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RESEARCH

Drought and aridity trends on the Algerian steppe

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Abstract

Arid regions are characterized by the fragility of their ecosystems, which are very vulnerable to climate change. The increase in aridity in these regions makes them more exposed to drought with serious consequences. This contribution analyzes the trend of aridity and drought in the Algerian steppes, during the period 1951–2022. Robust statistical tests (Mann–Kendall and Sen) and the Reconnaissance Drought Index (RDI) are used. Monthly rainfall data and monthly average temperature as well as potential evapotranspiration (PET) data from the Climatic Research Unit (CRU), characterized by a spatial resolution of 0.5°, were used. The results showed an increase in annual aridity, which led to an expansion of drylands. The change was characterized by the transition of 9.20% of the steppe surface from the semi-arid class to the arid class. At the same time, the entire subhumid class (1.67%) made the transition to the semi-arid class. On the other hand, a significant tendency towards drought over most of the steppe territory (81%) was recorded. The analysis of the results revealed the influence of precipitations and air temperatures in this enlargement. These changes have contributed to the degradation of the environment and natural resources and to an ecological and socio-economic imbalance.

1 Introduction

Across the world, air temperature and rainfall patterns have undergone considerable changes due to climate change (Wang et al. 2016; Khan et al. 2018). Strong increases in temperature will in turn affect evapotranspiration and atmospheric water storage, potentially modifying the magnitude, frequency and intensity of precipitation, as well as their seasonal and interannual variability and geographic distributions (Arnell 1999; Middelkoop et al. 2001; Chen and Xu 2005; Akhtar et al. 2008; Bates et al. 2008; Zhang et al. 2008; Elmahdi et al. 2009; Wang et al. 2013).

The increase in potential evapotranspiration (PET) and the decrease in precipitation led to the aridification of the climate, which ultimately led to the expansion of drylands; a phenomenon considered to be a major environmental impact of global warming. A significant expansion of arid zones is expected to be recorded by the end of the twenty-first century, in the context of imminent amplification of global warming (IPCC 2013).

Between 1980 and 2008, the drylands area increased by 3.1% compared to the period 1948–1979 (Dai 2013; Huang et al. 2016, 2017; Lickley and Solomon 2018; Li et al. 2019; Zhao et al. 2019; Wu and Chen 2019). Following global warming, the drying trend is expected to continue throughout this century (Feng and Fu 2013; Asadi Zarch et al. 2017). Koutroulis (2019) reported that drylands could increase by up to 7% by 2100. Other authors (Feng and Fu 2013) indicated that the increase can reach up to 10% compared to the period 1961–1990. Drylands could force up to 24% of the world's population to live in an arid environment compared to those currently alive (Park et al. 2018).

Arid regions have fragile ecosystems that are very sensitive to climate change. Increasing aridity makes them more vulnerable to climate-related impacts and risks. The situation in the steppe region is particularly alarming, because signs of degradation are increasing everywhere. This cartographic representation of land use in the Algerian steppe (Fig. 1), developed from images captured by Sentinel-2 in 2021, highlights the extent of the degradation occurring across this vast territory. It is particularly remarkable that the western steppes show the most worrying signs of this degradation. This area is home to a population essentially

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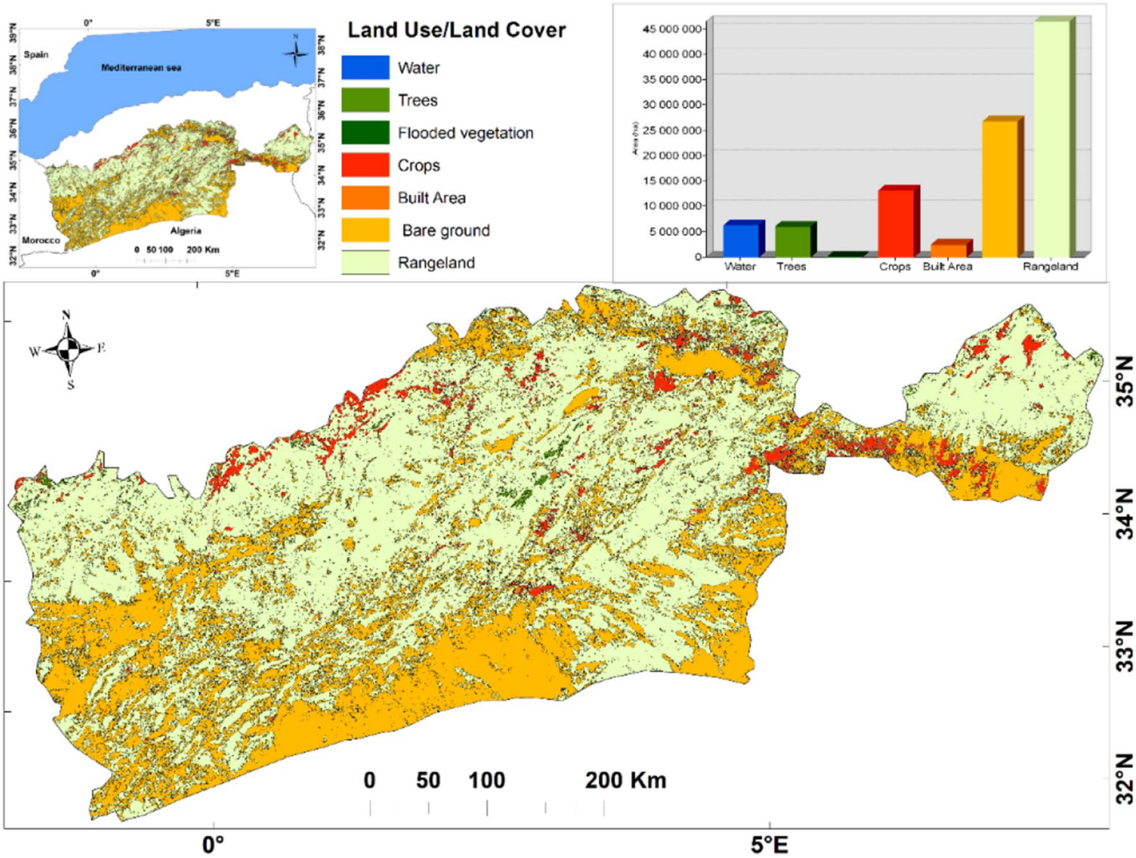


Fig. 1 Land cover map of the Algerian steppe. Data source: Karra et al. (2021)

made up of pastoralists, which aggravates the degradation of all components of the ecosystem (flora, plant cover, soil, and fauna). This land degradation and desertification, which is at an advanced stage, result in the reduction of biological potential and the disruption of ecological and socio-economic balances (Le Houérou 1985; Aidoud 1996; Bedrani 1999). The scale of this phenomenon has prompted the exploration of other causes of this degradation than those known such as overgrazing, recurrent droughts, and inappropriate land use. This reflection raises a relevant question: is there an aridification of the climate of arid and semi-arid regions? Despite its capital importance, few studies have been devoted to the evolution of aridity in Algeria.

The Mann–Kendall (MK) test was used for the evaluation of the geographical distribution of the trends in precipitation, temperature, PET, aridity, and drought. Besides, the spatial changes in arid lands between two periods, 1951–1980 and 1993–2022, were estimated. the Reconnaissance Drought Index (RDI) is proposed for drought characterization.

This contribution aims to show the contribution of climate to this degradation of the study area by evaluating patio-temporal changes in aridity and characterizing droughts using robust statistical tests. Drought can be understood as a temporary situation characterized by a lack of precipitation compared to normal values. Aridity, on the other hand, is a climatic characteristic of a given area; this is the permanent situation of low annual precipitation or seasonal (Lain 2005). Monthly Climate Research Unit (CRU) data with a resolution of 0.5° and covering the period from 1951 to 2022 was used.

2 Presentation of steppe regions

Physically, the Algerian steppes, located between the Tellian Atlas in the north and the Saharan Atlas in the south, cover a total area of more than 20 million hectares. They are limited to the North by the 500-mm isohyet which coincides with the extension of dry cereal crops and to the South, by the 100-mm isohyet (Fig. 2a) which represents the southern limit of the extension of esparto (*Stipa tenacissima*).

Ecologically, the steppe regions constitute a buffer between coastal Algeria and Saharan Algeria, limiting the negative climatic influences on the former.

Steppe soils are characterized by the presence of limestone accumulation, low organic matter content and a high

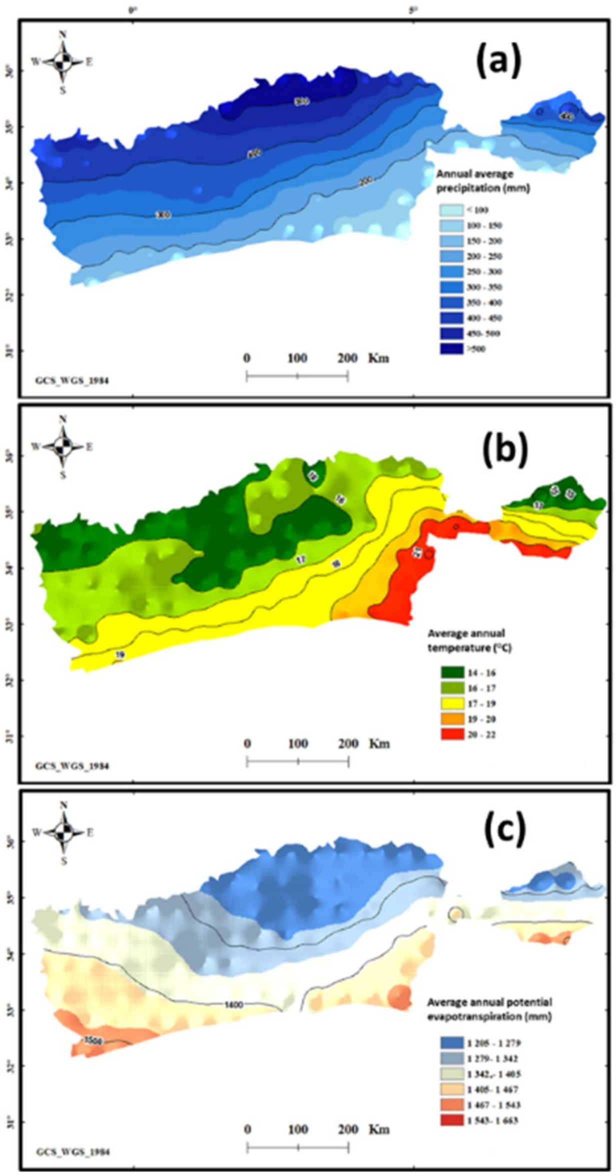


Fig. 2 Spatial distribution during the period 1951–2022 of **a** the annual average CRU precipitation (mm); **b** annual average of mean CRU temperature (°C); **c** The annual average of CRU potential evapotranspiration (mm), calculated using the FAO 56-PM equation

sensitivity to erosion and degradation. Water resources are weak, not very renewable, unevenly distributed and anarchically exploited (Nedjraoui and Bédrani 2008).

The Algerian steppes are dominated by four (04) main types of plant formations: the grass steppes based on esparto (*Stipa tenacissima*) and esparto (*Lygeum spartum*) which constitute mediocre rangelands and the chamaephytic steppes based on white mugwort (*Artemisia herba alba*) whose pastoral values are very appreciative and *Hammada scoparia* located on the Regs. Azonal formations are represented by psammophilic species and halophilic species with good forage values (Nedjraoui and Bédrani 2008).

Average annual temperatures have a considerable influence on climate aridity. In the steppe region, temperatures normally vary throughout the year, high in the summer season and low in the winter season. January remains the coldest month of the year and July is the hottest month. Temperatures become more contrasting in the north–south direction; the average annual temperature varies between 14 and 17 °C in the north and center of the region and between 17 and 22 °C in the south (Fig. 2b). The annual cumulative evapotranspiration has exceeded the threshold of 1500 mm in the South, and does not reach 1300 mm in the north. It appears from this that the PET is significantly higher than the rainfall; it is, respectively, 15 times and three (03) times higher than the cumulative precipitation in the south and north of the region (Fig. 2c). As a result, high PET generates and/or promotes the process of soil degradation and more particularly the silting of cultivated land and steppe rangelands.

3 Data and methods

3.1 Data sources

Climatic Research Unit (CRU) is a dataset that represents monthly variations in climate over the past century. These data are available from 1901 to 2022, at different resolutions (0.5° × 0.5°, 1° × 1°, and 2.5° × 2.5°), and are based on an archive of average monthly data provided by more than 4000 weather stations distributed throughout the world (Harris et al. 2014). These data are frequently used in hydroclimatic studies around the world (Dinku et al. 2008; Yang et al. 2014; Merabti et al. 2023) due to their good precision (Ahmed et al. 2017; Salman et al. 2019). In this study, we used monthly data on precipitation, potential evapotranspiration and average temperature with a spatial resolution of 0.5° × 0.5°, over the period (1951–2022) because of the exhaustiveness of the data time series from 1951. AgriMet-Soft-NetCDF-Extractor V2.1 software (https://agrimetsoft.com/netcdf) was used to extract climate data for the study area.

3.2 Aridity index

Different methods have been proposed to measure aridity using various meteorological variables (Asadi Zarch et al. 2017). The United Nations Environment Programme (UNEP) aridity index (AI) is most extensively adopted, it indicates the degree of aridity of the climate in a given location in relation to the evaporative demand of the atmosphere (UNEP 1997). It is defined as follows:

$$AI = \frac{P}{PET} \quad (1)$$

where P is the average annual precipitation in mm and PET is the mean annual potential evapotranspiration in mm.

This index is widely used to assess climate quality; it reflects the annual deficit between the amount of precipitation received (P) compared with the evaporative demand of the atmosphere (PET), which implies that the lower the index, the greater the aridity, and enables climates to be classified from hyper-arid to humid according to the following values: hyper-arid (AI < 0.03), arid (0.03 = AI < 0.20), semi-arid (0.20 = AI < 0.50), subhumid (0.50 = AI < 0.65) and humid (AI = 0.65) (Zhang et al. 2021; Ullah et al. 2022).

The PET CRU grid was calculated using the FAO 56-PM equation (Allen et al. 1998), but with variables estimated using the absolute values of monthly mean maximum and minimum temperature, vapor pressure and cloud cover, and from a fixed monthly climatology for wind speed (Harris et al. 2014). Cloud cover was used to estimate the number of hours of sunshine, and then to estimate solar radiation according to a procedure validated by almost 20 years of use (Harris et al. 2014).

3.3 Trend test

The non-parametric Mann Kendall or MK test (Mann 1945; Kendall 1975) is adopted to determine the presence or absence of a linear trend in time series (Pohlert 2016). Let X1, X2 …Xn be a data series where Xj is the corresponding data at time tj. The MK statistic is defined by the following:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(X_j - X_i\right) \quad (2)$$

$$\text{Where} \begin{cases} sgn\left(X_j - X_i\right) = 1, si\left(X_j - X_i\right) > 0 \\ sgn\left(X_j - X_i\right) = 0, si\left(X_j - X_i\right) = 0 \\ sgn\left(X_j - X_i\right) = -1, si\left(X_j - X_i\right) < 0 \end{cases} \quad (3)$$

Assuming that the data are independent and identically distributed, Kendall (1975) gives the following:

E(S) = 0

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i\left(t_i - 1\right)\left(2t_i + 5\right)\right] \quad (4)$$

where n is the amount of data in the series, m is the number of linked groups and t_i is the amount of data in the group of order i. If the sample contains ten or more data, the distribution of the test statistic Z below will be approximated by a centered reduced Gaussian.

$$\begin{cases} \frac{S-1}{\sqrt{Var(S)}}, si\ S > 0 \\ 0, si\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, si\ S > 0 \end{cases} \quad (5)$$

The null hypothesis H0 (no trend) is rejected when the significance level or eigenvalue (p-value) is greater than 5%.

3.4 Estimation of Sen's slope

When H0 is accepted, the slope of the trend (called the Kendall Theil slope or Sen slope) is estimated by Sen's method (Sen 1968), where the slope is the median of all slopes calculated between each pair of points.

For the peer set (i, Xi) where Xi is a time series. Sen's slope is defined as follows:

$$Sen^{'}s\ Slope = Median\left\{\frac{X_j - X_i}{j - i}; i < j\right\} \quad (6)$$

The robustness of the test has been validated by several comparison tests (Lubes-Niel et al. 1998; Yue and Wang 2004).

3.5 Characterization of drought

Regional drought assessment is conventionally based on drought indices for the identification of its intensity, duration and geographic extent. The Reconnaissance Drought Index (RDI), has been widely accepted, mainly in arid and semi-arid climatic regions. It has a significant advantage over other indices because, in addition to precipitation, another meteorological parameter is taken into consideration, namely potential evapotranspiration.

3.6 The Reconnaissance Drought Index

The first expression calls the initial value of the RDI

$$AI_i = \frac{P_i}{PET_i} \quad (7)$$

where P_i and PET_i are precipitation and potential evapotranspiration.

The initial formulation of the standardized RDI (RDIst) (Tsakiris and Vangelis 2005) proposed that the values of AI follow the log-normal distribution. Thus, RDI_{st} was calculated as follows:

$$RDI_{st} = \frac{Y_i - \overline{Y}}{\sigma} \quad (8)$$

$$\text{Such as, } Y_i = ln\left(AI_i\right) \quad (9)$$

$\overline{Y}$ is the arithmetic mean, and σ is the standard deviation.

3.7 Drought parameters

3.7.1 The magnitude of the drought

The duration of drought (D_d) is equal to the number of years between the start and the end of the drought (Ghosh 2018). A drought event begins when the RDI is continuously negative and reaches an intensity of – 1 or less, while the event ends when the RDI becomes positive.

The magnitude of drought corresponds to the cumulative water deficit over a period of drought (Seguin 2015).

$$D_M = \sum_{j=1}^{n} RDI_{ij} \quad (10)$$

$j = 1$ is the index of the first drought year, and $j = n$ is the index of the last drought year.

3.7.2 The intensity of the drought

The average of this cumulative water deficit over the drought period is the intensity of the drought:

$$D_i = \frac{D_M}{D_d} \quad (11)$$

4 Results

Application of the Mann Kendall test at the 5% threshold shows a significant upward trend in the average annual temperature across the entire steppe territory. The magnitude of this trend estimated using the Sen's slope estimator varies between 0.016 and 0.028 °C per year. Points are used to indicate a significant trend at the 5% level (Fig. 3).

A significant decrease in precipitation was recorded in the western steppes and the northeast of the central steppe. This reduction ranges between – 2.29 and – 0.34 mm per year. Although precipitation is also decreased in the eastern, central, and southern steppes, this decrease is not statistically significant (Fig. 4).

As for potential evapotranspiration, it has increased significantly throughout the territory of the steppe, as shown in Fig. 5. This increase is approximately 0.78 mm per year in the west, and this increase gradually increases heading east, reaching up to 2.07 mm per year. These results highlight complex trends in precipitation and potential evapotranspiration in the steppe, highlighting significant variations that have important implications for water resources management and adaptation to climate change.

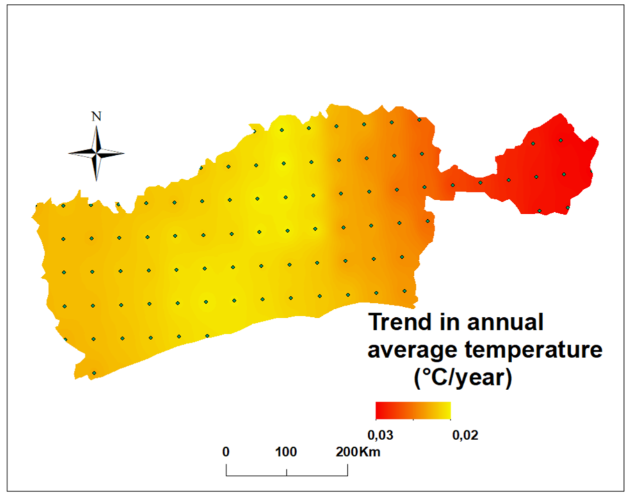


Fig. 3 Spatial distribution of trends in annual mean air temperature. (Trends significant at the 5% level are indicated by a dot)

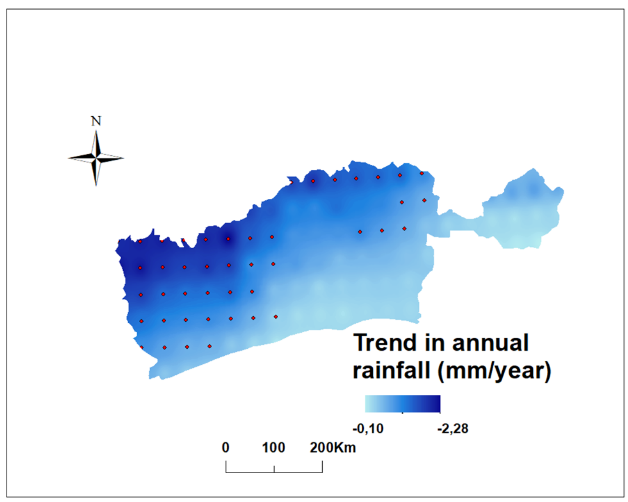


Fig. 4 Spatial distribution of the trend in average annual precipitation recorded by CRU (in mm), during the period 1951–2022. (Trends significant at the 5% level are indicated by a dot)

The significant downward trend in the annual aridity index shown in Fig. 6 indicates aridification of almost the entire steppe territory where this aridification is more intense in the north.

The comparison of results between two periods (Table 1) revealed that more than 1,900,000 ha, or 9.2% of the steppe surface, experienced the transition from the semi-arid class to the arid class, thus increasing the surface area of the arid territory to 42.79% of the entire territory of the steppe. At the same time, the entire subhumid class initially representing 1.67% of the steppe surface has made the transition to the semi-humid class, now covering 57.21% of the steppe surface. This transition led to a contraction on the southern

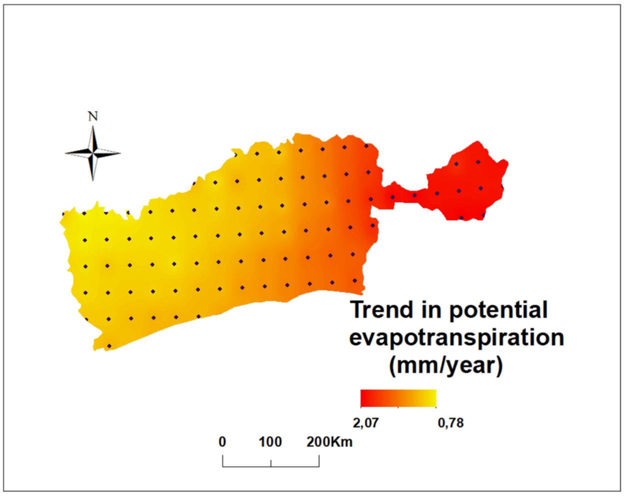


Fig. 5 Spatial distribution of the trend in potential evapotranspiration recorded by CRU (in mm), during the period 1951–2022. (Trends significant at the 5% level are indicated by a dot)

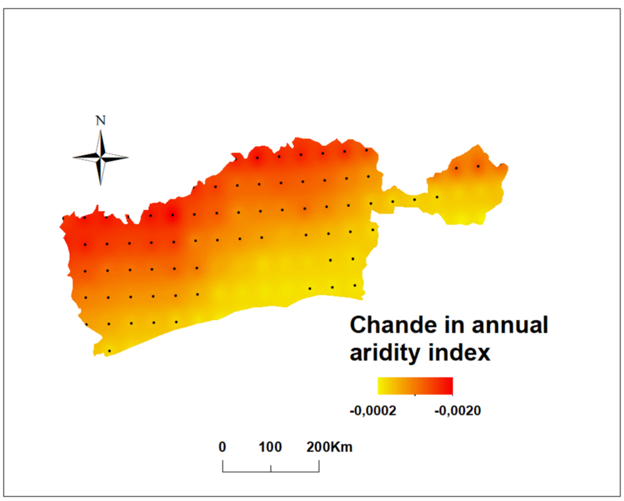


Fig. 6 Spatial distribution of the aridity trend following the UNEP method (1979); estimation of aridity using precipitation and potential evapotranspiration from the CRU, from the period 1951–2022. (Trends significant at the 5% level are indicated by a dot)

side and an expansion on the northern side of the semi-arid class, indicating the direction of aridification from south to north (Fig. 7).

Figure 8 clearly shows that there are variations in the number of cases and in the duration of drought during the study period. Droughts were less frequent (Fig. 8b) but persisted longer (Fig. 8a).

The magnitude and average intensity of drought based on RDI, were analyzed at each grid point as shown in Fig. 9, the south was exposed to the most severe and intense droughts.

The application of the MK test at the 5% threshold at each grid point shows that the RDI values have suffered a significant decrease over most of the steppe territory, which means a tendency towards drought in this region which represents 81% of the territory. The rest of this territory has not undergone any significant trend (Fig. 10). The rest of this territory has not undergone any significant trend, because the soils in these regions are decertified and characterized by sand displacement.

5 Discussion

The results obtained from this study revealed increasing trends in annual aridity (decrease in aridity index) at the steppe region, which is consistent with the findings of several authors across the world, reporting the drying of drier regions more intensively and more significantly than humid regions (Feng and Zhang 2015; Lickley and Solomon 2018). The Algerian steppe characterized by three bioclimatic stages; arid, semi-arid and subhumid; recorded the expansion of arid land at the expense of the semi-arid and the expansion of semi-arid land at the expense of subhumid, which confirm the results of previous studies on aridity trends in other regions of Algeria. Derdous et al. (2021) assessed aridity trends over northern Algeria between 1980 and 2018 and found a trend of increasing aridity in the driest regions. This latest study indicated that the majority of stations experienced a non-significant decrease in precipitation and a significant increase in air temperatures. By studying

Table 1 Climate class transition matrix (ha)

		1951–1980			Total
		Arid	Semi-arid	Subhumid	
1993–2022	Arid	7,101,864 (33.59%)	1,945,206 (9,20%)	0	9,047,070 (42.79%)
	Semi-arid	0	1,174,238 (55.54%)	353,763 (1.67%)	12,096,144 (57.21%)
	Subhumid	0	0	0	0
Total		7,101,864 (33.59%)	13,687,587 (64.74%	353,763 (1.67%)	21,143,214

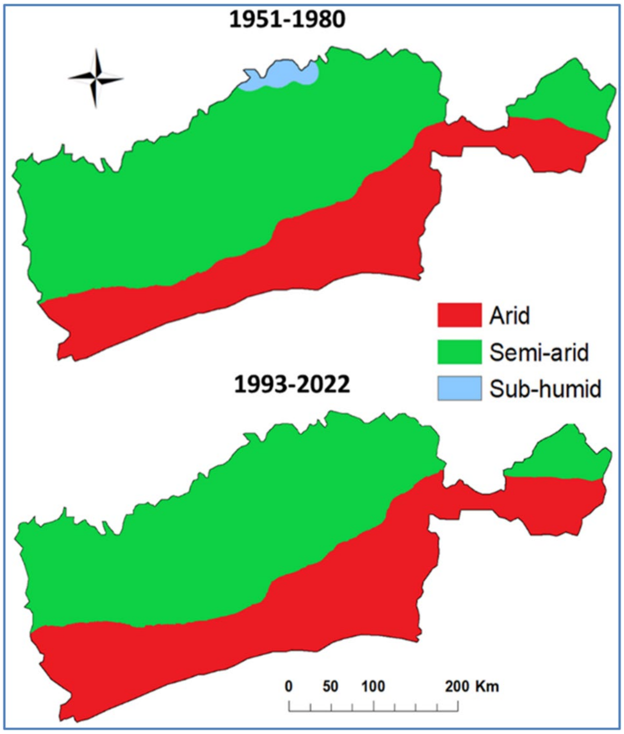


Fig. 7 Comparison of the evolution of annual aridity in the steppe zone between the periods 1951–1980 and 1993–2022. Arid class (0.03 ≤ AI < 0.20), semi-arid class (0.20 ≤ AI < 0.50), subhumid class (0.50 ≤ AI < 0.65)

the evolution of the minimum and maximum temperature over the period 1951–2010 at the Bechar station, a region bordering the study area, Oubadi et al. (2021) detected a significant upward break from the 1990s. Benyettou and Bouklikha (2017) revealed significantly positive trends in precipitation at the Tiaret and Saïda stations (Northwest Algeria), during the period 1982–2016. Similar results were obtained by Merniz et al. (2019), over northeastern Algeria, but with a non-significant decrease in annual precipitation. The studies by Taibi et al. (2015) and Zeroual et al. (2017) showed pessimistic precipitation projections where all scenarios predict a decrease in precipitation. Indeed, the persistence of the decline in precipitation in these regions, even with non-significant trends, could lead to a significant increase in aridity in a short period, especially in light of the significant trend in global warming. These results highlight complex trends in precipitation and potential evapotranspiration in the steppe, highlighting significant variations that have important implications for water resources management and adaptation to climate change in the region.

In Algeria, several studies have been devoted to the study of drought and rainfall variability (Djellouli et al. 2019; Achite et al. 2021; Zerouali et al. 2021; Faci et al. 2021). However, all these studies are either localized or focus on northern Algeria.

The severity of a drought is felt all the more if the year in question followed one or more dry years. A sequence of

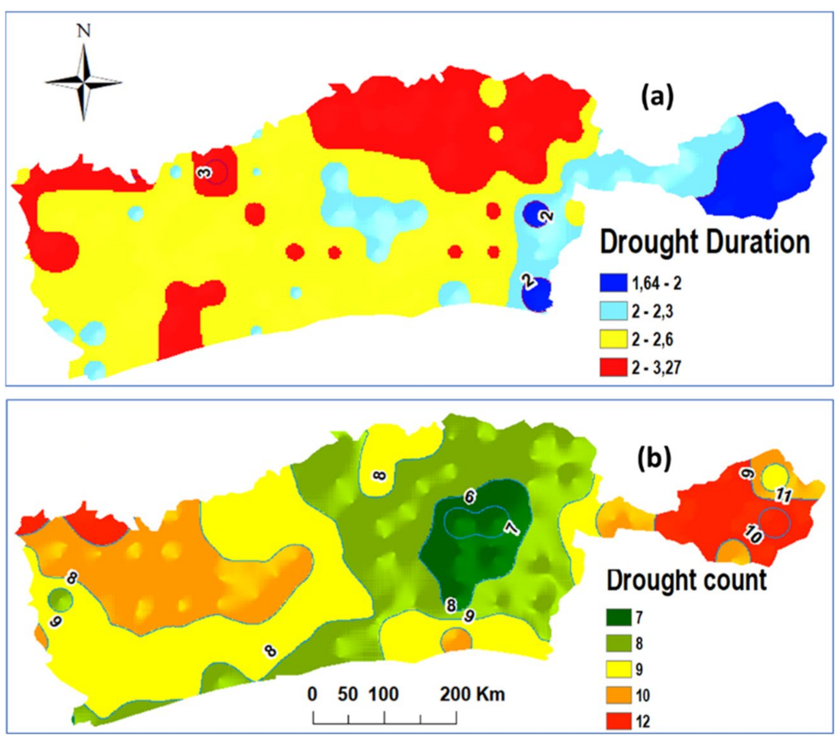
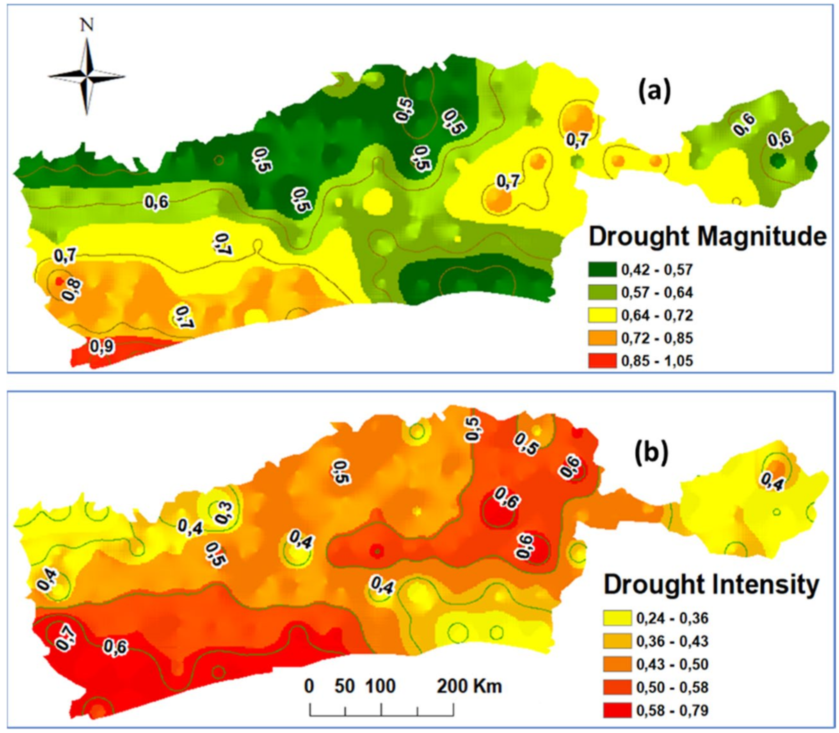


Fig. 8 Average duration (**a**) and number of droughts occurring in year (**b**) during the period 1951–2022

Fig. 9 The **a** magnitude and **b** average intensity of droughts occurring between 1951 and 2022



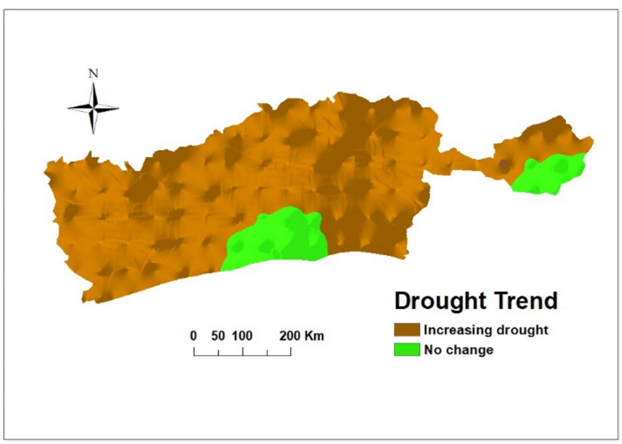


Fig. 10 Spatial trends in RDI

successive dry years is, of course, more serious than an isolated drought (Benzarti 1990). Several more or less complex drought indices have been used in many geographical areas. The aim of this contribution was to characterize drought and its trends in the steppe region of Algeria. Drought characterization was carried out using the Reconnaissance Drought Index (RDI), which is a robust index. It is based on the P/PET ratio and is mainly suitable for arid and semi-arid areas. In order to determine the severity of drought in the steppe region, the RDI was applied for each grid point covering the steppe territory.

The results obtained reveal that the region studied was subject to long, severe, and intense periods of drought. Similar conclusions obtained by Slimani and Aidoud (2004) by showing that the steppe region is subject to recurrent and persistent years of drought. The Man Kendall and Sen statistical tests show significant drought trends, which leads to the conclusion that droughts will be more frequent in this region.

From a meteorological point of view, drought is a recurring natural climatic phenomenon which characterizes a period during which the lack of water seriously disrupts the hydrological balance of a region (Tate and Gustard 2000). The events detected through this contribution nevertheless correspond to situations that could lead to serious consequences.

Aridity and meteorological drought are two very complex constraints, because they concern several negative aspects affecting the environment, they concern salinity, soil degradation, desertification, and silting with serious impacts on the plant cover and various threats affecting the agricultural sector and in particular that of irrigated areas. It is a phenomenon having a negative role on the evolution of the environment; it results in a large water deficit linked to the scarcity of rain and runoff and the increase in temperatures and evapotranspiration.

6 Conclusion

The Algerian steppe has suffered a remarkable degradation of its rangelands. The causes most often cited are overgrazing, due to the rapidly growing sheep herd and recurrent droughts. This contribution studied another parameter influencing the evolution of the environment, which is aridity, the variation of this parameter is dependent on rainfall and air temperature; and place it in its historical context. The results of statistical trend tests indicated the expansion of drylands, this is the consequence of accumulations of potential evapotranspiration, caused by the rise in temperature. On the other hand, statistical analyzes revealed a downward trend in precipitation.

The expansion of drylands is not limited to simple weather variation; it constitutes a concrete indicator of the considerable challenges we face. The repercussions of this aridification are widespread, affecting various sectors such as agriculture, water supply, biodiversity, and most crucially, the well-being of the population.

In this study, the applied DRI approach was able to adequately explain the drought conditions in the steppe region between 1951 and 2022. The drought characteristics, namely magnitude, duration and intensity, collectively explain drought severity levels in the study area. The RDI has a significant advantage over other indices by including, in addition to precipitation, an additional meteorological parameter, potential evapotranspiration. It is concluded that although the RDI index generally reacts similarly to the SPI index, it is more sensitive and more appropriate. The results show a significant trend towards drought over most of the steppe territory (81%). This trend is the consequence of the reduction in precipitation and the accumulation of potential evapotranspiration, caused by the increase in temperature.

Author contributions All authors contributed to the study conception and design. Data collection and analysis were performed by M.O and M.F. All the figures were prepared by M.O. The first draft of the manuscript was written by M.O and M.F, and Q.B.P supervision, revise, editing. All authors Read and approved the final manuscript.

Data availability The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent to publication Not applicable.

Competing interests The authors declare no competing interests.

Disclaimer This manuscript has not been published or presented elsewhere in part or entirety and is not under consideration by another journal.

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