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Impact of climatic variability on groundwater resources in the Eastern Mitidja plain, Algeria

Impatto della variabilità climatica sulle risorse idriche sotterranee nella pianura orientale di Mitidja, Algeria

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Riassunto

Lo scopo di questo studio è di valutare le principali caratteristiche climatiche e il loro impatto sul regime idrologico ed il funzionamento idrodinamico della falda acquifera nella pianura orientale di Mitidja (Algeria). Lo studio ha l'obiettivo di determinare la modalità di ricarica della falda acquifera, proporre un soluzione per lo sfruttamento eccessivo delle acque sotterranee e porre rimedio al problema di intrusione salina nella sua parte nord-orientale. L'applicazione di tre metodi statistici (test di Pettitt, test U di Buishand ed il test di Lee e Heghinian) e due indici di siccità (SPI e Ipmc) ha permesso di identificare i periodi umidi e secchi per l'intervallo di tempo 1906-2018. Inoltre, sono state effettuate le analisi delle mappe piezometriche per gli anni 1973, 1981, 2015 e 2020 per indagare il comportamento idrodinamico dell'area di studio e per determinare l'effetto del regime idrologico sul funzionamento della falda acquifera. I risultati ottenuti applicando i tre metodi statistici e l'indice di siccità indicano due periodi distinti. Il primo periodo è umido e si estende dal 1906 al 1973. Il secondo periodo, secco, dal 1974 al 2018, è caratterizzato da un deficit pluviometrico dal 15% al 19%. Inoltre, dal 1973 al 2020 si osserva un calo significativo dei livelli piezometrici, variabile tra 10 e 80 m. Si osserva un livello piezometrico negativo tra -10 e -35 m. Questo abbassamento coincide con il deficit di precipitazioni osservato durante il periodo 1973-2018. Inoltre, l'intrusione di acqua di mare è stata osservata nella parte nord-orientale della pianura. Per migliorare la gestione delle acque sotterranee, una strategia efficace di contrasto all'intrusione salina consiste nell'utilizzare una tecnica di ricarica artificiale utilizzando gli impianti di trattamento delle acque reflue esistenti nella regione, unita all'arresto del pompaggio dei pozzi nelle zone costiere interessate dall'intrusione di acqua di mare con l'integrazione di un monitoraggio idrochimico delle acque sotterranee.

Abstract

The aim of this study is to assess the main climatic characteristics and their impact on the hydrological regime at the watershed and the hydrodynamic functioning of the aquifer in the Eastern Mitidja plain (Algeria, 2,382 millions km^2). In detail, specific objectives are to determine the recharge mode of the aquifer, to propose solutions for the groundwater overexploitation and to remedy the seawater problem in its northeastern part. The application of three statistical methods (Pettitt's, Buishand's U statistic and, Lee and Heghinian's tests) and two drought indices (SPI and Ipmc) allowed identifying the wet and dry periods for the time interval 1906-2018. In addition, the piezometric maps analysis for the years 1973, 1981, 2015 and 2020 was carried out to investigate the hydrodynamic behavior of the study area and to determine the effect of the hydrological regime on the hydrogeological functioning of the aquifer. Results obtained by the application of the three statistical methods and two drought indices indicate two distinct periods. The first period is wet and it extends from 1906 to 1973, while the second period is dry and it goes from 1974 to 2018. It is characterised by a rainfall deficit between 15% and 19% compared to the previous period (1906-1973). Furthermore, a significant drawdown in the piezometric levels is observed from 1973 to 2020, varying between 10 and 80 m, that indicates a negative trend of piezometric levels. This drawdown coincides with the rainfall deficit noticed during the period 1973-2018. Also, seawater intrusion was observed in the northeastern part of the plain. To enhance groundwater management, an effective remediation strategy is to use an artificial recharge technique from the existing wastewater treatment plants in the region, complemented by stopping the pumping of wells in coastal zones that are affected by seawater intrusion supplemented by a hydro-chemical monitoring of the groundwater.

Introduction

Water resources are a key issue of the 21st century, causing political conflicts among various nations. The latest reports on water resources development indicate that the various crises observed recently are linked, especially, to climate change, energy, food security, economic and financial recession, all of which have an impact on water resources (WWDR, 2021). Accordingly, several researchers have conducted groundwater studies worldwide, with regard to several pressures, such as climate change, groundwater overexploitation and seawater intrusion (Hadjji et al., 2022).

Climate change is a global phenomenon that impacts continents across the world although some regions are affected more than others. The scientists have assessed the Mediterranean regions and shown that virtually all parts of it are vulnerable and face significant risks due to climate change. Identified regional key risks include increased water scarcity (notably in the South and East) and droughts (in the North), coastal risks due to flooding, erosion and saltwater intrusions, wildfire, terrestrial and marine ecosystem losses, as well as risks to food production and security, human health, well-being and the cultural heritage (IPCC, 2013). This phenomenon is known as climate change (global warming) and is manifested by increasing the temperature; as a response, processes in the hydrologic cycle are modified and the precipitation regime can vary. It is essential to analyze the rainfall series and to assess the impact of their variability over time by the frequency of extreme events such as heavy rains, floods and droughts. Climate change can also generate a rise in sea level due to melting continental glaciers, leading to numerous consequences such as coastal erosion and seawater intrusion in the coastal aquifers.

The spatiotemporal evolution of the rainfall regime of a watershed is essentially based on the history of precipitation. Droughts typically have a larger spatial-temporal extension than other natural hazards, and their impacts are often not limited to structural damage (Marengo et al., 2017). However, droughts are difficult to quantify and identify due to their gradual onset and end (Deo et al., 2017). This latter can be defined as an abnormal and recursive aspect of the climate essentially linked to the absence of precipitation in a given region in a well-determined period of time. The examination of the recurrence of this phenomenon by scientific methods contributes to establish strategic plans for the mobilization and rational management of surface and groundwater resources. Among the methods used to identify the accumulation of rainfall deficit for a period we have statistical methods (Pettitt's, Buishand's U statistic and, Lee and Heghinian's tests), drought indices (the standardized precipitation index (SPI) and rainfall index (RI)).

Researchers worldwide have conducted studies on the effect of climate variability and its impact on surface water and groundwater (Edwards and Mc Kee, 1997; Mayasari et al., 2017; Ekwueme and Agunwamba, 2020). For instance, groundwater quantity is caused by modifications of the rainfall regime, which have worsened over the years due to climate change (Sappa et al., 2018; Lentini, 2021). In the regions of northern Algeria, several authors have proven a significant drop in precipitation from the mid-1970s especially in the west regions where the rainfall deficit varies between 16% and 43% (Meddi, H. & Meddi, M., 2009; Bouguera, 2020; Gherissi et al., 2021).

This study focuses on the effect of rainfall variability over the period 1906-2018 and the impacts of uncontrolled overexploitation on the variation of the piezometric level of the Quaternary alluvial aquifer of the Eastern Mitidja plain. This aquifer has experienced a significant decrease in rainfall through the past few decades (Drouiche et al., 2019). The geographical context of the study area is characterized by a combination of urban, industrial and agricultural fabric. For example in 2010, water mobilized volume exceeded 0.329 km3, with surface water representing the 53%, groundwater the 28% and desalination produces the 19% of the mobilized volume (Drouiche et al., 2019). Also, the groundwater is the main source for agricultural, domestic, and industrial water supply in the study region (Boufekane et al., 2022). This resource is progressive anthropogenic pressure, which is a growing concern. Therefore it is about controlling the current state of the resource from a quantitative and qualitative point of view, of supplementing and updating the knowledge acquired previously on the balance sheet of flows. In this work, we will try to highlight the effect of climate variability on groundwater in the eastern Mitidja using statistical methods (Pettitt's, Buishand's U statistic and, Lee and Heghinian's tests) and two drought indices (SPI and Ipmc) combined with the analysis of the ancient and current state of the aquifer piezometry in order to propose solutions for the groundwater overexploitation and changing climate conditions along coastal zone of the study area. This evaluation become of mandatory importance as the Mediterranean regions was identified as climatic "hot-spot", due to the expected increase in temperature and anomalies in rainfall patterns which will influence the amount of available recharge.

Study Area

The Eastern Mitidja plain is situated in the northern region of Algeria and encompasses the eastern part of the Mitidja plain (Fig. 1). The study area covers the most productive area within the watershed. It extends from El Harrach wadi in the west to Boudouaou wadi in the east, following a WSW-ENE direction with a length of about 80 km and a width that varies between 10 and 20 km; covering an area of 650 km^2. The Sahel bulge separates the area from the Mediterranean Sea for 70 km in the north, while it is directly in contact with the Sea in the northeastern part. The Blidean Atlas naturally limits it to the south.

The study area is characterized by a relatively flat relief with altitudes varying between 0 and 20 m in the north and north-east part, reaching a maximum of 45 m in the south-western part. It is crossed by three main wadis: El Harrach wadi, El Hamiz wadi and Reghaïa wadi which flow directly into the sea without encountering the geomorphological obstacles. It has significant water potential.

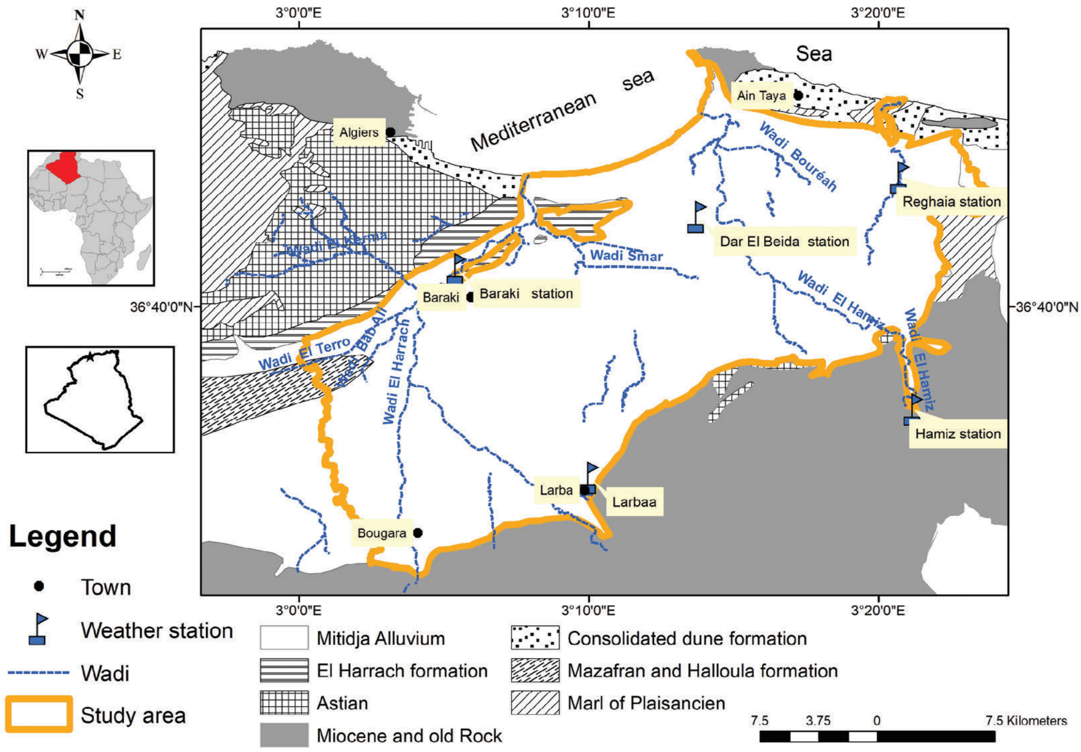

Fig. 1 - Location of the study area.

Fig. 1 - Ubicazione dell'area di studio.

Climatic framework

The climate of the region is semi-arid Mediterranean (wet in winter and dry in summer). The precipitation is less than 700 mm per year. The water balance was established using meteorological data from the five weather stations, namely Baraki, Dar El Beida, Larbaa, Hamiz dam and Reghaia, located in the study area (Fig. 1). The results for the period 1906-2018 are presented in Figure 1 and Table 1.

Geological and hydrogeological framework

For the geological context in the Eastern Mitidja plain, the synthesis of the various studies (Glangeaud, 1932; Bonneton, 1977; Bennie & Partners, 1983; Benziada, 1994; Toubal, 1998) show the presence, from top to bottom, of the following geological formations which have an hydrogeological interest:

a. The Quaternary: is distinguished by: i) Recent deposits (alluvial formation): including wadi bed deposits, gravel, sand, clay and silt, ii) The Mazafran and Halloula (Rharbian) formations constituted by the silty deposits formed in the low marshy areas, iii) The Mitidja formations (Soltano-Tensiftien), which mainly are alluvial formations: made up of sand, sandy clay, gravelly clay, gravel, pebbles, silt and sandstone, and iv) The El-Harrach formations (Villafranchian): are essentially formed by the yellow marl and clay formations. In addition, the water point logs (wells and boreholes) located in the Rouiba and Reghaïa regions (Eastern region of the study area) show the absence of this formation, with a direct passage from the Mitidja formations (Soltano-Tensiftien) to the Upper Pliocene (Astian).

Tab. 1 - Geographic location of weather stations and water balance results of the study area. P: Precipitation, R: runoff, ETa: Actual evapotranspiration, ETPc : Potential evapotranspiration, I: infiltration.

Tab. 1 - Ubicazione geografica delle stazioni meteo e risultato del bilancio idrologico nell'area di studio. P: precipitazione. R: ruscellamento. Eta: evapotrasporazione reale. ETPc: evapotraspirazione potenziale. I: infiltrazione.

Weather station	Station code	Latitude (°)	Longitude (°)	Z (m.a.s.l)	Climatic parameter
Baraki	21421	36.61 N	3.34 E	20	Precipitation
Hamiz Dam	20602	36.72 N	3.26 E	130	
Larbaa	21403	36.73 N	3.33 E	100	
Reghaia	20632	36.68 N	3.10 E	20	
Dar El Beida	20611	36.65 N	3.42 E	24	Precipitation and temperature
Water Balance results: Period 1936-2018					
Parameter	P	R	ETa	ETPc	I
Value (mm)	650	110.8	505.9	887.7	33.3

b. The Pliocene : it is formed by the Astian and Plaisancian deposits. The Pliocene is hidden in depth by the Quaternary formations which cover the Paleocene formations. The Pliocene includes: i) The Astian: described as a little exploited aquifer. It is marked by an insufficient number of water points and it is composed of limestone, sandy limestone, clayey limestone and sandstone and ii) The Plaisancian: outcrops locally in the foothills of the Sahel bulge (north) and in the south-eastern region (Khemis El Khechna).

For the hydrogeological conditions within the study area, two aquifer reservoirs have been distinguished (Fig. 2B): 1) Quaternary alluvial deposits (Mitidja formation) of the Soltano-Tensiftian age which is a shallow aquifer. It is the most important and the most exploited reservoir, and 2) The sandstone formation of the Astian which is poorly exploited and of which the hydrodynamic characteristics are poorly known. Moreover, the Astian aquifer is located between the Plaisancian (marly substratum) and the yellow marls of El Harrach except in the eastern part where it is in direct contact with the alluvial aquifer of the Mitidja.

The piezometric evolution in the Quaternary alluvial aquifer clearly indicates the overexploitation of this coastal aquifer where the piezometric level decreases to the values of 0 and - 5 m in the center and near the coast (north), respectively in the 1990s. Also, the seawater intrusion was observed and confirmed by the geophysical and hydrochemical studies (Toubal, 1998).

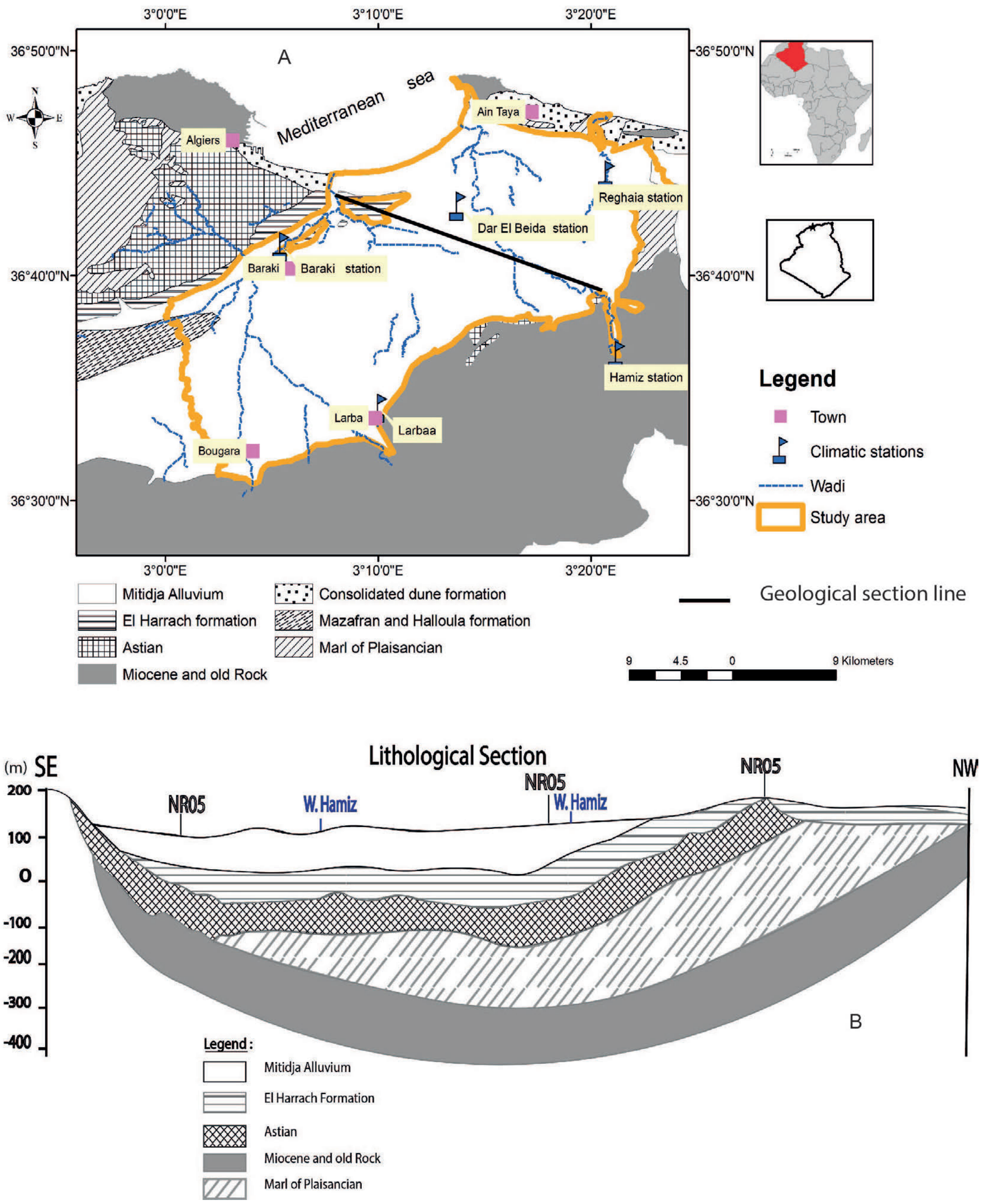

Fig. 2 - Hydrogeological section (SE-NW) in the study area (Bennie and Partners, 1983).

Fig. 2 - Sezione idrogeologica (SE-NW) nell'area di studio (Bennie and Partners, 1983).

Materials and methods

The weather and hydrogeological data were collected from the National Meteorological Office (NMO) and the National Agency for Hydraulic Resources (NAHR), respectively. The annual rainfall was analyzed for a period of 112 years (1906-2018) at five weather stations (Baraki, Baraki, Dar El Beida, Larbaa, Hamiz dam and Reghaia). Annual temperature was analyzed at the Dar El Beida station for the period 1936-2018 (Tab. 1). It is a long series for better temporal comparison of meteorological data, which should allow precise determination of the drought return period (Zhang et al., 2015; Zhao et al., 2017). The hydrogeological data (piezometric levels, piezometric maps, groundwater exploitation rates) were selected for May 1973, April 1981, May 2005 and July 2020. Data of 43 water points (31 piezometers, 7 wells and 5 unexploited boreholes) were analyzed. The choice of these years was motivated by the availability of piezometric measurements throughout the entire study area (data reliability).

Before the processing of the data collected from theses weather stations, anomalies in the monthly measures (temperature and precipitation) were deleted considering a potential entry error in the database. Next, we established a monthly gap-filling method using Markov Chain Monte Carlo Multiple Imputation (MCMC) (Buuren, 2007). The MCMC method based on the Fully Conditional Specification (FCS) algorithm (Takahashi, 2017) and is an iterative method used when the missing data pattern is arbitrary (monotonic or not). For each iteration and each variable, an univariate model (single dependent variable) is adjusted by taking the other variables of this model as predictors. Then, one proceeds to the imputation of the missing values for the variable to be adjusted. This procedure is repeated until the maximum number of iterations is reached. At this point, the imputed values will be stored in the dataset.

In this study,, the methodological approach was structured in three parts, which are described in detail in the following part of the manuscript:

Statistical approach

The statistical approach makes it clear to identify the break in the rainfall series. In this work, the statistical approach application begins with the temporal evolution description of the annual precipitation observed over 112 years at the Hamiz dam weather station. This station is considered as a reference station given the low rate of missing values recorded (10%). However, the non-parametric Mann Kendall (MK test) is adopted to determine the presence or absence of a linear trend in the pattern of the precipitation series analyzed (Mann, 1945; Kendall, 1975; Pohlert, 2018).

In order to study the stationarity or non-stationarity of precipitation, we chose three different methods: Pettitt's test (Pettitt, 1979), Buishand's U statistic (Buishand, 1984) and the Bayesian procedure of Lee and Heghinian (Lee and Heghinian, 1977) where a change in mean indicates the presence of a break, which implies that the precipitation series is non-stationary. The results evaluation of the Pettitt and Buishand tests is based on the values classification of the associated probability (AP) (Paturel et al., 1997). Depending on the AP values, the break can be: a) very significant (AP < 1%), b) significant (AP varies from 1 to 5%), c) not very significant (AP varies from 5 to 20%) and d) the precipitation series analyzed is considered homogeneous when AP > 20%.

The Pettitt test, which is derived from the Mann-Whitney test, is non-parametric. The absence of a break in the time series corresponds to the null hypothesis H_0. It is tested by the Ut, n statistic considered for all t values from 1 to n.

$$D_{ij} = \mathrm{sgn}(x_j - x_i) \qquad (1)$$

Where, x_j and x_i corresponds to the data vector and:

$$\begin{cases} \mathrm{sgn}(x_j - x_i) = 1 & \text{if } (x_j - x_i) > 0 \\ \mathrm{sgn}(x_j - x_i) = 0 & \text{if } (x_j - x_i) = 0 \\ \mathrm{sgn}(x_j - x_i) < 1 & \text{if } (x_j - x_i) < 0 \end{cases}$$

To test H_0, the variable k_n is used, with

$$k_n = \max\left|U_{t,n}\right|$$

In the Buishand approach, we define the U statistic as:

$$U = \frac{\sum_{k=1}^{n=1}\left(\frac{Sk}{Dx}\right)^2}{n(n+1)} \qquad (2)$$

Where, $Sk = \sum_i^k (x_j - \bar{x})$ for $k=1$,....... n and D_x is the standard deviation of the time series.

Buishand's U statistic and, Lee and Heghinian's Bayesian procedure assumes a series of random variables x_1, x_2, ..., x_n that are based on the following model:

$$X_i = \begin{cases} U + \varepsilon_i i = 1, 2, ..., \tau \\ U + \delta + \varepsilon_i i = \tau + 1, ..., n \end{cases} \qquad (3)$$

The ε_i are independent and normally distributed with mean zero and variance δ^2. The variables τ, μ, δ, and σ correspond to unknown parameters verifying: $1 \le \tau \le n-1$, $-\infty < \mu < +\infty$, $-\infty < \delta < +\infty$ and $\sigma < 0$.

The change in position and magnitude corresponds to the posterior distribution of τ (the position of the break in time) and δ (the magnitude of the change on the mean).

Although the Bayesian procedure provides a clear and rapid identification of the break (change in the mean), this approach assumes a single break in the series of variables and offers no test to verify this assumption (Lang et al., 2003). When a break is detected in a precipitation series, we are interested in calculating the variation of the mean on either side of this break expressed by the following formula (Ardoin-Bardin, 2004):

$$D = \left(\overline{x_j} / \overline{x_i}\right) - 1 \qquad (4)$$

Where $\overline{x_j}$ presents the average series to the period after the break and $\overline{x_i}$ the average series to the period before the break.

Finally, in order to detect the break in the precipitation records, the methods used in this work were chosen for their strong foundation and multiple advantages (Aka et al., 1996). The gap filling, trend test and homogeneity tests (Pettitt and Buishand statistics tests) were performed in Xlstat software, Heghinian test were carried out with Khronostat software (open source software of hydrosciences, University of Montpellier) and the cartography of the results has been established on the ArcGis software.

The Climatic indices

The drought indices have been used to identify the wet and dry periods. We can cite: the Rainfall index (RI), the index of the deviation proportional to the mean (Ipm), The index of the deviation proportional to the cumulative average (Ipmc) and the Standardized Precipitation Index (SPI) (Gherissi, 2021). In this study and in order to estimate the degree of rainfall and hydrological drought, it was decided to use the Ipmc and SPI. The motivation to use these two indices is the non-studied previously by the authors in the study area.

1) Index of the deviation proportional to the cumulative average (Ipmc): the accumulation of the indices of successive years makes it possible to identify the major trends while disregarding the slight fluctuations from one year to the next. When the sum of the indices increases, it is a wet trend; the trend is of the "dry" type, otherwise. The formula is:

$$Ipmc = \left(P_i / P_m\right) - 1 \text{ cumulative} \tag{5}$$

with P_i: annual precipitation of year and P_m: average annual precipitation.

2) Standardized Precipitation Index (SPI): the approach adopted in this part consists in applying the SPI index to the data of the study area. In order to determine the spatio-temporal variability of wet conditions and to assess the precipitation deficit during the period (1906-2018), SPI index created by McKee et al. (1993) has been used. The formula is:

$$SPI = \frac{\left(x_i - x_m\right)}{S_i} \tag{6}$$

Where x_i the cumulative rainfall for a year, i; x_m and S_i, are, respectively, the average and the standard deviation of the annual rainfall observed for a series.

The SPI index defines the severity of the drought in different classes (Tab. 2).

Tab. 2 - Classification of drought in relation to the value of the SPI index (Edwards & Mc Kee, 1997).

Tab. 2 - Classificazione della siccità in funzione del valore dell'indice SPI (Edwards & Mc Kee, 1997).

SPI classes	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

Impact of climatic variability on groundwater resources

The strategy adopted to study the hydrodynamic of the aquifer was:

– To determine the drought at the spatio-temporal scale, using the statistical parameters (x_m and S_i) of the entire observation period (1906-2018).
– To use the statistical parameters (x_m and S_i) of each period separately (1906-1973) and (1973-2018) to calculate the SPI index.
– To determine the spatial evolution of humidity for each period depending to the SPI values.

In addition, the use of piezometric maps drawn up in May 1973, April 1981, May 2015 and July 2020 will allowed us to study the spatio-temporal variability of the fluctuation of the water table. Finally, we rely on the results found previously to discuss the impact of the spatiotemporal variability of humidity on the hydrodynamic behavior of the alluvial aquifer and taking into account the overexploitation.

Results and discussion

Evolution of temperature

The temperature data are available in the Dar El Beida weather station for the period 1936-2018. In the study area, the average temperature increased with a general trend 1 °C (Drouiche et al., 2019). However, it is gradually increased since the year 1973 (Fig. 3).

Evolution of precipitation

Figure 4 shows the average annual rainfall variation recorded in the selected weather stations. Generally, spatio-temporal variability of rainfall is well illustrated with the

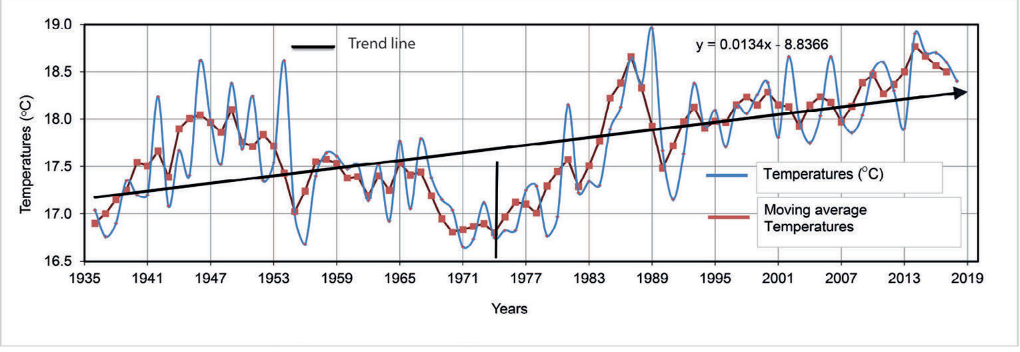

Fig. 3 - Annual average variation of the mean temperature in Dar El Beida weather station (Period: 1936-2018).

Fig. 3 - Variazione annuale della temperatura media presso la stazione meteorologica di Dar El Beida weather station (Periodo: 1936-2018).

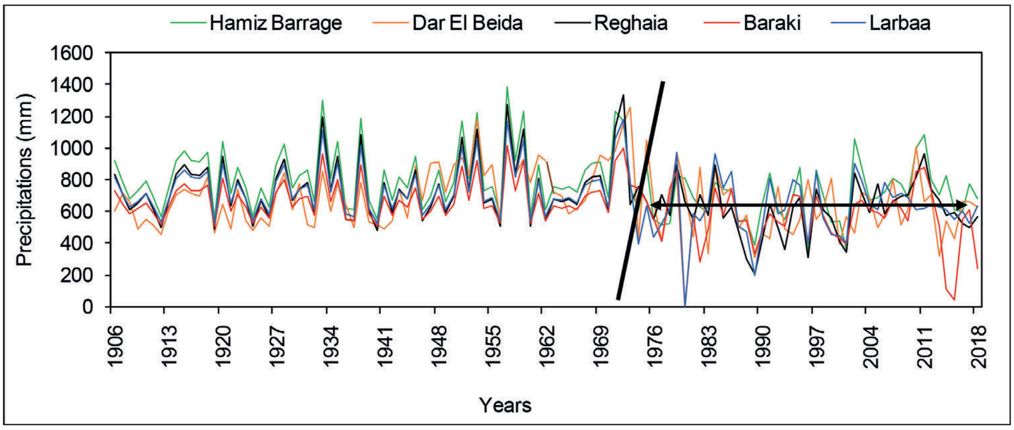

Fig. 4 - Annual average precipitation for the selected weather stations (Period: 1906-2018).

Fig. 4 - Precipitazione media annuale presso specifiche stazioni meteo (Periodo: 1906-2018).

maximun annual average precipitation observed in the Hamiz dam station (776 mm), and the minimun average annual precipitation recorded in the Baraki station with a value of 636 mm. Additionally, the analysis of the graph indicates the presence of two distinct periods: 1) a wet period from 1906 to 1973 and b) a dry period from 1974 to 2018. The most pronounced rainfall regression is recorded in the year 1989 at Larabaa station (201 mm). The coincidence of precipitation regression trends with the period of rising temperatures (1974-2018) to the possibility to consider this period as a period of drought compared to the 1906-1973 period.

Statistical approach

The three homogeneity tests (Pettitt, Buishand's U statistic and Lee and Heghinian tests) were used to determine the breakup year (Gherissi et al., 2021). The application results of data series (Period 1906-2018) for the five selected weather stations are presented in Table 3. It shows:

- The three tests for the Hamiz Dam and Larbaa stations present a significant break in 1973. However, Dar El Beida, Baraki and Reghaia stations indicate a break in the years 1980, 1979 and 1974 for the Pettit and Buishand tests and 1986, 1984 and 2013 for the Lee and Heghinian test, respectively.
- The two data series of Hamiz Dam and Larbaa are homogeneous because the associated probability compared to the other selected weather stations is higher than 20%.
- The average annual precipitation before and after break shows a precipitation regression rate of 15% (Reghaia station) to 19% (Baraki station), from east to west.
- Finally, the break year is considered to be 1973.

Tab. 3 - Results of statistical tests on rainfall series (Pettitt, Buishandt and, Lee and Heghinian tests).

Tab. 3 - Risultati dei test statistici sulle serie di pioggia (test di Pettitt, Buishandt e Lee and Heghinian).

		Weather stations				
Test	**Parameter**	Hamiz dam (1906-2018)	Dar El Beida (1906-2018)	Reghaia (1906-2018)	Baraki (1906-2018)	Larbaa (1906-2018)
Pettitt	Year of break	1973	1980	1974	1979	1973
	Statistical of Pettitt test	1128	1026	1164	1289	1175
	APBR (mm)	828.40	725.67	748.23	679.44	741.63
	APAR (mm)	695.24	597.73	604.99	549.69	626.52
	Associated probability (%)	0.73	2.74	0.534	0.146	0.479
	Rainfall variation (%)	-16.21	-17.63	-19.14	-19.09	-15.52
Buishand	Year of break	1973	1980	1974	1979	1973
	Statistical of Buishand (U)	18.2837	16.4203	19.7016	21.3493	3160.1
	APBR (mm)	828.40	725.67	748.23	679.44	741.63
	APAR (mm)	695.24	597.73	604.99	549.69	626.52
	Associated probability (%)	-	-	-	-	-
	Rainfall variation (%)	-16.21	-17.63	-19.14	-19.09	-15.52
Lee and Heghinian	Year of break	1973	1986	1984	2013	1973
	Probability-density	0.1743	0.1012	0.1104	0.5169	0.2201
APBR: Average precipitation before the break.						
APAR: Average precipitation after the break.						

Cumulative deviations from the mean precipitation

The results of the cumulative deviations from the mean precipitation (Pcdm) for the five selected stations (series data for the period 1906-2018), can be divided into two periods (Fig. 5). The first period extends from 1906 to 1973 with an increasing curve indicating a wet period and the second period from 1974 to 2018 a decreasing curve indicates the most intense and prolonged drought period. Also, these results confirm the previous ones for the break year (1973).

Variation of the Standardized Precipitation Index (SPI)

The evolution of the standardized precipitation index (Fig. 6) for the five selected weather stations (data series for the period 1906-2018), shows a wet period from 1906 to 1973 represented by a positive index. For example, for 1957, +3.14 in Hamiz dam station, +2.99 in Reghaia station and +2.44 in Baraki station. For 1972, +2.87 in Larbaa station and for 1957, +5.23 in Dar El Beida station. The deficit period (severe to extreme drought) extends from 1974 to 2018. It is represented by a large number of dry events with negative SPI values. For example, for 1996, -2.22 in Hamiz dam station. For 1989, -3.26 in Dar El Beida station and -2.96 in Larbaa station. For 2015, -3.18 in Baraki station. The rainfall deficit and surpluses are estimated at 55% and 45%, respectively, compared to the annual average precipitation for the five selected weather stations (Period: 1906-2018). The number of rainfall events is large but low in intensity.

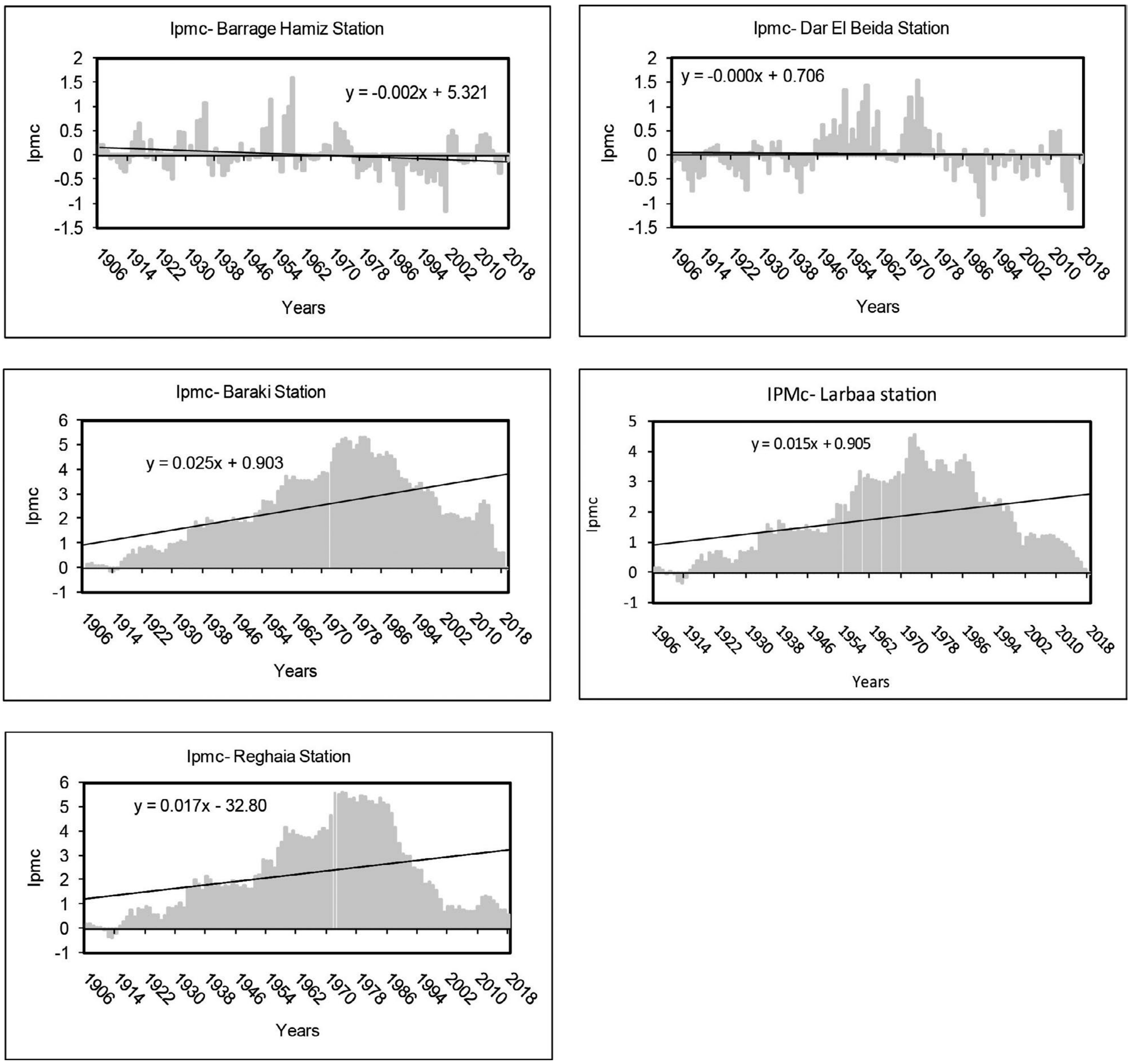

Fig. 5 - Cumulative deviations from the mean precipitation. Ipmc: Index of the deviation proportional to the cumulative average.

Fig. 5 - Differenze cumulate rispetto alla precipitazione media. Ipmc: Indice della deviazione proporzionale alla media cumulata.

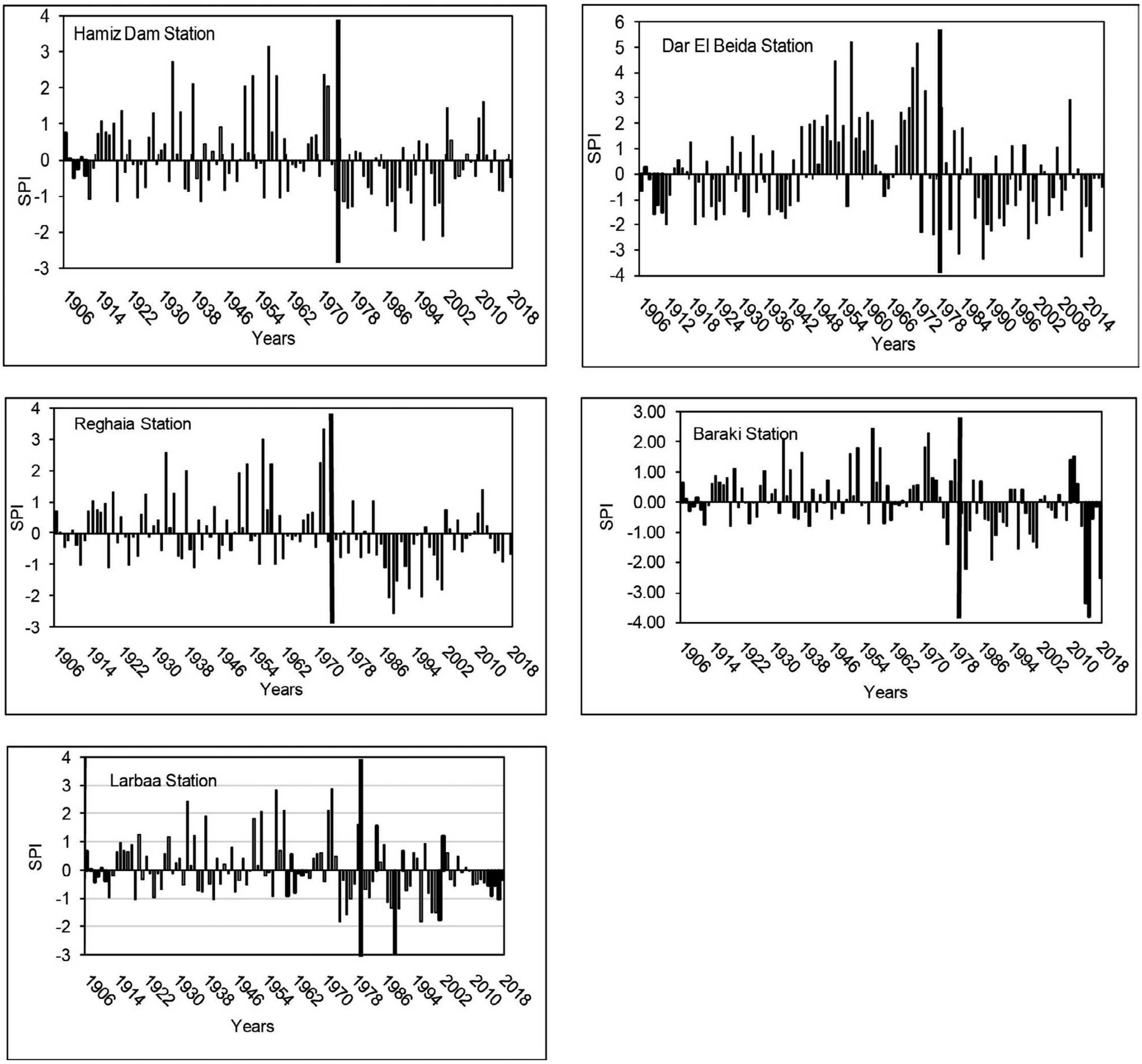

Fig. 6 - Variation of the Standardized Precipitation Index (SPI) in the study area.

Fig. 6 - Variazione dell'indice di precipitazione standardizzato (SPI) nell'area di studio.

Spatiotemporal evolution of humidity

The spatial representation of the humidity for the five selected weather stations (series data for the period 1906-2018), as derived from SPI values, has been represented in Figure 7. It is shown that the humidity rate has declined sharply from the north to the south-west of the study area, during the study period. For example, the humidity rate reached 22-26% during the period 1906-1973 in the Dar El Beida region and continued to expand to cover half of the study area during the period 1974-2018 (Tab. 4). Whereas, the year 1973 is considered as a transition year (break year) where the humidity rate marked at 55% for the 1906-1973 period (Tab. 4 and Fig. 7A) decreased to 27% for the period 1974-2018 (Tab. 4 and Fig. 7B). Conversely, the rate of the drought increased from 45% for the period 1906-1973 to 68% for the period 1974-2018 (Tab. 3).

Tab. 4 - Frequency (in %) of appearance of humidity and drought during the periods 1906-2018.

Tab. 4 - Frequenza (come %) della comparsa di anni umidi e siccitosi nel periodo 1906-2018.

Periods	1906-1973			1974-2018		
Classification	Number of years	%	Σ%	Number of years	%	Σ%
Moderate humidity	115	34	55	52	23	32
High humidity	33	10		16	8	
Extreme humidity	36	11		3	1	
Moderate drought	124	37	45	91	41	68
Severe drought	27	8		46	21	
Extreme drought	0	0		12	6	
Total (%)			100			100

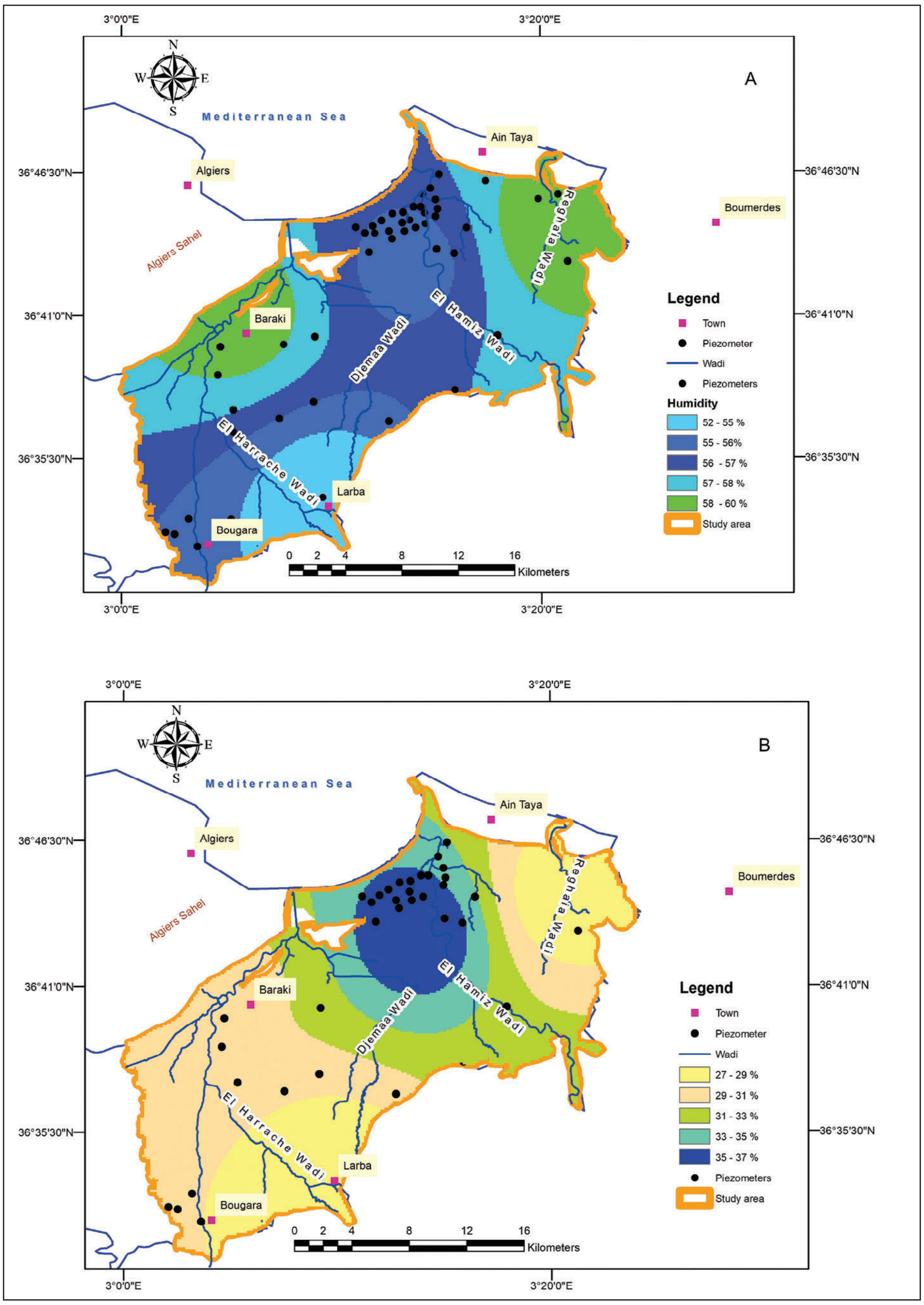

Fig. 7 - Spatiotemporal evolution of humidity (A: Period 1906-1973, B: Period 1974-2018).

Fig. 7 - Evoluzione spaziotemporale dell'umidità (A: Periodo 1906-1973, B: Periodo 1974-2018).

Impact of climatic variability on groundwater resources

To understand the effect of climatic variability on groundwater, we performed an analysis of piezometric maps of the Quaternary alluvial aquifer from May 1973, April 1981, May 2015 and July 2020. A significant drawdown was observed between the years 1973 and 2020, ranging from 10 to 80 m.

For the years 1973 and 1981 (Figures 8A and 8B), the piezometric maps show that the general flow direction was south-north, from the Blidean Atlas piedmont towards the sea. These piezometric maps were considered as the best available data of the permanent regime since it represents the values observed at the end of the dry season and before the increase in abstractions for the water demand (realization of new wellfields).

In 2015 (Fig. 9A), the surface of the piezometric map was completely changed. The piezometric level was several meters below sea level in the north part and a reversal of the flow direction (from the sea toward the continent), implying a hydrodynamic imbalance responsible for the seawater intrusion. we note the presence of a depression in the Hamiz wellfield with a piezometric value of -30 m. Moreover, this depression increased in 2020 (Fig. 9B) and reached values varying between -10 and -35 in the entire aquifer surface. The observed intense decrease in the piezometric values due to the overexploitation (increase in water demand) and to the decrease in groundwater recharge (drought period). As an example, 217 boreholes were drilled in 2019 to relieve the water demand in agriculture, industry and drinking water supply of the Algiers, Blida and Boumerdes cities. Unfortunately, the overexploitation of groundwater has contributed to a significant drawdown.

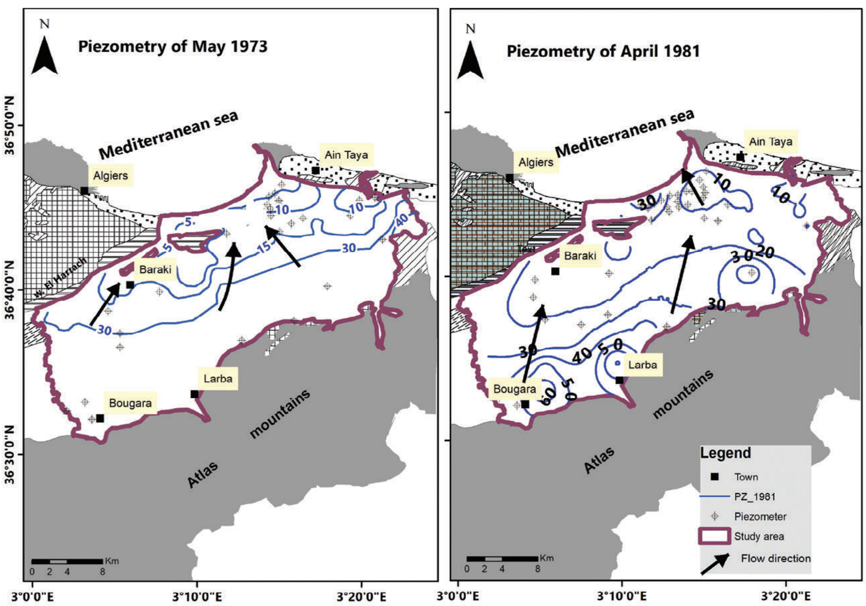

Fig. 8 - Piezometric maps: A) May1973 and B) April 1981.

Fig. 8 - Carte piezometriche A) Maggio1973 e B) Aprile 1981.

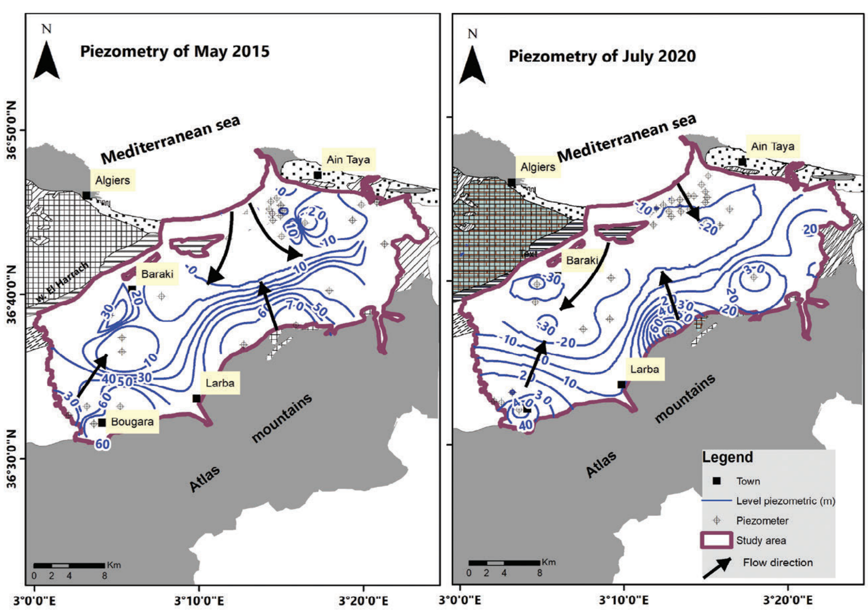

Fig. 9 - Piezometric maps A) May 2015 and B) July 2020.

Fig. 9 - Carte piezometriche A) Maggio 2015 e B) Luglio 2020.

Relationship between drawdown and overexploitation of the study area

Nowadays, the quaternary alluvial aquifer of the Eastern Mitidja contains 41 water points in exploitation. Between August 1999 and October 2021, the aquifer experienced an important piezometric fluctuation which resulted in a decrease of the water table, reaching 10 to 80 m. For the PZ1 Hamiz piezometers (Fig. 10), located in the northeastern part (Hamiz wellfield), the decrease in the piezometric level was observed with a value of -3 m in 1995 and -14 m in 2020. These results demonstrate the overexploitation of groundwater in this region, which is also inducing a seawater intrusion phenomenon. For example, the exploitation rate in the study area passed from 43.74 x 10^6 m^3 in 2001 to 77.32 x 10^6 m^3 in 2013 and 46.56 x10^6 m^3 in 2021 (Fig. 11). A drop in production is marked in 2021 following the drop in rainfall which is confirmed in the previous parts.

Conclusions

This study was conducted on the quaternary alluvial aquifer of the Eastern Mitidja plain, which is currently being overexploited. This overexploitation could have severe consequences on the future of the aquifer and highlights the impact of rainfall variability and drought on the drawdown of the aquifer. If the rainfall decreases, this drawdown can evolve negatively over time.

By applying the three statistical tests (Pettitt's, Buishand's U statistic and Lee and Heghinian's test) and two drought indices (SPI and Ipmc), we concluded that over the observation period (1906-2018), the Eastern Mitidja plain precipitation identified two distinct periods: i) the first period is wet and extends from 1906 to 1973 and ii) the second period is dry from 1974 to 2018 which is characterized by a rainfall deficit of 15% to 19% compared to the first period. Moreover, research on climate variability has been conducted by many authors in the southern part of the Mediterranean basin, we cite: 1) in Algeria Meddi M and Meddi H, 2009, Drouiche et al., 2019, Gherissi et al., 2021 who estimated a rainfall deficit between 15% and 26%, 2) in Morocco and Tunisia, the rainfall deficit was estimated at 10% to 35% causing a decrease in surface flows (Ouhamdouch et al., 2018; Kingumbi et al., 2005). We can conclude that the climate variability response in the study area shows a behavior identical to that identified in the southern part of the Mediterranean basin.

Among the consequences of this drought there are the decrease in surface flows as well as the decline of the piezometric level in the aquifer. Moreover, the water demand is constantly increasing and the groundwater recharge by rainfall is insufficient. This situation caused an alarming

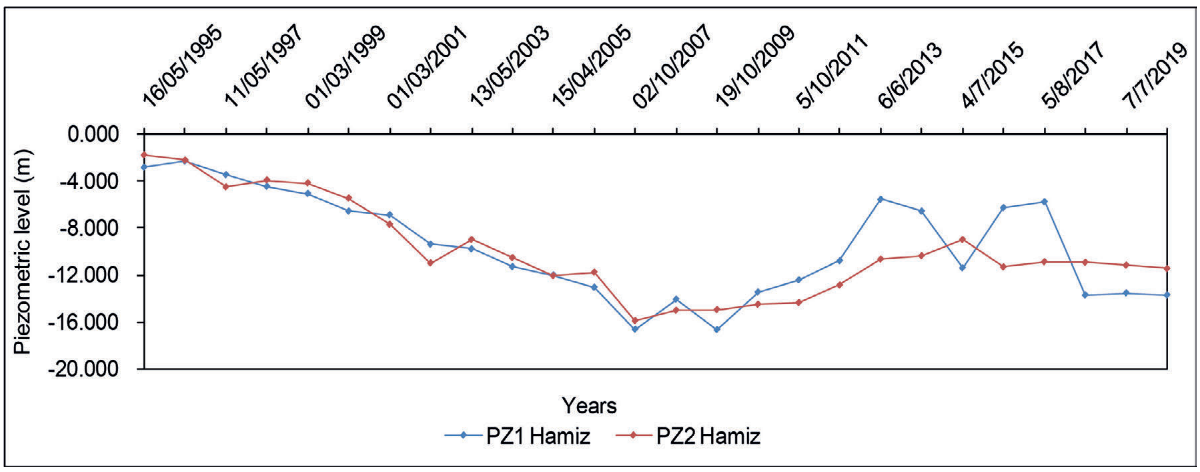

Fig. 10 - Evolution of the piezometric level (1995-2020).

Fig. 10 - Evoluzione del livello piezometrico (1995-2020).

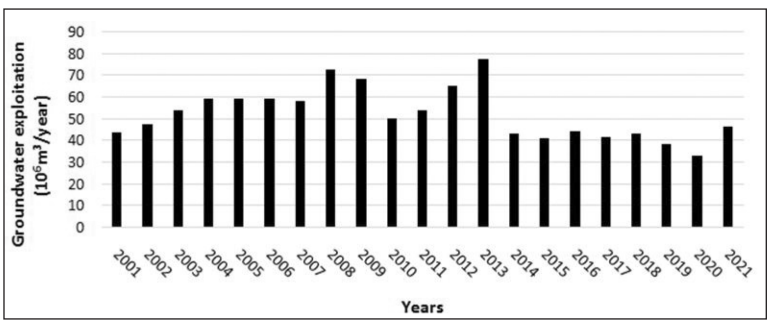

Fig. 11 - Groundwater exploitation in the eastern Mitidja aquifer.

Fig. 11 - Prelievo di acque sotterranee dall'acquifero Mitidja orientale.

drawdown of the piezometric level which reflects the evolution of the seawater intrusion in the north-eastern part of this aquifer. For instance, the analysis of the piezometric maps of the years 1973, 1981, 2015 and 2020 indicate significant drawdown in the piezometric levels. It varies between 10 and 80 m in 2020; where a negative piezometric values (between -10 and -35 m) are observed in the northern and north-eastern part of the study area.

Finally, in order to achieve better groundwater management, several measures need to be taken: i) the continuous monitoring of the drought evolution by the application of new indices to highlight it like the Standardized Stream Flow Index (SSFI) ii) stop the realization of new boreholes in the aquifer and pumping well in coastal zone affected by seawater intrusion, iii) control its quality (hydrochemical control) and its piezometric levels periodically (during the wet and dry periods for each hydrological year) iv) use the artificial recharge method from the existing wastewater treatment plants in the study region; this technique has been successfully tested in arid and semi-arid regions by several authors (Sundaram et al., 2008; Javadi et al., 2021; Rodriguez et al., 2021; Boufekane et al., 2022), and v) perform the regionalization of the results found.

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Competing interest

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Author contributions

All authors contributed to the data collection, data processing, results interpretation, writing, review, study conception and design. All authors read and approved the final manuscript.

Additional information

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