

# Exploring climatic variability and drought characteristics in Morocco's Sais Plateau and Middle Atlas: A statistical and spectral analysis

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**Abstract.** Extreme climate change phenomena are a global reality with major repercussions on hydrosystems. Drought is particularly concerning in the southern Mediterranean region, threatening water availability and related behavior. Morocco, located in North Africa and the southern Mediterranean, is highly exposed to climate change and its consequences, particularly drought. This study aims to investigate the impact of climate variability and drought characteristics on the Sais plateau and the Middle Atlas region, using statistical and spectral indices. By analyzing annual variations in precipitation and using the Standardized Precipitation Index (SPI) and normalized difference water index (NDWI) to elucidate the temporal dynamics of water, this study highlights significant irregularities in precipitation patterns between wet and dry years, offering insight into the severity and occurrence of drought at different altitudes. In addition, the study uses the normalized difference water index (NDWI) to elucidate temporal water dynamics, revealing cyclical patterns of water availability and identifying regions sensitive to hydrological activity or drought. Furthermore, thanks to a correlation analysis between the NDWI and the SPI12 index, the study highlights the complementary relationship between spectral and statistical indices in the assessment of drought phenomena. The results show a significant difference in precipitation between the Middle Atlas and the Sais Plateau, with the Middle Atlas receiving around double the precipitation. From 1980 to 1985, drought was followed by even drier conditions until 1995, with sporadic wet years such as 1995 and 2002. During the 1980–1994 period, a persistent drought was observed until 1995, when precipitation picked up again, with notable records in 2009–2010. Positive NDWI values, with marked peaks between 2010 and 2012, indicate periods of high-water content, while negative values, such as those in 1995, 2003, and 2006, denote periods of low water content or drought.

## 1 Introduction

In recent years, the impact of climate change has become a concrete reality in different regions of the world. One of its effects is water scarcity, water stress and drought, the latter phenomenon, through its catastrophic impacts, remains one of the most devastating risks to ecosystems all over the world [1, 2, 3]. Several researchers mention concerns about the future potential for more severe and frequent droughts with global warming in different regions of the world [4]. The (IPCC) Assessment Report (AR6), highlights that continued global warming and increased atmospheric evaporation demand will lead to more severe and frequent droughts [5].

According to the World Meteorological Organization, Drought is an insidious scourge that results from a decline in rainfall from levels considered normal. This means that the nature of precipitation varies greatly from one region to another and the situation of the drought phenomenon can last for a whole season or for an even longer period when precipitation is insufficient to meet the needs of the environment. In addition, the risk of drought has a very acute impact on the state and situation of water resources through the reduction of water storage. This has widened the gap between water supply and projected water demand for irrigation, domestic and industrial consumption.

Drought and its impacts can be assessed from a meteorological, hydrological, agricultural and socio-economic perspective, leading to different indices relating to each of these highlighted concepts. [6, 7, 8] defined meteorological drought as a result of a period of dry weather, and other types of droughts, for example, having impacts on available water and crops and leading to environmental and socio-economic consequences, are evident when the impacts of meteorological drought extend over time.

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Morocco, due to its location in the Mediterranean region, is not immune to the phenomena of climate change and its acute impact on water supply. according to several studies have recently shown that Morocco is a country characterized by a high spatio-temporal variability of its climate. This variability is determined by low average annual rainfall and high intra- and inter-annual rainfall variability. Over the past few decades, Morocco has suffered from several episodes of drought, jeopardizing agricultural production and confronting herders with shortages of water and fodder. These drought situations lead to the deterioration of the living conditions of the populations and the environment [9], this situation has put in place important alerts, structures and programs to combat the effects of drought and save water since the 1980s which characterized Morocco by a very pronounced drought period [10]. In this regard, according to the report of the World Resources Institute (Word Recources Instute (WRI), published in August 2019, Morocco is on the list of countries with high water stress due to drought and water scarcity, which means that its water needs are greater than its available water potentials. In 2016, the said Institute reported that the Kingdom will experience an extremely high level of water stress by 2040. In addition, according to the UN, Morocco has gone from 2500 m<sup>3</sup> of water available per inhabitant in 1960, to less than 500 m<sup>3</sup>/inhabitant today.

Methodologically, several indices are proposed by several researchers who have studied the phenomena of drought in order to characterize the different types of drought according to well-defined indices [7, 11, 12, 8, 13, 14]. Drought monitoring involves various meteorological-statistical methods and remote sensing-based indices, with over a hundred known approaches [15-7]. To calculate the Standardized Precipitation Index (SPI), a precipitation dataset spanning at least 30 years is essential. The empirical probability distribution of this dataset is fitted with a gamma distribution, which is then transformed into a normal distribution. The resulting probabilities represent the SPI values [16].

On the other hand, the Normalized Difference Water Index (NDWI) is a valuable tool for water resource assessment, responding faster to drought conditions than NDVI. Utilizing satellite bands NIR and SWIR, NDWI considers changes in vegetation water content and mesophyll structure, enhancing accuracy by eliminating variations from leaf internal structure. As a remote sensing-based indicator, NDWI is highly sensitive to changes in leaf water content [17-18].

## 2 Methods

### 2.1 Study area

The study area is part of the Sais plateau and its Middle Atlas borders, of which two watersheds bordering the Fez and Mikkes wadis occupy a transitional zone between the Rif and the Middle Atlas.

Because of their contrasting topography, the Sais plateau and its Middle Atlas borders are characterized by a variation in temperature between upstream and downstream [19]. The hottest months in the region are July and August, with outbreaks of Chergui winds, while the average extreme lows are in January and February, characterized by sometimes negative temperatures. As for the wind system, they are generally common to the whole territory of Morocco, they are North-Atlantic winds, linked to the displacement of the Azores anticyclone [19].

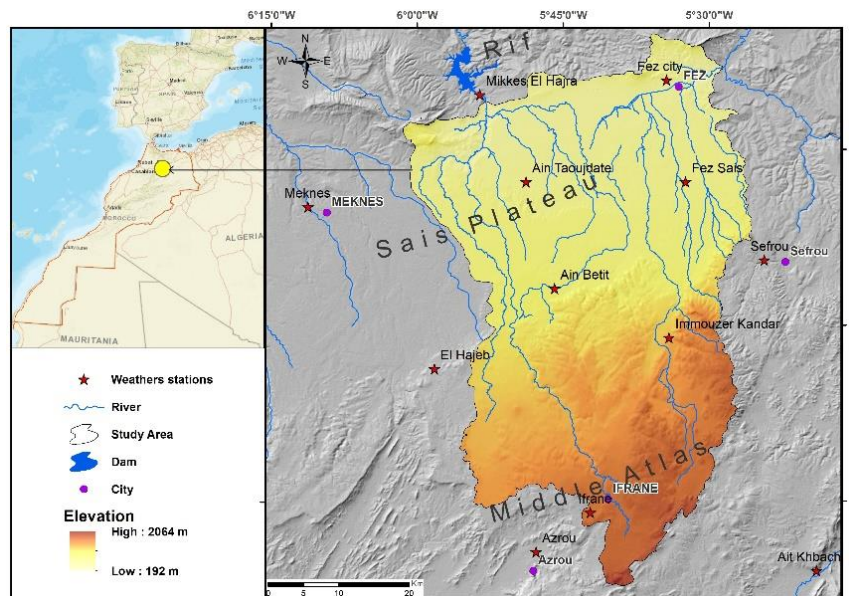


Fig. 1. Geographical location of study area

## 2.2 Data

The study of drought is based on the analysis of time series of a fairly dense network of meteorological stations and long series of observed climate data. In this study, 9 meteorological stations and stations are operated, including 6 inside the Plateau de Sais and 2 in the bordering areas (Tab. 1).

**Table 1.** Meteorological stations used

Station	Topographic unit	Basin	Latitude (DD)	Longitude (DD)	Altitude (m)
Fez Saïss	Fez Saïss Plateau	Oued Fez	33.92	-4.97	570
Fez ABHS	Fez Saïss Plateau	Oued Fez	34.03	-5.00	410
Sefrou	Middle Atlas	Agay	33.82	-4.83	989
Ifrane	Middle Atlas	Oued Fez	33.52	-5.10	1649
Meknes	Saïss Plateau	Mikkes	33.88	-5.57	487
Aïn Bittit	Piedmont	Mikkes	33.79	-5.16	790
El Hajeb	Piedmont	Boufkrane	33.69	-5.37	1017
Dar El Arsa	Fez-Taza Corridor	Inaouan	34.16	-4.92	164
Imouzzer Kander	Middle Atlas	Oued Fez	33.72	-5.014	1308

Before the study and analysis of the database in question, a step was taken to criticize the rainfall data in terms of quality and homogeneity. According to [20], any statistical study must above all rely on a network of reliable and controlled information. Checking the selected series is a step prior to any analysis. With this in mind, an inventory on the quality of the series aims to carry out a critical analysis, in order to ensure the consistency of the data at the regional level. The main objective of these treatments is to make the quality of the series raw, readable and usable. In Morocco, climatological data of precipitations, temperature, winds, and evaporation come from different sources, such as meteorological services, hydraulic basin agencies, agricultural offices as well as water and forests. To ensure the homogeneity and reliability of the data obtained, several methods and treatments have been developed by hydrologists and climatologists. These operations can be simple primary processing to fill gaps or complete missing data in data sets [19].

The main objective of these treatments is to make the quality of the series raw, readable and usable. This step was based via the Regional Vector model (VRM) and requires three complete and homogeneous stations in the same climatic region and at the same altitude on the one hand, and by the methods of simple accumulations and double accumulations.

**Table 2.** Correlation coefficients obtained by the regional vector method

Station	Correlation by vector	Coefficient of variation	Quality /10
Fez Saïss	0.4	0.32	2.9
Fez ABHS	0.9	0.36	8.5
Sefrou	0.9	0.34	8.4
Ifrane	0.9	0.34	8.9
Meknes	0.6	0.37	7.3
Aïn Bittit	0.9	0.33	9.2
El Hajeb	0.9	0.32	8.3
Dar Arsa	0.9	0.34	9.2
Imouzzer Kenddar	0.9	0.34	8.7

The findings from the regional vector model indicate that most stations exhibit a quality rating exceeding 7 out of 10, indicating satisfactory overall quality. This suggests that these stations function effectively without significant issues following data collection. However, it's noteworthy that the Fez Sais resorts demonstrate poorer quality. This discrepancy may arise from errors in data acquisition or, more plausibly, from the geographical positioning of these four stations, which likely differs from neighboring stations and consequently impacts precipitation levels.

## 2.3 Methodology

Many researchers have used SPI for drought forecasting and analysis. It is an index designed to assess drought conditions based on the probability distribution of long-term precipitation using the gamma function [16]. SPI gives a good and reliable estimate of the magnitude, severity and spatial extent of droughts. When the precipitation is above the long-term average value, the SPI is positive and if the precipitation falls below the long-term average, the SPI is negative. Unlike other drought indices, the SPI is less cumbersome to use because it requires only one set of long-term rainfall input data [21]. Because it is based on normalized data. To carry out the SPI index calculations, it is ideally necessary to have monthly series which are spread over at least 20 to 30 years, and

preferably over a long series of 50 years or more, which constitutes the optimal period [21] The SPI index is expressed mathematically as according to [16] as follows (Equation 1):

$$SPI = (P_i - P_m) / S \quad (1)$$

With  $P_i$ : the rain of month or year  $i$ ;  $P_m$ : the average rainfall of the series on the time scale considered;  $S$ : the standard deviation of the series on the time scale considered. Drought categories based on SPI values are presented in table 3.

**Table 3.** Drought intensity classification according to SPI [16].

SPI range	Drought intensity	Abbreviation
$SPI > 2.0$	Extremely wet	EW
$1.5 < SPI < 1.99$	Very wet	VW
$1.0 < SPI < 1.49$	Moderately wet	MW
$(-0.99) < SPI < 0.99$	Near normal	NN
$(-1.0) < SPI < (-1.49)$	Moderately dry	MD
$(-1.5) < SPI < (-1.99)$	Strongly dry	SD
$SPI < (-2)$	Extremely dry	ED

The SPI index can be calculated at different time scales 1, 3, 6, 9, 12 or even more [23]. The 12 -month spinnaker is more suitable for identifying dry and humid periods of relatively long duration and relates better with the drought impacts on hydrological diets, while the 6 -month SPI is the most recommended for drought studies that affect groundwater, however for short-term time scales respectively 3 and 1 month SPI are more suitable for monitoring agricultural and meteorological drought [24].

In this research, Google Earth Engine served as the primary tool. The required materials included Landsat 5 and 7 satellite imagery that had undergone radiometric correction (Top of Atmosphere/ToA Reflectance) for the available period (1984-2015). These images were sourced from the Earth Engine Data Catalog. The NDWI calculation equation (2) is expressed as follows:

$$NDWI = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}} \quad (2)$$

Where:

$\rho_{NIR}$ : spectral reflectance band near-infrared (band 4)

$\rho_{SWIR}$ : spectral reflectance band short wave infrared (band 5)

Drought categories based on NDWI values are presented in table 4.

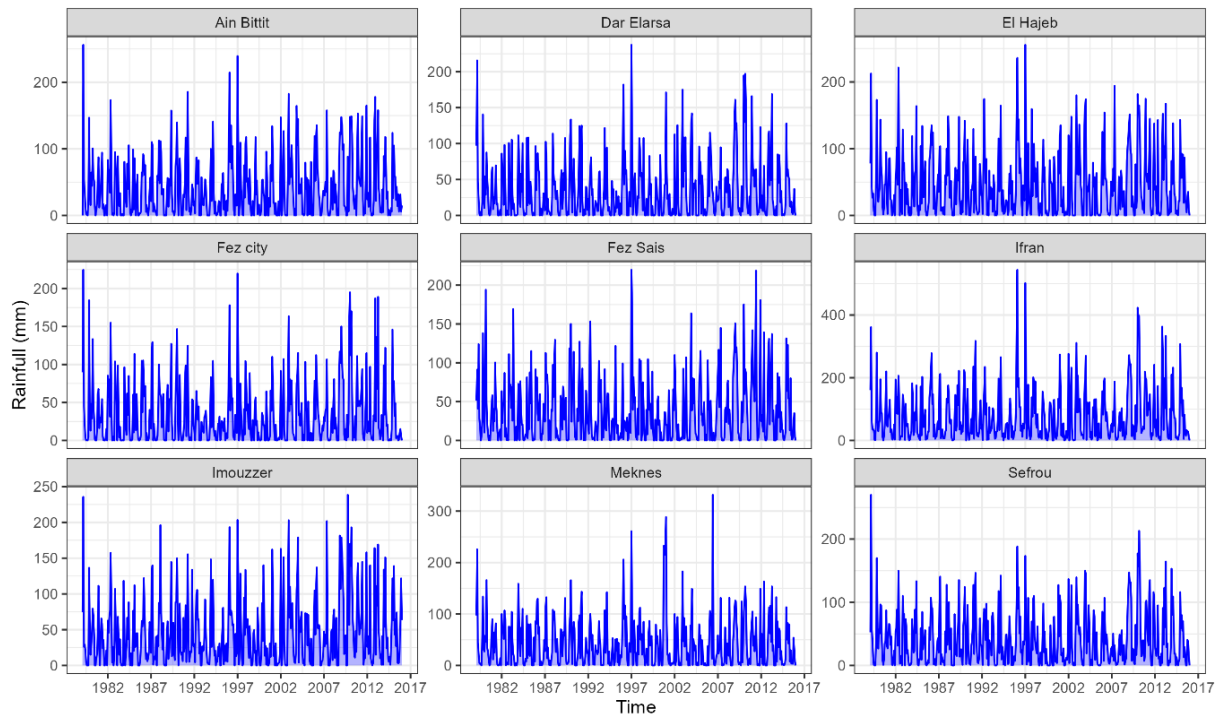
**Table 4.** Drought intensity classification according to NDWI [17]

NDWI categories	Description
$0.7 \leq NDWI$	Very high moisture content
$0.6 \leq NDWI < 0.7$	High moisture content
$0.5 \leq NDWI < 0.6$	Moderate moisture content
$0.4 \leq NDWI < 0.5$	Low moisture content
$0.3 \leq NDWI < 0.4$	Weak drought
$0.2 \leq NDWI < 0.3$	Moderate drought
$0 \leq NDWI < 0.2$	Strong drought
$NDWI < 0$	Very strong drought

### 3 Results and discussion

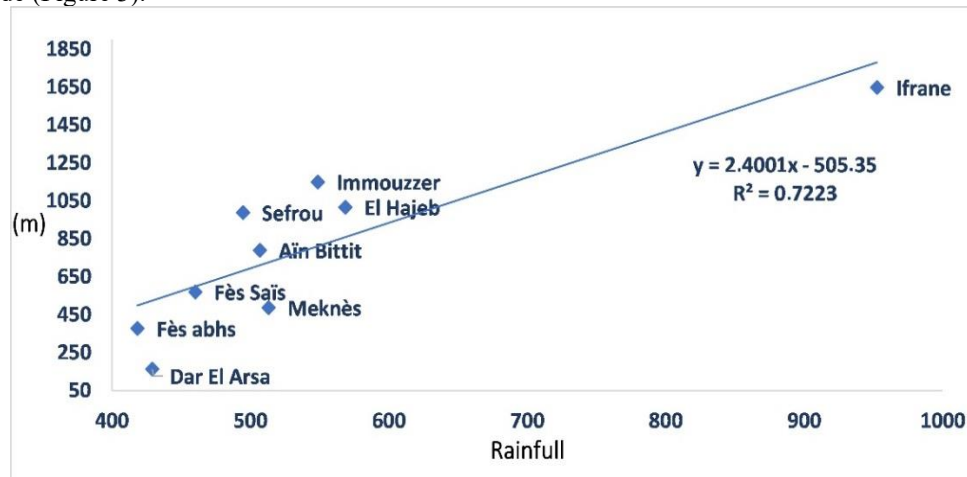
The results show a large spatial and temporal variation of precipitation characterizing the Sais plateau and its middle Atlas borders. The average annual rainfall recorded in the period from 1980 to 2015 in the 9 stations shows that the annual rainfall increases from the Sais plateau towards the Middle Atlas part of the study area in question.

The second remark is that the irregularity of the rains from one year to another is very striking with a large fluctuation of the precipitation between wet and dry years (Figure 2).



**Fig. 2 .**Temporal dynamics of precipitation across nine studied stations

The analysis of rainfall variability in the study area reveals that dry periods always begin from June to September. These dry periods are characterized by a rainfall deficit and the wet periods begin in October until April; and have a great impact on the hydrological regime [19]. This annual irregularity of rainfall in the Sais plateau leads to an understanding of its effects, in particular drought and its severity. The periods of drought characterized the period studied from 1980 to 2015 is marked by different degrees of drought from one station to another and according to their altitude (Figure 3).

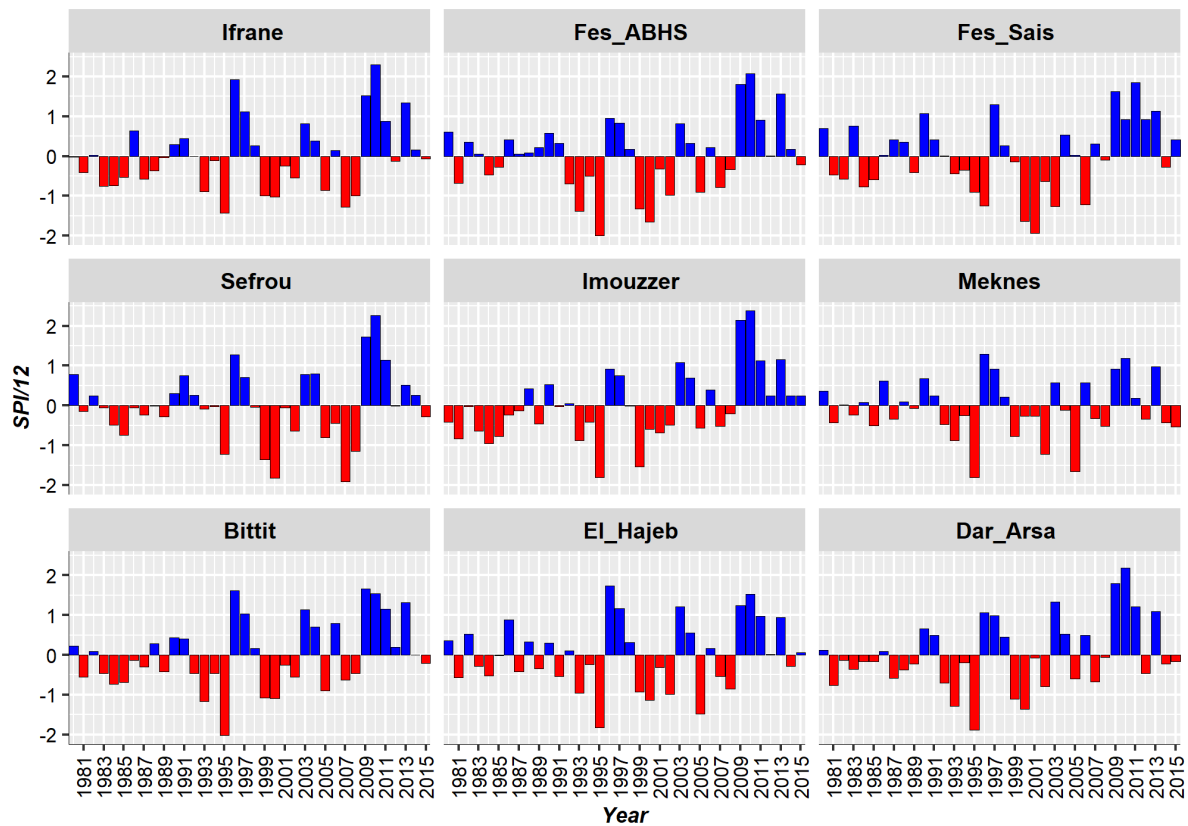


**Fig. 3.** Elevation's influence on annual precipitation patterns

It can be seen that the degree of drought in the Middle Atlas differs to a greater or lesser degree at the stations locating in the Sais plateau. This is justified that the two stations of Ifrane and Imouzzer locating are located in the middle atlas at an altitude of more than 1000 meters compared to the other stations on the Sais plateau with an altitude lower than 1000 meters, Fez Sais, Fez ABHS, El Hajeb, Meknes, Bittit and Dar El Arsa (Figure 4).

### 3.1. Standardized Precipitation Index

The use of the SPI index has made it possible to assess the phenomenon of drought in the Saïs plateau and its Middle Atlas borders. Figure 5 shows the results of SPI-12 months applied to the 9 stations to analyse the behaviour and spatial variability of drought for the period from 1980 to 2015.



**Fig. 4.** SPI time-series at 12 months in the study area

Before delving into an analysis of drought periods in the specified area, it's crucial to recognize the comprehensive classification of drought proposed by Wilhite [25]. They categorize drought into four main types: meteorological (extended deficit in precipitation), agricultural (shortfall in soil moisture), hydrological (decrease in water flow or groundwater storage), and socio-economic [26]. Understanding this classification framework provides a foundational understanding for our analysis.

In this context, examination of drought patterns in the Saïs Plateau and adjacent regions of the Middle Atlas reveals a consistent manifestation of these characteristics, notably varying in duration and intensity across different periods. Moreover, numerous instances of drought, ranging in severity, have impacted the entire study area.

The initial period under scrutiny, spanning from 1980 to 1985, is characterized by drought across most of the monitored precipitation stations. This phase is typified by a precipitation deficit resulting in a drought that aligns closely with historical norms. Stations such as Bittit, Ifrane, Imouzzar, Dar El Arsa, Fez Sais, and El Hajeb notably experience these conditions. The years following saw a transition to even drier conditions, although punctuated by sporadic wet years, such as 1995 and 2002. Despite slight disparities between stations, the Standardized Precipitation Index (SPI) underscores the uniformity of precipitation distribution throughout the region, corroborating observations from various monitoring stations.

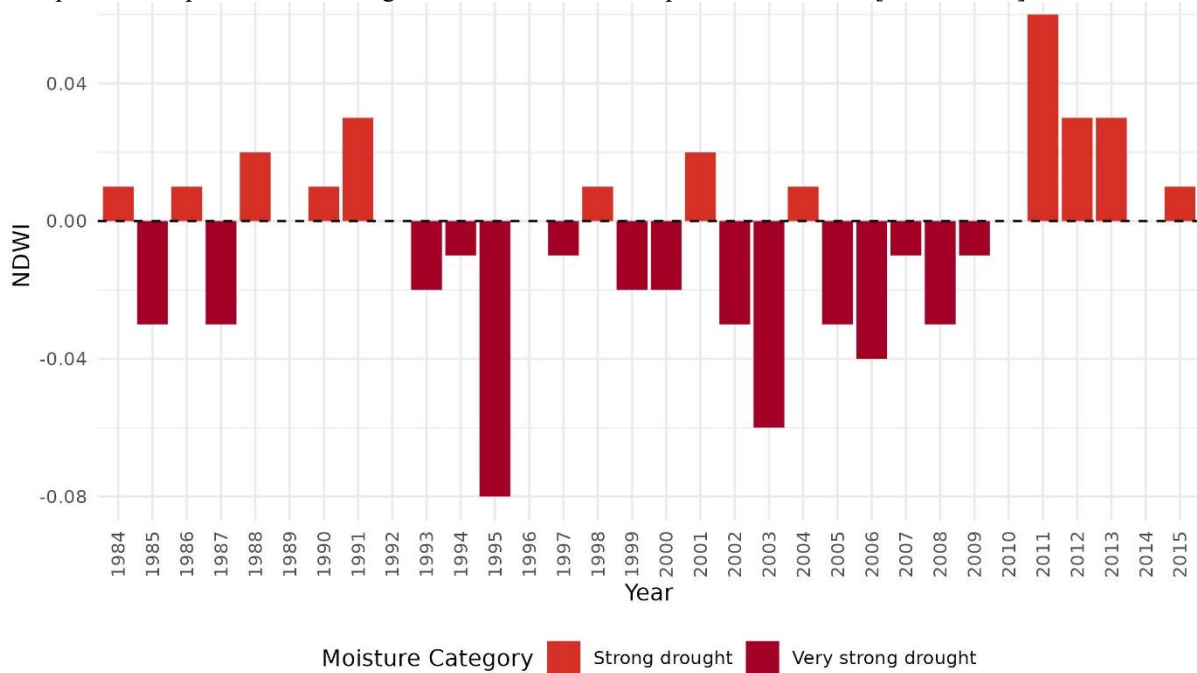
The second period, straddling from 1980 to 1994, is marked by a sustained drought until 1995, when precipitation resumes across different sectors of the study area. Notably, wet periods are concurrently observed across all stations. The years 2009 and 2010 stand out for their substantial precipitation in Morocco, with Fez recording a record 878 mm in 2009-2010.

### 3.2 Normalized Difference Water Index (NDWI)

The NDWI dataset spanning 1984 to 2015 provides (figure 5) a nuanced depiction of the temporal dynamics of water content within the studied area. The recurring oscillations around the zero mark in NDWI values underscore a discernible cyclical pattern, suggesting periodic shifts in water availability.

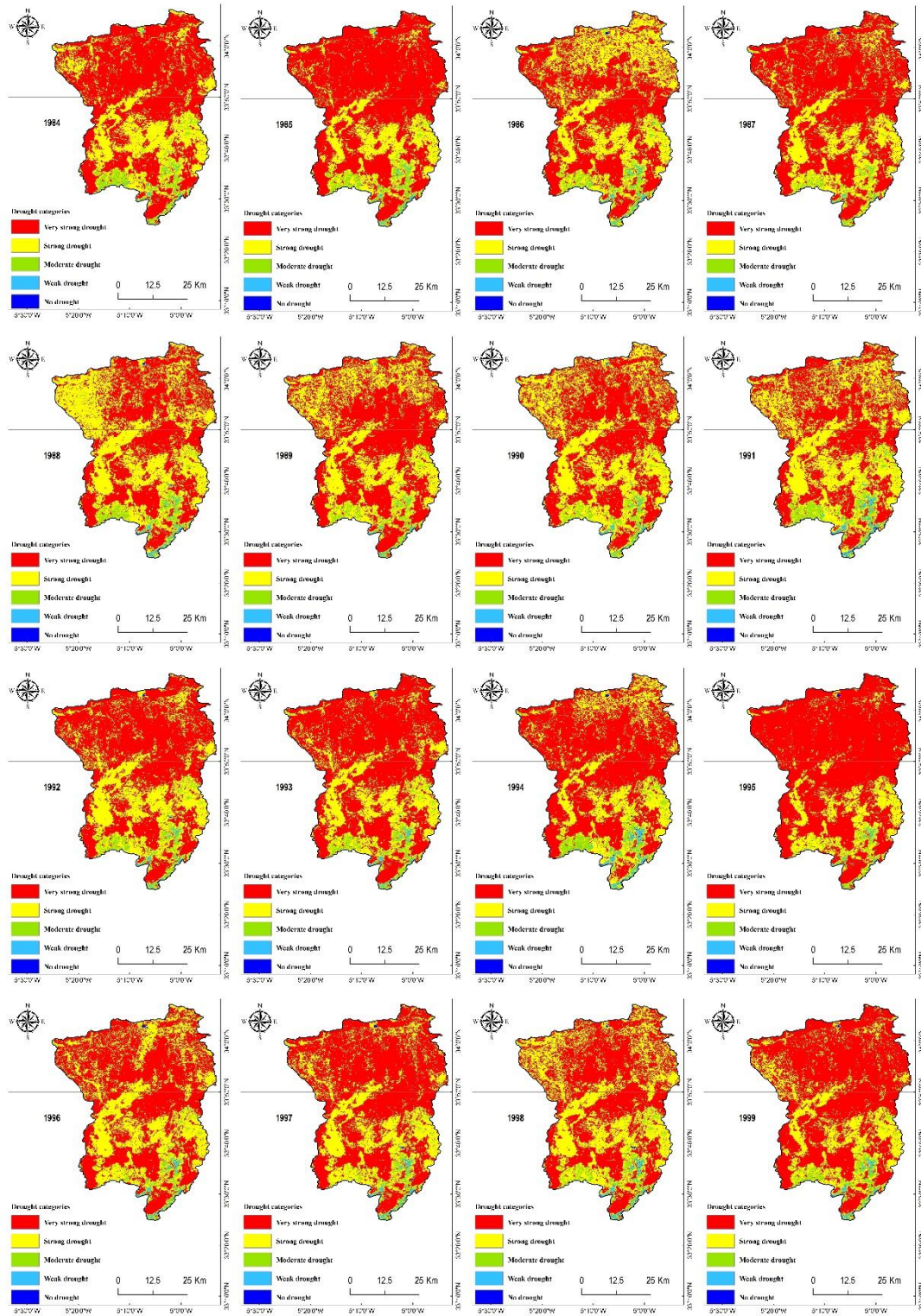
Positive NDWI values, notably the pronounced peaks in 2011 and 2012, signify periods characterized by elevated water content. Such instances could be associated with increased precipitation, enhanced surface water, or favorable hydrological conditions. Conversely, the years with negative NDWI values, such as 1995, 2003, and 2006, delineate periods of reduced water content or drought conditions. The sustained low NDWI values during these years highlight a potential strain on water resources, which could have cascading effects on ecosystems, agricultural productivity, and water-dependent industries. The overall trajectory of NDWI reveals a complex interplay of factors influencing water content. The shift from a relatively stable pattern in the early years to a more erratic one in subsequent periods raises questions about the resilience and vulnerability of the studied ecosystem to changing environmental conditions.

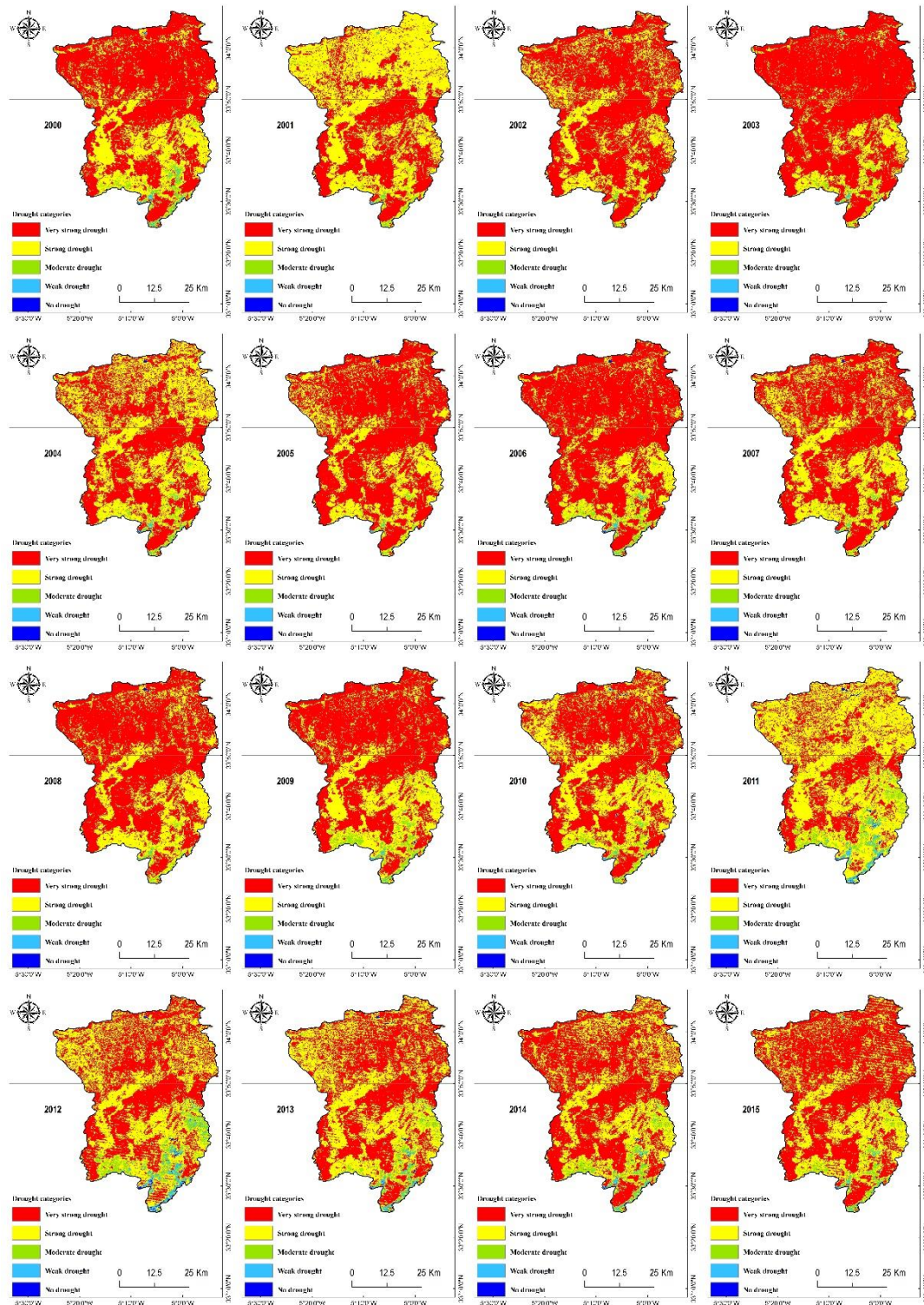
To fortify the veracity of the analysis, alignment with climatic data is imperative. Correlation of NDWI fluctuations with SPI can yield nuanced insights into the environmental dynamics steering water availability. In a broader context, the NDWI analysis contributes to a nuanced comprehension of temporal hydrological patterns, with pertinent implications for drought evaluation within the specified timeframe [27, 8, 28, 29].



**Fig. 5.** Time series plot of NDWI in the study area extracted using Google Earth Engine and Landsat satellite datasets

The spatial interpretation of NDWI maps (Figure 6) in the study area reveals significant nuances in the spatial distribution of water. Areas with high NDWI values, especially around water bodies in the Middle Atlas region characterized by elevated zones, indicate hydrologically active regions to the south of the studied watershed. This positive response of NDWI underscores the index's ability to distinguish areas with greater water availability [30-31].



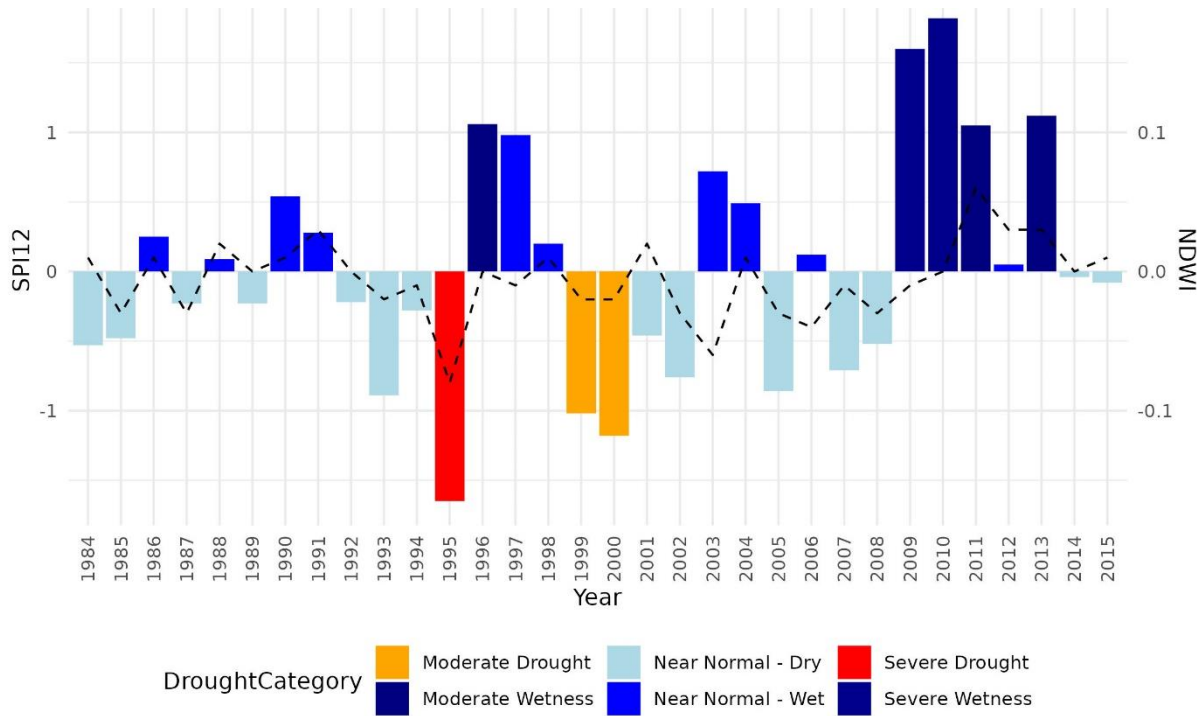


**Fig. 6.** Spatial distribution of NDWI in the study area retrieved from Landsat Satellites for the period of 1984–2015

Conversely, areas with lower NDWI values, situated in less favorable water retention zones, indicate drought conditions or reduced water availability, particularly in the downstream part of the studied basin. Additionally, we observe that the majority of the territory in the study area is subject to severe to very severe drought. Thus, the altitudinal impact is discernible, with the Middle Atlas regions showing distinct responses compared to the Sais Plateau.

### 3.3 Correlation between NDWI and SPI

The analysis of the provided NDWI and SPI dataset (figure 7) reveals a complex interplay between trends and variations in water content and precipitation conditions over the specified years (1984-2015). Noteworthy positive trends in NDWI, indicative of increased water content, align with corresponding positive SPI values during pivotal years like 1990, 1991, 1996, 1998, 2004, 2009, 2010, 2011, 2012, and 2013. This synchronicity implies a strong correlation between elevated water content and favorable precipitation conditions.



**Fig. 7.** Time series plot of NDWI and SPI12 in the study area

Conversely, instances of negative trends in NDWI, signifying potential drought conditions, align with corresponding negative SPI values. Prominent years exhibiting this synchronous pattern include 1993, 1995, 1999, 2000, 2002, 2005, 2007, and 2008. These occurrences emphasize the correlation between decreased water content and unfavorable precipitation conditions, underscoring the sensitivity of NDWI to drought events.

However, there are instances of inverse trends, as observed in 2006, where NDWI exhibits a negative trend while SPI indicates a positive trend. Such disparities between NDWI and SPI trends suggest that factors beyond precipitation may contribute to variations in water content. This underscores the need for a more comprehensive exploration of additional variables such as land use changes, vegetation dynamics, or soil characteristics that may influence the hydrological response independently of precipitation.

The utilization of Pearson correlation analysis reveals a robust and statistically significant ( $p < 0.05$ ) moderately positive linear relationship ( $r = 0.466$ ) between NDWI and SPI12. This indicates a meaningful contribution of SPI12 in elucidating the observed fluctuations in NDWI, and reciprocally, NDWI provides valuable insights into the variations present in SPI12. This correlation has already been pointed out by other studies [32].

Consequently, the findings from the NDWI analysis harmonize with those derived from SPI, prompting the conclusion that both spectral and statistical indices synergistically reinforce one another. This emphasizes the intrinsic complementarity of these indices, elevating their combined efficacy for a thorough evaluation of drought phenomena.

While the correlation between NDWI and SPI provides valuable insights into the influence of precipitation on water content, it is crucial to recognize the nuanced nature of hydrological dynamics. Factors beyond precipitation, such as anthropogenic interventions or ecosystem changes, may introduce complexities that impact the observed trends. Further investigation into these localized influences and a holistic consideration of environmental variables are essential for a comprehensive interpretation of the observed trends in water content and precipitation conditions within the studied area.

## 4. Conclusion

The comprehensive analysis of precipitation variability and its impact on water content dynamics within the Sais plateau and Middle Atlas borders from 1980 to 2015 underscores significant spatial and temporal variations, influenced by altitude and seasonal fluctuations. The study reveals a discernible pattern of irregular rainfall, with distinct dry and wet periods, impacting hydrological regimes and highlighting the prevalence of drought conditions across the region. Through the integration of the Standardized Precipitation Index (SPI) and the Normalized Difference Water Index (NDWI), our findings emphasize the nuanced understanding of drought phenomena, supported by the robust correlation between NDWI and SPI. This holistic approach not only enhances our comprehension of hydrological dynamics but also underscores the complementary role of spectral and statistical indices in drought assessment, facilitating informed water resource management strategies for the region.

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