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The use of GIS and remote sensing to evaluate climate change effect on groundwater: application to Mostaganem Plateau, Northwest Algeria

Utilizzo di GIS e telerilevamento per valutare l'effetto del cambiamento climatico sulle acque sotterranee: Applicazione all'Altopiano di Mostaganem, Algeria Nord-Occidentale

Cherifa Hanene Kamelia CHEMIRIK[a], **Djelloul BAAHMED**[a] ✉, **Rachid NEDJAI**[b], **Djamel BOUDJEMLINE**[c], **Ikram MAHCER**[a]

[a] Civil and Environmental Engineering Laboratory (LGCE), Hydraulic Department, Faculty of Technology, University of Djillali Liabes, 22000 Sidi Bel Abbes, Algeria. E-mail: *chemirikcamelia@gmail.com*; ✉ *baahmed78@yahoo.fr; ikrammahcer13@gmail.com*

[b] CEDETE Laboratory EA 1210, University of Orleans, 10 Rue de Tours, 45069 Orléans, France. E-mail: *rachid.nedjai@univ-orleans.fr,*

[c] Laboratory of Management and Water treatment (LGTE), Faculty of Architecture and Civil Engineering, University of Science and Technology of Oran-Mohamed Boudiaf, BP 1505, El M'Naouer, Oran 31000, Algeria. E-mail: *djamel.boudjemline@univ-usto.dz*

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Correspondence to:
Djelloul Baahmed ✉
baahmed78@yahoo.fr

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Parole chiave: cambiamento climatico, LST, NDVI, precipitazioni, MLR, GIS, acque sotterranee, Algeria.

Riassunto

Gli effetti del cambiamento climatico nelle aree semiaride si manifestano in eventi di siccità che influenzano le falde acquifere, la cui ricarica è strettamente dipendente dalle precipitazioni. L'obiettivo di questo studio è quello di valutare la relazione tra profondità delle acque sotterranee (DTW), precipitazioni, Normalized Difference Vegetation Index (NDVI) e la temperatura superficiale del suolo (LST), nelle falde acquifere alluvionali di Mostaganem Plateau, Algeria nel 2000, 2005, 2010-2011 e 2014-2015. L'analisi è stata condotta utilizzando una metodologia che integra il telerilevamento, i Sistemi Informativi Geografici (GIS) e l'analisi statistica: analisi di correlazione e modelli di regressione lineare multipla (MLR). I risultati indicano un calo di 62mm nelle precipitazioni dal 2000 al 2015 inducendo cambiamenti nei pattern spaziali. Ciò ha provocato un aumento di DTW (4m a 10m). Una significativa correlazione negativa tra la riduzione delle precipitazioni e l'incremento della DTW, confermata da un valore R^2 di -0,80, è evidente. I valori di NDVI e LST sono incrementati rispettivamente di 0,034 e di 3,38 °C. Le relazioni tra DTW, NDVI e LST hanno evidenziato una correlazione negativa decrescente. La MLR ha confermato l'influenza delle precipitazioni evidenziando inoltre l'impatto dell'attività umana sull'efficacia degli indicatori DTW e siccità. Alti valori di NDVI hanno indicato un pompaggio intensivo delle acque sotterranee, mentre un elevato LST ha contribuito alla diminuzione di DTW a causa di una maggiore velocità di evaporazione causata da cambiamenti nei tipi di colture derivanti da azioni umane. Questo studio contribuisce alla comprensione delle interazioni dinamiche tra DTW, precipitazioni e attività antropogeniche e fornisce informazioni ai decisori in materia di strategie di irrigazione.

Abstract

Effects of climate change in semi-arid areas occur in drought events, which affect aquifers whose recharge depends essentially on precipitation. The objective of this study is to evaluate the relationship between depth to groundwater (DTW), precipitation, Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST), in the alluvial aquifer of Mostaganem Plateau, Algeria over 2000, 2005, 2010-2011 and 2014-2015. This is caried out through an adaptive methodology, using remote sensing, Geographic Information Systems (GIS), and statistical analysis: correlation analysis and Multiple Linear Regression (MLR). The results indicate a 62 mm decline in precipitation from 2000 to 2015, inducing shifts in spatial patterns. This resulted in an increase of DTW (4 m to 10 m). The strong negative correlation between decreased precipitation and increased DTW, supported by an R^2 *value of -0.80, is evident. Moreover, NDVI and LST values increased notably by 0.034 and 3.38°C, respectively. The relationship between DTW, NDVI, and LST showed a diminishing negative correlation. The MLR reaffirmed the influence of precipitation and highlighted the impact of human activity on DTW and drought indicators effectiveness. High NDVI values indicated intensive groundwater pumping, while elevated LST contributed to DTW decrease due to increased evaporation rates caused by changes in crop types resulting from human actions. This study contributes to the understanding of the dynamic interactions between DTW, precipitation, and anthropogenic activities and gives insight to decision makers regarding irrigation strategies.*

Introduction

Groundwater sustains multiple aspects of human and ecological systems. Recent advancements in hydrological science, such as the work by (Birylo, 2020; Lu et al., 2021; Thomas et al., 2016), have furthered our understanding of how climate change is altering the global water cycle. These studies reveal significant trends affecting water availability, emphasizing the urgency of adapting our water management strategies to ensure sustainability amid evolving environmental conditions. The latest Intergovernmental Panel on Climate Change reports underline the escalating global climate crisis, which is intensifying extreme weather events in Africa, as a result of anthropogenic climate change (IPCC, 2023). Further, the projected decline in precipitation and the prolonged arid periods in north Africa will have an impact on surface water resources, thereby leading to a greater dependence on groundwater (Tramblay et al., 2020). In fact, the last thirty years, Algeria have seen a surge in water demand attributed to population migration driven by rising temperatures (Stambouli et al., 2016). This has led to the densification of urban areas, resulting in decreased runoff and infiltration (Touitou & Abul Quasem, 2018). Moreover, the recent occurrences of heatwaves and droughts in North African regions during spring and summer 2023, Algeria included, serve as tangible manifestations of the effects of climate change (Oxford Analytica, 2023; Philip et al., 2023).

The relationship between climate change and groundwater levels is crucial for effective groundwater management, especially in arid and semi-arid regions where meteorological droughts is of increasing concern (Barkey & Bailey, 2017; Fistikoglu et al., 2016; Henrique et al., 2020). (Barkey & Bailey, 2017) observed that drought episodes have depleted approximately 55% of the water storage of the aquifers in the Marshall Islands. In California's Central Valley, where irrigation primarily depends on groundwater, (Liu et al., 2022) noted that during drought periods, water allocated for irrigation fell below 50% in 12 out of the 18 years studied. And throughout the last fifty years, north African countries proved to be exceptionally vulnerable to climate change and endured several severe droughts, including those in the 1940s, 1980s, and present period (Abdelhamid et al., 2023; Madene et al., 2023; Ndehedehe et al., 2023; Tramblay et al., 2020). These droughts have led to a massive population movement from south to north, inducing a rise of urban area (Ceola et al., 2023).

Studies by (Jasechko et al., 2024; Ngo et al., 2024) demonstrate the susceptibility of alluvial aquifers to precipitation decline, emphasizing their reliance on consistent meteorological inputs, disrupted precipitation patterns, and increased evapotranspiration rates. These findings are crucial for devising effective strategies to preserve and manage groundwater resources in impacted areas. Additionally, a growing body of literature explored the relationship between precipitation and Depth To Groundwater (DTW) in semi-arid regions (Nassery et al., 2021; Tabari et al., 2012; Tsuyuguchi et al., 2020; Venkatesan et al., 2021). While previous studies have established frameworks for assessing the influence of precipitation on groundwater resources, they often necessitate long temporal series. In response to this limitation, there is a growing trend in utilizing remotely sensed indices such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and Land Surface Temperature (LST) for evaluating groundwater depletion (Pei et al., 2019; Song et al., 2021; Zhang & Wang, 2020). Nevertheless, groundwater drought assessment demands a more comprehensive approach beyond these two parameters, especially in agricultural regions like Mostaganem Plateau where groundwater is intensively pumped. Using a GIS induced correlation and multiple linear regression (MLR) among DTW, precipitation, and remote sensing indices offers a holistic perspective for evaluating these variables relationships and interactions.

In this study, we attempt to evaluate the potential relationship between DTW, precipitation, NDVI and LST, in the alluvial aquifer of Mostaganem Plateau, within the context of climate change, through correlation in QGIS and multiple linear regression (MLR), for the years 2000, 2005, 2010 and 2014. This approach will allow us to understand the dynamic relationship of these parameters in an intensive agricultural region. The adoption of this methodological approach is prompted by the paucity of available data. As far as the authors are aware, there are no studies investigating the effect of climate change on DTW and its relationship with NDVI and LST in this region. The presented methodology will provide decision-makers with crucial insights into the refinement of irrigation strategies, thereby facilitating informed and strategic planning for proactive interventions.

Site study

The Geographic and Climatic Situation

The study region is located in the northwest part of Algeria, along latitude 35° 45' 58.5" - 36° 0' 49.5"N and longitude 0° 0' 14.49" - 0° 26' 34.5"E (Fig. 1). The Mostaganem Plateau covers an area of 700 km^2 and is mostly used for agriculture (65%). It is bordered by the Mediterranean Sea to the west, the Ennaro and Belhacel mountains to the east, the Cheliff River to the north, and the Bordjias plain to the south. The terrain elevation declines from east to west with elevations ranging from 338 m to 10 m, and is affected by NE-SW oriented ripple lines. Due to its proximity to the Mediterranean Sea, the climatic characteristics are similar to the predominant climate in the Mediterranean region of North Africa, characterized by a semi-arid climate with mild, wet winters and hot, dry summers. Since 1990, a recent dry period has resulted in an average annual temperature of around 19.4 °C and an annual average precipitation of approximately 281 mm from 1990 to 2015 (Benfetta & Ouadja, 2020).

Geology and hydrogeology context

The main aquifer on the Mostaganem plateau is essentially located in Plio-quaternary sandstones and sands. This watertable aquifer rests on the low permeability marl formations of the Lower Pliocene and Miocene formations,

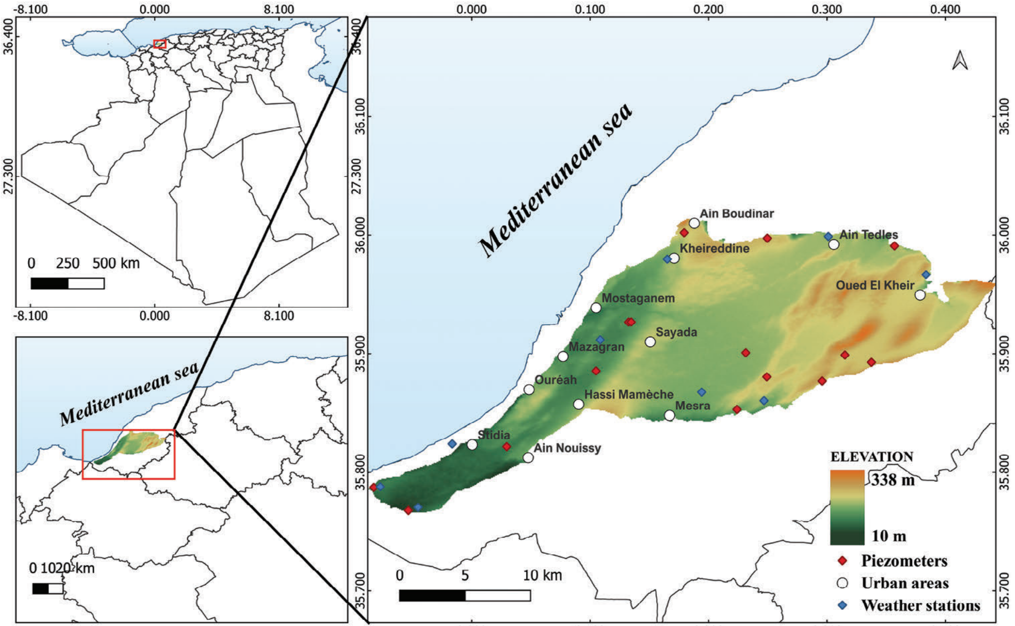

Fig. 1 - Location and elevation map of Mostaganem Plateau, and its delimitation according to Baiche et al., 2015.

Fig. 1 - Ubicazione e carta altimetrica del Mostaganem Plateau, e sua delimitazione secondo Baiche et al., 2015.

with a thickness ranging between 100 and 200 m, decreasing from east to west, an average depth to water table ranging from 4 to 10 m (Baiche et al., 2015; National Agency of Water Resources, 1975).

The aquifer primarily recharges from its impluvium and was exploited by over 201 wells in 2000, 57 springs, and monitored by 16 piezometers. The region has two main rivers: Ain Sefra and Kheir rivers that mainly feed on the aquifer due to scarce precipitations, the drainage system is very poorly developed (Benfetta & Ouadja, 2020). The region is mostly characterized by synclinals that promote the accumulation of precipitation water. Additionally, permeability measurements range from 1.10^{-4} to $7.5.10^{-4}$ m/s, with the highest values observed in a distinct V-shaped zone south of Ain Tedles, and varying significantly across other regions influenced by lumachellic formations (Bellal et al., 2020). The average transmissivity is 0.8.10-5 m^2/s, according to the piezometric investigations of 1975 (Benfetta & Ouadja, 2020), From (Fig. 3), the flow is from North-east to west. Overall, the flow converges toward the regions of Mesra and Ain Nouissy. The south-eastern and central parts have two domes, resulting in localised recharge zones. In the south and south-west, there are four depressions, reflecting localised drainage. These areas of drainage can be explained by over-exploitation of this part of the water table. The density of the contour lines in the south and the west, indicates a fairly steep hydraulic gradient.

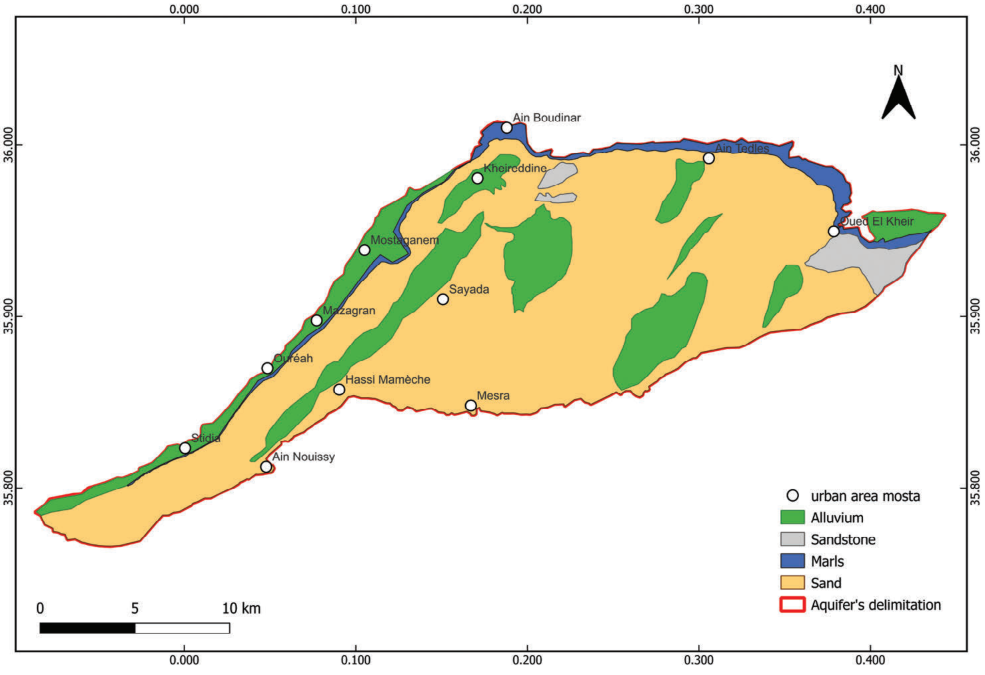

Fig. 2 - Geology and delimitation of Mostaganem Plateau aquifer based on the geological map of Algeria by general government of Algeria 1951-1952, second edition.

Fig. 2 - Geologia e delimitazione dell'acquifero del Mostaganem Plateau, basate sulla carta geologica dell'Algeria del governo generale dell'Algeria 1951-1952, seconda edizione.

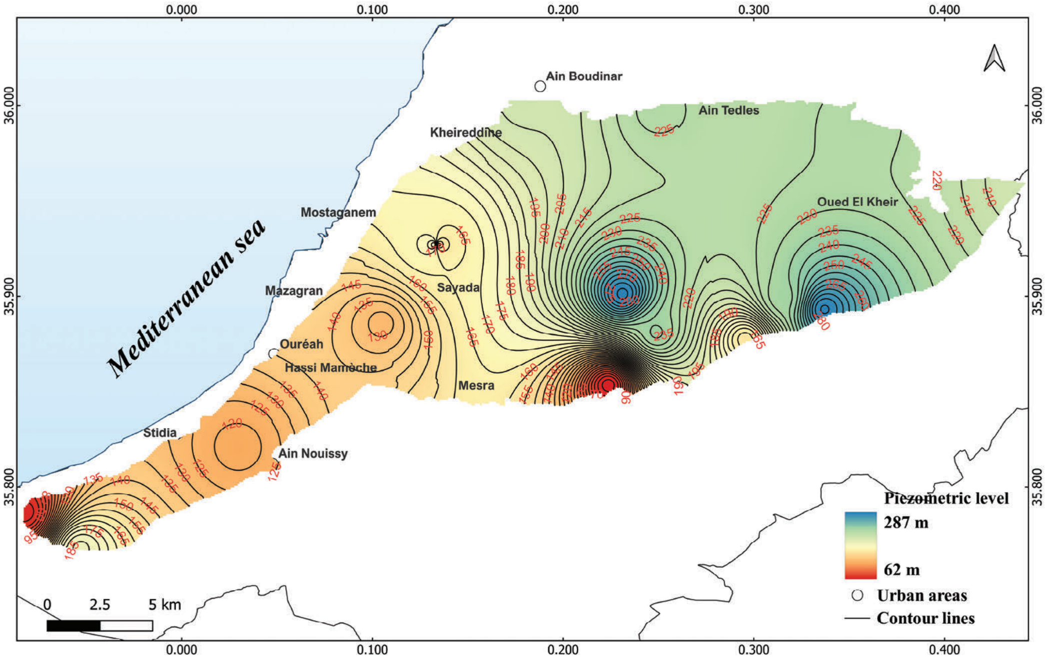

Fig. 3 - Piezometric map for the year 2005.

Fig. 3 - Carta della piezometria relativa all'anno 2005.

Materials and Methodology

This section pertains to the materials utilized in the research, the data preprocessing procedures (Fig. 3), and the methodological framework(Fig. 4) employed in the study.

Precipitation and groundwater: dataset collection and pre-processing

Precipitation and DTW, obtained from past site investigations by the "Algerian Water Agency" (ANRH), comprise data from 10 weather stations and 16 piezometers. The hydrologic year classification, starting in September and ending in August, was applied to both DTW and precipitation. Due to monitoring constraints, the study focused on the periods: September 2000 – August 2001, September 2005 – August 2006, September 2010 – August 2011, and September 2014 – August 2015.

For precipitation and DTW, spatial distribution mapping and yearly mean calculation were performed using inverse distance weighted (IDW) interpolation in GIS. IDW was selected for its dependence on maximum neighbouring observations, improvement of predictions at unsampled locations, and reduction of errors, as highlighted by (Ikechukwu et al., 2017). Additionally, (Keblouti et al., 2012) identified IDW as the optimal method for interpolating precipitation and groundwater data in Algerian basins..

Remote sensing applications in drought detection: dataset collection and pre-processing

This study uses remotely sensed indices NDVI and LST as drought indicators, which are widely used in arid and semiarid regions for drought detection. Their suitability for low latitude and elevation regions, deems them applicable for the study region (Karnieli et al., 2010).

Google Earth Engine (GEE), an online platform for remote sensing analyses, facilitated NDVI and LST calculations. Initial cloud correction, involving JavaScript adjustments for NIR and RED bands from Landsat 5 TM Collection 2 and Landsat 8 OLI Collection (Tab. 1). Then, the NDVI was calculated using the "raster calculator" in QGIS 3.22.

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad (1)$$

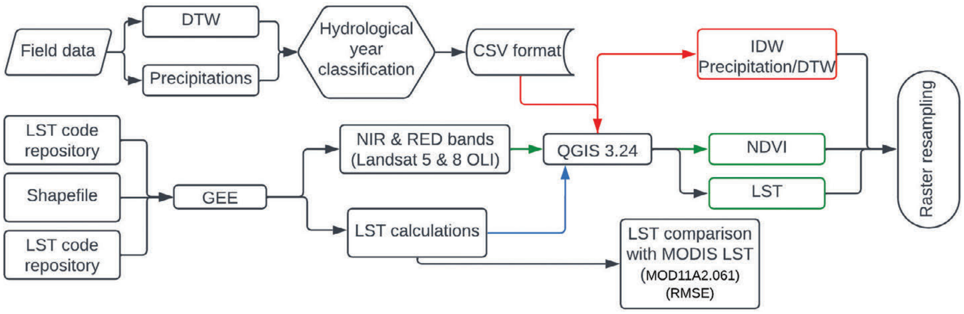

Fig. 4 - Flowchart illustrating pre-processing steps employed in this study.

Fig. 4 - Flusso di lavoro che illustra le fasi di pre-elaborazione dei dati.

Further, LST was calculated using GEE platform and JavaScript code (Ermida et al., 2020) repository (https://earthengine.googlesource.com/users/sofiaermida/landsat_smw_lst) from NDVI imagery. The LST datasets were exported in raster format to align with precipitation data resolution for consistent integration. The accuracy of the LST is evaluated by comparing the root mean square error (RMSE) with the MODIS LST dataset (MOD11A2.061 Terra Land Surface Temperature and Emissivity) (Wan, 2014).

Tab. 1 - Satellites and bands used in NDVI calculation.

Tab. 1 - Satelliti e bande usate per il calcolo del NDVI.

Satellite	TM-Landsat 5	OLI-Landsat 8
Bands	NIR: Band 4 RED: Band 3	NIR: Band 5 RED: Band 4
Wavelength (µm)	NIR: 0.76 - 0.90 RED: 0.63 - 0.69	NIR: 0.85-0.88 RED: 0.64-0.67
Resolution (m)	30	30

Methodological framework for evaluating precipitation, DTW, NDVI, and LST relationships

A common way to identify relationships between factors and their mutual influence on one another is the use of geostatistical methods. This paper assesses the interrelation of specified parameters using QGIS 3.22's "create grid" processing tool (Van DenHooven, 2020), applying raster values to the grid's centroid. Correlation analysis utilizes the geometric tool and the "Data Plotly" plugin. This spatial correlation employed a pixel-by-pixel correlation approach, where we compared the values of the raster datasets on a per-pixel basis. Applying an adaptive QGIS methodology used by (Venkata Sudhakar et al., 2022), we correlate satellite imagery outputs in this study. Subsequently, we conducted a Multiple Linear Regression (MLR), an extension of simple linear regression predicting variable values using two or more variables (Liou & Mulualem, 2019). It determines the overall fits of the model and the contribution of each predictor to the variance. MLR is applied in this study to evaluate DTW's susceptibility to precipitation in the alluvial aquifer of the plateau and to explore the relationship between DTW, NDVI, and LST for drought detection. The mathematical expression on a MLR model with k predictors is as follows (Holder, 1985; Nimon & Oswald, 2013):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ...\beta_k x_k + \varepsilon \qquad (2)$$

Where i=1, 2,…,k; ε is the residual term of the model; y is the dependent variable (DTW); x is the independent variable (precipitation, NDVI, LST); β_0 is the intercept, and β_1, β_2,…, β_k are the coefficient of x_i. This method was considered linear because groundwater responds linearly to precipitations in unconfined aquifers (F. Hussain et al., 2022). The nearest neighbour method in QGIS 3.22 was used to uniformly resample (30 m) the raster images to maintain spatial representation and alignment across layers and avoid interpolation variable effects. This resampling step ensures relationship analysis accuracy and reliability (Alsamadisi et al., 2020).

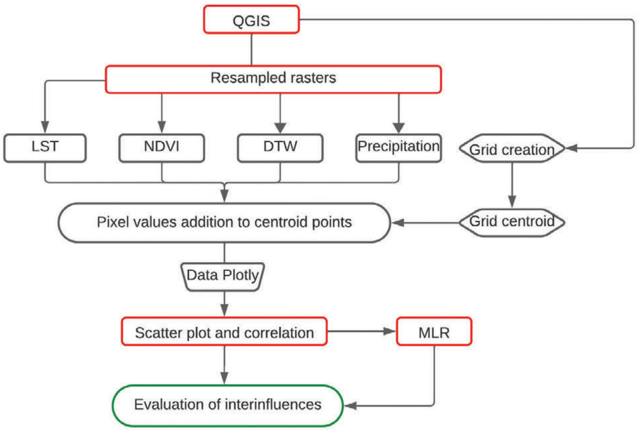

Fig. 5 - Flowchart illustrating the methodology employed in this study.

Fig. 5 - Flusso di lavoro che illustra la metodologia impiegata in questo studio.

Results and discussion

This section presents the main findings of the study, which focuses on assessing the impact of climate change on DTW variations, precipitation patterns, NDVI, and LST. It also discusses the impact of anthropogenic activities on the sensitivity of NDVI and LST in detecting drought conditions.

Evaluating precipitation's impact on DTW

The yearly minimum and maximum for each period of precipitation and DTW are provided in (Tab. 2). From 2000 to 2006, the amount of precipitation was most pronounced in the northwest and central areas of the plateau, gradually decreasing as it spread outward from the centre (Fig. 6 a & b). During this same period, the study area's southern, southeastern, and central northern regions exhibited high DTW values, while the lowest values were observed in the south and coastal areas (Fig. 7 a & b).

Tab. 2 - Inter-annual comparison of P and DTW.

Tab. 2 - Confronto inter-annuale di P e DTW.

	Precipitation (mm)			DTW (m)		
	Min	Mean	Max	Min	Mean	Max
2000-2001	301.71	413.88	526.59	3	16.49	29.99
2005-2006	283.52	390.55	497.6	4.23	15.35	26.48
2010-2011	297.72	361.03	424.34	6.77	17.97	29.17
2014-2015	280.9	351.89	422.89	8.65	19.69	30.73

In 2010–2011, precipitation rise near Ain Tedles, Ain Boudinar, Mostaganem, and Mazagran coincide with the increase in DTW in the southern plateau (Fig. 6. c). However, Ain Tedles and Oued El Kheir displayed lower DTW levels. The southwestern region, including Hassi Mamèche, south, and east of Ain Nouissy, and Mesra, experienced a notable DTW increase during 2010-2011 (Fig. 6. c), persisting into 2014-2015, except for Mazagran and the periphery of Hassi Mamèche. These findings align with (Baiche et al., 2015),

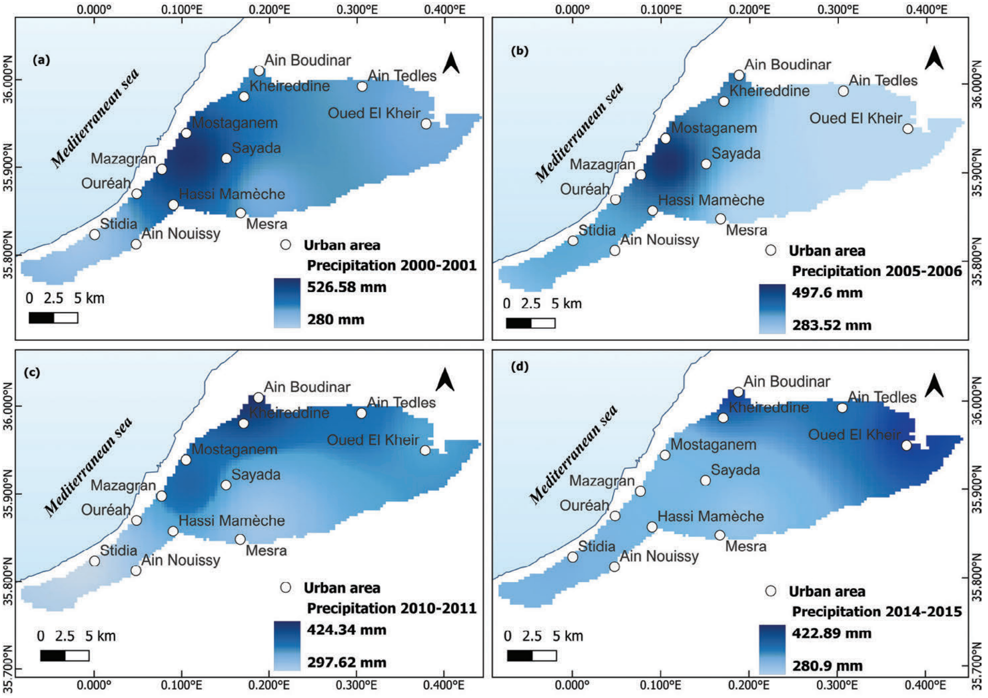

Fig. 6 - Average annual precipitation for (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, and (d) 2014-2015.

Fig. 6 - Precipitazione media annua per (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, e (d) 2014-2015.

indicating that the aquifer experienced a considerable increase in DTW near Mazagran, Ouréah, Ain Nouissy, Mesra, and the south of the plateau, which corroborates with the findings of this study

The variations of DTW mimic precipitation fluctuations and changes in their pattern. Giving that the Mediterranean region is considered a major climate change hotspot, the changing pattern of precipitation can be explained by the increased moisture divergence by the time-mean flow, due to anomalous anticyclonic circulation in the region (Seager et al., 2014; Tuel.A & Eltahir.E.A.B, 2020). While the alterations in precipitation patterns observed in the Mostaganem plateau region since 2010, may be influenced by various factors, the role of greenhouse gas emissions from the local ammonia production industry has not been conclusively established as the primary driver of these changes. According to (Hennane et al., 2019), the production of ammonia resulted in 588 tonnes of carbon dioxide in 2014 and 554 tonnes in 2015. Greenhouse gases affect precipitation patterns and intensity by altering cloud properties indirectly through atmospheric heating and changes in ice nuclei and cloud condensation nuclei (IPCC., 2022). Anthropogenic air pollution may also worsen water scarcity by suppressing rainfall processes, as suggested by (Maboa et al., 2022). These modifications include changes in size, location, and concentration of precipitations (Tang et al., 2018). The strong negative correlation between DTW and precipitation (R^2 = 0.80 for all the periods) (Fig. 8) indicates that reduced precipitation leads to increased DTW.

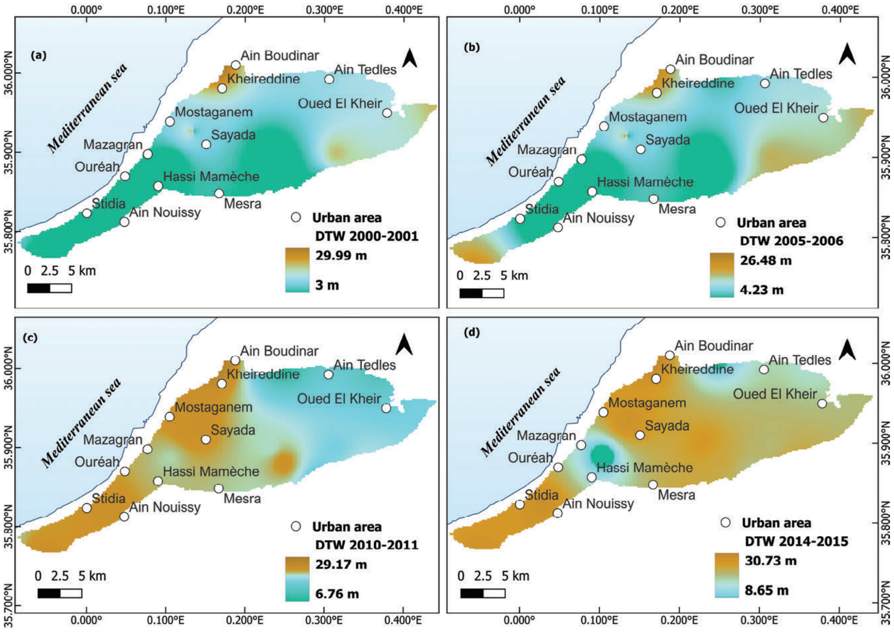

Fig. 7 - Average annual precipitation for (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, and (d) 2014-2015.

Fig. 7 - Soggiacenza media annua della falda per (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, e (d) 2014-2015.

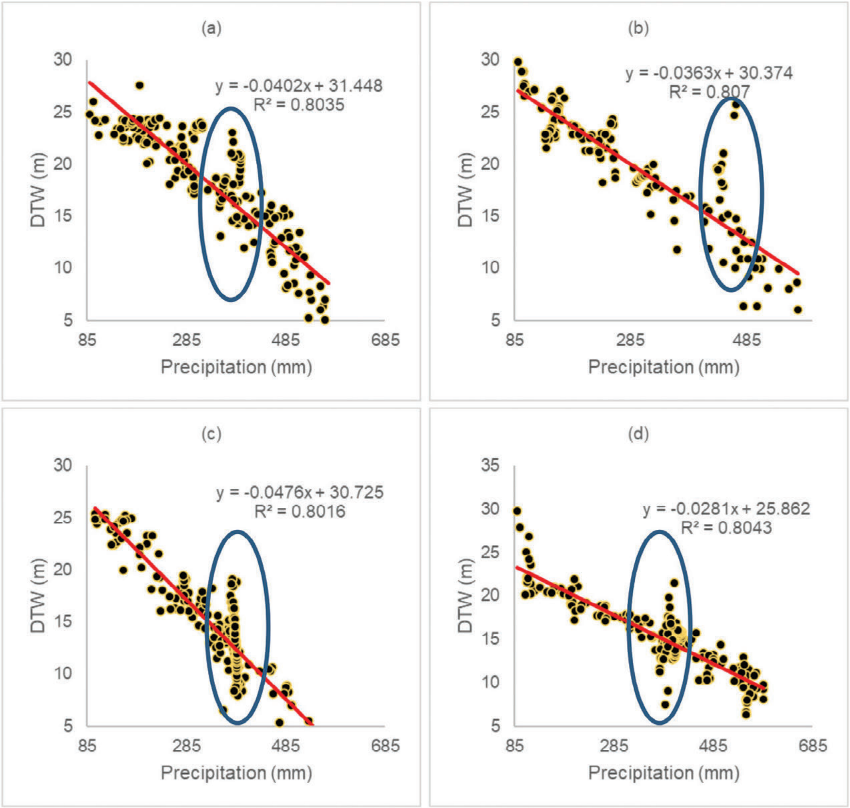

Fig. 8 - Linear correlation of DTW and precipitation for (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, and (d) 2014-2015.

Fig. 8 - Correlazione lineare tra la soggiacenza della falda e la precipitazione per (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, e (d) 2014-2015.

This is because precipitation is the primary source of recharge for the aquifer, consistent with the findings of (Boukrentach et al., 2017). Consequently, natural recharge of the aquifer is reduced.

Further, the anomaly of stacked values around 300mm can be observed in (Fig. 9). This anomaly may be caused by a recurring precipitation pattern, and is worsened by the interaction of excessive pumping with the effects of this precipitation pattern, leading to high DTW values. On the other hand, for low DTW values, values around 300mm can serve as the threshold at which water collection in lineaments is effective for infiltration.

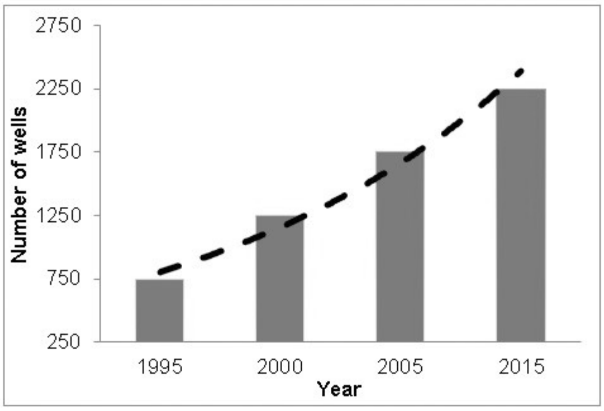

Fig. 9 - Evolution of Licensed Wells in Mostaganem Plateau: Histogram and Trend (from Water resources department).

Fig. 9 - Evoluzione del numero di pozzi autorizzati nel Mostaganem Plateau: Istogramma e Trend (dal dipartimento delle risorse idriche).

The study reveals an increasing DTW in Mostaganem which can be attributed to a combination of factors. The exposed bedrock aquifer located on the northwestern outskirts of the city, renowned for its many springs and water sources exploited by the local community, is a significant factor influencing the hydrogeological processes in the region. With insufficient rainfall, the population heavily relies on groundwater, facing threats from illegal pumping wells and drought-induced aquifer challenges. In 2014, the Department of Hydraulics in Mostaganem's wilaya documented 2,000 boreholes and wells on the plateau (Fig. 9), excluding clandestine wells, particularly in agricultural areas. The proliferation of electromechanical wells may contribute to DTW depletion. Drought on the plateau has led to the drying of boreholes, wells, and springs, compelling farmers to dig new wells and deepen existing ones.

Evaluating DTW, NDVI and LST dynamic:

The yearly minimum and maximum for each period of NDVI and LST are provided in (Tab. 3).

Figure 10 and Figure 11 show, during 2000 to 2015, that NDVI indicates a slight increase, while LST displays a more pronounced rise during this period. The mean NDVI showed that the urban fabric has become denser and that the modest vegetation cover has increased slightly from 2000 to 2005 (Fig.10 a & b). However, in 2010–2011, NDVI increased to 0.32, to finally drop in 2014–2015, in the plateau's southwest and southern borders. The weak vegetation has been replaced by barren lands and built-up areas (Fig. 9 d). Low NDVI values near Mostaganem city, Mazagran, Sayada, Oued El

Kheir, and Hassi Mamèche, suggest increased land expansion, contributing to decreased vegetation cover and rise of runoff. Changing natural environments into managed land use types results in elevated surface runoff due to decreased infiltration rates, ultimately leading to the depletion of groundwater resources.

Given the region's agricultural nature (Baiche et al., 2015; Bellal et al., 2020), the NDVI increase in the central and eastern parts of Mostaganem Plateau from 2000 to 2015 may be attributed to the intensive use of previously abandoned agricultural land. (Boualem et al., 2015), reported that only 5.4% of the plateau's agricultural lands and crops are irrigated by surface water mobilized by dams, while 96.6% is irrigated by groundwater from wells, boreholes, and springs.

Tab. 3 - Inter-annual comparison of LST and NDVI.

Tab. 3 - Confronto inter-annuale degli indicatori LST e NDVI.

	LST (°C)			NDVI		
	Min	Mean	Max	Min	Mean	Max
2000-2001	21	26.05	31.11	0.026	0.113	0.27
2005-2006	21.96	26.61	31.26	0.029	0.156	0.29
2010-2011	23.13	27.29	31.46	0.032	0.176	0.32
2014-2015	25.7	29.43	33.17	0.01	0.150	0.29

LST accuracy was assessed with RMSE, comparing results with MODIS LST across the four periods (RMSE values: 2.2°C, 2.1°C, 2.2°C, 2.5°C). These moderate values may stem from downscaling MODIS LST data to match with Landsat 5 and Landsat 8 OLI resolutions and differing atmospheric correction methods: RTM for Landsat, split-window algorithm for MODIS (Li et al., 2023).

The mean LST value increased by 3.38°C between 2000-2015 (Tab. 3). LST shows a slight increase between 2000 and 2011 in the maximum and minimum temperature; about 2.13°C for the minimum and 0.35°C for the maximum. However, the minimum and maximum temperatures in 2014-2015 were notably higher, with a 4.7°C and 2.7°C difference compared to 2000-2001, respectively. In 2000 and 2005, the southern, southeastern, and some central northern areas of the study region had the highest LST values (Fig. 11 a & b). In 2000 and 2005, the northeast and central plateau regions, near Kheireddine and Sayada, had lower LST values. In the same periods, these regions had also low DTW. These results corroborates with those of (Malik et al., 2021), who found that regions with shallow groundwater display low LST values.

Coastal and southern areas have the lowest values. These areas are characterized by low NDVI values, indicating the presence of bare land and urban areas, and have lower LST values, contrary to what is indicated in the literature (Hussain & Karuppannan, 2023; Roy & Bari, 2022). This finding is surprising, given that urban and low-vegetation areas are frequently associated with high LST values in the literature. These results are in line with those of (Al-ruzouq et al., 2022), who found that, in arid and semi-arid regions, the cooling influence of the wind and the Mediterranean breeze from the sea might explain this phenomenon. The LST of barren and urbanized land along the coast is low, and it rises as the distance from the coastline increases. Furthermore, DTW increased gradually and significantly from 2000 to 2015, which contributed to the augmentation of LST values. Nevertheless, in this coastal area, the effect of high DTW

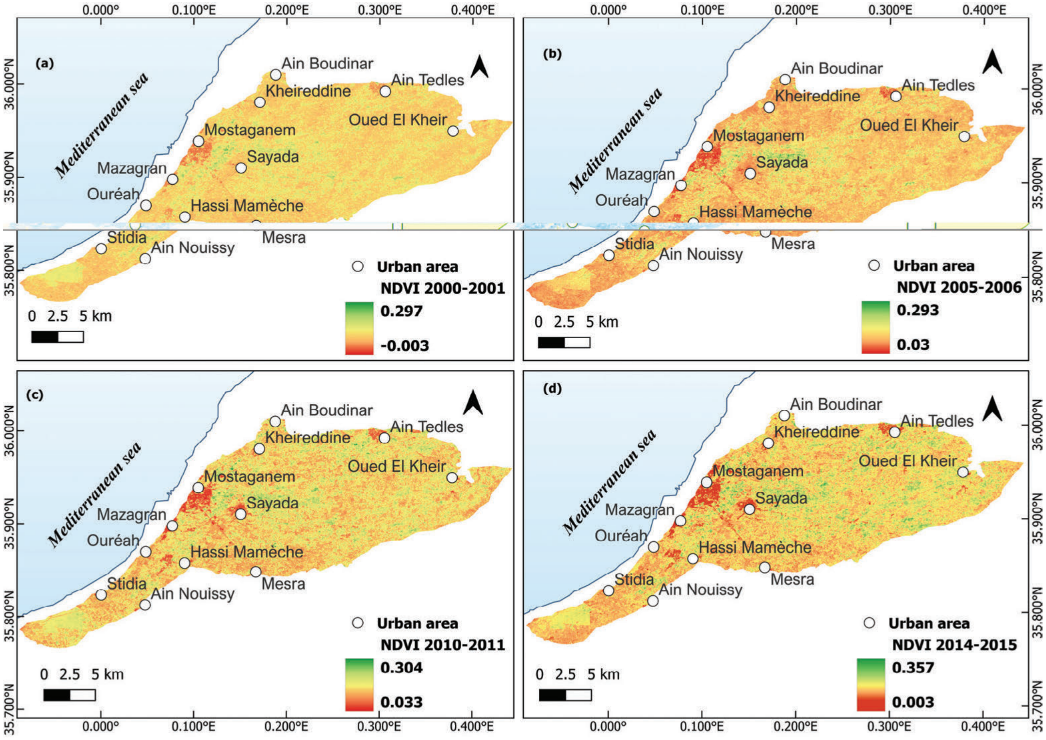

Fig. 10 - Average annual NDVI for (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, and (d) 2014-2015.

Fig. 10 - NDVI medio annuale per (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, e (d) 2014-2015.

and barren land on LST values is dampened by the effect of cold winds.

From 2000 to 2015, LST values were highest in the south and south-eastern regions. Southern and southeast areas had consistently high LST values, while coastal areas saw a slight increase. In 2010–2011 and 2014–2015, the plateau's southern, northcentral, and longitudinal axis linking northeastern to western areas had higher mean temperatures (Fig. 11 c & d). Alterations in crop types and land conversion to urban areas may contribute to an increase in LST. The agricultural practices prevalent in Mostaganem plateau involve the cultivation of vegetable crops, fruits, corn, and whole-grain cereals. These activities have been observed to contribute to elevated levels of land surface temperature (Medina-Fernández et al., 2023). The rise in LST may increase evaporation in shallow groundwater areas, depleting it (Condon et al., 2020).

The correlation coefficient (R^2) of DTW/ NDVI and DTW/ LST are (0.6632, 0.6074, 0.3110, and 0.2024) (Fig. 12) and (0.7138, 0.7817, 0.7779 and 0.7718) (Fig. 13), respectively. The DTW/NDVI relationship is strongly negative for 2000 and 2005, the years with the lowest NDVI. This suggests that vegetation rely on groundwater supplies (Robinson et al., 2008). These findings align with similar studies by (Jin et al., 2019; Song et al., 2021), which also observed a negative correlation between NDVI and DTW in unconfined aquifers in semi-arid climates. However, as the low R^2 indicates a marginal relationship between NDVI and DTW in 2010 and 2014. As mentioned earlier, the croplands on Mostaganem Plateau depend on extracted groundwater for irrigation, which is currently the only water source in arid and semi-arid regions (Fayech & Tarhouni, 2021). This dependence on pumped groundwater is a key factor shaping local vegetation and soil conditions. Additionally, areas with high DTW (a consequence of excessive pumping) have deep vadose zone compared toregion with low DTW. This difference in DTW directly impacts soil moisture content, with the high DTW areas experiencing lower soil moisture levels (Hamzeh et al., 2018). In the high DTW areas, vegetation is primarily nourished by the extracted groundwater used for irrigation, rather than relying on limited soil moisture. This can impact the soil thermal properties and LST (Malik et al., 2021).

The conversion of native vegetation to rangelands in semi-arid regions tends to reduce groundwater recharge. This is because grazing animals compact the topsoil, reducing water pore volume and saturated soil hydraulic conductivity, which in turn destroys macropores (Owuor et al., 2016). Evapotranspiration (ETP) also has an impact on the correlation between DTW and LST. Higher ETP depletes groundwater, leading to elevated LST (Condon et al., 2020).

Further, the anomaly of stacked values for more than 30°C for 2000 and 2005, and less than 30°C for 2010 and 2014, can be noticed from (Fig. 13). For values greater than 30°C, this

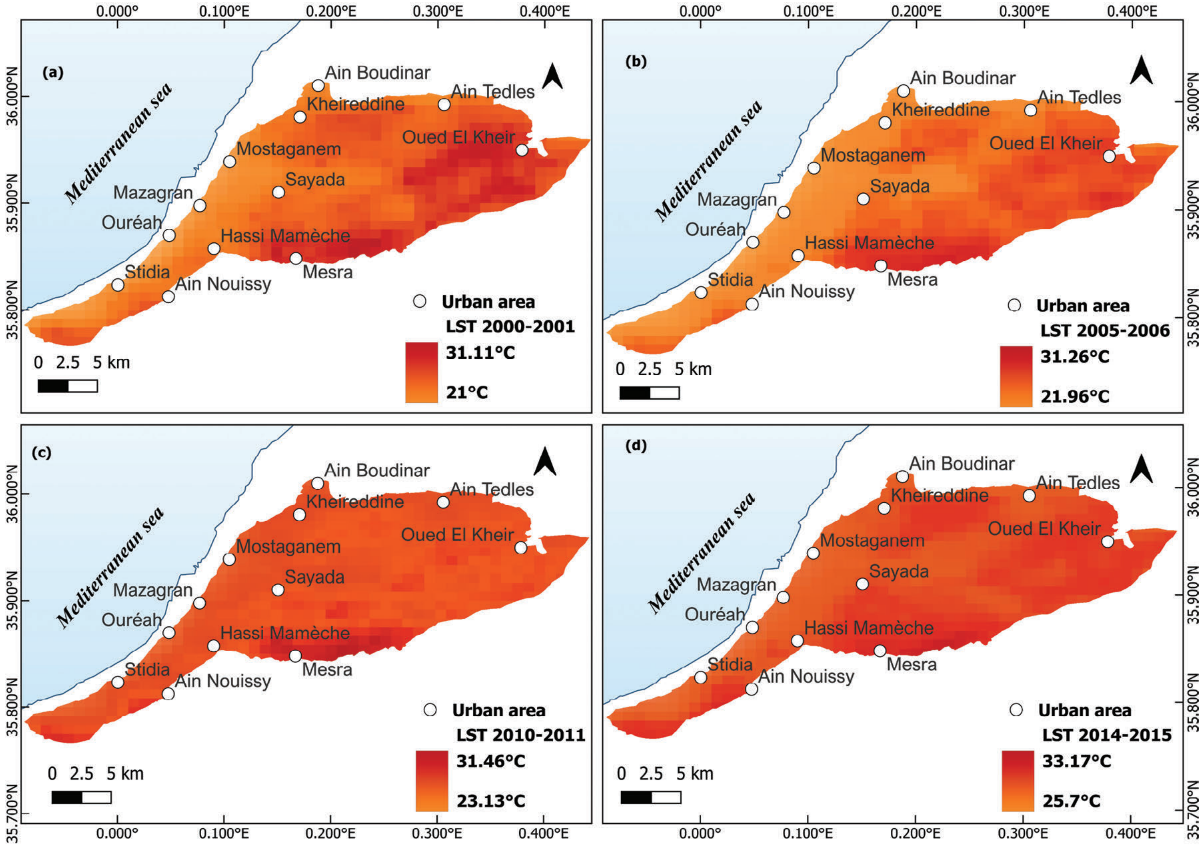

Fig. 11 - Average annual LST for (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, and (d) 2014-2015.

Fig. 11 - LST medio annuale per (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, e (d) 2014-2015.

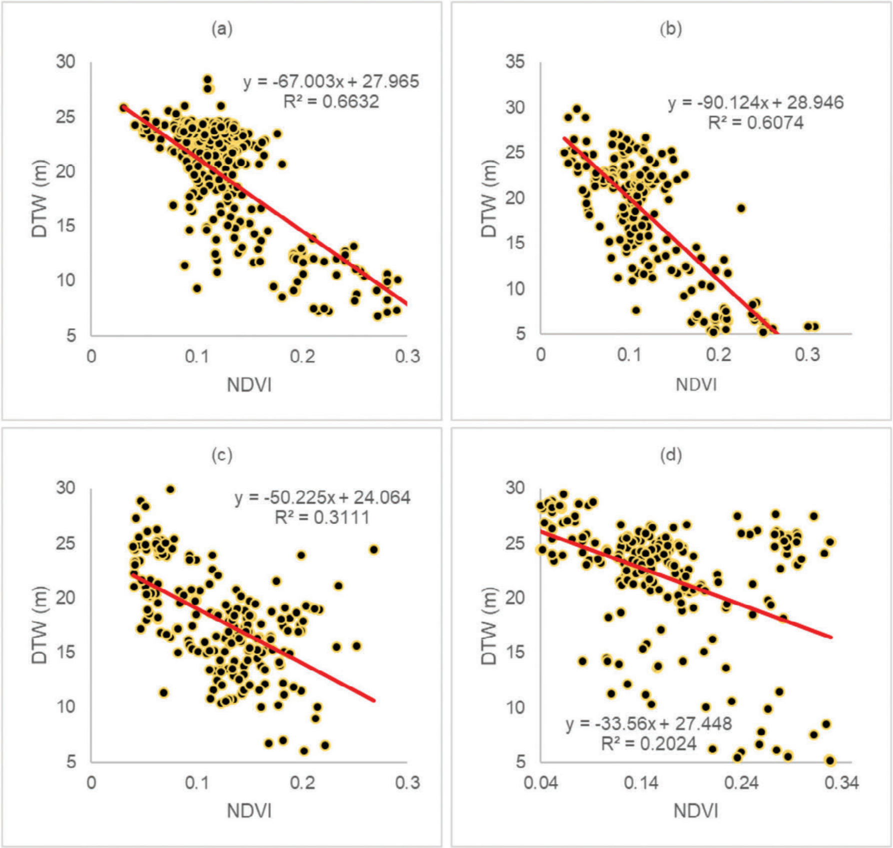

Fig. 12 - Linear correlation of DTW and NDVI for (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, and (d) 2014-2015.

Fig. 12 - Correlazione lineare tra la soggiacenza della falda e NDVI per (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, e (d) 2014-2015.

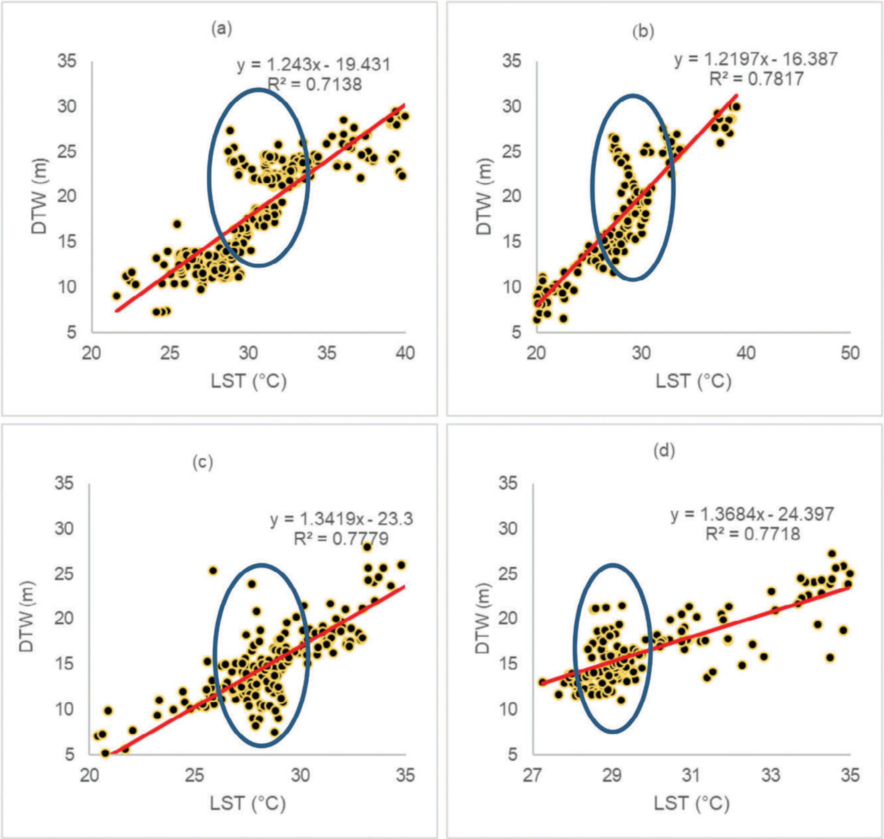

Fig. 13 - Linear correlation of DTW and LST for (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, and (d) 2014-2015.

Fig. 13 - Correlazione lineare tra la soggiacenza della falda e LST per (a) 2000-2001, (b) 2005-2006, (c) 2010-2011, e (d) 2014-2015.

anomaly can be caused by the presence of sparse herbaceous crops, that have hight LST values, as evidenced by the low NDVI in 2000 and 2005. Conversely, for values lower than 30°C, it can be caused by a change in cultivated vegetation, and shifted from sparse to denser vegetation, as evidenced by the NDVI of 2010 and 2014. Additionally, for every year under investigation, the stacked values indicate high DTW because of over-pumping for agricultural purposes.

MLR analysis: ranking DTW's influential factors

The results in (Tab. 4) reveal the statistical significance of the relationship between DTW, precipitation, NDVI and LST. The MLR results show that precipitation is the main influencing factor of DTW fluctuations through all the studied periods, with a p-Value less than 0.001. This significant relationship between DTW and precipitation reaffirms the claim of Mostaganem Plateau aquifer's sensitivity to precipitation variation.

For 2000, 2005, 2010, and 2014, the multiple linear regression is significant with multiple R^2 of 0.85, 0.90, 0.91, and 0.87 and adjusted R^2 of 0.74, 0.82, 0.84, and 0.77. LST and NDVI have insignificant regression coefficients with DTW because their p-Values are far greater than 0.05. The delay between precipitation events and the corresponding groundwater recharge in the aquifer system may play a role in this relationship, but it is not the sole explanation. It also could be attributed to the correlation between the independent variables, and there is frequently no single rule for determining the "significance" threshold (Senn et al., 2016), as the p-value is frequently a function of sample size and variance.

Variance inflation factor (VIF) diagnostics were used to check for significant multicollinearity in the MLR model. VIF results are all satisfactory and less than 5. Even though NDVI/LST correlates, it is not severe enough to require corrective action. The interaction between DTW, LST, and NDVI pertains to evaporation, water soil reserves, and the physical characteristics of the vegetation and soil. High temperature and atmospheric demands increase evaporation and vegetation activity, decreasing soil water reserves. (Zeng et al., 2018) affirmed that in arid and semi-arid regions such as the Mediterranean coast, the pattern of evaporation differs from the vegetation greening pattern which is precipitation-induced. These regions intensify the water cycle by increasing evaporation, which decreases soil moisture, increases DTW, and groundwater extraction for crop irrigation. LST creates soil crust, connecting LST and DTW implicitly. In fact, high LST can cause the formation of physical soil crust, which can reduce soil moisture, soil porosity, and infiltration rate, and increase runoff, ultimately affecting groundwater replenishment (Belnap, 2006)

Tab. 4 - Output of the linear regression model, in which DTW was the dependent variable and precipitation, NDVI and LST were the independent variable.

Tab. 4 - Risultati del modello di regressione lineare, in cui DTW (soggiacenza della falda) era la variabile dipendente e la precipitazione, NDVI e LST erano le variabili indipendenti.

Period	Variable	Estimate	t-Value	p-Value	VIF
2000	Precipitation	1.2397	23.5181	$1.2447.10^{-60}$	1.1125
	NDVI	-0.0649	-0.0207	0.9835	1.0049
	LST	0.0027	1.7352	0.0841	3.9549
2005	Precipitation	0.0354	29.4695	$5.2794.10^{-75}$	4.9351
	NDVI	-0.9532	-0.3359	0.7372	1.0532
	LST	0.1232	1.5497	0.1227	1.0164
2010	Precipitation	0.0460	32.4132	$2.0842.10^{-82}$	4.9862
	NDVI	0.0805	0.5249	0.6001	2.6657
	LST	-0.8386	-0.1760	0.8605	2.7013
2014	Precipitation	0.0280	26.4245	$1.0421.10^{-68}$	4.3367
	NDVI	0.0766	0.0434	0.9654	1.0009
	LST	0.0349	0.6777	0.4987	1.0058

Concerning the anthropogenic effect on groundwater drought detection using NDVI and LST

The use of NDVI/LST for drought detection is built on the assumption of the complementarity of the information in their wave bands to provide a more robust characterization for different phenomena at the land surface (Karnieli et al., 2010). NDVI is negatively correlated with LST, strongly positively correlated with precipitation, and strongly negatively correlated with DTW, since droughts are more common at low latitudes (Karnieli et al., 2010). Although the study area meets the requirements for using the NDVI and LST to identify drought, the latter has undergone human influence. The performance of the NDVI and LST indices in 2010 and 2015 was adversely affected by the dependence of agricultural regions on pumped water as a result of surface water scarcity. The relationship between DTW, NDVI, and LST is indirect and primarily affected by human activities. The rise in NDVI in our case indicates heavy groundwater use, not availability. In areas with limited human activity, DTW strongly affects NDVI and LST. Anthropologic effects from intensive agriculture and groundwater overexploitation dampen drought detection indices like NDVI and LST. Climate change and anthropogenic disturbances have been shown to be responsible for temporal and spatial variation in evaporation.

Effective groundwater management in this region should include strategies for improved monitoring of groundwater levels and usage, intensified regulatory mechanisms to prevent over-extraction, and encouraging sustainable agricultural practices such as drought-resistant crops (Hoogesteger, 2022). Artificial recharge structures and enhancing public awareness on groundwater conservation will further help in sustainable management of the groundwater resources (Mseli et al., 2023).

Conclusion

This study aims to evaluate climate change effects on Mostaganem plateau alluvial aquifer through the relationships of DTW with precipitation, NDVI and LST, using an adaptive methodological framework that incorporates the integration of remote sensing, Geographic Information Systems (GIS), and statistical analyses, such as correlation analysis and Multiple Linear Regression (MLR).

The study underscores the sensitivity of Mostaganem Plateau to variations in precipitation. The distribution and availability of DTW are affected by changes in patterns and decreases in precipitation, resulting from anomalous anticyclonic circulation caused by climate change. The significant correlation between these factors shows their strong relationship and the impact of reduced precipitation on DTW. Additionally, the correlation between DTW, NDVI, and LST decreased during the study period, indicating a weakened relationship. Furthermore, NDVI, commonly used as a measure of vegetation health, appeared to reflect human activities, prominently, contributing to a decline in DTW levels. Additionally, high LST contributes partially in reducing DTW, through the intensification of evaporation caused by changes in crop types and the formation of soil crust. The Multiple Linear Regression (MLR) analysis reinforced the significant impact of precipitation on DTW, providing further evidence of the plateau's vulnerability to precipitation patterns. Furthermore, the interference of human activities, including land-use changes and intensive groundwater usage for agriculture, has complicated the traditional relationship of NDVI/LST.

This research has also limitations. The analysis does not consider factors such as lag time in aquifer recharge, evapotranspiration losses, soil moisture, humidity, and crop types. These variables are important in understanding the complex interactions within the aquifer system. However, this study enhances our understanding of the complex interactions between DTW, precipitation, and human activities. Continuing this line of research, with the inclusion of additional data and field tests, could offer significant insights for policymakers in developing irrigation strategies and methods to reduce evapotranspiration through effective agricultural practices.

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Competing interest

All authors state that there is no conflict of interest.

Author contributions

Data collection and processing: Cherifa Hanene Kamelia Chemirik; results interpretation: Cherifa Hanene Kamelia Chemirik, Djelloul Baahmed, Rachid Nedjai, Ikram Mahcer, Djamel Boudjemline, Abdelkader Iddou. Original draft: Cherifa Hanene Kamelia Chemirik; writing-review and editing: Cherifa Hanene Kamelia Chemirik, Rachid Nedjai, Djelloul Baahmed, Djamel Boudjemline, Ikram Mahcer. All authors have reviewed and approved the final manuscript.

Additional information

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