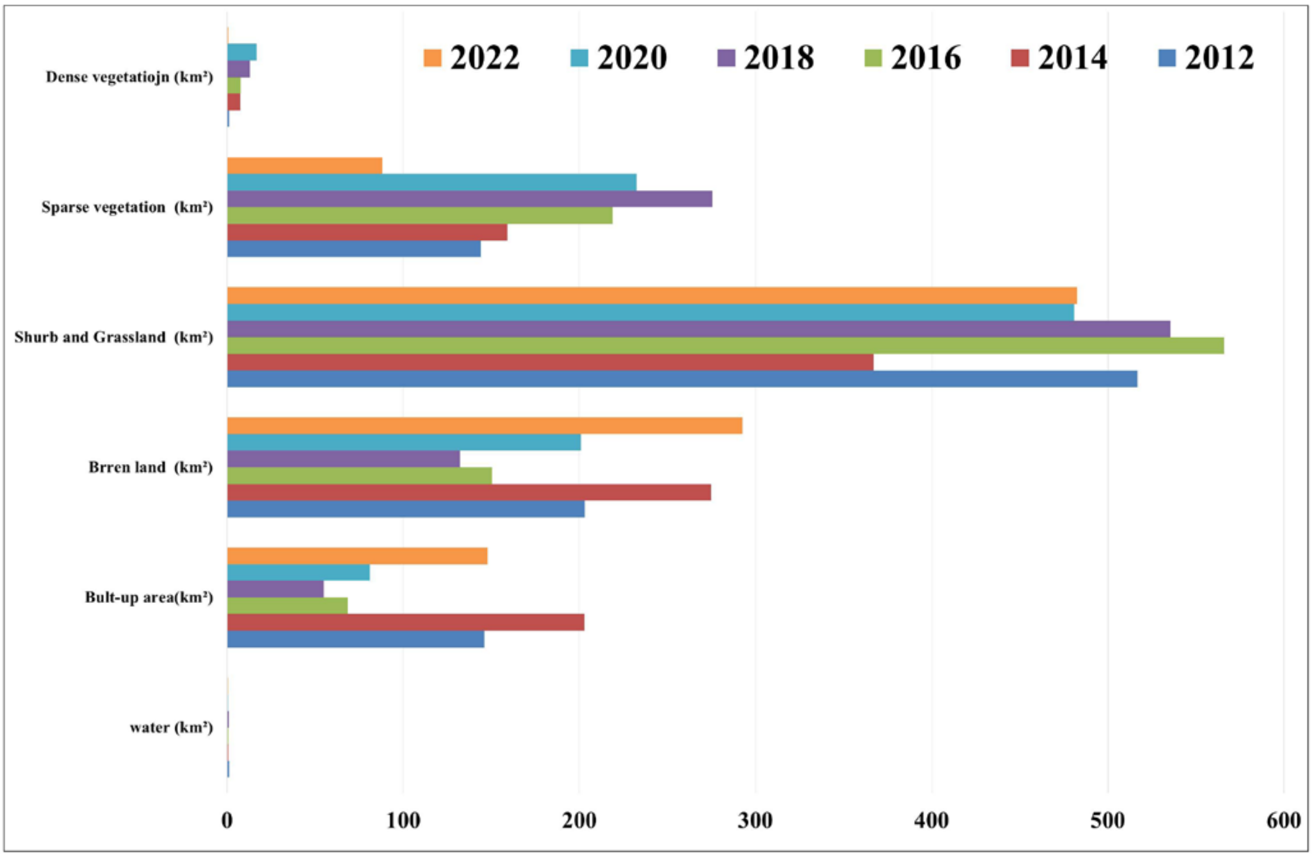

Fig. 4. Area of vegetation land cover classes from 2012 to 2022.

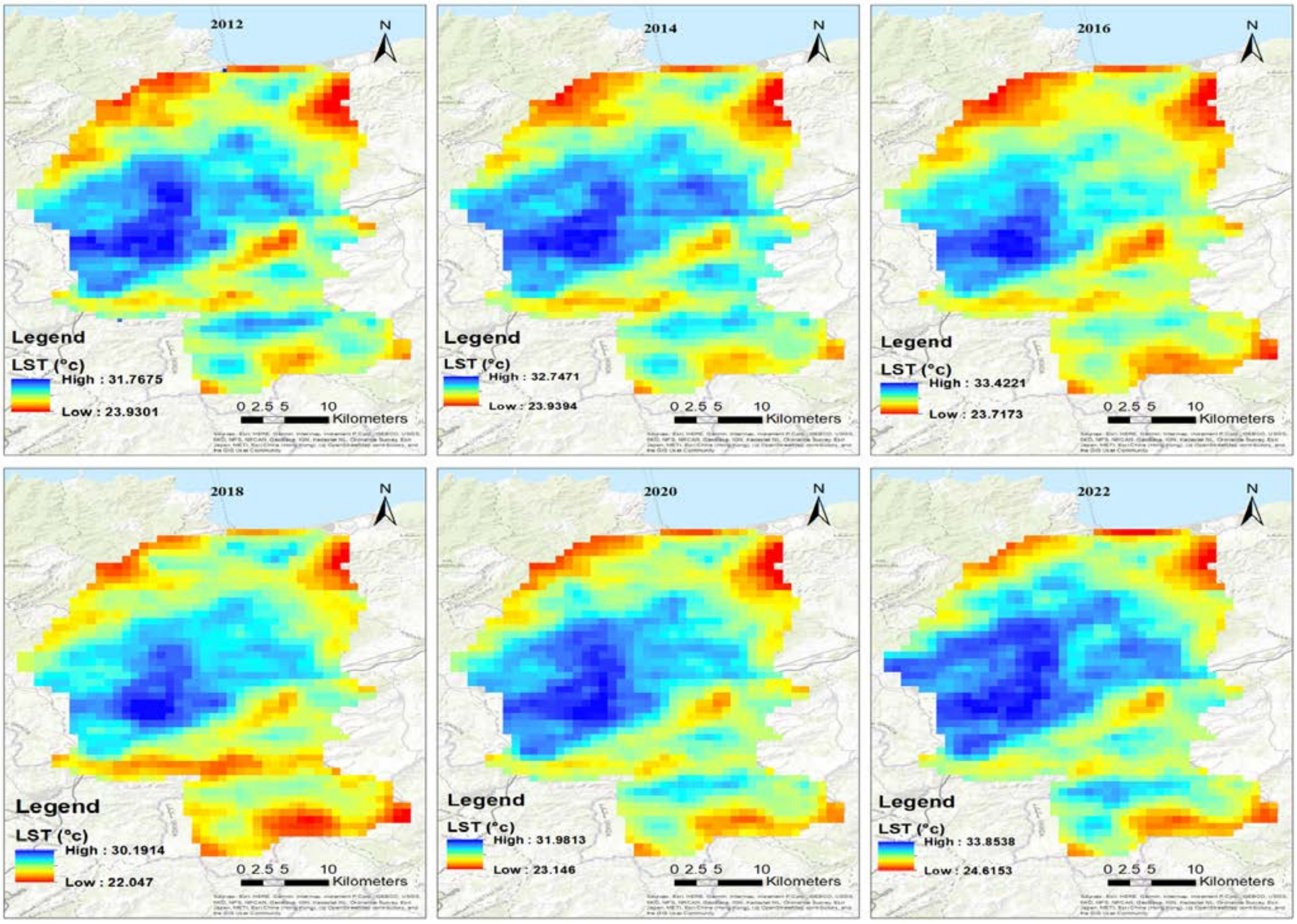

Fig. 5. Land surface temperature of Safsaf watershed from 2012 to 2022.

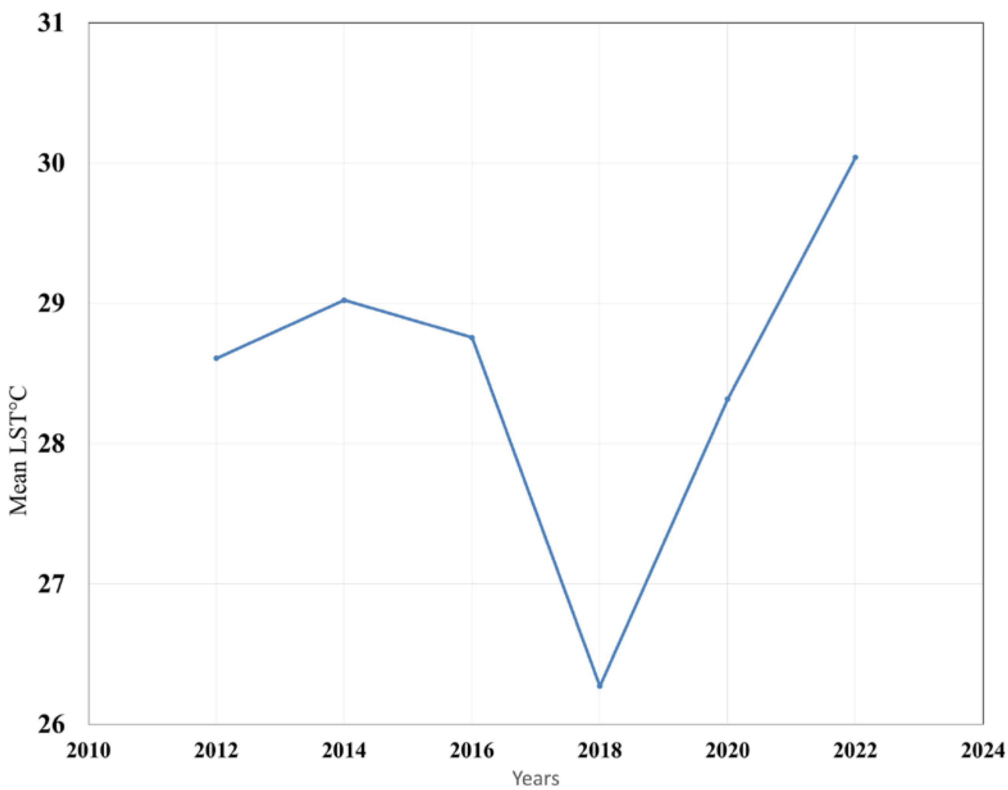

Fig. 6. Variability of land surface temperature from 2012 to 2022.

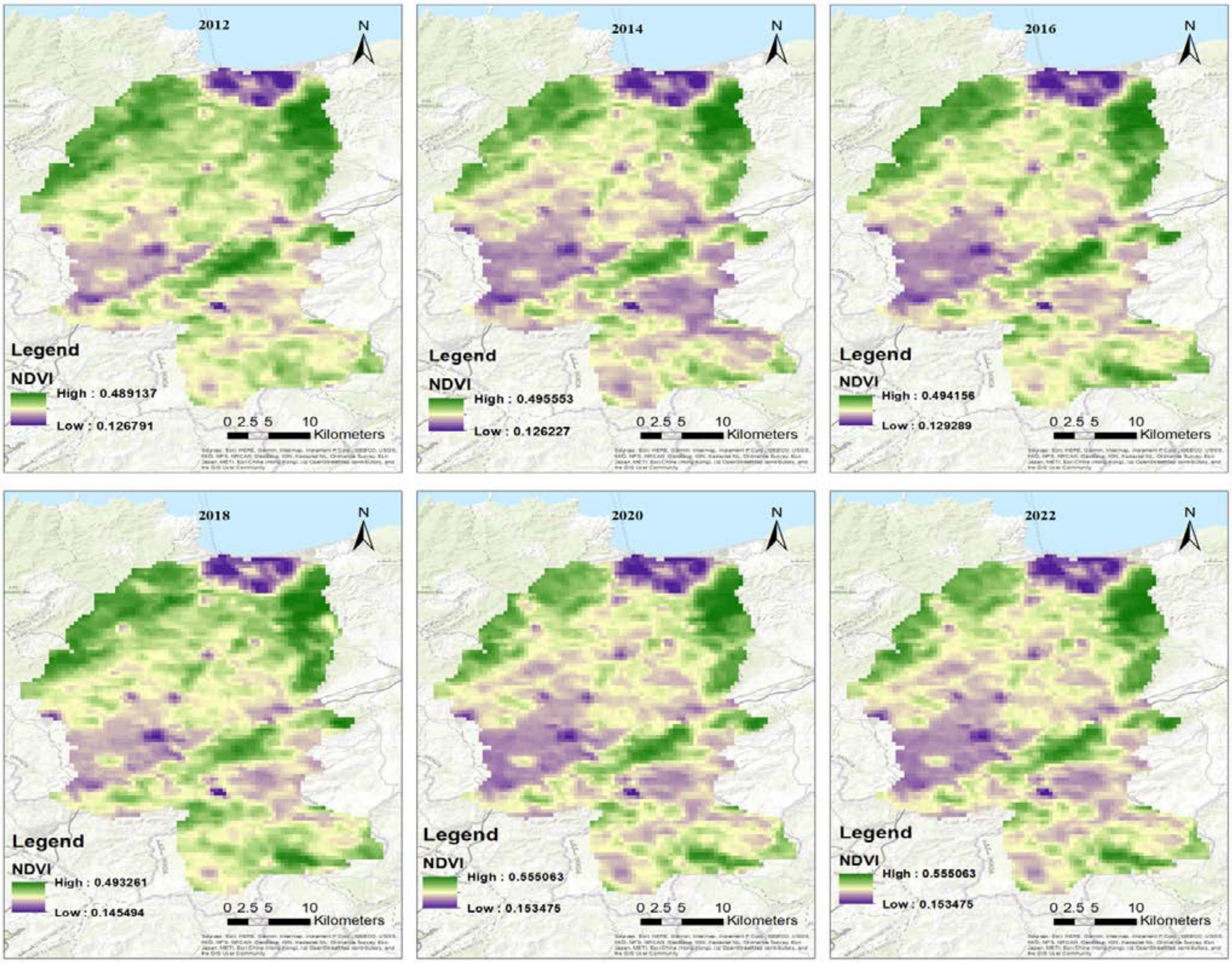

Fig. 7. Normalized difference vegetation index in Safsaf watershed from 2012 to 2022.

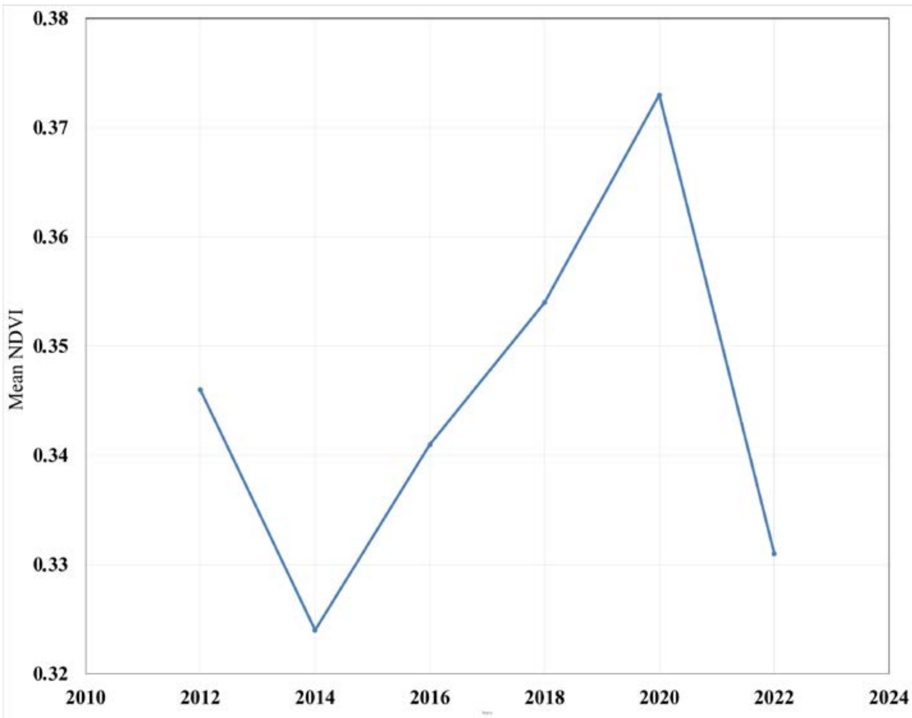

Fig. 8. Variability of normalized difference vegetation index from 2012 to 2022.

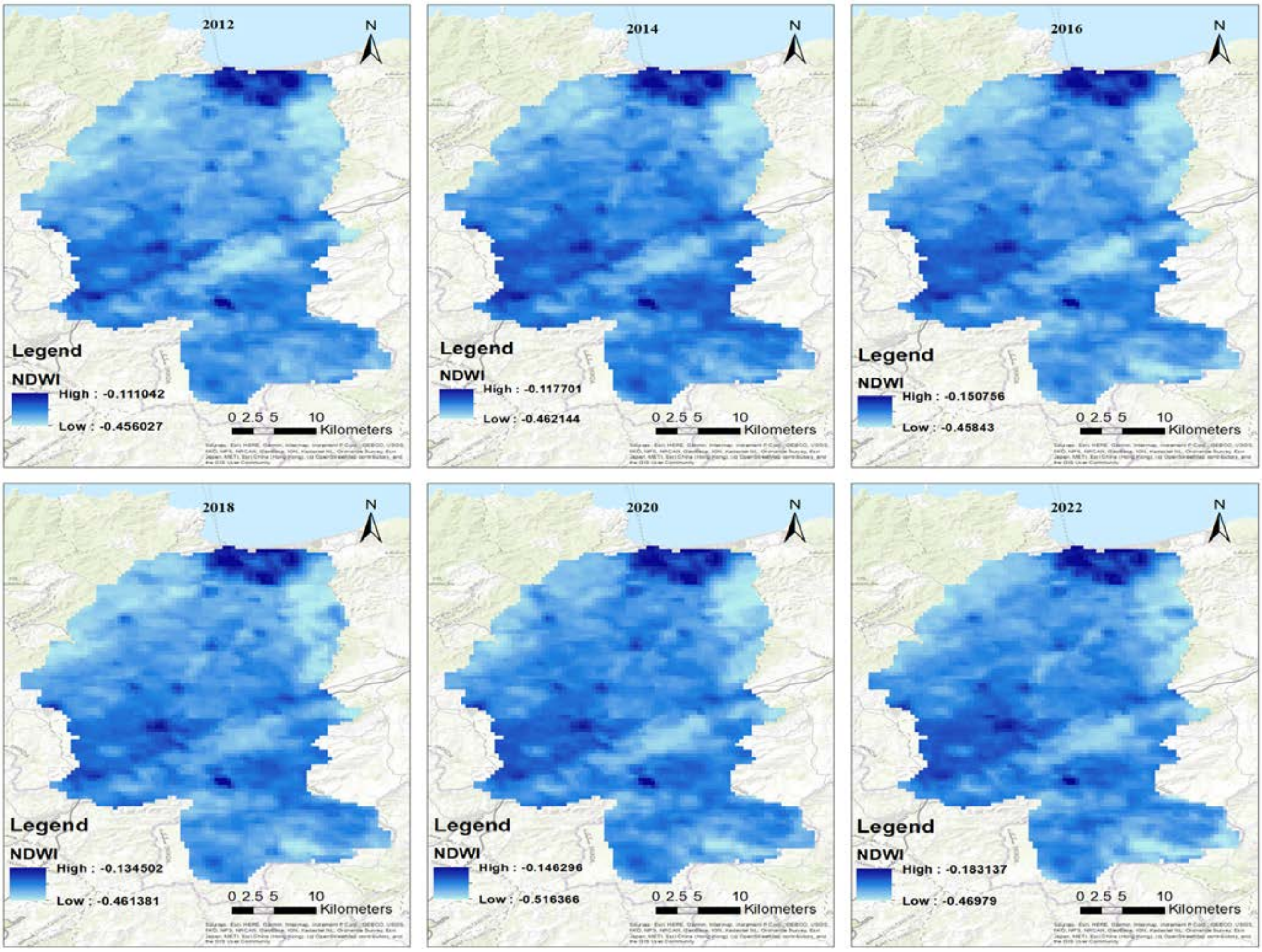

Fig. 9. Normalized difference water index in Safsaf watershed from 2012 to 2022.

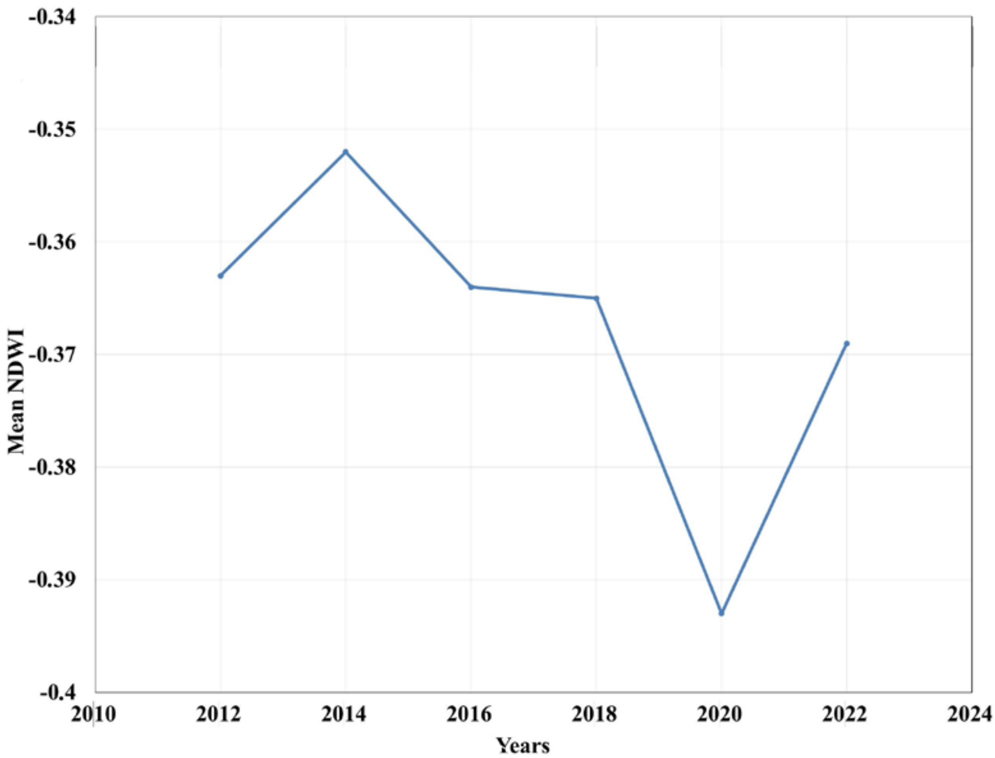

Fig. 10. Variability of normalized difference water index from 2012 to 2022.

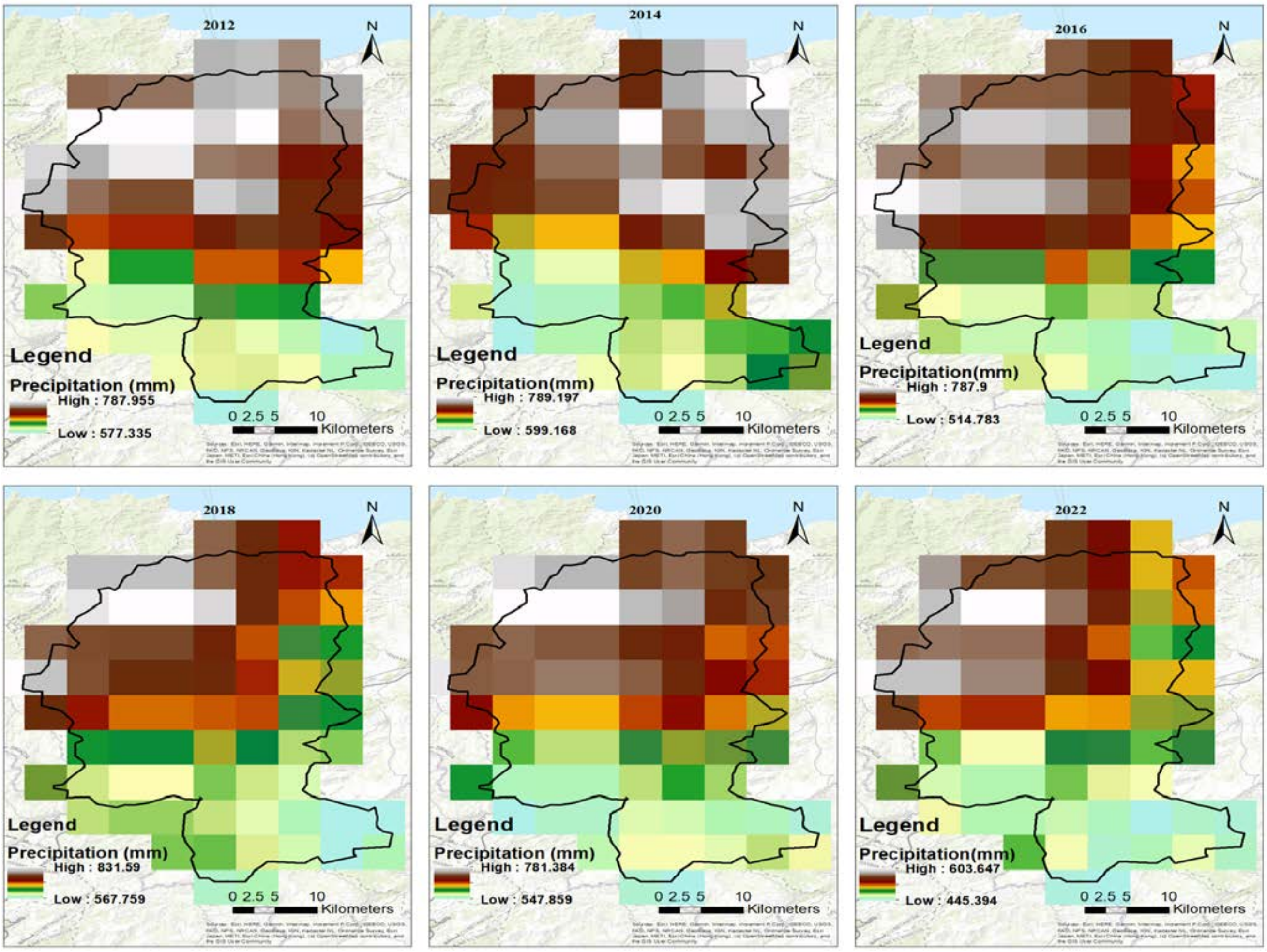

Fig. 11. Precipitation in SafSaf watershed from 2012 to 2022.

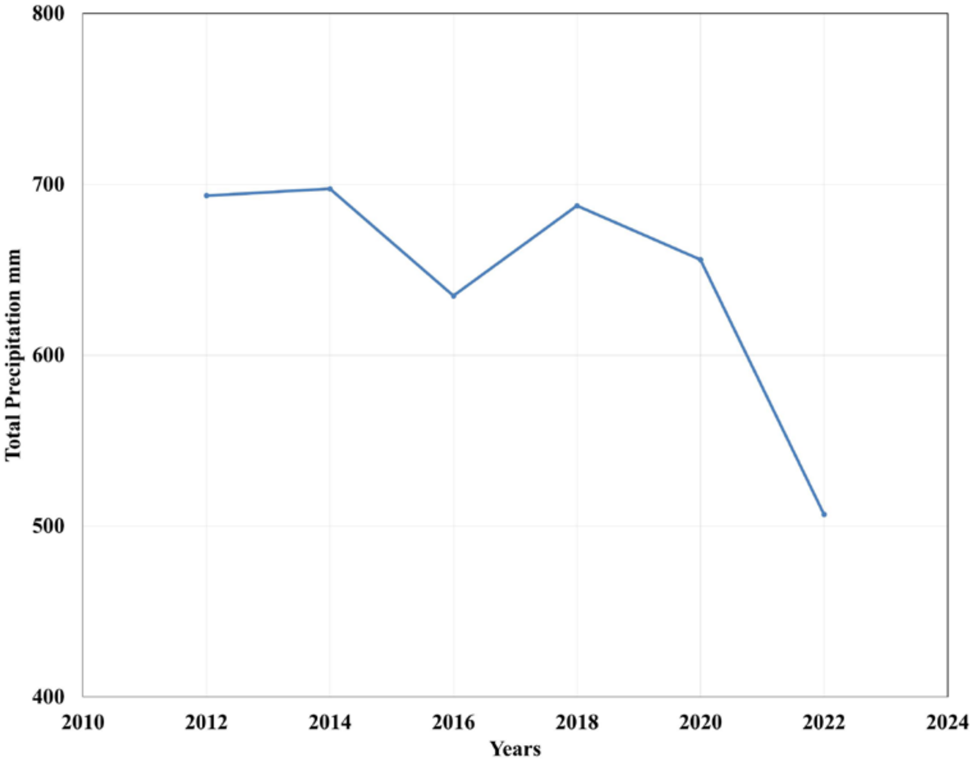

Fig. 12. Variability of precipitation from 2012 to 2022.

from 143.99 km² in 2012 to 159.01 km² in 2014, peaking at 218.87 km² in 2016, and reaching 275.35 km² in 2018. However, this category experienced a decline to 232.37 km² in 2020, followed by a significant drop to 87.96 km² in 2022.

In contrast, dense vegetation demonstrated substantial growth from 2012 to 2020, with areas recorded at 1.04 km² in 2012, rising sharply to 7.55 km² in 2014 and 7.76 km² in 2016. By 2018, the area expanded to 12.99 km², peaking at 16.63 km² in 2020. Nevertheless, a striking decrease to 0.62 km² was observed in 2022. The accompanying bar chart (Fig. 4) visually represents the distribution of the various classes of vegetation land cover over the span of 2012 to 2022.

Changes in Land Surface Temperature (LST)

The land surface temperature (LST) for this study was derived from the MOD11A1 dataset. The annual mean LST maps illustrate the fluctuations in temperature over the examination period (Fig. 5). The maximum LST values ranged from 30°C to 33.9°C, while the minimum values varied between 22°C and 24.6°C. The average LST across the years (Fig. 6), reveals the following annual temperatures: 28.61°C in 2012, 29.02°C in 2014, 28.76°C in 2016, 26.27°C in 2018, 28.32°C in 2020 and 30.04°C in 2022.

Changes in Normalized Difference Vegetation Index (NDVI)

Using the MOD09GA dataset, the mean annual normalized difference vegetation index (NDVI) was computed, (Fig. 7). The NDVI maps show values ranging from a maximum of 0.48 to 0.56, and a minimum range between 0.11 and 0.15. The average NDVI values over the years (Fig. 8), are as follows: 0.346 in 2012, 0.324 in 2014, 0.341 in 2016, 0.354 in 2018, 0.373 in 2020 and 0.331 in 2022.

Changes in Normalized Difference Water Index (NDWI)

The mean annual variation of the normalized difference water index (NDWI) was assessed using the MOD09GA dataset for the study period (Fig. 9). The results indicate a maximum NDWI range from -0.11 to -0.184, with minimum values fluctuating between -0.45 and -0.52. The average annual NDWI for each year is as follows: -0.363 in 2012, -0.352 in 2014, -0.364 in 2016, -0.365 in 2018, -0.393 in 2020 and -0.369 in 2022 (Fig. 10).

Changes in Precipitation

The maps depict the total annual precipitation in the study area, estimated by CHIRPS for the years 2012, 2014, 2016, 2018, 2020 and 2022 (Fig. 11). During this timeframe, maximum precipitation levels ranged from 603.7 mm to 831.6 mm, while minimum values varied between 445.4 mm and 599.2 mm. The average annual precipitation for the study duration, showing the following results: 693.4 mm in 2012, 697.4 mm in 2014, 634.7 mm in 2016, 687.5 mm in 2018, 655.9 mm in 2020 and 506.9 mm in 2022 (Fig. 12).

Correlation between LST and NDVI

To deepen the understanding of the relationship between mean annual Land Surface Temperature (LST) and

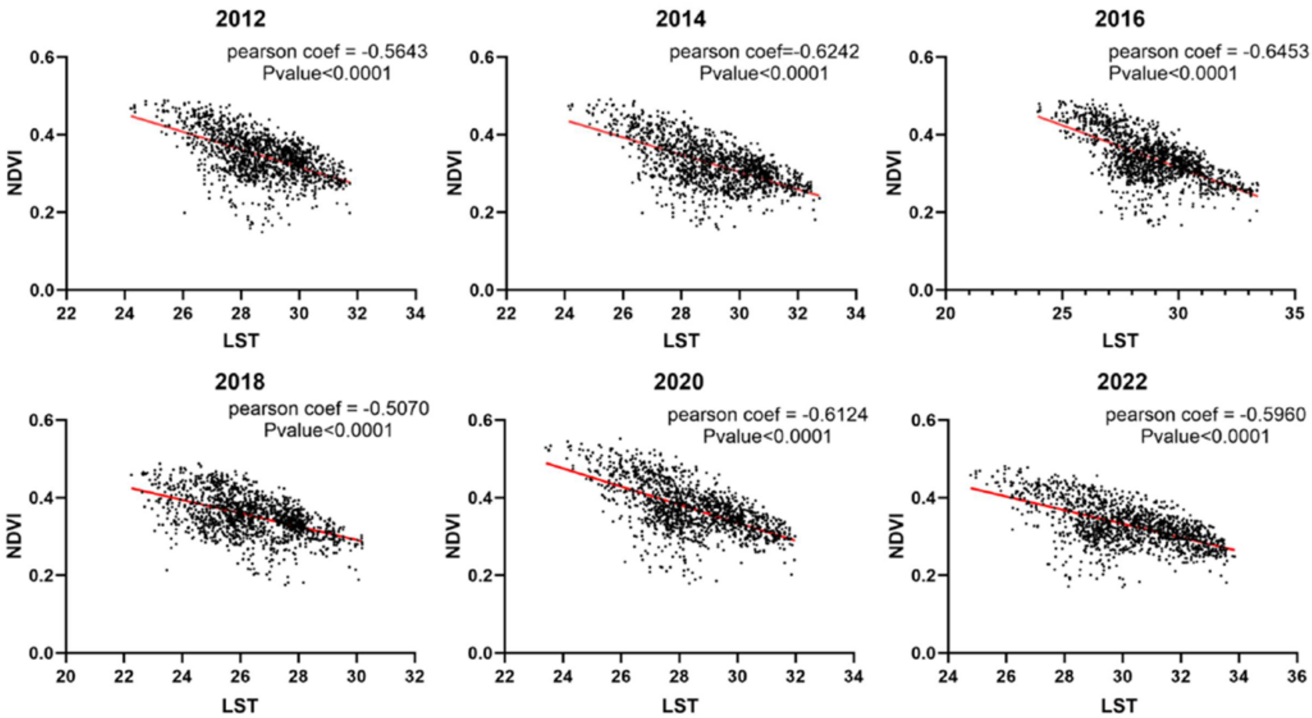

Fig. 13. Correlation between NDVI and LST in SafSaf watershed from 2012 to 2022.

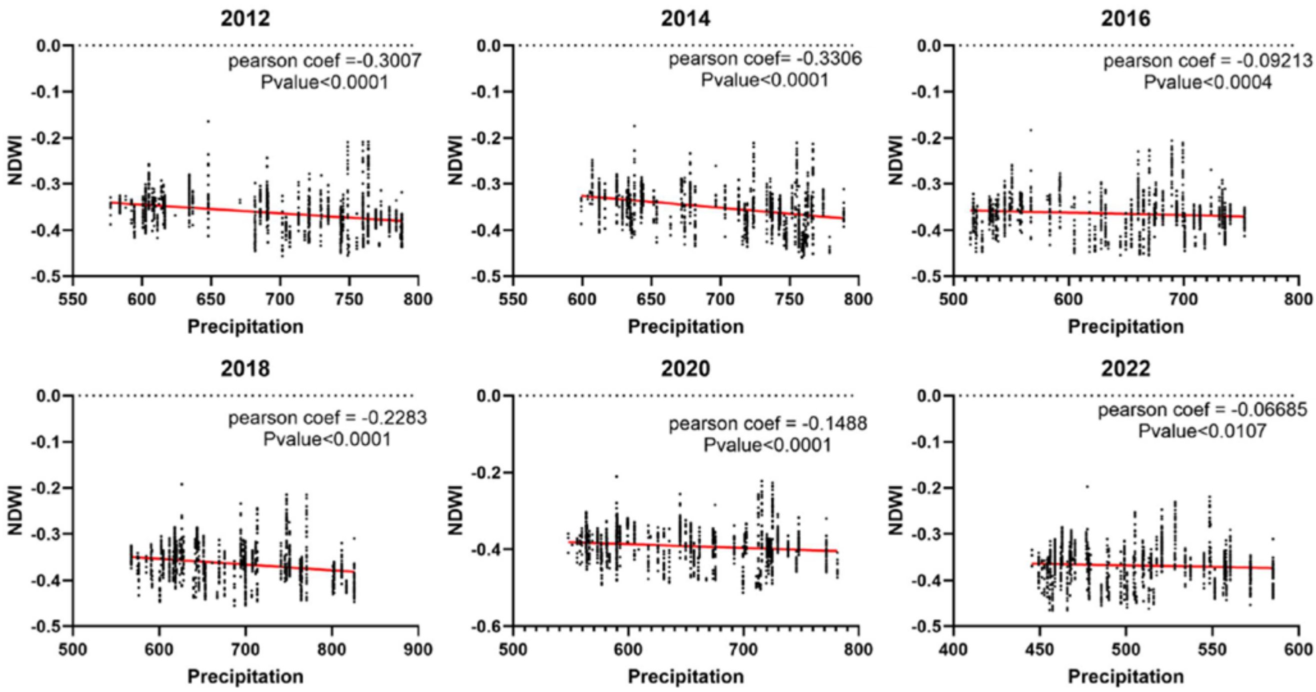

Fig. 14. Correlation between NDWI and Precipitation in SafSaf watershed from 2012 to 2022.

mean annual Normalized Difference Vegetation Index (NDVI), Pearson's correlation coefficient was calculated using the GraphPad statistical tool. The results highlight the correlation for each year from 2012 to 2022 (Fig. 13). The analysis reveals a moderate negative correlation between LST and NDVI that is statistically significant ($p < 0.0001$). The most substantial negative Pearson's coefficient was observed in 2016 ($r = -0.6453$), while the least negative correlation occurred in 2018 ($r = -0.5070$). These results suggest that as LST decreases, NDVI tends to increase, indicating a moderate inverse relationship between the two variables.

Correlation between NDWI and Precipitation

The correlation between mean annual Normalized Difference Water Index (NDWI) and total annual precipitation is illustrated in Fig. 14 for the years 2012, 2014, 2016, 2018, 2020, and 2022. Pearson's correlation analysis was conducted using GraphPad to assess this relationship. The findings indicate a weak negative correlation between NDWI and precipitation, with highly significant p-values ($p < 0.0004$, $p < 0.0001$) for all years except 2022, which showed a p-value of <0.0107. The observed r-values were relatively low, with the highest negative Pearson's coefficient recorded in 2014 ($r = -0.3306$) and the lowest in 2022 ($r = -0.06685$). Consequently, it can be concluded that NDWI exhibits a weak negative association with precipitation, suggesting that variations in precipitation have a statistically significant negative effect on NDWI.

DISCUSSION

This study examines the variations in different land cover classes within the Safsaf watershed, as illustrated in bar chart (Figs. 3, 4 and Table 2). Notably, the analysis reveals a consistent decline in the water surface area associated with the Zerdaza Dam, coupled with fluctuating built-up areas. This trend can be largely attributed to population growth and the increasing demand for water resources (Leulmi *et al.*, 2023). Additionally, the observed decrease in vegetation cover is linked to human activities, wildfires, and the broader impacts of climate change, all contributing to a significant reduction in the diversity and extent of various vegetation classes. The increase in land surface temperature (LST) alongside a decline in precipitation can be attributed to multiple interrelated factors, including urbanization, deforestation, and climate change (Hussain *et al.*, 2024). Elevated LST and diminished precipitation levels may lead to increased rates of evapotranspiration, reduced soil moisture, and alterations in the local microclimate (Soares and Lima, 2022). These climatic changes can adversely affect vegetation health, as evidenced by decreased NDVI values in certain areas, indicating stress on plant life. The observed NDVI trends, in conjunction with rising temperatures, suggest that vegetation stress has been exacerbated in some regions (Ullah *et al.*, 2023). Furthermore, the fluctuations in the Normalized Difference Water Index (NDWI) from 2012 to 2022 indicate a potential reduction in surface water availability, particularly during periods of elevated temperatures (Roy and Bari, 2022; Sharma *et al.*, 2024). Pearson's correlation analysis reveals a moderate negative relationship between LST and NDVI, suggesting that areas with higher plant biomass tend to have lower LST values (Hussain *et al.*, 2023). This implies that regions exhibiting the lowest NDVI values are characterized by sparse vegetation and reduced plant distribution.

Additionally, the weak negative correlation between NDWI and precipitation indicates that rainfall does not exert a strong influence on NDWI levels. This may be attributed to the limited presence of significant water bodies within the study area, apart from the Zerdaza Dam. The findings suggest that while precipitation plays a role in influencing water availability, its impact on NDWI is mitigated by the overall hydrological context of the region.

CONCLUSION

This study reveals the complex interplay among land cover changes, temperature fluctuations, and precipitation patterns within the Safsaf watershed. The findings emphasize the critical need for ongoing monitoring and the implementation of adaptive management strategies to address the impacts of climate change and human activities on this essential ecosystem. Future research should concentrate on understanding the long-term consequences of these changes and developing sustainable water and land management practices tailored to the region's unique challenges.

Utilizing Landsat imagery and ArcMap classification tools, this research classified vegetation land cover in the Safsaf watershed into six distinct categories: water, built-up areas, barren land, shrubland, grassland, sparse vegetation, and dense vegetation. Additionally, the study employed statistical analysis through GraphPad to examine correlations among various indices, supported by data from MODIS images and CHIRPS. Google Earth Engine (GEE) was utilized to access satellite imagery and meteorological data.

The study reveals several key insights: The Safsaf watershed has experienced significant changes in its vegetation land cover, driven by both climate change and anthropogenic activities.

Alterations in land surface temperature (LST), normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and precipitation patterns underscore the necessity for future climate adaptation strategies. These strategies should not only address water resource management but also consider the implications of rising temperatures.

The moderate negative correlation observed between LST and NDVI indicates that increasing temperatures adversely affect vegetation health. Conversely, the weak negative correlation between NDWI and precipitation suggests that precipitation does not exert a substantial influence on NDWI in the Safsaf watershed.

Author Contributions

N.Ch., K.B. and Y.H. contributed to the conceptualization of the study; F.Z. handled the methodology; R.H. managed the software aspects; M.G., Y.H., and R.H. were responsible for validation; F.Z. conducted the formal analysis; K.B. led the investigation; M.G. provided resources; K.B., K. Z., and N.C. oversaw data curation; R.H. prepared the original draft; Y.H. performed the review and editing; R.H. also handled visualization; A.M. and K.B. provided supervision; and A.M. managed the project administration. All authors have reviewed and approved the final version of the manuscript.

Acknowledgments

This study was conducted under the supervision of the IAWRSMB-Tunisia and the Laboratory of Applied Research in Engineering Geology, Geotechnics, Water Sciences, and Environment at Setif 1 University, Algeria

Funding

This research did not receive any external funding.

Data Availability Statement

No new data were generated for this study.

Conflicts of Interest

The authors declare no conflicts of interest.

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