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Climate Change and Water Resources Management in the Ghis-Nekor Watershed (North of Morocco) – A Comprehensive Analysis Using SPI, RDI and DI Indices

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ABSTRACT

Morocco is currently facing significant challenges due to the ever–changing climate, with its critical water sources crucial for agriculture, economy, and daily life being greatly affected. In order to thoroughly understand the impact of climate change on the Ghis–Nekor watershed, an in–depth study spanning 38 years (1978–2016) was conducted. This involved examining the meteorological data from three stations and utilizing advanced indices, such as SPI, RDI, and DI. The findings of this study revealed prominent shifts in precipitation patterns, indicating a vulnerability in the region. While there was a general increase in annual rainfall during the specified time period, a sharp decline was observed post–2008. Further analysis of drought confirmed the presence of persistent dry spells and recurring episodes, highlighting the urgent need for effective water management strategies. These crucial findings must be considered by decision–makers for successful climate adaptation, emphasizing the key role played by this study in mitigating the effects of climate change.

Keywords: climate change, drought, SPI, RDI, DI, water resources.

INTRODUCTION

The escalating impact of climate change on global water management poses a significant threat (Alavian et al., 2009), particularly in developing countries like Morocco, where agriculture is integral to the economy (Diao et al., 2010). Despite a considerable focus on the Mediterranean region, limited research has delved into the unique challenges faced by Morocco, one of the driest countries globally (Saouabe et al., 2022).

Climate change profoundly influences critical elements, such as rainfall, river and groundwater levels, temperature, and soil moisture (Aimar, 2019). The recurrence of drought emerges as a pressing concern, impacting socio–economic activities and ecosystems (Hachem et al., 2023). This is especially alarming in Morocco, where water scarcity is exacerbated by climate change, particularly in semi–arid areas (Bouchaou et al., 2011).

Accurate drought assessment and prediction are crucial in combating these challenges. Various indices, each with its strengths and limitations, have been developed for this purpose. Notable indices include the Palmer drought severity index (PDSI) (Palmer, 1965), rainfall deficit index (RDI) (Bhalme and Mooley, 1979), surface water supply index (SWSI) (Shafer and Dezman, 1982), standardized precipitation index (SPI) (McKee et al., 1993), effective drought index (EDI) (Byun and Wilhite, 1999), reconnaissance drought index (ReDI) (Tsakiris et al., 2007), drought index of effective drought index (IDE) (Nalbantis and Tsakiris, 2009), standardized maximum soil moisture index (IMSM) (Vicente–Serrano et al., 2010), regional agricultural drought index (RAI) (Fleig et al., 2011), and agricultural drought reference index (ADRI) (Woli et al., 2012), the rainfall index (RI) and the drought index (DI) (Hachem et al., 2023). Despite the simplicity of calculating the Standardized Precipitation Index (SPI), its drawback lies in neglecting crucial factors like temperature, potential evapotranspiration (PET), wind velocity, and soil moisture, making it less reliable in a warming climate (Vicente–Serrano et al., 2010). Although the reconnaissance drought index (ReDI) (Tsakiris et al., 2007) has made improvements by incorporating PET, it still has limitations. It fails to accurately account for the temperature–related drought variations and also ignores the significant contribution of soil moisture in identifying agricultural droughts (Vicente–Serrano et al., 2010; 2015).

This study addressed the impact of climate change on the Ghis-Nekor watershed in northern Morocco, an area with limited prior research. Analyzing 38 years of precipitation data and utilizing advanced indices such as SPI, RDI, and DI, this research revealed a pattern of prolonged dry spells and increasing drought occurrences. The findings underscore the urgent need for accurate assessment methods to inform effective adaptation strategies for sustainable water management.

MATERIALS AND METHODS

Presentation of the study area

The Ghis-Nekor area, located in the northeastern region of Morocco (Figure 1), is surrounded by the Mediterranean Sea to the North, the Ajdir municipality and the commune of Aït Youssef O'Ali to the West, the Mohammed Ben Abdelkarim Khattabi

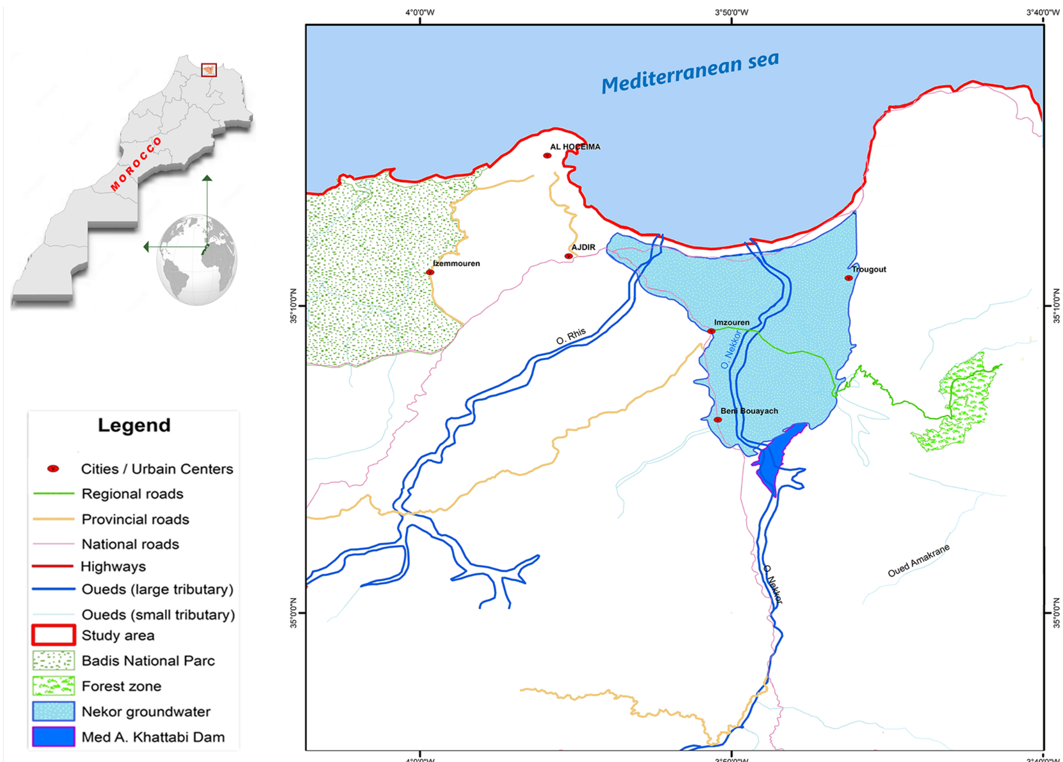

Figure 1. Geographical location of the Ghis-Nekor watershed

Dam (MBAK–Dam) to the South, and the Trougout municipality to the East (Benyoussef et al., 2022).

Covering over 790 km² at the MBAK–Dam, the Nekor River watershed embodies the characteristic features of the Rif region, namely intricate geomorphology, rugged terrains, various lithological formations predominantly consisting of fragile shale, a high population density of 76 inhabitants per km², and widespread vegetation degradation. This combination makes it highly vulnerable to erosion (Niazi et al., 2005). The area of study experiences a semi-arid Mediterranean climate that showcases dynamic seasonal and yearly changes. These changes are reflected in the hydrological patterns of the Nekor River, which undergoes both intense floods and extended periods of low water flow.

According to the research conducted by Niazi et al. (2005), the average yearly precipitation is 340 mm, while the Tamallaht station located downstream records an average discharge of 1.88 $m^3 \times s^{-1}$. However, the data from 2017, as cited by Quinquis, shows an increase in discharge to 2.54 $m^3 \times s^{-1}$. The Ghis-Nekor watershed, spanning 1760 km², boasts a highest elevation of 2009 meters and a varying slope of 9.45% to 12.56% (Quinquis, 2017).

The hydrological regime of the region, combined with its physiographical characteristics, results in mechanical erosion rates among the highest in Morocco, estimated at approximately 5×10^3 tons×km²×year^{-1} (Mriouah, 1982; Niazi, 1994). The MBAK–Dam, commissioned in 1981, has a lake surface area of 3.86 km², with an initial capacity of 43.3×10^6 m³, significantly reduced due to substantial silting (Niazi et al., 2005).

Methodology

Analyzed climate data

For this study, the rainfall data were collected from three climatic stations in the study area over a period of 38 years (1978–2016). These records were obtained from reliable sources, such as the Moulouya and Sebou Hydraulic Basin Agencies, local meteorological stations, and by using the weighted average method for station annual evolution (Anctil et al., 2012).

The chosen stations ensure homogeneous climatic coverage, and their coordinates and characteristics are detailed in Table 1.

To evaluate drought severity and sustainability, three indices were applied: standardized precipitation index (SPI), rainfall deficit index (RDI), and drought index (DI) (Bhalme and Mooley, 1979; McKee et al., 1993; Hachem et al., 2023).

Standardized precipitation index

Developed by McKee et al. (1993), SPI monitors meteorological droughts, assessing precipitation deviations from the average over a specific time scale. Its adaptability across time frames allows comprehensive evaluations of short– to long–term water reserves. Adopted globally by the World Meteorological Organization (WMO) in 2009 as a global instrument for measuring meteorological droughts (Jouilil et al., 2013; Hachem et al., 2023), SPI efficiently quantifies precipitation deficit, enabling analysis of wet and dry periods. SPI is calculated following the equation (1):

$$SPI = \frac{Xi - Xm}{Si} \tag{1}$$

where: Xi – Cumulative rainfall for year i (mm);
Xm – Average annual rainfall observed for a given series (mm);
Si – Standard deviation of the annual rainfall observed for a given series.

Drought intensity is determined by SPI values, with consecutive negative values indicating drought onset. A classification system categorizes drought events at different time scales (Table 2), facilitating comparisons across diverse climatic regions.

Normalization allows assessing drought infrequency (Table 3) and the probability of precipitation needed to terminate it, facilitating comparisons between past and present droughts across diverse climatic regions.

Table 1. Coordinates and climatic characteristics of selected weather stations

Station	Coordinates		Attitudes Z (m)	Observation period (years)	Size of the series (years)	Average rainfall P (mm)	Standard deviation (SD)	Coefficient of variation (%)
	X (m)	Y (m)						
Tamallaht	425172.824	3886521.517	76	1978–2016	38	299.7	96.8	32.31
Tamassint	409829.756	3882699.411	180	1978–2016	38	296.8	111.4	37.52
Tighza	407441.882	3879995.787	316	1978–2016	38	328.0	116.9	35.64

Table 2. SPI classification system (McKee et al., 1993)

SPI Index	Category	Number of times over 100 years	Frequency (years)
0 to -0.99	Mild drought	33	1/3
-1.0 to -1.49	Moderate drought	10	1/10
-1.5 to -1.99	Severe drought	5	1/20
< -2	Extreme drought	2	1/50

Table 3. SPI normalization for assessing drought infrequency (McKee et al., 1993)

SPI Index	Category	Number of times over 100 years	Frequency (years)
From 0 to -0.99	Mild drought	33	1/3
From -1.0 to -1.49	Moderate drought	10	1/10
From -1.5 to -1.99	Severe drought	5	1/20
< -2	Extreme drought	2	1/50

Rainfall deficit index

The RDI, or deviation from normal, estimates variations in rainfall relative to normal levels, identifying "wet" years if RDI is positive and as "dry" years if it is negative. RDI is computed basing on the equation (2):

$$RDI(\%) = \frac{Pi - Pm}{Pm} \times 100 \tag{2}$$

where: Pi – annual rainfall in mm;
Pm – average rainfall in mm.

Positive RDI indicates surplus or wet years, while a negative RDI suggests a deficit or dry year.

Drought index

DI evaluates annual rainfall deficit by comparing precipitation in a given year (Pi) to the series' average (P). The DI is calculated using the formula (3).

$$\mathrm{DI} = \mathrm{Pi} - \mathrm{P} \tag{3}$$

Thus, positive values indicate above–average precipitation and negative values indicate dry years.

RESULTS AND DISCUSSION

Trends of annual and monthly rainfall in the Ghis-Nekor watershed

Linear regression, a suitable method for studying progressive phenomena like climate change impacts, was employed to analyze the trends in annual precipitation across the Ghis-Nekor watershed (Figure 2). The annual rainfall data from three meteorological stations in the Ghis-Nekor watershed, reflecting the Mediterranean semi–arid climate, exhibit substantial temporal variability.

The analysis revealed a general increasing trend from 1978 to 2016. The Tamallaht station experienced a rise from 250 mm to 410 mm, Tamassint from 245 mm to 445 mm, and Tighza from 248 mm to 390 mm. However, an alarming decline in overall precipitation averages is evident post–2008, sharply decreasing from 619.9 mm to 173 mm at Tamallaht, 624.8 mm to 72.2 mm at Tamassint, and 736.5 mm to 178 mm at Tighza. Global trends in annual precipitation indicate a rise, as seen in the Marmara region (Aalijahan et al., 2023) and the Manjalar sub–basin of the Vaigai river (Janapriya and Bosu, 2014).

However, Mahmood and Jia (2017) observed decreasing trends in both precipitation and streamflow in the Jhelum River basin, emphasizing that while overall precipitation trends may be increasing, specific regions can experience significant declines.

Overall, linear regression revealed a general increasing trend in annual precipitation from 1978 to 2016 across all stations. However, a critical decline is observed from 2008 onwards, emphasizing the noteworthy decrease in rainfall during this period. On other hand, meticulous analysis of the climatic data from the Tamallaht, Tamassint, and Tighza stations from 1978 to 2016 reveals significant monthly variations (Figure 3).

February is known for its unusually high rainfall, while both November and December consistently have the lowest precipitation levels. In November, Tamallaht typically receives 3.9 mm of rain, Tamassint receives 1.5 mm, and Tighza receives 6.3 mm. December sees even less precipitation. On the other hand, March consistently

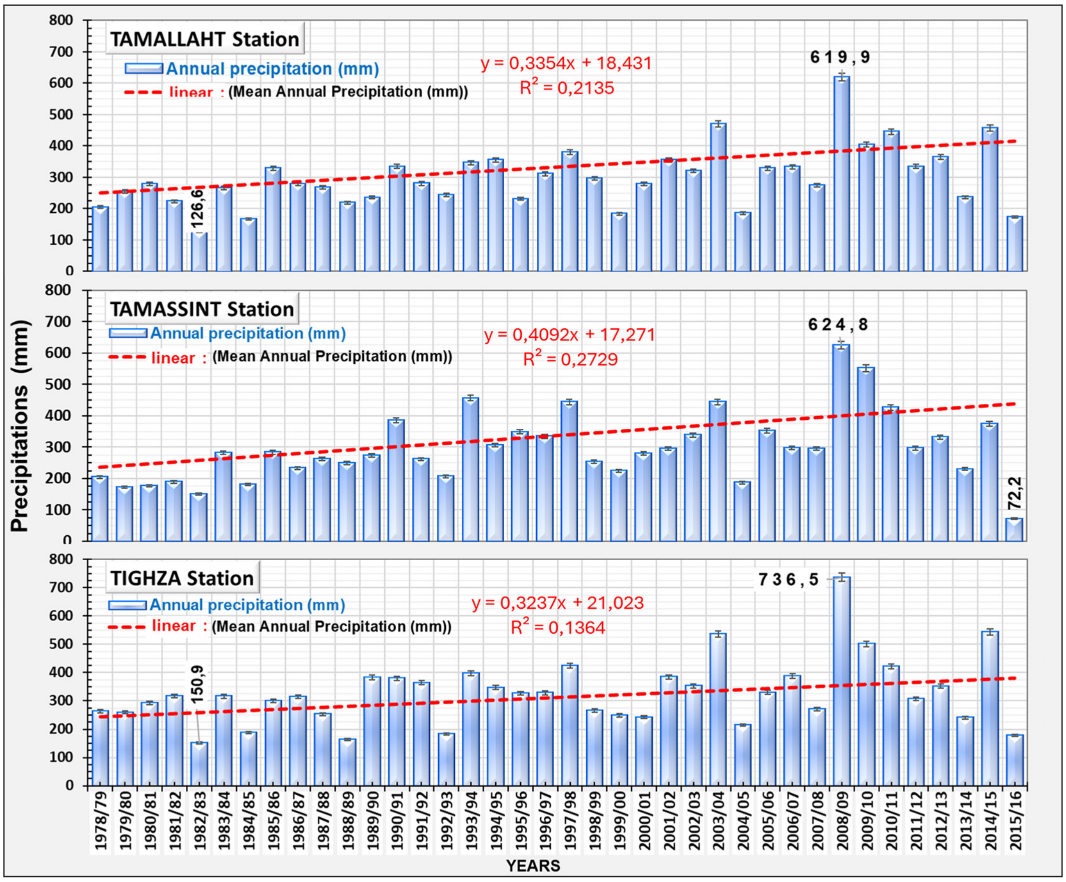

Figure 2. Evolution of annual rainfall at three stations in the Ghis-Nekor watershed (1978–2016)

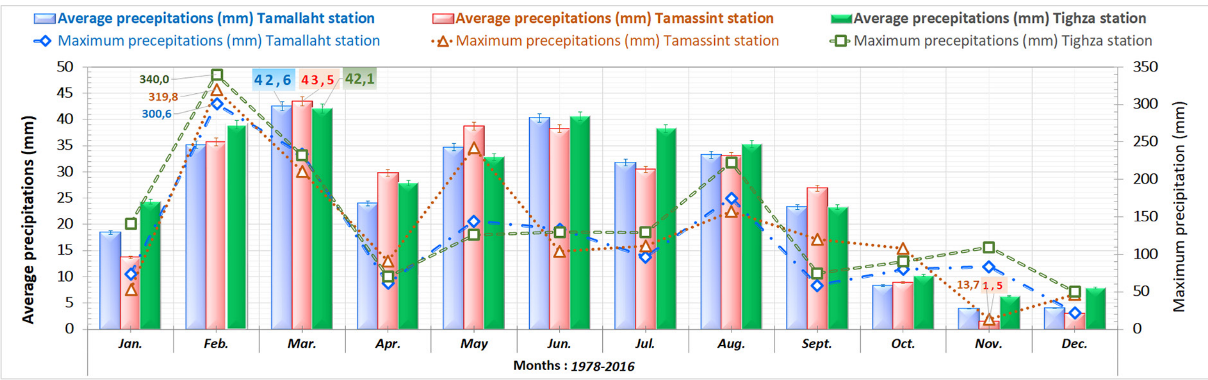

Figure 3. Average and maximum monthly precipitation observed at the three stations of the Ghis–Nekor watershed (1978–2016)

experiences significant rainfall, with all stations receiving more than 42 mm. It is important to recognize and understand these changes in precipitation over time in order to assess the effects of climate change on the hydrological system of the region. Figure 3 specifically highlights these inconsistencies, emphasizing the need for precise and comprehensive climate monitoring. While overall long–term trends show an increase in rainfall, the decrease in precipitation since 2008 highlights the vulnerabilities of the region.

The monthly patterns observed also suggest the potential impact on hydrological systems, highlighting the necessity for customized water resource management.

Drought dynamics in Ghis-Nekor: an SPI perspective

SPI, crucial for assessing drought intensity based on precipitation relative to the median (McKee et al., 1993), plays a pivotal role in water resource management and climate change adaptation. Analyzing the Standardized Precipitation Index (SPI) at three key meteorological stations (Tamallaht, Tamassint, and Tighza) provides nuanced insights into the evolution of droughts in the Ghis-Nekor watershed (Figure 4).

For the Tamallaht station, the SPI data reveals significant drought frequency trends, notably during 1978/1979–1989/1990. Intense rainfall occurs from 2009/2010 to 2012/2013. However, conditions worsen post–2015/2016, marking a new drought cycle. SPI–based severity categorization showcases substantial moderately dry (36%), moderately severe (12%), and extremely severe (2%) drought episodes. At the Tamassint station, SPI exhibits drought sequences insights, notably during 1978/1979–1989/1990 and slightly dry periods from 2007/2008–2013/2013. During the 2008/2009 season, there was a high level of precipitation (SPI +2.9), while the 2015/2016 season experienced a notably low SPI (-2).

A thorough examination of the weather patterns revealed a significant prevalence of somewhat dry (37%), moderately dry (11%), and severely dry (2%) phases. The Tighza station data analysis showed a substantial predominance of drought from 1978/1979–1988/1989, making it the driest recorded period. Additionally, moderate dry spells were also observed in 1995/1996, 1996/1997, and 2004/2005. Overall, there were frequent occurrences of slightly dry (41%) and moderately dry (11%) periods.

Different regions have mirrored the same SPI patterns, as shown by Mehdaoui et al. (2018) in the Ghis–Nekor watershed and Zerouali et al. (2021) in the Oued Sebaou basin in Algeria, where they have highlighted varying degrees of drought intensity. Additionally, Mehdaoui and Mili (2018) in the Guir watershed and Hirko et al. (2021) in East Hararge Province, Ethiopia, have also uncovered distinct periods of drought. The results emphasize the immediate need to tackle drought in these regions. The SPI classification data reinforces this sense of urgency, showing a concerning pattern of extended periods of dryness (53%) and severe drought events (3%). In contrast, moderate drought (13%) and wet conditions with SPI above 2 (3%) have only occurred for short periods of time, as displayed in Table 4.

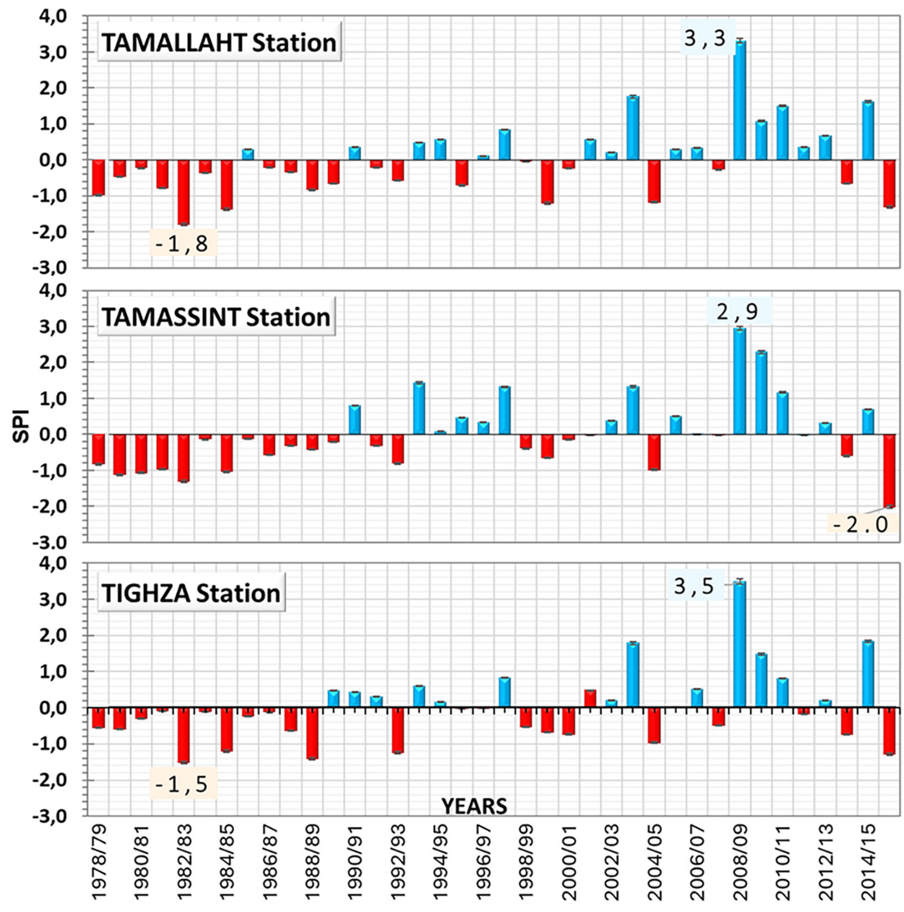

Figure 4. The trend of SPI at the three stations of the Ghis-Nekor watershed (1978–2016)

Table 4. Frequencies of SPI classes at meteorological stations at the three stations of the Ghis-Nekor watershed (1978–2016)

SPI values	Category	Stations								
		Tamallaht	Tamassint	Tighza	Tamallaht	Tamassint	Tighza	Tamallaht	Tamassint	Tighza
		Number of years			Number of times (in 100 years)			Frequency (years)		
> 2.0	Extreme humidity	1	1	1	3	3	3	1/38	1/38	1/38
1.5 to 1.99	Severe humidity	3	3	3	8	8	8	1/13	1/13	1/13
1.0 to 1.49	Moderate humidity	1	*NO*	*NO*	3	*NO*	*NO*	1/38	*NO*	*NO*
0 to 0.99	Light humidity	13	14	14	34	37	37	1/3	1/3	1/3
0 to -0.99	Light dryness	14	14	14	37	37	37	1/3	1/3	1/3
-1.0 to - 1.49	Moderate dryness	5	5	5	13	13	13	1/8	1/8	1/8
-1.5 to - 1.99	Severe drought	1	1	1	3	3	3	1/38	1/38	1/38
< -2	Extreme dryness	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*
NO : no occurrence										

This illustrates the significant variability in drought severity, stressing the importance of implementing flexible strategies for efficient water resource management. Overall, the Ghis–Nekor watershed experiences predominantly mild drought and mild wetness at every station, with frequencies exceeding 37%. Moderate drought, which occurred 15% of the time, follows behind. Notably, severe drought was only observed for one year at each station over the evaluated timeframe, making up just 8% of the occurrences.

Rainfall deficit index

The RDI results of the Ghis-Nekor watershed at the Tamallaht, Tamassint, and Tighza stations provide crucial perspectives on the drought evolution of the region (Figure 5), using RDI to assess deficient precipitation against the average (Pm).

At the Tamallaht station, notable drought sequences occurred between 1978/1979 and 1984/1985, with surplus periods from 2003/2004 to 2014/2015. From 2015/2016, precipitation deficits marked a new drought episode. RDI–based drought severity classification indicates 21% moderately deficit and 11% severely deficit sequences. Similarly, the Tamassint station displayed continuous deficit dominance between 1978/1979 and 1989/1990, with slight deficits from 2000/2001 to 2007/2008. Intense surplus in 2008/2009 and severe deficit in 2015/2016 were noted. The drought severity classification shows 40% slightly deficit and 11% moderately deficit sequences. In turn, at the Tighza station, predominant deficit years were noted between 1978/1979 and 1988/1989, with slight deficits in 1995/1996, 2007/2008, and 2011/2012. The drought severity classification reveals 28% slightly deficit and 11% moderately deficit sequences.

Overall, analyses underscore significant variability in drought conditions in the Ghis-Nekor watershed, alternating between moderate to severe drought and relative wetness periods. Several researchers around the globe have effectively utilized the rainfall deficit index to gain a deeper understanding of drought dynamics. For example, Topçu and Seçkin (2021) conducted a study in Turkey and identified a mild drought, while Guhan et al. (2020) in Tamil Nadu detected severe and mild drought events. Similarly, Asadi and Vahdat (2013) highlighted the efficacy of RDI in monitoring drought in Iran. This index has also been utilized to assess the impact of climate change in various regions with similar climates, such as the Mediterranean and semi-arid areas. Ouatiki et al. (2019) studied the Oum Er-Rbia River Basin, Sadiq (2022) analyzed Nigeria’s Yola South LGA.

Drought index

The drought index provides a nuanced understanding of annual rainfall deficits in the Ghis–Nekor watershed (Figure 6). At the Tamallaht station, severe drought periods occurred between

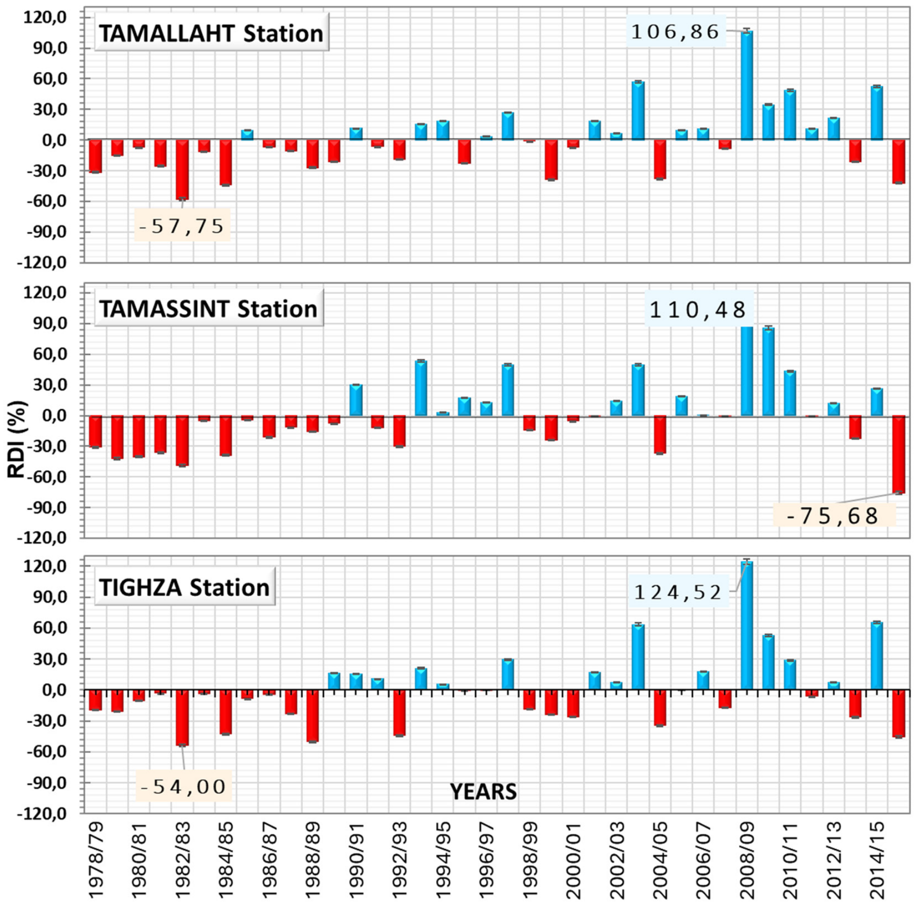

Figure 5. Evolution of the Rainfall Deficit Index (RDI) at the three stations of the Ghis-Nekor watershed (1978–2016)

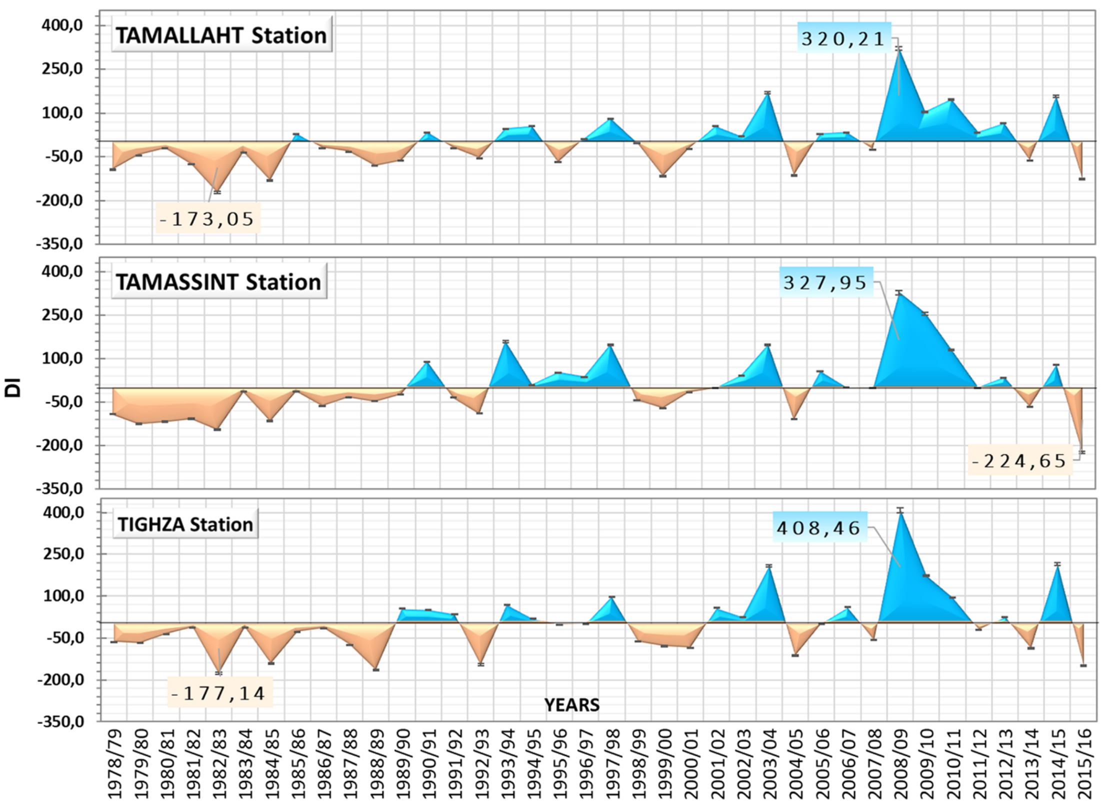

Figure 6. Evolution of the Drought Index at the three stations of the Ghis-Nekor watershed (1978–2016)

1982/1983 and 1983/1984 and again between 1999/2000 and 2000/2001, marked by extremely low DI values. Conversely, relative humidity prevailed between 2001/2002 and 2003/2004, and then from 2007 to 2012. Similarly, at Tamassint, severe drought spanned 1978/1979 to 1988/1989 and 1999–2001, with very low DI values. Contrarily, relative humidity phases occurred between 1993/1994 and 1997/1998, 2001/2002 and 2003/2004, and 2007–2012. The Tighza station exhibited severe drought between 1978/1979 and 1988/1989, in 1992/1993, and 1998/1999 to 2000/2001, signified by very low DI values. Conversely, relative humidity phases appeared during 2002–2004, 2007–2011, and finally in 2014/2015.

These extreme drought conditions persisted at the Tighza station 1978–1989, 1992/1993, 1997/1998 and 2000/2001, with significantly low DI values. Prolonged severe drought occurred between 1993/1994, 2001/2002, 2006/2007 and 2011/2012. However, periods of relative humidity were recorded between 1992/1993 and 1998/1999, 2002–2004, and 2007 and 2014/2015, indicating atmospheric moisture shifts. The DI analysis aligns, showing decreased drought severity during these years. Over 50% of studied years witnessed predominantly dry periods at Tamallaht, Tamassint, and Tighza, with minimum DIs of -173.05, -224.65, and -177.14 respectively.

The studies conducted by Larabi et al. (2019; 2020) in Morocco shed light on the profound effects of climate change on the Ghis and Oum Er–Rbia river basins. Their findings suggest that rising temperatures, decreased rainfall, and the possibility of seawater intrusion are imminent. Likewise, Hachem et al. (2023) delve into the impact of drought on the Upper Moulouya watershed, echoing patterns of dry spells and diminishing precipitation. Similarly, Echakraoui et al. (2018) bring to the fore the concerning decrease in spring rainfall in Oum Er–Rbia, raising important questions about the sustainability of agriculture and water resources. The conducted research on the Ghis–Nekor Watershed, utilizing SPI, RDI, and DI indices (1978–2016), further solidifies the evidence of recurring drought, aligning with the projections of both Larabi et al. (2019) and El Asri et al. (2019). This collective evidence underscores the need for urgent water resource management strategies, urging policymakers to prioritize adaptive actions amid climate change.

CONCLUSIONS

Through an in-depth analysis spanning 38 years, this study has illuminated a nuanced and multifaceted understanding of hydroclimatic dynamics and precipitation trends in Morocco's Ghis-Nekor watershed. A significant discovery is the evident decline in annual rainfall since 2008, pointing to an increased susceptibility to drought. The use of advanced indices including SPI, RDI, and DI has allowed for a thorough examination of the changing precipitation patterns of the region. The focus of the research extends beyond annual trends, delving into monthly variations and emphasizing the irregular distribution of rainfall.

This nuanced understanding highlights the urgency of implementing adaptive water management strategies that are specifically tailored to address the challenges posed by changing climatic conditions. The need for region-specific measures to build resilience becomes increasingly clear in light of these findings.

This groundbreaking study serves as a crucial contribution to the ongoing scientific discourse on hydroclimatic dynamics. With its insightful insights, it offers policymakers valuable perspectives that are vital for decision-making. By identifying the strategic priorities for the sustainable management of water resources, this study provides invaluable guidance in the face of increasing uncertainty surrounding climate change. Moreover, through its confirmation of the cyclic nature of droughts, it highlights the urgent necessity for targeted and proactive interventions. As such, it is a vital resource for policymakers navigating the complex intersection of climate change and water resource management.

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