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Characterization of the temporal variability of climate and climatic drought in the Doukkala irrigated perimeter (Morocco)

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Summary

Morocco's climate is highly variable in space and time, influenced by its geographical location from north to south and from west to east. In recent decades, this variability has been accentuated by global climate change. In the Doukkala region, which is the subject of this study, this trend towards climatic variation has not been spared. For this reason, climate monitoring has become essential to anticipate and take appropriate measures in the face of the devastating impact on natural resources and the sustainability of agriculture. In our study, we used numerical and geometric methods to characterize climate and its temporal variability, and the Standardized Precipitation Index (SPI) to characterize drought. All the methods used converge on a finding of aridification of the climate in the study area. Use of the Standardized Rainfall Index revealed alternating wet and dry periods, with a higher proportion of dry years (37.9%). The most significant dry periods occurred between 1980 and 1987, as well as between 2016 and 2022. These prolonged periods of drought have led to severe water stress in the study region, highlighting the challenges posed by climate variations on the sustainability of agriculture and natural resources.

Keywords: Climate change, Standardized Precipitation Index (SPI), climatic indices, drought, Doukkala irrigated perimeter.

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Introduction

Morocco stands out as a country firmly rooted in agriculture, a sector that plays a key role in its economic and social progress. Nevertheless, Moroccan agriculture remains closely dependent on weather conditions and the supply of water from dams or underground, which links it closely to the climatic changes underway worldwide. Indeed, climate change currently represents a major challenge for Morocco, given its many harmful and sometimes even irreversible repercussions.

Morocco's climate is Mediterranean, with long, hot, dry summers and short, cold winters, especially at higher altitudes. It is regulated by the Azores anticyclone and the Saharan depression. The risk of drought is a key factor in the sustainability of agriculture in this country. This risk is linked to the high variability of the climate, due essentially to natural and geophysical causes, and to climate change attributed to human activities altering the composition of the atmosphere. As a result, the notion of climate risk needs to be integrated into any water resource management strategy to avoid long-term scarcity (**Balaghi R. et al., 2007**).

A study analyzing recent climate trends and changes in weather patterns has been carried out in Morocco, Mauritania, Senegal and the neighboring ocean. It was based on statistical data on annual temperatures, atmospheric pressure at sea level, precipitation and wind dynamics. The results revealed a climatic shift during the 1970s and 1980s. In some areas, notably over the Atlantic Ocean between 40°N and 14°N, in Morocco and Senegal (northern region), temperatures rose, while south-eastern Mauritania cooled. Atmospheric pressure strengthened, leading to a change in wind direction with an increase in the eastern component of the harmattan (**Amraoui L.et al, 2011**).

On the other hand, the indicators of climate change were reported in 2013 by the GIEC in its report N°5 and can be summarized on a global scale as an increase in the earth's temperature of 0.8 ± 0.2°C since 1870, an increase in ocean temperature and thermal energy content since 1980, a reduction in the surface area of ocean ice and a rise in the average level of the oceans of 0.7 mm/year between 1870 and 1930 and around 1.7 mm/year after 1930 (**GIEC, 2013**).

In Morocco, between 1980 and 2015 there was an increase in semi-arid climates and a decrease in sub-humid climates in Morocco, depending on their respective geographical distribution. This evolution is the result of a change in the distribution of precipitation in the country, leading to a trend towards drier conditions. Climate change is likely to have consequences in all regions of Morocco, although their impact will vary according to climatic zone. Changes in rainfall distribution have led to a significant decrease in precipitation, directly affecting agriculture and reducing the water resources available to a steadily growing population. (**El Ajhar et al., 2018**).

The country's climate is characterized by two extreme and frequent events: the subtropical influence, which generates drought, and the North Atlantic influence, which leads to flooding (Sebbar, 2013). Rainfall irregularity increases from north to south, decreases in altitude and increases towards the east and away from the ocean or sea (**Sebbar A. et al., 2019**).

Human activities have already caused global warming of around 1 ± 0.2°C compared with pre-industrial levels. Currently, average temperature is rising at a rate of around 0.2 ± 0.1°C per decade due to past and present gas emissions. At this rate, warming is likely to exceed 1.5°C between 2030 and 2052. The consequences of a 2°C warming would be more damaging to human and natural systems than those of a 1.5°C warming. According to climate models, there are significant differences between current climate conditions and those resulting from 1.5°C warming, as well as between 1.5°C and 2°C warming. These variations translate into higher average temperatures in most countries and ocean regions, periods of extreme heat in populated areas, intense precipitation in many regions, and an increased risk of drought and lack of precipitation in some areas (**GIEC, 2023**).

Over the last few decades, the Doukkala irrigated perimeter, our study area, has been experiencing an increasingly accentuated water deficit, with adverse repercussions on the sustainability of agricultural production. Indeed, over the last four decades, the perimeter has experienced major climatic disturbances and a shortage of irrigation water that worsens from one year to the next. This situation is exacerbated by climate change phenomena (irregular and low rainfall, violent downpours, disturbances to the temperature regime, frequent droughts, floods).

In view of this climatic risk, it is imperative to pay close attention to monitoring the region's climate using all the methods and technologies available, with a view to preserving its natural resources and maintaining economic activity that makes the most of the major investments made. The objectives of our study are: **i**) to study climate variability and analyze its overall trend in the Doukkala irrigated perimeter, using numerical and geographical methods; **ii**) to characterize climatic drought in the study area.

1. Materials and methods

1.1. Study area

The Doukkala irrigated perimeter, which is the subject of this study, is located in western Morocco, approximately 150 km from the city of Casablanca (figure 1). It lies between 32°32'N and 33°47'N latitude and between 8°14'W and 8°32'W longitude, at around 120-130 m below sea level (**Ferré and Ruhard, 1975**).

The Doukkala irrigated area is part of the central Doukkala plain. It comprises four major irrigated sectors: Faregh, Sidi Bennour, Zemamra and Gharbia. The Doukkala plain, to which our study area belongs, is a vast depression of fertile soils formed from silt and suitable for an intensive cropping system. According to French classification, the region contains a mosaic of soil types. Indeed, the main soil types encountered are: (i) poorly evolved soils (18.9%); (ii) Vertisols (29.8%); (iii) calcimagnesic soils (6.4%); (iv) isohumic soils (32%); (v) iron sesquioxide soils (7.5%) and (vi) hydromorphic soils (5.5%) (**CPCS, 1967**; **ORMVAD, 2020**).

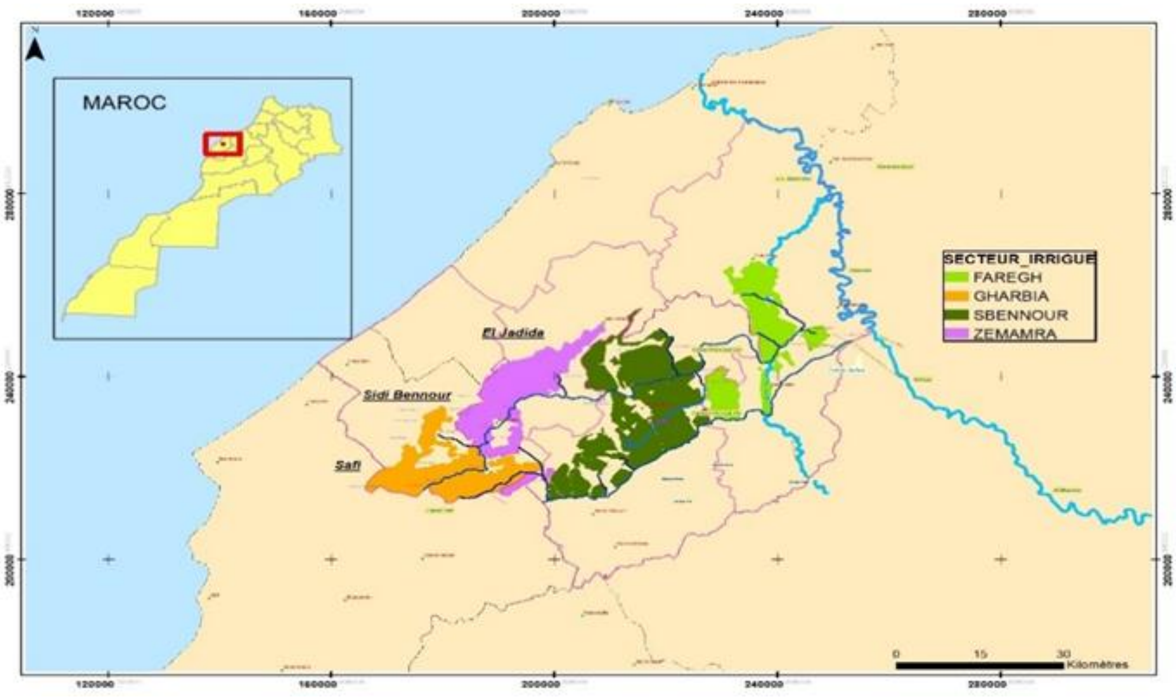

Figure 1: Study area

The climate in this area is semi-arid Mediterranean, characterized by mild, temperate winters and generally hot, dry summers. This climate is characterized by inter- and intra-annual rainfall irregularities.

This perimeter is characterized by the existence of basins irrigated by large-scale hydraulics, zones irrigated by groundwater pumping and rain-fed zones. It has a total irrigated area of around 100000 hectares, suitable for an intensive cropping system. In fact, this perimeter has benefited from considerable investment as part of the Oum Er-Rbia Basin Master Plan, which provides for the eventual irrigation of 125,000 Ha. Irrigation is provided by mobilizing surface water from the Oued Oum-Er-Rbia, regulated by the Al Massira dam and diverted by the Im'Fout dam (**ORMVAD, 2000**).

1.2 Data used

For the purposes of this study, we used climatic data from the network of weather stations available in the area covered by the Doukkala Regional Agricultural Development Office (ORMVAD). In this zone, there are 2 complete weather stations, one at the Zemamra experimental agricultural development station (SEMVA) and the other at the Khémis Métouh experimental station. These two stations are complemented by 19 pluviometric stations at the level of the Irrigation Network Management Centers (CGR) throughout the Doukkala irrigated perimeter.

1.3 Methodology adopted

The characterization of the temporal variability of the climate and the study of the evolution of weather conditions in the study area were approached through the use of two main methods widely used to describe the climate of a region or country, namely: Numerical and graphical methods. To characterize climatic dryness, we used the Standardized Rainfall Index (SPI). This index is used to determine whether a given year is dry or wet.

1.3.1. Methods used to characterize the climate and its temporal evolution

To characterize the climate of the study area and its temporal evolution, we used both numerical and graphical methods.

a) Numerical methods

Numerical methods use climatic indices to characterize the climate of a given area in general, or to identify and study a natural climatic phenomenon such as drought. The indices used are:

- **De Martonne climate index (I)**:

This is a measure of the aridity of a place, taking into account the amount of precipitation and temperature. It is mainly used to characterize the climates of semi-arid and arid regions, where water availability is a crucial issue for agriculture and human activities in general. This index was defined by De Martonne in 1926 according to the following formula:

$$I = P / (10 + t)$$, where:

- t = mean annual temperature in °C;
- P= total annual rainfall (in mm).

The classification used by De Martonne to identify the different types of climates is as follows:

Tableau 1: De Martonne climate classification (I)

I value	Climate type
I < 5	Hyper arid or desert climate
5 < I < 10	Arid or steppe climate
10 < I < 20	Semi-arid climate
I > 20	Subhumid to humid climate

- **The Amann Index (AI): Continentality or oceanicity**

The Amann index is an indicator for assessing the continental or oceanic nature of a climate. It was developed by the German climatologist Wladimir Köppen, and is also sometimes referred to as Köppen's continentality index. It is calculated using monthly temperature averages for the warmest and coldest months of the year. It is based on the temperature difference between these two months.

$$I = P / Tmax - Tmin$$, where:

- P = Total annual rainfall (in mm);
- Tmax = Average temperature of the hottest month "July" in °C;
- Tmin = Average temperature of the coldest month "January" in °C.

The Amann index is used to assess the overall characteristics of a climate, distinguishing continental from oceanic climates. A high index indicates a continental climate with marked temperature variations between hot and cold seasons, featuring hot summers and cold winters. Conversely, a low index indicates an oceanic climate with less pronounced temperature variations between hot and cold seasons, leading to more moderate summers and milder winters.

However, it is essential to understand that the Amann index does not take into account other important climatic factors such as precipitation, wind or altitude. For a complete climatic analysis, it is necessary to consider other indices and parameters.

- **The P. Moral index (1954)**:

The P. Moral index is defined as follows:

$$IM = P / (T2 - 10T + 200)$$, where:

- P= total annual rainfall (in mm);
- T= mean annual temperature in °C.

If IM<1, the climate is said to be dry; if IM>1, it is said to be humid.

- **The Emberger rainfall index:**

The Emberger rainfall index, developed by French climatologist Albert Emberger (1942), is a meteorological tool for assessing the amount and distribution of precipitation in a given region over a given period. It can be used to determine whether a region is more or less arid by comparing actual precipitation with normal for the same period. It classifies regions according to their annual rainfall, ranging from very dry to very wet, and is useful for assessing aspects such as agricultural potential and the impact on water resources in a given region. The index is calculated according to the following formula:

$$Q_2 = \frac{P}{[(M+m)/2] * (M-m)} * 1000$$

Where:

- M = the average maximum temperature of the hottest month in °C. The warmest month's has highest temperature is July;
- m = the average minimum temperature of the coldest month in °C. The coldest month has the lowest temperature in January;
- P = average annual total precipitation in mm.

The Emberger index is inversely proportional to aridity: a higher Q_2 indicate a more humid climate.

b) Graphical methods

The most widely used graphical methods for characterizing climates are the umbrothermal diagram by Gaussen, Walter and Lieth and the Emberger climagram.

- **umbrothermal diagram by Gaussen, Walter and Lieth:**

This is a visual tool for monitoring and comparing the relationship between precipitation and temperature on a monthly basis. The graph consists of a horizontal line representing the 12 months of the year on the x-axis, and two parallel vertical lines on the y-axis. The first line represents total monthly precipitation in millimeters, while the second line shows average monthly temperatures in degrees Celsius. It's important to note that the precipitation scale is twice as large as the temperature scale (Figure 2).

When the temperature curve exceeds the rainfall curve, this indicates a dry period. Months are dry when the rainfall curve is below the temperature curve, and conversely months are wet when the rainfall curve is above the temperature curve. Thermal amplitude is defined as the difference between maximum and minimum temperature. The xerothermic index is defined as all dry months.

- **Emberger climagram**:

Emberger used a system of axes to classify climates according to temperature in °C and rainfall in the Mediterranean region. Drought is represented on the (Y) axis by the rainfall quotient Q_2, and the temperature "m" in °C of the coldest month is used in (X) axis (figure 3).

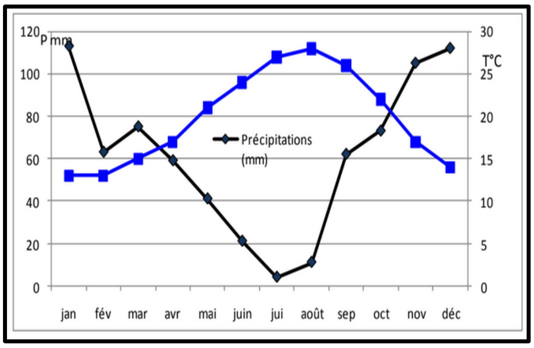

Figure 2: Example of an umbrothermal diagram of Gaussen

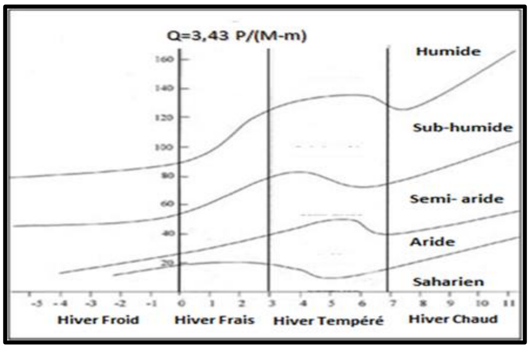

Figure 3: Emberger Climagram

1.3.2. Method used to characterize climatic drought

- **Standardized Precipitation Index (SPI):**

The Standardized Precipitation Index was developed by **McKee T. B., et al. B., et al, in 1993**. These researchers introduced the SPI as a new tool for assessing drought conditions. Since then, the SPI has been widely used in the fields of climatology, water resources management and agriculture to assess precipitation variations at different temporal and spatial scales.

The Standardized Precipitation Index is defined as follows:

$$I_S = \sum_{j=1}^{n_i} [(P^i_j - P_j) / \rho_j]$$

Where:

- P_{ij}: rainfall in year i at station j;
- P_j : interannual mean rainfall at station j;
- ρ_j: the standard deviation of the cumulative series at station j.

This index is a statistical measure that evaluates rainfall anomalies in relation to a normal year over a given period. It can be used to detect periods of drought or excessive humidity by comparing observed precipitation with a historical average in the form of standard deviations.

The SPI is used to monitor drought conditions, the risk of water shortages and the impact of climate change on precipitation patterns. It complements other climate indicators to assess the effects on ecosystems and human activities. SPI calculations are based on reliable precipitation data and can be carried out over different periods, ranging from a few months to several years.

Table 2: Drought classification

SPI class	Degree of dryness
SPI > 2	Extreme humidity
1 < SPI < 2	High humidity
0 < SPI < 1	Moderate humidity
-1 < SPI < 0	Moderate drought
-2 < SPI < -1	Severe drought
SPI< -2	Extreme drought

2. Results and discussion

2.1. General climate characterization of the Doukkala irrigated perimeter

2.1.1. Overall meteorological parameters of the study area's climate

The study area is characterized by a semi-arid climate with the following average annual meteorological parameters (Table 3): average rainfall (308 mm), average temperature (19.4°C), average relative humidity (76%), average wind speed (2.6 m/s) and average annual evapotranspiration (3.8 mm), annual evaporation reaches 1700 mm, sunshine duration is 3000 hours/year and winds are predominantly north-westerly.

Table 3: General characterization of the climate in the Doukkala irrigated perimeter (Period from 1966 to 2022)

Parameters		Min.	Mean	Median	Max.	Standard deviation	CV (%)
Rainfall (mm)		125	**308**	282	592	116	**38**
Temperature (°C)	Avg	16,96	**19,4**	18,2	22,8	1,3	**7**
	Max	24,2	**27,2**	25,7	35,6	3,1	**11**
	Min	7,4	**11,5**	9,4	13,9	1,5	**13**
Wind speed (km/s)		1,9	**2,6**	2,3	4,4	0,7	**29**
Humidity (%)		72,2	**75,8**	75,5	79,7	2,2	**3**
Evapotranspiration (mm)		**3,5**	**3,8**	**3,8**	**4,4**	**0,2**	**6**

2.1.2. Temporal variability of the main meteorological parameters

a) Temperature trends

It is essential to monitor and understand temperature as a crucial climatic component, as it exerts a considerable influence on crop growth and development.

As shown in figure 4, the mean annual temperature in the Doukkala irrigated perimeter was almost stagnant at below 20°C from the 1966-1967 crop year to the 1999-2000 crop year, with a relatively low coefficient of variation (7%). After the 1999-2000 crop year, this temperature rose slightly, then fell from 2008-2009 to 2019-2020.

As for maximum temperature, during the period 1966 to 2000, there was stagnation around an average of 25.7°C, with little fluctuation (CV = 3%). However, from 1999-2000 onwards, there was a sharp rise from 25.6°C to 34.2°C in 2006-2007, with a peak of 35.6 in 2002-2003. From this last crop year onwards, the maximum temperature showed a downward trend.

Minimum temperatures averaged 11.5°C, with a coefficient of variation of 13%. It fluctuated cyclically from 1966-1967 to 2019-2020. There was a drop from 1966-1967 to 1983-1984, from 12.2°C to 7.8°C, then an increase from 1983-1984 to 1999-2000, from 7.8°C to 12.9°C, followed by a sharp drop from 12.9°C to 7.4°C from 1999-2000 to 2004-2005, and finally a steady increase from 2004-2005 to 2019-2020, from 7.4°C to 13.6°C.

Generally speaking, an examination of Figure 4 shows that temperature in the Doukkala irrigated perimeter was almost stagnant from 1966-1967 to 1999-2000, with slight fluctuations. However, over the last two decades, we have noticed two distinct periods: i) a period from 1999-2000 to 2006-2007, characterized by an increase in mean and maximum temperature, while minimum temperature has decreased; ii) a period from 2007-2008 to 2019-2020, which has seen a drop in mean and maximum temperature, while minimum temperature has increased.

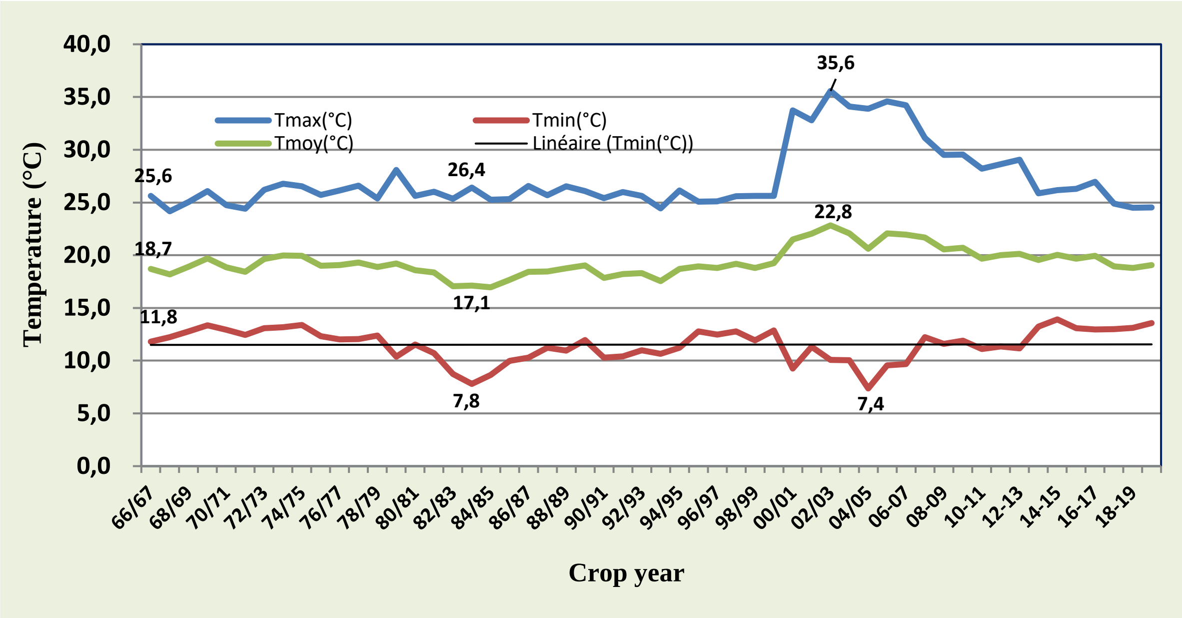

Figure 4: Temperature trend (°C) in the Doukkala irrigated perimeter

b) Rainfall trends over time

Cumulative annual rainfall over the period 1964-2022 is characterized by high interannual and decadal variability. Average rainfall over the 58-year period is 308 mm, with a coefficient of variation of 38%.

The ten-year average fluctuated around the general mean, stagnating from 1982-1983 to 2001-2002. It fell from 373 mm during the period 1964-1972 to 254 mm during the period 2012-2021, a reduction of 32%; and in general, there was a continuous fall, except for the period 2002-2011 when this ten-year average increased to 338 mm (figure 5).

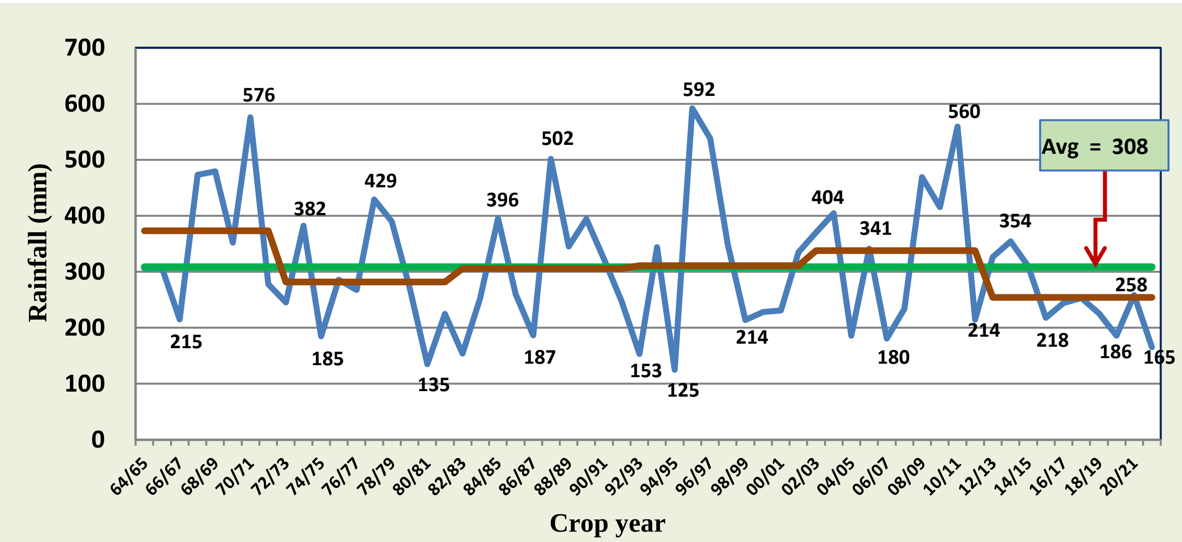

Figure 5: Rainfall trends in the Doukkala irrigated perimeter over a 58-year period (1964 to 2022)

Examination of monthly rainfall trends shows that the rainy period during the crop year is between October and March. Peak rainfall is recorded in December (figure 6).

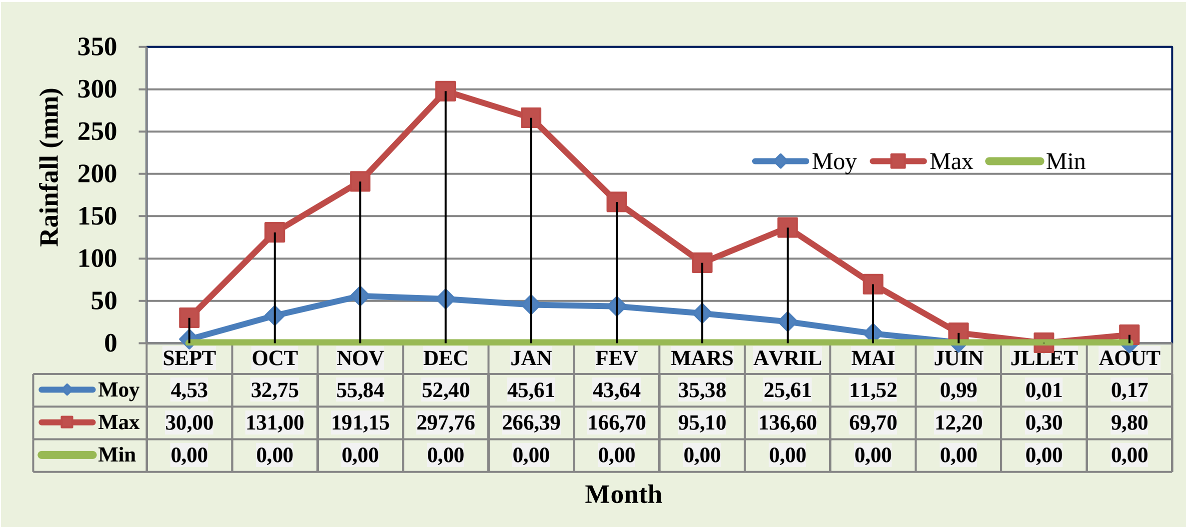

Figure 6: Monthly rainfall trends (mm) in the Doukkala irrigated perimeter 1964-2022 (58 crop years)

Climate indices are measures used to assess and monitor variations in climate over a given period. They can include parameters such as temperature, precipitation and others. The indices used in our study are: **i**) the De Martonne Aridity Index (I); **ii**) the Amann Index (IA); **iii**) the P. Moral Index (IM) and **iv**) the Emberger Rainfall Index (Q_2) (Table 4).

Analysis of these climate indices provides essential information for understanding climate change in the region under study. It can also serve as a basis for more in-depth studies aimed at developing strategies for adapting to changing climatic conditions and mitigating the potential impacts of aridification on local communities and ecosystems.

Table 4: Evaluation of the main climatic indices in the study area

Designation	I	AI	IM	Q2
Average	10,6	23,0	0,8	541,6
Standard deviation	04,1	10,1	0,3	251,2
Min	04,4	08,8	0,3	172,9
Max	20,5	56,0	1,6	1366,6
Median	7,5	16,6	0,6	396,4
CV %	38,3	44,0	39,4	46,4

2.2.1. De Martonne aridity index (I)

De Martonne's aridity index (I) is used to determine the type of climate in a region. High index values indicate wetter regions. If the index is below 5, the region is considered to have a hyperarid or desert climate, between 5 and 10 an arid or steppe climate, between 10 and 20 a semi-arid climate and above 20 a sub-humid to humid climate.

For our study area, this index averages 10.6 over a 54-year period, with a minimum of 4.1 and a maximum of 20.5. It indicates a semi-arid climate for this study area. The coefficient of variation is 38%, indicating a high degree of variability in this index from one crop year to the next.

As shown in figure 7, this index has an overall downward trend, especially over the last decade. It has dropped from 18.9 in 2010-2011 to 6.4 in 2019-2020, underlining an overall trend in the climatic context towards aridity.

2.2.2. Amann Index (AI)

The Amann index calculated for the study area for the period 1966 to 2020 averages 23, with high interannual variability (CV = 44%) (figure8).

This index has no universally defined specific threshold. It is used as a tool to assess the continental or oceanic nature of a climate, based on the temperature difference between the warmest and coldest months of the year. Classification as a continental or oceanic climate depends on the climatic norms of each region and local characteristics. Some classifications consider an average temperature difference between the warmest and coldest months of at least 22°C as a criterion for characterizing a continental climate. Consequently, the climate of our study area can be considered continental.

2.2.3. P. Moral Index (IM)

As shown in figure 9, the P. Moral Index shows a downward trend over the period 1966-2020. It averages 0.8, with high variability (CV=39%) (figure 8). This downward trend implies convergence towards a much drier climate. Indeed, of the 54 crop years in the rainfall time series studied, 39 crop years (72%) have an IM <1 defining a dry climate, while 15 crop years have an IM>1 defining a wet climate.

2.2.4 Emberger rainfall index (Q_2)

The Emberger rainfall index averaged 542 over the period 1966 to 2020, with a minimum of 173 and a maximum of 1,367, with high inter-annual variability (46%). This index is inversely proportional to aridity: the higher Q_2, the wetter the climate. The overall trend of this index in the Doukkala irrigated perimeter is downwards, indicating a trend towards aridity (Figure 10).

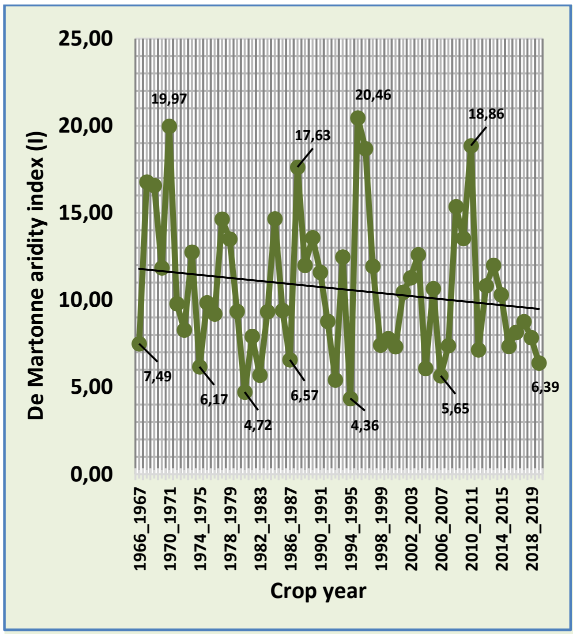

Figure 7: Change in aridity index of De Martonne (I)

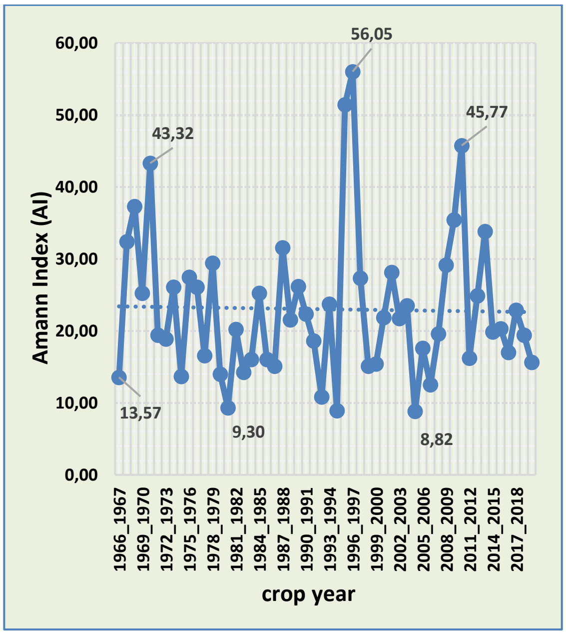

Figure 8: Evolution of the Amann index (IA)

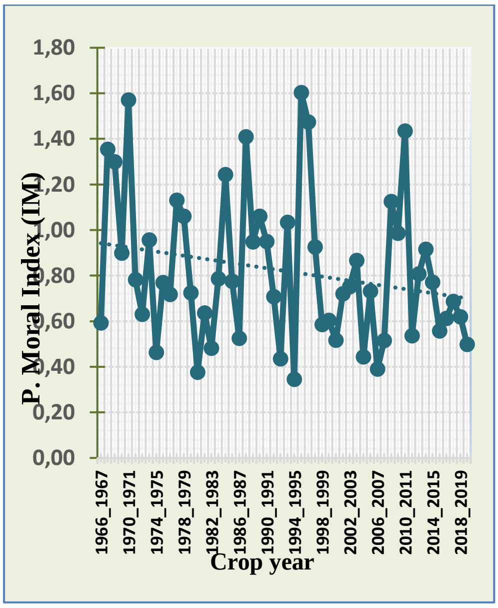

Figure 9: Evolution of the P. Moral Index (IM)

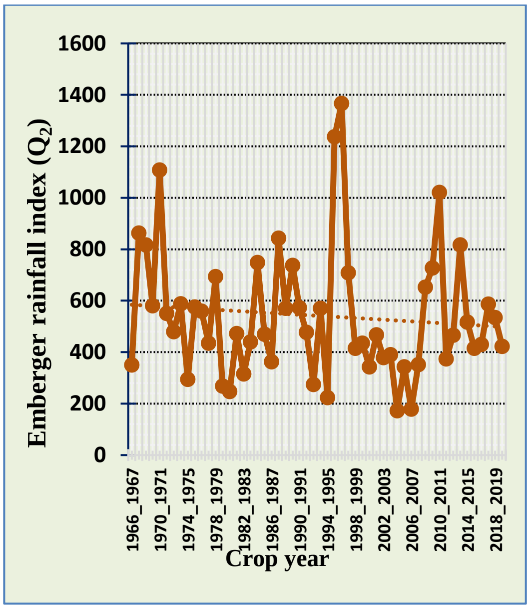

Figure 10: Evolution of Emberger rainfall quotient Q_2

2.3. Climate characterization using graphical methods

2.3.1. Umbrothermal diagram by Gaussen, Walter and Lieth

In our study area, the umbrothermal diagram is drawn up for two main weather stations: Station of Métouh and SEMVA (Zemamra experimental agricultural development station) in Zemamra. According to this diagram, a month is considered dry if its total rainfall is less than twice the average temperature for the month. The two figures below show that for both stations, the months between November and March are considered biologically wet, while the months between April and October are considered biologically dry. A comparison of these results with those found by **Badraoui et al. in 1993** shows that the months of October and April, declared wet at the time, are currently considered dry.

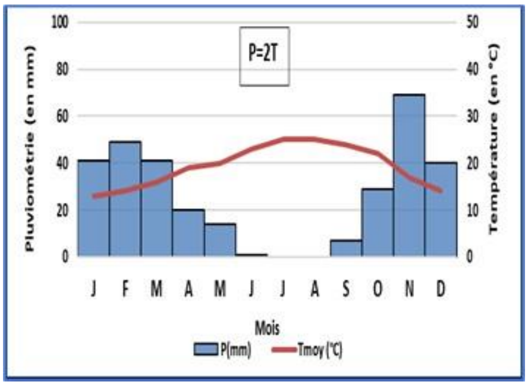

Figure 11: Umbrothermal diagram of SEMVA_Zemamra station

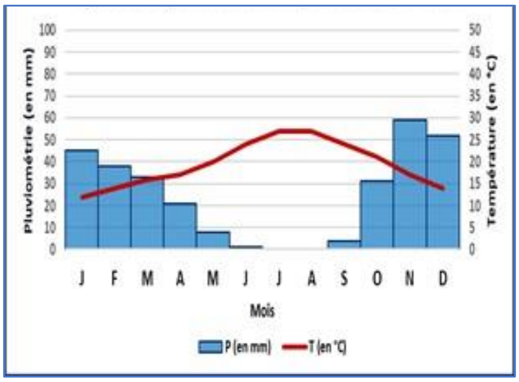

Figure 12: Umbrothermal diagram of Métouh station

As a result, the dry period in our study area, the Doukkala irrigated perimeter, is becoming increasingly longer than the wet period, with a consequent tendency towards aridity.

2.3.2. Emberger climagram

The Emberger index, as defined by Emberger in 1955, integrates annual precipitation (P), the mean maximum temperature of the warmest month (M in °C) and the mean minimum temperature of the coldest month (m in °C). Emberger's climagram classifies the current climate in our study area as arid.

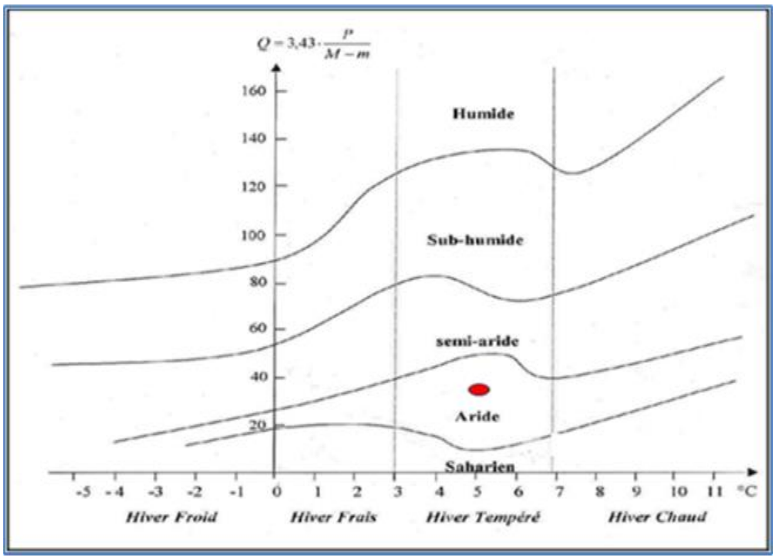

Figure 13: Climate classification according to the Emberger climagram

2.4. Characterization of climatic drought in the Doukkala irrigated perimeter

Climatic drought in the Doukkala irrigated perimeter is characterized using the Standardized Precipitation Index (SPI). This is a statistical measure that evaluates rainfall anomalies in relation to a normal over a given period. It can be used to detect periods of drought or excessive humidity by comparing observed precipitation with a historical average in the form of standard deviations.

This index is used to monitor drought conditions, the risk of water shortages and the impact of climate change on precipitation patterns. It complements other climate indicators to assess the effects on ecosystems and human activities. The calculation of the standardized precipitation index is based on reliable precipitation data and can be carried out over different periods, ranging from a few months to several years.

2.4.1. Average rainfall in the Doukkala irrigation basins

The Doukkala irrigated perimeter is made up of 4 main irrigation basins. Rainfall variability in these basins is shown in Table 5 below:

Table 5: Rainfall variability in the main irrigation basins

Designation	Average rainfall (mm)	Standard deviation	CV %
Doukkala irrigated perimeter	**308**	**118**	**38**
Faregh irrigation basin	289	109	38
Sidi Bennour irrigation basin	294	109	41
Zemamra irrigation basin	312	100	32
Gharbia irrigation basin	321	141	44

2.4.2. Evolution of the standardized precipitation index in the Doukkala irrigated perimeter

The standardized precipitation index has been calculated for the Doukkala irrigated perimeter for the period from the 1966-1967 crop year to the 2021-2022 crop year. The evolution of this index is shown in figure 14. It shows that the number of dry, normal and wet years during this period is 21 (37.5%), 19 (33.9%) and 16 (28.6%) respectively. The overall trend in the evolution of this index indicates a steady decline over this period. This is indicative of a general trend towards drought.

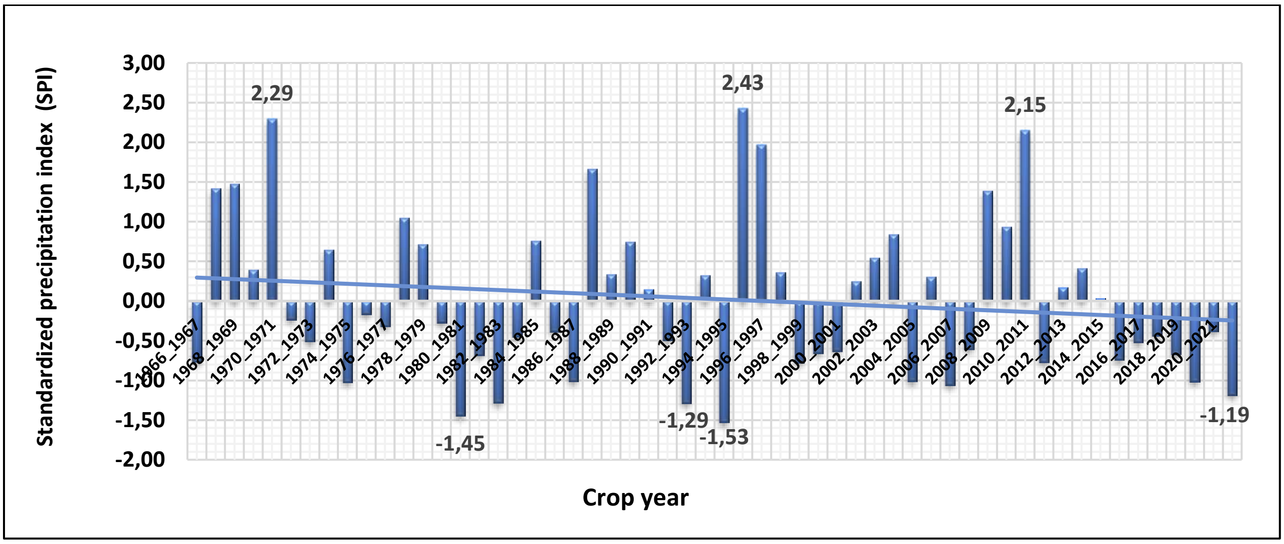

Figure 14: Evolution of the standardized precipitation index in the Doukkala region between 1966-2020.

Figure 15 below also shows that, over the period 1966-2022, there are alternating wet and dry periods in our study area:

- A wet period from 1967 to 1971;
- A dry period from 1974 to 1977;
- Another dry period from 1979 to 1984;
- A wet period from 1987 to 1991;
- An alternation of wet and dry periods of three crop years for each of them from crop year 1995_1996 to crop year 2010_2011;
- From the 2015_2016 crop year onwards, we see the onset of another very marked dry period until the 2021_2022 crop year;
- Moderately to severely wet crop years are: 67-68, 68-69, 77-78, 87-88, 96-97, 08-09, and 09-10;
- Extremely wet crop years are: 70-71, 95-96 and 10-11;
- Moderately and severely dry crop years are: 74-75, 80-81, 82-83, 86-87, 92-93, 94-95, 04-05, 06-07, 19-20 and 21-22.

N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
CA	94_95	80_81	92_93	82_83	21_22	06_07	74_75	19_20	04_05	86_87	98_99	11_12	66_67	15_16	81_82	18_19	99_00	00_01	07_08	16_17	72_73
IPS	-1,53	-1,45	-1,29	-1,28	-1,19	-1,06	-1,02	-1,02	-1,01	-1,01	-0,78	-0,77	-0,77	-0,74	-0,68	-0,67	-0,66	-0,63	-0,61	-0,52	-0,51
Classes	DRY YEAR																				
%	37,5																				
N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
CA	91_92	83_84	17_18	85_86	19_21	76_77	79_80	71_72	75_76	14_15	90_91	12_13	01_02	05_06	93_94	88_89	97_98	69_70	13_14		
IPS	-0,49	-0,45	-0,44	-0,39	-0,38	-0,32	-0,27	-0,23	-0,17	0,03	0,15	0,17	0,25	0,30	0,33	0,33	0,36	0,39	0,41		
Classes	NORMAL YEAR																				
%	33,9																				
N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16					
CA	02_03	73_74	78_79	89_90	84_85	03_04	09_10	77_78	08_09	67_68	68_69	87_88	96_97	10_11	70_71	95_96					
IPS	0,55	0,65	0,72	0,75	0,76	0,84	0,93	1,05	1,39	1,42	1,47	1,66	1,97	2,15	2,29	2,43					
Classes	WET YEAR																				
%	28,6																		CA= Crop year		

Figure 15: Classification of crop years according to SPI.

The most significant drought periods in our study area were between 1980 and 1987 and between 2016 and 2022. These two periods resulted in very severe water stress in the area. These results are in line with those reported by (**Sebbar et al., 2019, Stour et al., 2008 and Serra et al., 2006**).

Indeed, the regions along the Atlantic seaboard experienced intense droughts, which seems to be linked to a decrease in the frequency of disturbances linked to the polar front. Normally, these regions benefit from the disturbances brought by the north-westerly regime, characterized by wet, cold conditions. However, the persistence of the Azores anticyclone in the central Atlantic seems to have contributed to the installation of drought in Morocco (**Sebbar et al., 2019**).

The standardized precipitation index is also evaluated for the different irrigation sectors of the Doukkala irrigated perimeter. The number of normal, wet and dry crop years per irrigation sector is shown in the following table:

Table 6: Number of normal, wet and dry seasons per irrigation sectors

Designation	**Sector of Faregh**		**Sector of Sidi Bennour**		**Sector of Zemamra**		**Sector of Gharbia**	
	Nbre	%	Nbre	%	Nbre	%	Nbre	%
Normal crop year	**13**	**32,8**	12	35,3	11	32,4	09	26,5
Wet crop year	08	23,5	08	23,5	**11**	**32,4**	10	29,4
Dry crop year	13	38,3	14	41,2	12	35,2	**15**	**44,1**

The maximum number of normal, wet and dry crop years is recorded for the Faregh, Zemamra and Gharbia sectors respectively. The overall trend in this index for the four sectors is much more marked for the Zemamra and Gharbia sectors. These two sectors are close to the oceanic influence (Figures 16 to 18).

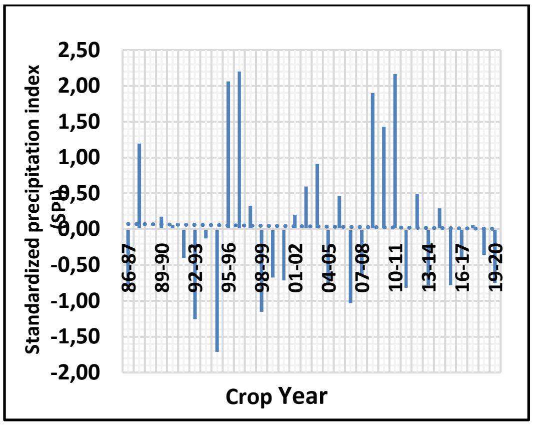

Figure 16: Evolution of the SPI in the Faregh irrigation sector

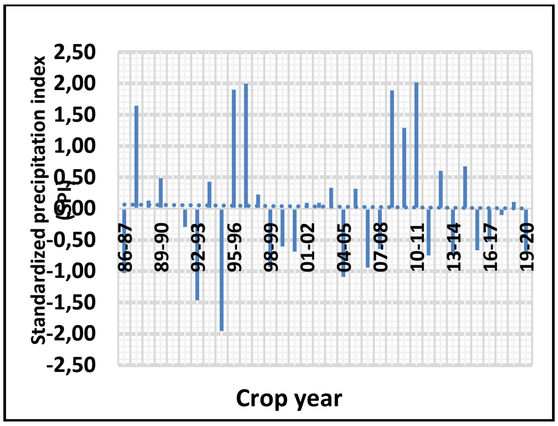

Figure 17: Evolution of the SPI in the Sidi Bennour irrigation sector

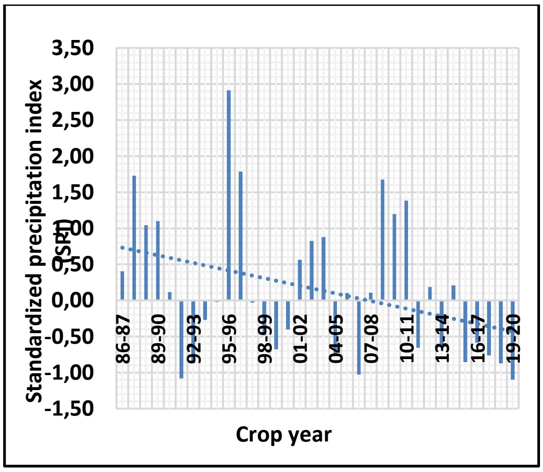

Figure 18: Evolution of the SPI in the Gharbia basin

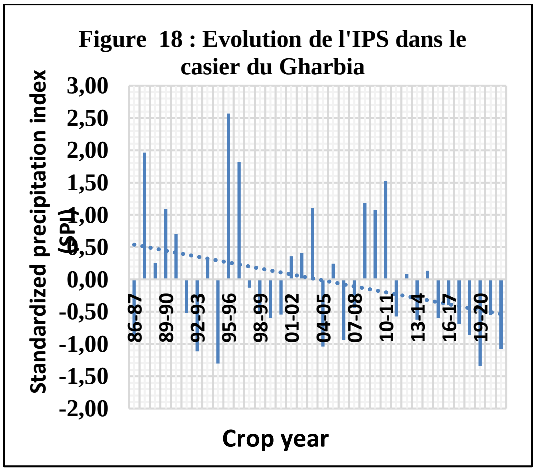

Figure 19: Evolution of the SPI in the Zemamra basin

Morocco's Atlantic coast is influenced by a number of regional and global climatic factors, and the interactions between them. The Azores anticyclone and the ENSO (El Niño-Southern Oscillation) climatic phenomenon, with its two El Niño and La Niña phases, appear from the literature to be the most important factors in creating drought situations in this country.

The Azores anticyclone exerts a significant influence on Morocco's climate, particularly in coastal regions. This anticyclone is characterized by high atmospheric pressure and generally dry, stable weather. Research conducted by Mahé, G. and others, examined the impact of climate change on water resources in West Africa, including Morocco. It highlighted how variations in high pressure systems, notably the Azores High, have the potential to influence rainfall patterns and water resources in the region. The Azores High tends to block atmospheric disturbances and moist air masses from the Atlantic, resulting in drier conditions in northwest Morocco, particularly from Casablanca to Rabat. However, it can also favor rainier conditions in the north of the country, particularly in Tangier, due to the convergence of air masses near this anticyclone (**Mahé, G. et al., 2005**).

The Atlantic seaboard, encompassing several countries in Africa, Europe and North America, presents variable climatic conditions due to its proximity to the ocean. Some parts of this region have experienced prolonged droughts, notably in Morocco, Spain, Portugal and France, due to natural fluctuations such as El Niño and La Niña, as well as climate change. El Niño and La Niña represent two phases of the ENSO climate phenomenon, which occurs in the tropical Pacific Ocean. El Niño is the warm phase of ENSO, characterized by unusually warm surface waters in this ocean region (**Trenberth, K. E.,1997**). Conversely, La Niña represents the cold phase of ENSO, characterized by abnormal cooling of the surface waters of the tropical Pacific Ocean (**McPhaden, M. J.,1999**).

These two phenomena can exert indirect climatic influences on Morocco, due to induced alterations in global atmospheric circulations associated with El Niño and La Niña. For example, a study of climate teleconnections, including those associated with El Niño and La Niña, and their impact on climate patterns in the Northern Hemisphere during the winter season, demonstrated that these phenomena could impact precipitation patterns and temperatures in various regions, notably in North Africa, including Morocco (**Ghaout H. et al., 2003**).

It is also important to note that climate change can influence precipitation patterns and exacerbate drought phenomena in certain regions. However, it should be stressed that not all droughts are exclusively attributable to climate change, as other meteorological and environmental factors are also involved.

Conclusion

The Doukkala region, known for its agricultural potential, plays an extremely important role in the country's economic and social development. However, its agriculture remains highly dependent on climatic conditions and the availability of water from dams, and consequently on the climate change that humanity is currently experiencing. Hence the importance of rigorously monitoring the climate and these changes using all available approaches and technologies.

In this study, we used numerical approaches based on climatic indices and geometric methods to characterize the climate of the Doukkala irrigated perimeter and its temporal variability, as well as the Standardized precipitation index to characterize drought.

Generally, the study area is characterized by a semi-arid climate with an average annual rainfall of 308 mm, with high inter-annual variability (CV=38%). The mean annual temperature is 19.4°C.

The values of the climatic indicators taken into account in this analysis are as follows: De Martonne's Aridity Index (I) is around 11, Amann's Index (IA) is around 23, P. Moral's Index (IM) is around 0.8 and finally, Emberger's Rainfall Index (Q_2) is around 542. These climatic indices provide an assessment of various aspects of the climate of the region studied. When interpreting these data, it is important to note that all these climatic indices indicate an overall trend towards an increasingly arid climate in our study area. This means that climatic conditions in this region are showing signs of drying out over time. This trend towards aridity can have a significant impact on many sectors, such as agriculture, drinking water, biodiversity and other socio-economic and environmental aspects.

This trend towards aridity was also confirmed by geometric methods. The standardized precipitation index revealed that, over the past 56 years, there has been an alternation between wet and dry periods. The number of dry years is the highest (37.9%). The most significant droughts during the study period were between 1980 and 1987, and between 2016 and 2022. Both of these periods were long and caused severe water stress in the study area.

In-depth analysis of the climate of the region under study, and assessment of its variability in time and space, are of crucial importance for natural resource management and the sustainability of vital sectors. In this perspective, we advocate the integration of traditional approaches with geospatial technologies in order to generate complementary and reliable data, which are essential to inform decisions relating to the reasoned management of resources with a view to achieving sustainable development. This combined approach will enable a better understanding of local climate trends and their impacts on natural resources, while providing the information needed to effectively guide management strategies and ensure the sustainability of crucial economic activities.

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