GEOSPATIAL AND TEMPORAL ASSESSMENT OF SOIL SALINIZATION AND DROUGHT USING THE SPI INDEX IN AN IRRIGATED AREA IN A SEMI-ARID ZONE: THE CASE OF BENI-AMIR (CENTRAL MOROCCO)

*G*hizlane El hamri [1*], *H*icham Bouzekraoui [1], and Abderrahim Ettaqy [2]

[1] Laboratory for Research on Landscape Dynamics, Risks, and Heritage, Faculty of Arts and Humanities, Sultan Moulay Slimane University, PO Box 524, 23000, Beni Mellal, Morocco.
[2] Laboratory of Environmental, Ecological, and Agro-Industrial Engineering, Faculty of Science and Technology, Sultan Moulay Slimane University, Beni Mellal, Morocco.

[*]Corresponding author:elhamrighizlane@gmail.com

Abstract. Soil salinization is one of the main factors contributing to the degradation of agricultural land in arid and semi-arid regions. It permanently compromises the productivity and sustainability of irrigated systems in these areas. In the irrigated area of Beni Amir in central Morocco, recurring droughts exacerbate this phenomenon. This study aims to evaluate the spatial and temporal evolution of soil salinity from 2013 to 2023, characterize drought trends using the Standardized Precipitation Index (SPI) from 1990 to 2023, and explore the relationship between climate variability and salinization. The results show a notable increase in electrical conductivity, particularly in the deep profile (20–40 cm). The most vulnerable areas are located in the southern and eastern parts of the perimeter. Analysis of the SPI reveals a succession of moderate to severe droughts over the last three decades, peaking in 2019 and 2022. A statistical comparison of the two variables highlights a negative relationship between the SPI and salinity. This suggests that water deficits directly contribute to salt accumulation. These results confirm the role of droughts in exacerbating salinization and highlight the importance of incorporating climate variability into sustainable irrigation and soil conservation management strategies.

1 Introduction

Soil salinization is now one of the most serious threats to the sustainability of irrigated agriculture, particularly in arid and semi-arid regions. It leads to lower productivity, alters soil structure and fertility, and increases the socioeconomic vulnerability of rural communities. Globally, it is estimated that more than 20% of irrigated land is affected by salinity levels that exceed the thresholds tolerable for crops. This proportion is increasing due to the combined effects of agricultural intensification and climate change [1,2]. There are many mechanisms that cause salinization, including the use of salt-laden irrigation water, insufficient drainage, intense evaporation, and rainfall deficits that limit natural soil leaching [3–5].

In the Mediterranean basin, several studies have shown that salinization is greatly exacerbated by recurrent droughts [6–8]. By reducing effective infiltration and leaching, dry spells promote salt accumulation in the root zone. Recent studies have confirmed this dynamic. For example, the use of multi-date satellite images (1983–2019) in the Tafilalet plain in Morocco revealed a negative relationship between rainfall anomalies and the extent of saline areas [9]. In the Rheris Oasis (southeastern Morocco), [10] showed through the evaluation of several spectral salinity indices that years marked by water stress greatly accentuated salinization. These results illustrate the importance of combining climate variability analysis and salinity monitoring in order to understand degradation dynamics.

Morocco, located at the confluence of Atlantic, Saharan, and Mediterranean influences, is particularly vulnerable to these processes. The increasing scarcity of water resources, combined with the growing demand for irrigation, puts greater pressure on the soil. In the irrigated areas of Tadla, several studies [11–15] have documented a significant increase in soil electrical conductivity, which compromises the sustainability of farms. Recent research confirms this trend : studies[16] have shown that irrigating with saline water not only degrades soil quality, but also significantly reduces durum wheat yields ; [17] Another study reviewed 25 years of salinity mapping in Morocco and highlighted the increase in affected areas. Finally, [18] another study estimates that production losses due to salinity represent a major economic challenge requiring urgent adaptation.

The irrigated area of Béni-Amir, located in the Tadla plain, is a good example of this situation. This agricultural area is characterized by intensive farming, soil heterogeneity, and an almost exclusive dependence on water resources to maintain productivity. Repeated exposure to droughts, particularly in 2019 and 2022, has increased the perimeter's vulnerability and promoted salt accumulation in the soil. Understanding the interactions between drought and salinity is essential for anticipating the future impacts of climate change and designing adaptation strategies.

The Standardized Precipitation Index (SPI), developed by [19], is widely used around the world to characterize the intensity, duration, and frequency of droughts at different time scales [20]. In Morocco, an increase in meteorological droughts and greater rainfall variability has been observed since the 1990s [21,22]. Its use in conjunction with salinity data is a promising approach for quantitatively assessing the role of water deficits in the dynamics of salinization [10,23].

In this context, the present study aims to (i) analyze the spatio-temporal evolution of soil salinity in the irrigated area of Beni Amir between 2013 and 2023 at two depths (0–20 cm and 20–40 cm), (ii) characterize drought trends in the region using the SPI index calculated over the period 1990–2023, and (iii) explore the statistical relationship between drought and salinity in order to better understand the mechanisms of degradation and identify avenues for sustainable management of agricultural land in semi-arid environments.

2 Materials and methods

2.1 Study area

The Tadla plain, located in the Oued Oum Erbia basin about 165 miles from Rabat, is a vast synclinal depression covering an area of approximately 3,600 square miles. It is crossed by the Oued Oum Erbia river, which runs for approximately 160 km and divides it into two large irrigated areas with different hydrological characteristics: Beni Amir in the north and Beni Moussa in the south, with irrigated areas of 33,000 ha and 69,500 ha respectively [24].

The Beni Amir irrigated area is located on the right bank of the Oued Oum-Er-Rbia, in the northern part of the Tadla depression, approximately 200 km southeast of Casablanca, at an average altitude of 400 meters. It is bordered to the north by the Khouribga et Oued Zem plateau, and beyond that by the Oued El Abid [25]Massoni, 1967(Fig.1). The climate in this area is semi-arid with an average temperature of 19°C [26] and average annual rainfall generally below 280 mm [27].

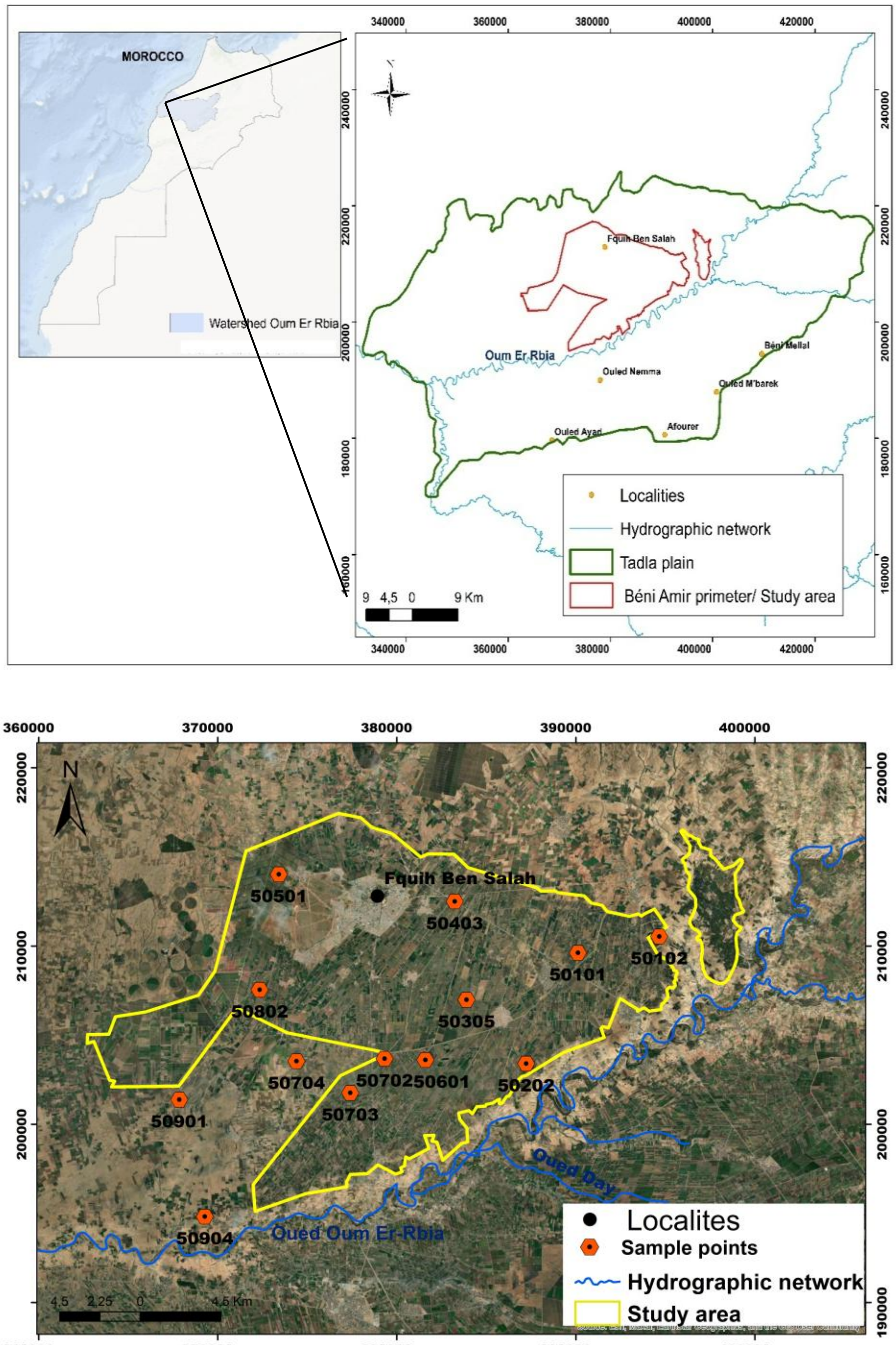


Fig. 1. Study area geographical location and distribution of sampling locations in the study area

2.2 Salinity data

Soil sampling campaigns were carried out in 2013, 2019, 2021, and 2023, at depths of 0–20 cm and 20–40 cm. The samples were analyzed to determine electrical conductivity (EC, dS/m), used as an indicator of salinity. The sampling points were georeferenced and integrated into a Geographic Information System (GIS) for mapping.

2.3 Climate data

Annual rainfall data covering the period 1990–2023 were collected from ORMVAT. These data were used to calculate the standardized precipitation index (SPI) at 1-, 3-, 6-, 12-, and 24-month scales, allowing for the characterization of interannual variability and drought episodes.

2.4 Methods of analysis

2.4.1 Calculation of the SPI normalized precipitation index

Several indicators have been developed to characterize droughts [19,28–31]. We have chosen to use the Standardized Precipitation Index (SPI). This indicator is widely recognized and used for drought analysis at the local and regional levels. Its main advantage is that it is based solely on precipitation data, which allows for the analysis of long time series. This choice is particularly relevant for Mediterranean regions, where irregular rainfall is the main cause of droughts. Calculating the Standardized Precipitation Index (SPI) requires accumulating precipitation data over long periods, ideally between 30 and 50 years, to ensure reliability[19]. The SPI index is mathematically expressed as follows:

$$SPI = \frac{Pi - Pm}{S}$$

Where:
Pi: Rainfall for month or year i (mm).
Pm: The average annual rainfall for the series over the time scale considered.
S: Standard deviation of the series over the time scale considered.

Table 1. Drought Severity Classification According to (McKee etal.,1993).

SPI Values	Type of Drought
2,0 and above	Extreme humid
1,5 to 1,99	Very humid
1,0 à 1,49	Moderate humid
99 à 0,99	Near normal
-1,0 à -1,49	Moderate drought
-1,5 à -1,99	Very drought
-2,0 and below	Extreme drought

The Standardized Precipitation Index (SPI) is a flexible tool that can be calculated on different time scales, typically ranging from 1 to 24 months. These scales allow us to distinguish the impacts of drought on various water resources. For example, one might want to examine an SPI of 1 or 2 months for meteorological drought, 1 to 6 months for agricultural drought, and something like an SPI of 6 months to 24 months or more for hydrological drought analyses and applications. Positive values correspond to wet conditions, while years with negative values indicate dry conditions. It is important to note that the SPI index does not indicate an absolute state of drought. Rather, it indicates a relative state compared to the average situation over the observation period in question. This takes into account the interannual variability of rainfall [19,20,32,33]

2.4.2 Spatial interpolation of salinity

Electrical conductivity (EC) data from the 2013, 2019, 2021, and 2023 campaigns were interpolated to produce continuous salinity maps. Two geostatistical methods were compared: inverse distance weighting (IDW) and ordinary kriging. The choice of method was based on leave-one-out cross-validation using root mean square error (RMSE) and the coefficient of determination (R^2). Ordinary kriging performed best, confirming its suitability for modeling spatial variability in salinity in heterogeneous contexts.

2.4.3 Statistical analysis and modeling

The analysis of the relationship between drought and salinity focused on the years 2013, 2019, 2021, and 2022, corresponding to the periods for which both datasets were available. The link between the SPI12 index and the average electrical conductivity of soils was examined using Pearson's correlation and simple linear regression. Statistical significance was tested at the 5% threshold ($p < 0.05$) and the quality of fit was assessed using the coefficient of determination (adjusted R^2) and graphical examination of the residuals. Statistical processing was performed using Python, while salinity mapping was carried out using ArcGIS 10.x.

3 Results and discussion

3.1 Spatio-temporal evolution of soil salinity

Analysis of soil salinity data collected between 2013 and 2023(Fig.2) reveals a gradual and worrying deterioration in soil quality within the irrigated area. Measurements in the 0-20 cm profile show a significant and continuous increase in salinity over the entire period. The values, which were initially low in 2013 (1.55-1.73 dS/m), nearly doubled in 2019 (3.25-3.32 dS/m) before reaching an alarming peak of 8.14 dS/m in 2023, classifying some soils as very highly saline. In addition, the spatial study indicates a change in the distribution of salinization. Although the trend of higher salinity from west to east remained constant from 2013 to 2021, with areas such as Fquih-Ben-Salah and Bradia particularly affected, the situation in 2023 shows that the highest values are now found in the southern part of the perimeter, particularly in the Béni Amir region. This phenomenon underscores the urgency of corrective measures to preserve soil fertility by highlighting the spread of the salinization problem to new areas.

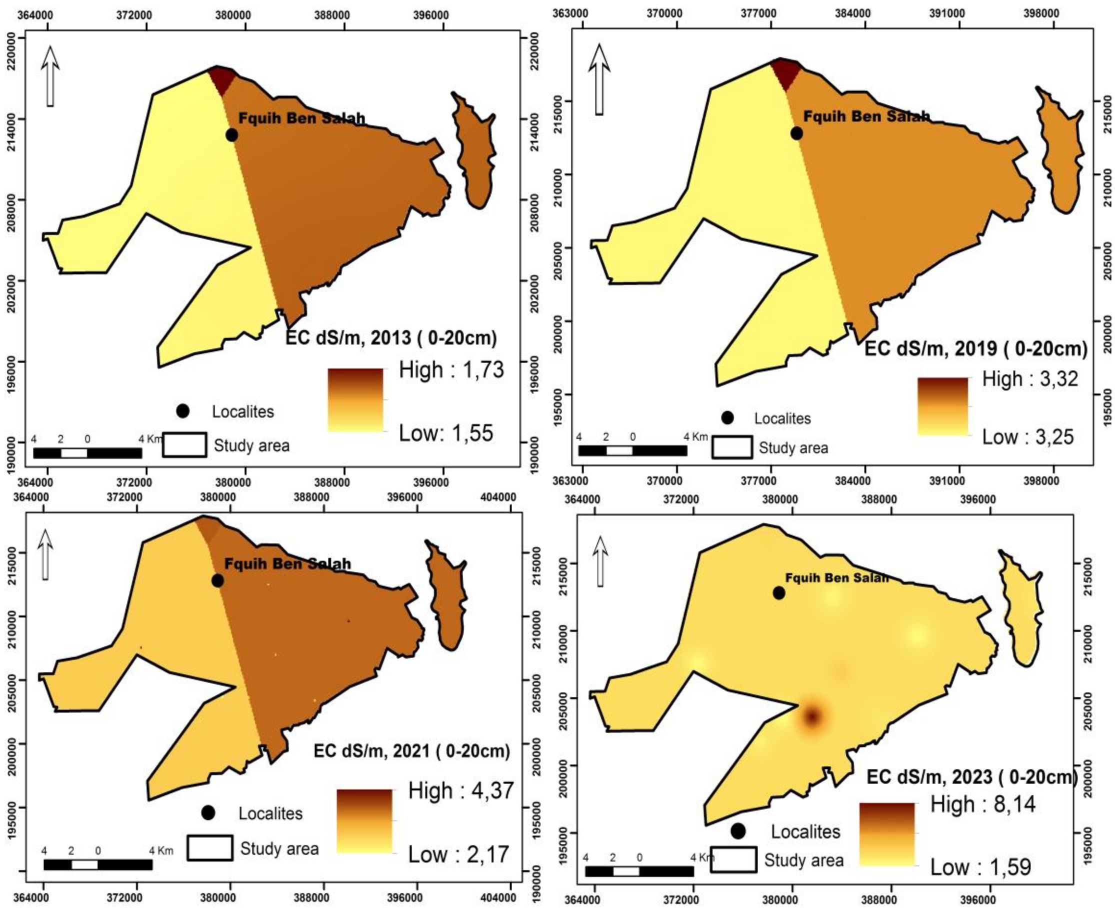


Fig. 2. Spatial variation of soil electrical conductivity (EC) in the 0-20 cm profile

Analysis of soil salinity in the 20-40 cm profile between 2013 and 2023 (Fig. 3) reveals distinct trends in its temporal evolution and spatial distribution compared to the surface profile. The data show a general increase in salinity over the study period. The minimum and maximum values increased significantly from 1.60–1.74 dS/m in 2013 to 2.76–2.85 dS/m in 2019. In 2021, salinity levels reached a significant high point, showing greater variation and a maximum value of 6.48 dS/m, suggesting a short-term deterioration. Curiously, the values appear to have decreased slightly from the 2021 peak in 2023, ranging between 2.99 and 3.15 dS/m. This suggests a possible fluctuation or local improvement; however, the values remain higher than in 2013. The distribution of salinization in the 20-40 cm layer has changed. From 2013 to 2021, salinity steadily increased from west to east along the Oued Oum-Er-Rbia. This persistence indicates that the factors responsible for salinization, such as drainage, irrigation, water quality, and evaporation, are more pronounced in these areas. However, in 2023, the spatial trend reversed. The interpretation states that the variation is now distributed 'from east to west.' This change in direction is a crucial point that warrants further analysis. It could be related to changes in irrigation practices, the introduction of salt-tolerant crops, or varying drainage system effectiveness in different areas.

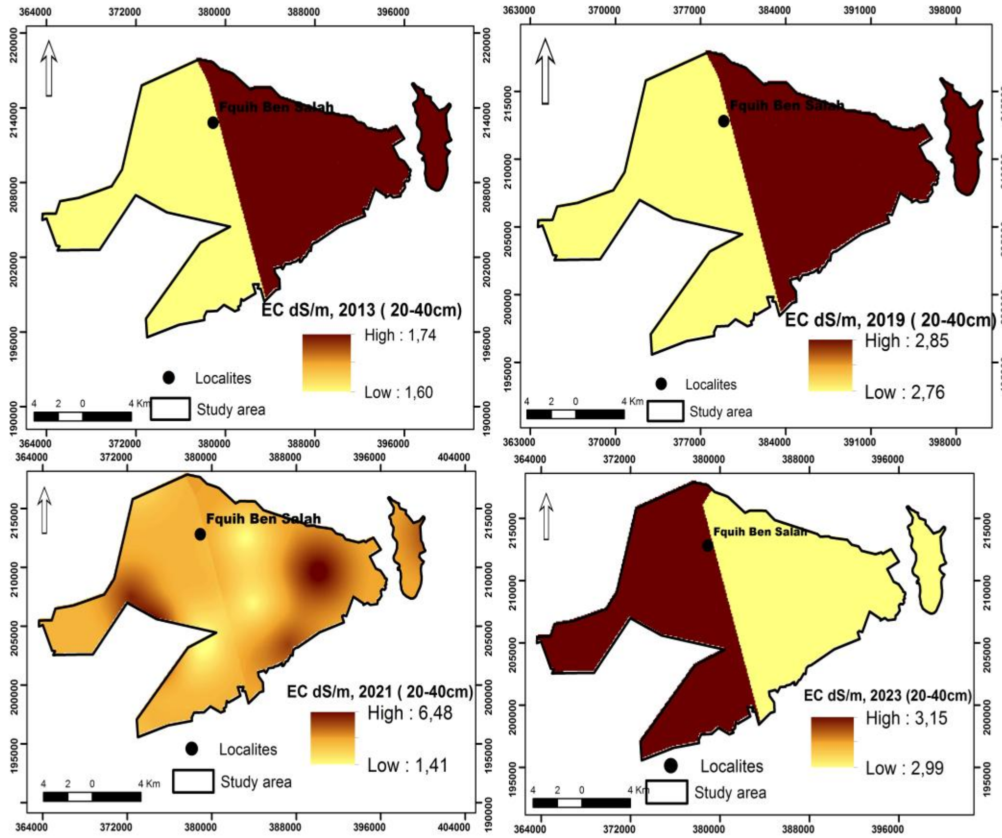


Fig. 3. Spatial variation of soil electrical conductivity (EC) in the 20-40 cm profile

The temporal variation in soil salinity in the Beni Amir region from 2013 to 2023 shows that values have increased over time. This can be explained by irrigation water, decreased precipitation, increased evaporation, and the depletion of organic matter. The spatial distribution of salinity over time shows that the highest salinity values are concentrated in the east and downstream of the Beni Amir irrigation project for both profiles. In conclusion, it is evident that the soils in the Beni Amir area are affected by salinization, a trend also confirmed by the work of [11] and [12].

The following factors are contributing to the acceleration of this phenomenon:

• Natural Factors: The waters of the Oum Er Rbia have a high salt content, which can contribute to increased soil salinity. Additionally, the nature of the Beni Amir aquifer is salty, which can influence soil salinization as well. Decreased rainfall can also reduce the natural leaching of salts from the soil, leading to salt accumulation in the area.

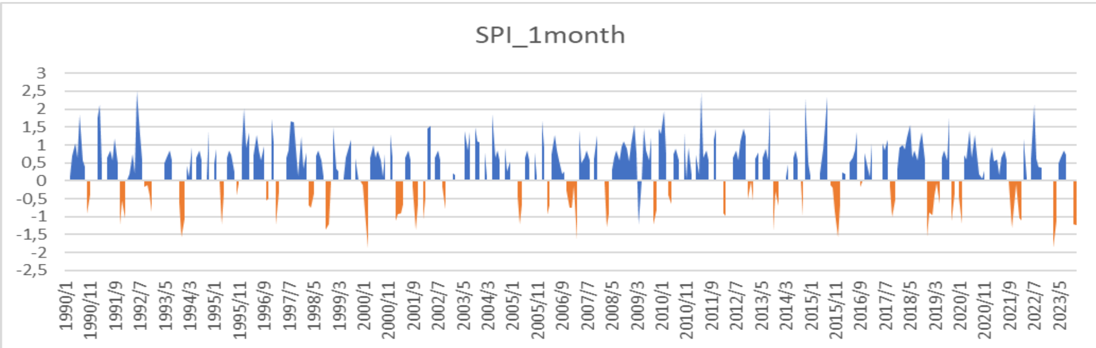
• Anthropogenic factors: The intensification of crops such as cereals, sugar beets, and fodder plays an important role in soil salinization. The excessive use of fertilizers and pesticides on these crops can lead to the buildup of salts in the soil. Additionally, adopting modern irrigation techniques, such as drip irrigation, in this area can exacerbate salinization. These irrigation methods do not allow water to penetrate deep into the soil, resulting in salt accumulation on the soil surface.

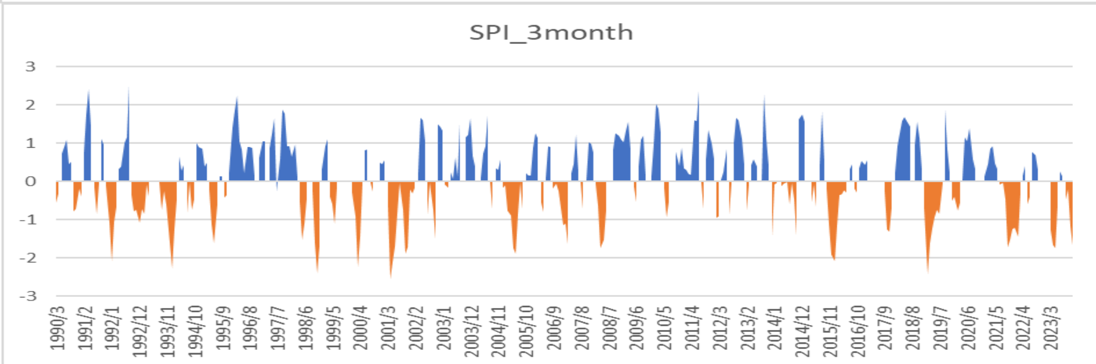
3.2 Hydroclimatic variability and droughts (SPI 1990–2023)

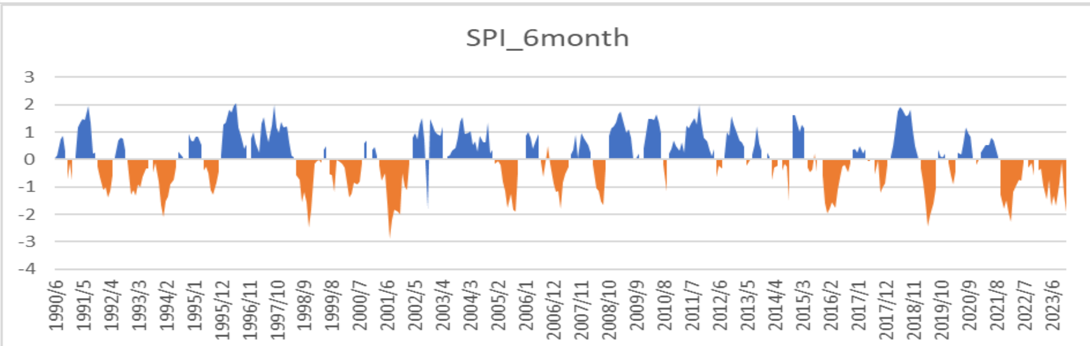
According to the aforementioned methodology, the monthly SPI was calculated from 1990 to 2024 at five time scales (1, 3, 6, 12, and 24 months) for the irrigated area of Beni-Amir in order to characterize dry or wet conditions. The analysis in Figure 3 shows the temporal evolution of the SPI with lags of 1, 3, 6, 12, and 24 months. The most severe drought was recorded between 1993 and 1994, and between 1998 and 2001. Thus, although the last period (2021-2023) is dry, the short-term periods (1 and 6 months) reveal detailed seasonal variations, while the long-term periods (12 and 24 months) offer a more stable view of rainfall deficits and surpluses (**Table2**). Between 1990 and 2023, SPI analysis shows a predominance of near-normal conditions, with variations in time scales. For the 1-month SPI, the Béni-Amir station shows 73.8% normal values, 10% dry periods, and 16% wet periods, with 1994, 1999, 2007, and 2022 being particularly dry. For the 3-month SPI, 70.2% of values are normal, with 13% dry periods and 16.7% wet periods. For the 6-month SPI, 64.98% of values are normal, with 18.6% dry periods and 16.42% wet periods. The 12-month SPI reveals 59.66% normal values, 20.53% dry periods, and 19.8% wet periods, with the years 1993, 1994, 2001, 2006, and 2024 being particularly dry. The 24-month SPI shows 62.97% normal values, 18.89% dry periods, and 18.13% wet periods, with the years 1993, 1994, 1999, 2023, and 2024 being particularly dry.

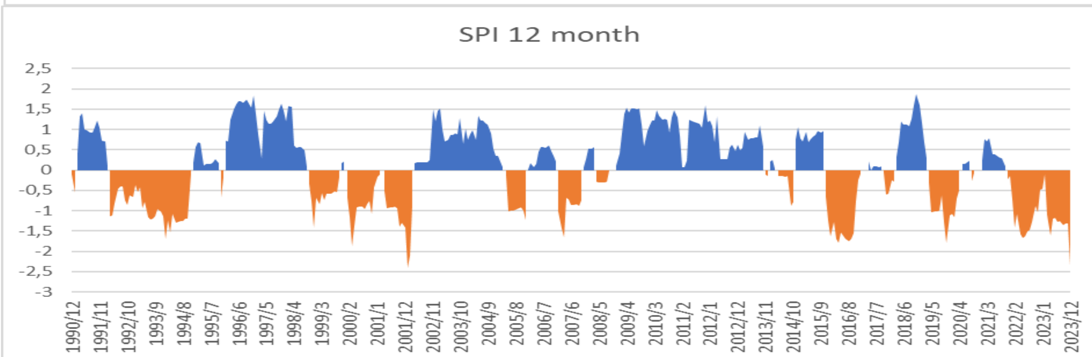
Table2. Percentage of the SPI index in the study area at different scales.

Station	Classes (SPI)	Extreme drought (%)	Severe drought (%)	Moderate drought (%)	Near normal (%)	Moderate wet(%)	Very wet (%)	Extreme wet(%)
Béni Amir	1month	0	1,4	8,6	73,8	10,7	3,3	2,1
	3months	2,4	5	5,7%	70,2	9,3	6	1,4
	6 months	1,69	7,49	9,42	64,98	11,11	5,07	0,24
	12months	1,22	5,62	13,69	59,66	14,91	4,89	0
	24 months	1,76	6,55	10,,58	62,97	12,09	5,54	0,5









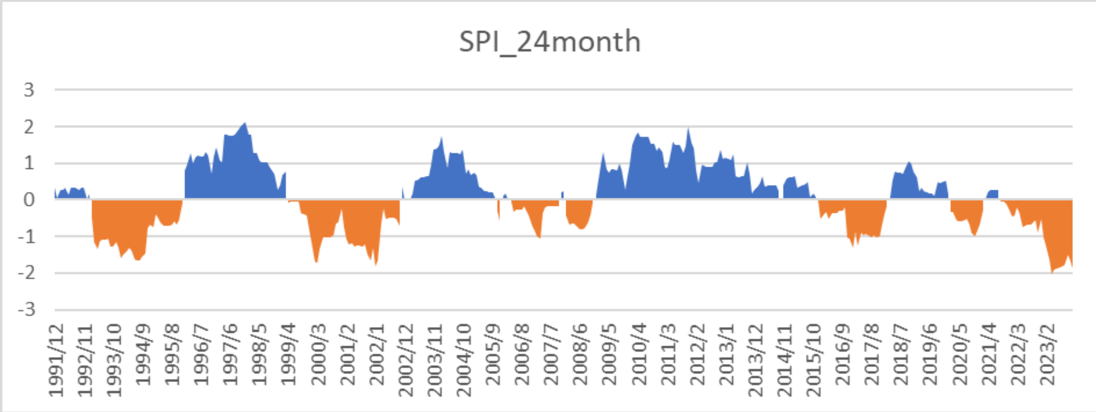


Fig. 4. Temporal evolution of SPI values on 1-, 3-, 6-, 12-, and 24-month time scales from 1990 to 2023

3.3 Relationship between drought and salinity

Analysis of the scatter plots (Fig.5) reveals a negative relationship between SPI12 values and average soil salinity. This trend appears in both profiles studied (0–20 cm and 20–40 cm), but is more pronounced at greater depths. Specifically, years with low SPI values, which reflect dry conditions, correspond to higher salinity levels. Meanwhile, wetter years (positive SPI values) are associated with lower salt content

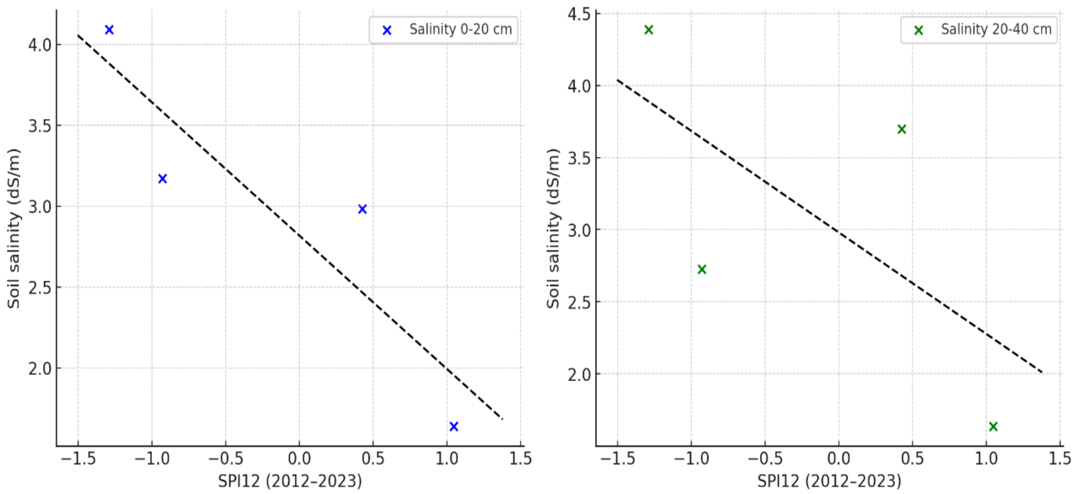


Fig.5. Soil depths (0–20 cm on the left and 20–40 cm on the right) in the irrigated perimeter of Béni Amir (2013, 2019, 2021, and 2022). The dashed regression lines indicate a negative relationship between drought intensity (low SPI12 values) and soil salinity, which is more pronounced at the 20–40 cm depth**.**

The comparative evolution of SPI12 and salinity (Fig. 6) confirms this relationship. From 2012 to 2023, the years 2019 and 2022, which were marked by severe drought (negative SPI), coincided with significant increases in salinity in both profiles. Conversely, 2013, a relatively wet year (positive SPI), had the lowest salinity levels. These results underscore the sensitivity of irrigated soils in Beni Amir to rainfall variability and the role of recent droughts in exacerbating salinization.

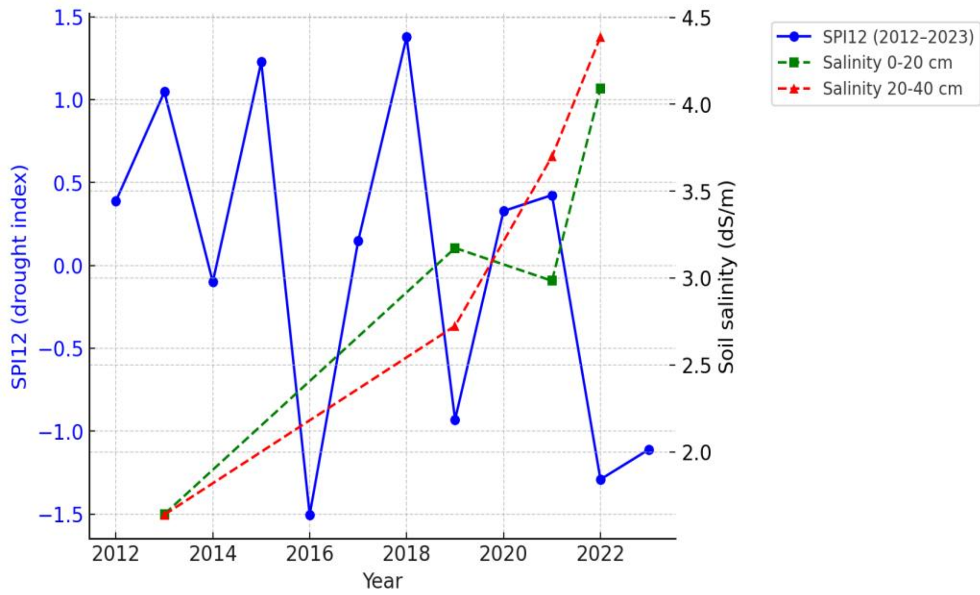


Fig.6. Comparative Time Series of SPI12 (2012–2023) and Soil Salinity (0–20 cm and 20–40 cm) in the Béni Amir Irrigated Perimeter." The SPI12 curve shows how drought conditions vary from year to year, while the salinity curves show how soil salinity has increased sharply during recent drought years, such as 2019 and 2022.

Correlation and linear regression analyses reveal a negative relationship between SPI12 and average soil salinity at both the surface (0–20 cm) and at a depth of 20–40 cm. Although the number of observations remains limited to four field campaigns, the trend is robust. Years with severe rainfall deficits, such as 2019 and 2022, correspond to the highest salinity levels. In contrast, relatively wet years, like 2013, show significantly lower levels. The regression slope is steeper for the 20–40 cm profile, reflecting the increased sensitivity of deep salinization to water deficits. These results corroborate those reported in Tafilalet and the Rheris oasis [9] who emphasize that drought amplifies salinization by reducing natural leaching

The temporal comparison in Figure 2 clearly illustrates this dynamic: Salinity peaks coincide with the most severe drought episodes. This finding is consistent with the conclusions of 32], which state that sustainable irrigation management in arid areas requires considering both water stress and the risk of salinization..

These results highlight the dual vulnerability of the Beni Amir irrigated area: its dependence on water resources and its increased sensitivity to salinization. They underscore the need to integrate climate variability into land and water management strategies. Several options can be considered, such as improving drainage to limit salt accumulation, diversifying crop rotations with salt-tolerant crops, optimizing irrigation rates, and resorting to periodic leaching during years of excess rainfall. Similar approaches have been proposed in other Mediterranean regions facing similar constraints [7,18].

Although this study highlighted the direct impact of drought on salt accumulation, other factors also play a decisive role in soil salinity dynamics. These factors include the quality of irrigation water, the capillary rise of the water table, inadequate drainage, and certain farming practices (e.g., the excessive use of nitrogen fertilizers) [4,15]. The absence of these parameters in our analysis is a methodological limitation but opens up prospects for integrated research on the determinants of salinization.

4 Conclusion

The study conducted in the irrigated area of Béni Amir shows a significant increase in soil salinity between 2013 and 2023, particularly at depths of 20–40 cm). Analysis of the SPI from 1990 to 2023 reveals an increase in droughts. The episodes in 2019 and 2022 coincided with the sharpest rise in salinity. The observed negative relationship between drought and salinity confirms that rainfall deficits exacerbate salt accumulation in irrigated soils. These results call for integrated management combining improved drainage, optimized irrigation, and the introduction of more tolerant crops in order to preserve agricultural sustainability in the Tadla plain.

5 Acknowledgments

The authors would like to thank the Tadla Regional Agricultural Development Office (ORMVAT) in Fquih Ben Salah for providing the data essential to the completion of this work.

References

[1] FAO 2002 Defining and mapping of soil salinity. FAO Soils Bulletin 39. Rome.
[2] FAO 2020 Global Forest Resources Assessment
[3] Hamzeh S, Naseri A A, Alavipanah S K, Mojaradi B, Bartholomeus H M, Clevers J G and Behzad M 2013 Estimating salinity stress in sugarcane fields with spaceborne hyperspectral vegetation indices *International Journal of Applied Earth Observation and Geoinformation* **21** 282–90
[4] Qadir M, Quillérou E, Nangia V, Murtaza G, Singh M, Thomas R J, Drechsel P and Noble A D 2014 Economics of salt-induced land degradation and restoration *Natural Resources Forum* **38** 282–95
[5] Rhoades J D, Kandish A and Mashali A M 1992 The use of saline waters for crop production.
[6] Chaves M M, Flexas J and Pinheiro C 2009 Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell *Annals of botany* **103** 551–60
[7] Daliakopoulos, Tsanis, I. K, Koutroulis, A. G, and Kourgialas, N. N. 2018 The threat of soil salinity: A European perspective. Science of the Total Environment, 642, 857-868.
[8] Oweis T, Hachum, A. and Pala, M 2012 Water use efficiency of winter-sown chickpea in a Mediterranean environment. Agricultural Water Management 107, 104-110.
[9] Rafik A, Ibouh H, El Alaoui El Fels A, Eddahby L, Mezzane D, Bousfoul M, Amazirh A, Ouhamdouch S, Bahir M and Gourfi A 2022 Soil salinity detection and mapping in an environment under water stress between 1984 and 2018 (case of the largest oasis in Africa-Morocco) *Remote Sensing* **14** 1606
[10] Ait Lahssaine I, Kabiri L, Messaoudi B, El Hafyani M, Essafraoui B, Kretzschmar H A, Kurz E C, Hellriegel U and Hoinkis J 2025 Performance assessment of 14 soil salinity spectral indices in a drought Oasis environment: Rheris Oasis, Southeastern Morocco *Scientific African* e02822
[11] Badraoui M 2003 La salinisation des sols irrigués au Maroc : état des lieux et perspectives. INRA Maroc.
[12] Chaaou, A. 2020 Dynamique de la salinisation et gestion durable des terres irriguées au Maroc. Rabat : OCP Policy Center.
[13] Chikhaoui, M, Malki, M, Bensaid, S, and Bensaid, S 2020 Impact of climate change on agricultural water use and soil salinization in irrigated perimeters of Morocco. Environmental Challenges, 1, 100004.
[14] El Housni, El Amrani, M, and Badraoui, M. 2018 Soil salinity dynamics in irrigated systems of Morocco. Agricultural Water Management, 203, 259-267.
[15] El Housni, El Amrani, M, and Badraoui, M 2021 Soil salinity dynamics and irrigation management in semi-arid regions of Morocco. Agricultural Water Management, 248, 106781. https://doi.org/10.1016/j.agwat.2021.106781
[16] Manhou K, Moussadek R, Yachou H, Zouahri A, Douaik A, Hilal I, Ghanimi A, Hmouni D and Dakak H 2024 Assessing the impact of saline irrigation water on durum wheat (cv. Faraj) grown on sandy and clay soils *Agronomy* **14** 2865
[17] Silatsa F B and Kebede F 2023 A quarter century experience in soil salinity mapping and its contribution to sustainable soil management and food security in Morocco *Geoderma Regional* **34** e00695
[18] Aryal J P, Becerra Lopez-Lavalle L A and El-Naggar A H 2025 Crop Loss Due to Soil Salinity and Agricultural Adaptations to It in the Middle East and North Africa Region *Resources* **14** 139
[19] McKee T B, Doesken N J and Kleist J 1993 The relationship of drought frequency and duration to time scales *Proceedings of the 8th Conference on Applied Climatology* vol 17 (California) pp 179–83
[20] Guttman N B 1999 ACCEPTING THE STANDARDIZED PRECIPITATION INDEX: A CALCULATION ALGORITHM[1] *J American Water Resour Assoc* **35** 311–22
[21] Bouderbala 2021 Spatiotemporal variability of drought based on SPI in northern Morocco. Arabian Journal of Geosciences 14, 987.
[22] Nouaceur and Murărescu 2020 Recent trends of drought in North Africa and the Mediterranean region. Theoretical and Applied Climatology, 141(1–2), 203–217.
[23] Ivushkin K, Bartholomeus H, Bregt A K, Pulatov A, Kempen B and De Sousa L 2019 Global mapping of soil salinity change *Remote sensing of environment* **231** 111260
[24] Aghzar N, Berdai H, Bellouti A and Soudi B 2005 Pollution nitrique des eaux souterraines au Tadla (Maroc) *rseau* **15** 459–92
[25] Massoni C 1967 Les sols du périmètre irrigué des Béni Amir (Ministère de l'Agriculture et de Réforme Agraire, Office Régional de Mise en Valeur Agricole du Tadla). Morocco.
[26] El Baghdadi M, Barakat A, Sajieddine M and Nadem S 2012 Heavy metal pollution and soil magnetic susceptibility in urban soil of Beni Mellal City (Morocco) *Environ Earth Sci* **66** 141–55
[27] Barakat A, El Baghdadi M, Rais J and Nadem S 2012 Assessment of heavy metal in surface sediments of Day River at Beni-Mellal region, Morocco *Research Journal of Environmental and Earth Sciences* **4** 797–806
[28] Choukri M, Naimi M and Chikhaoui M 2023 Drought characterization: A systematic literature review *SAINS TANAH-Journal of Soil Science and Agroclimatology* **20** 250–64
[29] Dai A 2011 Drought under global warming: a review *WIREs Climate Change* **2** 45–65
[30] Vicente-Serrano S M, Beguería S and López-Moreno J I 2010 A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index *Journal of climate* **23** 1696–718
[31] Zargar A, Sadiq R, Naser B and Khan F I 2011 A review of drought indices *Environ. Rev.* **19** 333–49
[32] Svoboda, M., Fuchs, B. A., & Knutson, C. L. 2012 The Standardized Precipitation Index: Its development, applications, and future directions *Drought Mitigation Center Faculty Publications,* 1–12
[33] World Meteorological Organization & Global Water Partnership 2016 Handbook of Drought Indicators and Indices. Integrated Drought Management Programme (IDMP), Geneva
[34] Wichelns D and Qadir M 2015 Achieving sustainable irrigation requires effective management of salts, soil salinity, and shallow groundwater *Agricultural Water Management* **157** 31–8