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THE PHENOMENON OF CLIMATIC DROUGHT AND ITS SPATIAL IMPACTS IN THE ALGERIAN SAHARA REGIONS - TIDIKELT REGION, IN SALAH PROVINCE, FOR THE PERIOD 2000-2020

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Abstract: Climate change is a global phenomenon that threatens natural regions and represents a vital environmental challenge for life on the surface. Algeria, like other countries, has suffered and continues to suffer from this phenomenon, especially in the regions of the Sahara Desert, which are characterized by a dry climate and natural environment, where its effects are strongly felt at all levels. This research paper, examining climate drought in the Tidekilte region for the period 2000-2020, aims to address the phenomenon's effects on fragile ecosystems. It also aims to analyse the severity, manifestations, and impacts of this drought, highlighting adaptation methods for the region's population. The study's results conclude that the impact of climate drought has affected several vital sectors, most notably: A large deficit in the water balance, estimated at 500 mm during the summer, has caused a drop in the groundwater level and the disappearance of the underground water channel (foggara), with salinity and poor soil fertility, as the ion exchange capacity of the sample taken does not exceed 12.5 mg/100 g. In addition, there is an increasing deterioration of oases agriculture due to high temperatures (exceeding 60 degrees Celsius in the summer) with an increased rate of evaporation due to wind erosion, which threatens agricultural systems with desertification.

Keywords: climate change, Algeria, ecosystems, oases agriculture, desertification

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Introduction

Semi-arid and arid regions are among the most vulnerable areas to climate change and its associated impacts. In recent years, the effects of prolonged dry spells on surface water resources have become increasingly evident. This highlights the urgent relevance of climate change and its influence on water availability—an issue that continues to attract the attention of researchers (Giorgi, 2006; IPCC, 2007; Lee et al., 2021). According to the United Nations Development Programme (UNDP, 2009, p. 19), this situation calls for a thorough analysis to better understand the driving factors, socio-economic impacts, and the challenges these regions face.

In the Algerian context, semi-arid and arid regions occupy the majority of the national territory. These areas are characterized by unique environmental systems and specific activities, particularly in the field of agriculture. Numerous studies have explored the impacts of climate change across various regions of Algeria (Bachouche et al., 2024), revealing a range of effects. For instance, the studies by (Rouibah, 2022; Rouibah & Belabbas, 2022) addressed regional variations, while (Tatar, 2013) examined broader implications. Additional research by (Rouabhi et al., 2014; Rouabhi et al., 2016) further contributed to understanding the issue. Moreover, works by (Mohammed & Al-Amin, 2018; Nichane & Khelil, 2015) focused specifically on the vulnerability of water resources to climate change in Algeria.

Despite its significance, the region has not been the subject of a comprehensive study that provides detailed spatial analyses of its environmental and socio-economic impacts within the context of climate change. Such studies remain extremely limited in this part of the country. This issue with the lack of research led us to select the Tidekilte region - found in the deep southern part, in the heart of the Algerian desert - as the research area. Tidekilte is in an arid zone (Côte, 1996), and is an important part of the desert environment and its fragile and very sensitive ecological conditions. The region faces a range of harsh geographical, climatic, and environmental constraints that significantly hinder both biological and human activity (Voinot, 1994). Among the most telling indicators of climatic drought in the area are extremely high evaporation rates, compounded by the scarcity—or at times, complete absence—of rainfall. This combination contributes substantially to both climate-induced and environmental drought in the region (Toutain & Saharienne, 1979). The research study deals with climate-induced drought, and looks at its conceptual framework, contributing factors, how to assess it and what consequences it inflicts upon the environment, particularly in the Tidekilte region. The analysis ultimately relies on a data set of climate data, acquired from various institutes and meteorological centers. The Tidekilte region has been plagued with persistent drought for a long time, which has seriously hampered development in the region. The issue of you being able to observe the local cricket teams to the degenerative effects in extreme situations, the region is now struggling to find ways to mitigate the effects of drought and to establish sustainable development (Dubost, 1991). In addition, this research is framed within larger scale, global environmental issues. Drought, for one, is undoubtedly a global phenomenon that has permeated various scientific and political debates at multiple levels. For example, the 2022 Climate Summit in Sharm El-Sheikh, Egypt concluded that all countries need to share the burden of climate change and its associated impacts, including drought and their lack of awareness of longer-term consequences (Smati, 2008).

Materials and Methods

A comprehensive methodological approach was utilized to accomplish the objectives of this study. It was based on a combination of climate data (observational, and statistical processing), and field observations. The meteorological data were obtained from the observation station located in Saleh Airport (Coordinates-Latitude: 27°15′ N, Longitude: 02°30′ W, with a height of 268 meters); they provided the main necessary parameters to evaluate climate-based drought conditions in the Tidekilte region.

This climatic data were utilized to compute some indicators related to drought, mainly the water deficit, which was calculated using the calculation of the regional water balance. Also, to study the drought durations, the Thornthwaite (1948) equation - based on temperature and potential evapotranspiration - were utilized.

As there are landforms in the study area that would suggest that wind erosion (which increases during long-term drought) is a serious issue, quantitative statistical methods were used to estimate the intensity of erosion and the spatial extent of erosion in the study area.

Field surveys and field observations provided additional insights that assisted in analysing the climate data. The field survey and observations added contextual detail about local spatial dynamics and adaptive strategies of desert communities associated with their climate. This knowledge is ingrained in traditional ecological knowledge, including such responses as utilizing windbreaks, and experiencing the impact of sand encroachment on dry palm branches, which illustrates how better to cope with the constraints of the dry climate.

Geographical location of the study area

The Tidekilte region is situated in the far south of Algeria, at the heart of the Sahara Desert. Geographically, it extends between latitudes 25° and 30° North and longitudes 1° West to 6° East (Deporter, 1890) It is bordered to the north by the Tademaït Plateau, to the south by the Hoggar Mountains, to the east by the Egergarne Valley, and to the west by the Touat region and the Tanezrouft Desert (Côte, 2005).

The name "Tidekilte" derives from the Berber language, meaning "palm of the hand," a reference to the geographical shape of this low-lying basin that fans out along the edge of the Tademaït Plateau. The region is an integral part of the broader Touat area, renowned for its fertile oases that serve as vital lifelines amid the arid expanse of the desert. Tidekilte comprises three primary zones—Tidekilte, Tinquraren, and Touat (Champault, 1969) - each representing distinct micro-environments of the Sahara where traditional water management practices, oasis-based agriculture, and natural constraints intersect and shape the local way of life.

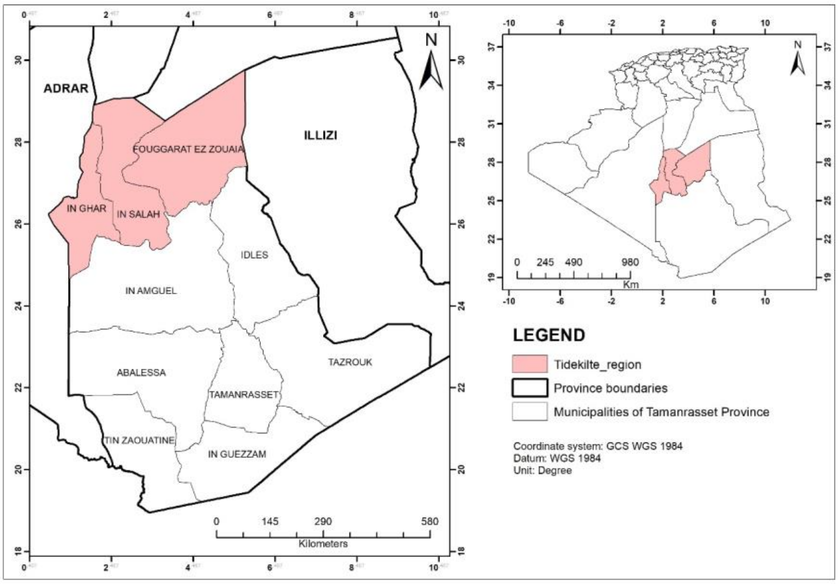

Fig. 1. Location of the Tidekilte region (Source: Authors)

The Digital Elevation Model (DEM) of In Salah and its surrounding area depicts the unique topography of this part of the Algerian Sahara. The broader view, to the left in the image, helps situate In Salah in a familiar topographic context, including the Plateau du Tademaït to the north and the elevated ridges near D'janetH'rar in the southeast. The red-to-blue color gradation also shows that In Salah is located in a relatively low-lying area in comparison to the surrounding highlands (Côte, 2005).

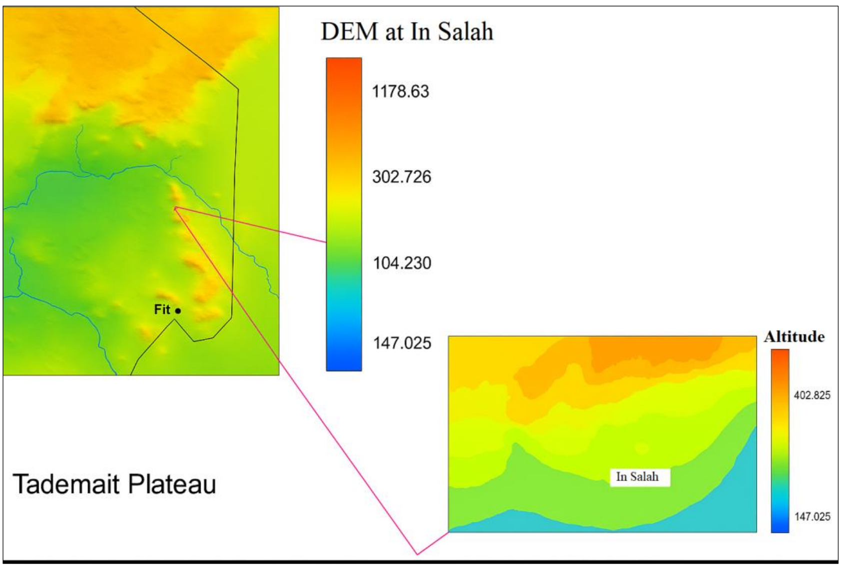

Fig. 2. The Digital Terrain Model of the In Salah region (Source: Authors)

This topographic setting positionIn Salah within an intermountain transition zone nestled between rugged plateaus and expansive desert plains. The enlarged view on the right further highlights the town's location within a depression-like area, where elevations range from near sea level up to approximately 800 meters.

Sucha site implies an open and flat environment, one that in the past-facilitated trade and travel but one that also exposes the town to environmental risks such as wind erosion and sand invasion. The topography near the city influences local climate regimes, water runoff and ecological processes of the region. Such a spatial environment is important to decide the natural constraints and possibilities in urban development and sustainable development for In Salah.

Results

Soil is fundamental to natural and biological processes on the Earth's surface. It is inherently variable and adaptable to environmental conditions at each location, yet it also has a great deal of fragility and vulnerability when its ability to adapt to development is compromised (Cissokho et al., 2019). During our research on climatic drought and its consequences in the hot desert conditions in the region of Tidekilte, we identified soil as one of the most affected elements, based on climate induced stress shown at many different environmental and or ecologic effects, that have become increasingly typical of the conditions in Tidekilte (Bisson, 1991).

Soil conditions in Tidekilte fluctuate like any other desert area based on recurring climatic drought cycles. These cycles have significantly impacted Tidekilte's soils, particularly its agricultural soils(Smati, 2007). The primary observable effects of soil degradation due to climatic drought in Tidekilte include:

a- Soil salinization: This is mainly due to several climatic conditions, perhaps the most important of which is the high seasonal and annual temperatures with the scarcity of precipitation, which necessarily leads to high evaporation rates in the soil, causing it to become salinized and lose the moisture necessary for plant development and the stability of other living organisms (El-Rawy et al., 2023). The table below shows the physical and chemical composition of the soil and its salinity levels.

Table 1. Physical and chemical characteristics of saline soil in the Tidekilte region

Depth	0-20 cm	20-35 cm	36-70 cm
Clay%	5,6	5,85	33,00
Fine silt%	10,3	7,92	6,71
Coarse silt%	16,1	2,53	3,09
Fine sand%	25,2	32,9	19,20
Coarsesand%	42,8	50,8	38,00
Ion exchange capacity (mg equivalent/100g)	4,5	3,1	12,5
Ca co3 %	4	5,2	3,8
Gypsum%	31,69	32,28	13,20

Source: Forest Governorate in Tidekilte Province, In Salah State, 2023.

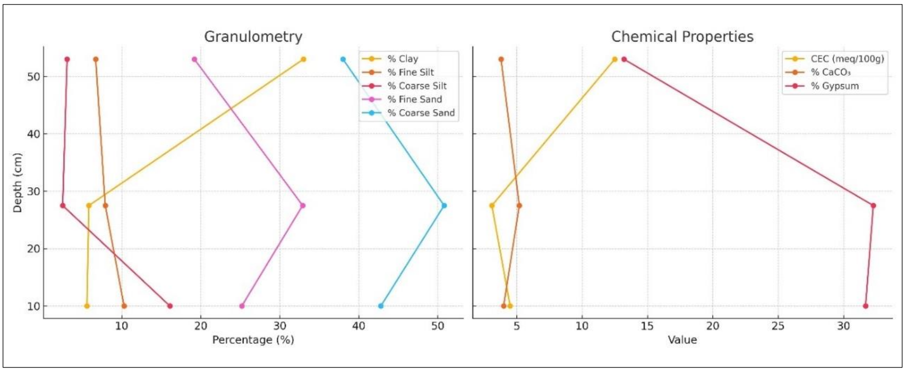

Fig. 3. Variation of soil granulometric and chemical characteristics by Depth

Saline soil is the dominant soil type in the extremely saline area and soil mainly consisted of sand. The coarse sand percentage of a sample from the region was estimated at 43.8%. This soil is characterized by its high permeability to water, weak texture and fertility, as the ion exchange capacity for that sample did not exceed 12.5 mg. Equivalent/100 g. The salinity of the soil is due to its groundwater aquifer being located near the surface, as the water is drawn upward via capillary rise and evaporates, leaving behind salts that are eventually crystallized at the soil surface. Salinity is the primary challenge of agricultural lands in this area, and the soil can be prepared to obtain good agricultural yields through either salt removal, or treatment of the salinity. Excessive salinity can be treated chemically.

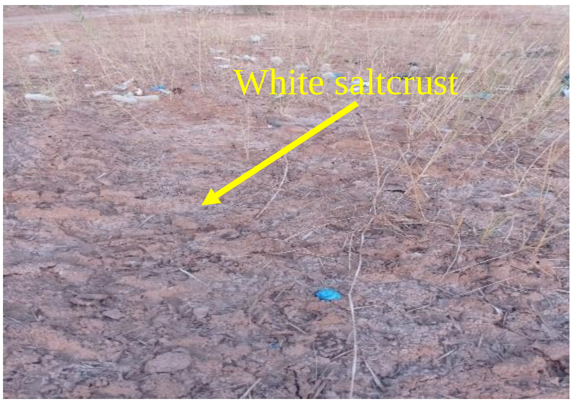

Fig. 4. Land Salinization in the Tidekilte Region Due to Climatic Drought Factors. Source: The lens of the researcher in the region, January 7, 2024.

b- Soil degradation and the phenomenon of widowhood:

One of the most serious environmental issues in the Tidekilte region is the high degree of soil erosion and the associated advancement of sand. This is particularly troubling in this area, where the prevailing winds are typically large and persistent year-round. Wind and the inherent loose and granular soil texture greatly exacerbate the geomorphological processes of deflation, transport, and sedimentation (Salih et al. 2021).

It is noted in the meteorological data that calm winds only applicant 6% of the time, while moderate winds (1-5 s/h) accounted for 38% of wind speeds, and winds greater than 5 s/h accounted for 56%. This wind information presents many challenges for agriculture, as winds did fill the canals and irrigation ditches with sand, and uprooted palm trees. The winds have negatively affected agriculture, but also provided many benefits laid out through the pollination of palm trees for date production.

Northeast winds are the most frequent wind direction in the study area (approximately 25% of the total wind flow each year). The winds being examined in this study impact the municipality of Foggara2Ezzawi, its cities, and its oases. The north wind, which is responsible for about 16% of the year's total wind, is moving from the Tademaït Plateau, and uplifting the surface depressions (areas where the oasis is located). These winds dominate most of the year, except for in July and August when it is easterly and northeasterly predominately. The strong south-westerly winds in March and especially April (when the sandstorms coincide with the palm tree pollination season) are extremely important for agricultural activities in the area.

Nevertheless, the prolonged exposure to these winds contributes significantly to soil desiccation and the decline in soil fertility, particularly in agricultural zones (Benmedjahed et al., 2015).

Table 2. Results of analysis of soil samples from the Jafou agricultural areaIn the In Salahregion

Characteristics of the soil sample		Analyticalresults
Gypsum		---
Limestone		0,83
activelimestone		---
Water pH		8,8
C.E (mmhos/cm) ratio 1/5		0,32
C.O %		0,15
M.O %		0,26
Assimilable phosphorus (P2O5 in ppm) Joret-Hebert method.		139
Nitrogène ‰		0,160
Granulometry	A %	8,62
	LF %	3,17
	LG %	3,07
	SF %	34,37
	SG %	50,77
	Textural class	Soundblaster

Source: National Hydraulic Resources Agency; Soil Analytical Results from the In Salah region

The analysis of soil samples from the Jafou agricultural area in the In Salah region provides essential data for evaluating the agricultural potential of this Saharan zone. The water pH is 8.8, indicating a slightly alkaline environment, which is typical of desert soils. This level of alkalinity may reduce the availability of certain micronutrients, therebyinfluencing crop productivity. The electrical conductivity (EC) is 0.32 mmhos/cm, showing that the soil is non-saline and suitable for agriculture from a salinity perspective.

[2] Foggara: The foggara is simply a system used to transport groundwater to the surface for use in drinking, irrigation, and watering livestock. As an irrigation technology, the foggara is also linked to a social system of collective action, led by a committee of elders known as thecommunity, whose job is to monitor and maintain the foggara and distribute the water.

The organic carbon (0.15%) and organic matter (0.26%) levels are extremely low, indicating poor fertility and little biological activity. The nitrogen content, at 0.160‰, confirms a deficit in this nutrient, which could limit plant growth for those not adding fertilizer or compost. In contrast, the assimilable phosphorus content is relatively high at 139 ppm (Joret-Hebert method), which provides good conditions for root development and establishing crops at transplanting operation. The physical composition indicates a considerable amount of sand, with 50.77% coarse sand and 34.37% fine sand. The clay value is low (8.62%) and the silt component is negligible (LF 3.17% and LG 3.07%). This composition has sandy texture, and it is likely to be classified in the sandy or loamy sand texture class. This kind of soil has good drainage but poor water and nutrient retention, which presents a challenge for sustainable agriculture unless soil improvement techniques are employed.

These results are pertinent to the study objectives to evaluate the land potential for agricultural purposes in arid areas such as In Salah. The soil's chemical and physical properties indicate considerable limitations—low fertility and poor water holding capacity—must be addressed to allow for productive and sustainable land use. This proportionally supports the recommendations for land management options that are better targeted and detailed for soil management such as organic amendments, efficient irrigation, and the crop selection fitted to desert conditions.

Table 3. Analysis of soil samples in the agricultural surroundings of the Foggara Ezwa area

Characteristics of the soil sample		Analyticalrésulte
Gypsum		---
Limestone		1,16
activelimestone		---
Water pH		8,7
C.E (mmhos/cm) ratio (1/5)		0,31
C.O (%)		0,22
M.O (%)		0,38
Assimilable phosphorus (P2O5 in ppm) Joret-Hebert method.		153
Nitrogen (‰)		0,252
Granulometry	A (%)	8,70
	LF (%)	3,12
	LG (%)	3,61
	SF (%)46	33,73
	SG (%)	50,84
	Textural class	Soundblaster

Source: National Hydraulic Resources Agency; Soil Analytical Results from the In Salah region.

In spite of this, the soil has assimilable phosphorus (153 ppm) and a slightly higher nitrogen content (0.252‰) than other similar soils of the Sahara, demonstrating some nutrient strengths. The granulometric profile of the soil, exhibiting coarse (50.84%) and fine sand (33.73%), classifies the soil as sandy, which aligns with good drainage characteristics and bad retention of moisture and nutrients. The properties of this soil adhere to the main goal of the study which was to evaluate soil limitations and potential, and use that information to inform, sustainable agricultural practice in an arid landscape. The findings emphasized the need for soil specific management practices in the Foggara Ezwa Region.

The results presented in the two previous tables on the compositional analysis of soil in selected agricultural areas of the Tidekilte region confirm earlier observations regarding its low fertility. The findings highlight a significant deficiency in both organic and mineral matter, which contributes to reduced soil productivity and increased susceptibility to erosion and degradation.

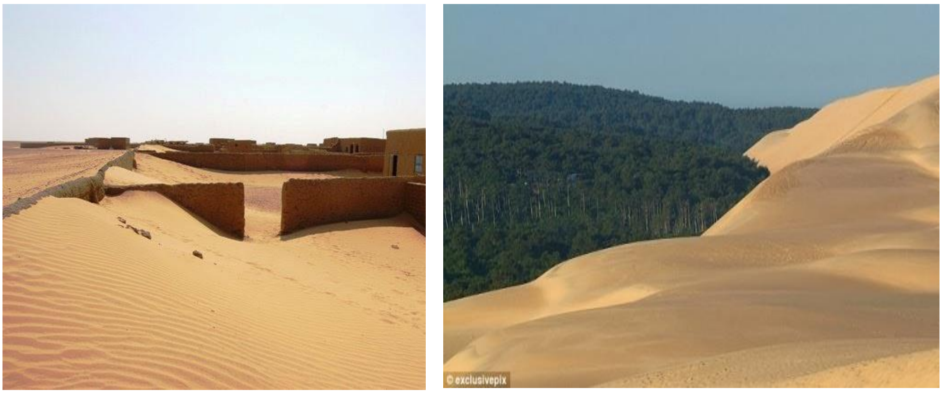

Fig. 5. The phenomenon of sand encroaching on population centers and agricultural areas in the oases. Source:Images of the area taken from the Internet, 2023.

This is due to the intensity of winds and wind erosion in the Tidekilte region in general and Ain Saleh in particular, which causes weakness and fragility of the surface soil and difficulty in exploiting it.

Fragile of structure and composition the soil:Local environmental and natural factors, especially climate, have a significant effect on the configuration and composition of the soils in the area of Tidekilte. Climatic aridity is the chief feature of Tidekilte and other regions in Algeria's desert climates and has greatly restricted soil productivity. In addition to soil productivity, aridity has influenced soil structure and decreased granularity. This fragility is clearly evident in the study area.

Climate also greatly affects water resources, especially in arid areas (Agnew & Anderson, 2024). The data collected in this study in terms of drought measurements and water budget ratios suggests that over the majority of the month, there is a deficit of water and high evaporation that severely afflicts agricultural practices. There is a significant and noticeable reduction in groundwater levels due to limited recharge providing sufficient amounts to take the funds needed to sustain surface water when drought occurs. The continued increasing need to find alternative water sources specifically for agricultural use and irrigation stress this importance in light of the expected ongoing development programs with reliance on agriculture by expanding on cultivated land.

Indicators of water deficit due to climate drought: The following table indicates a high annual evaporation rate exceeding annual precipitation, as the monthly (P–E) values are negative throughout the year. This reflects a state of water scarcity, characteristic of climatic drought conditions in the region.

Table 4. Monthly water deficit indicators in Tidekilte Region for the period 2000-2022

Months	(P mm)	(E mm)	(P-E mm)
January	37	197	**-160**
February	8,8	225	**-216,2**
March	22,3	313	**-290,7**
April	15,4	350	**-334,6**
May	5,7	453	**-447,3**
June	3,1	500	**-496,9**
July	2	553	**-551**
August	14	451	**-516**
September	10,7	323	**-440,3**
October	26,8	221	**-296,2**
November	10,1	176	**-210,9**
December	4	197	**-172**
Annual rate	**13,32**	**329,92**	**-344,34**

P: precipitation/ E: Evaporation/ P-E: Water deficit.

Source: The researcher's calculations based on meteorological data at In Salah Airport 2020.

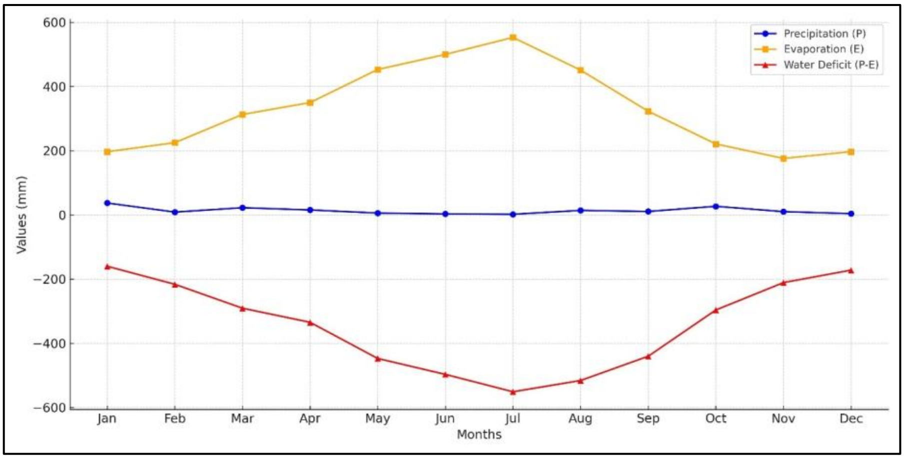

Fig. 6. Monthly Variation of Precipitation, Evaporation, and Water Deficit

The plot identifies a continued monthly water deficit for the Tidekilte forecasting region between 2000 and 2022. On all months of the year evaporation (E) exceeds precipitation (P) at a monthly average. The driest months, especially June, July, and May, show large negative deficits at their extreme, given July's -551 mm deficit, on an average basis, indicating a time during the year when water input and loss is not even close to being in balance. Even the relatively "wetter" months like January and October remain deficit-bound, confirming the region's hyper-arid climate. With an annual average precipitation of only 13.32 mm against an evaporation rate of 329.92 mm, the area experiences chronic water scarcity, posing serious challenges for agriculture, water resource management, and sustainable development.

c- Degradation of the traditional irrigation system Foggara: The foggara represents a unique and ingenious traditional water management system developed by Saharan communities to cope with the extreme aridity of the desert environment. It operates by channeling groundwater from the Tadmit Plateau - considered the recharge zone—downward toward the depressions of desert oases, which serve as discharge zones (Remini 2018). However, prolonged climatic aridity and the persistent lack of rainfall needed to recharge the aquifers have led to the system's progressive degradation. In many areas, including the study region, numerous foggara networks have fallen into disuse or ceased functioning entirely.

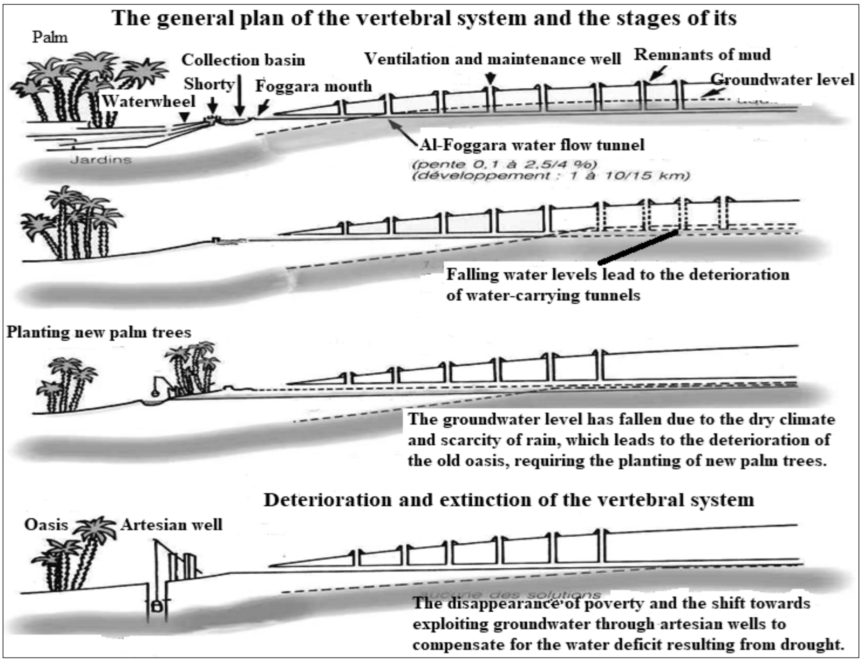

Fig. 7. Stages of deterioration of the Al-Foggara system due to climate drought (high temperature, rare rain, strong winds...) and deterioration of the groundwater level. Source: (Dubost, 1991)

The decline of the foggara system in the Algerian Sahara - specifically in the Tidekilte area - demonstrates the significant impact of climatic droughts on one of the critical water resources in the region. There has been less rainfall, higher temperatures, and evaporation has increased, which has practically ceased the recharging of groundwater indications. Climate coupled with human action (poor maintenance and the excessive drilling of modern wells), has contributed to the lowering of the groundwater levels, which, in combination to other factors, has reduced the flow of foggara channels.

No one disagrees that climatic drought is primarily responsible for the obstacles to plant and agricultural life in the dry regions, due to its impact on water and soil, and the reason for this water deficit is in the hydrological outcome of the region, in addition to the loss of a large portion of surface water due to evaporation. Moreover, severe transpiration(Abahussain et al., 2002). The significant impact of the phenomenon of drought on natural vegetation and oases has been observed. Weak vegetation cover, low vitality, density, and ground coverage, ease of installation and lack of plant diversity characterize the region. From an economic standpoint, the rate of plant productivity per unit area is low compared to regions that do not suffer from drought.

d- Degradation of the palm oases in the region: In the past few years, waves of drought have further deteriorated the oasis ecosystem in the world. With a correspondent reduction in the amount of traditional oasis areas and only limited successes of horizontal extension projects to restore these oases, the degradation can be clearly traced. One the most significant impacts is the severe decline in groundwater levels, which has reduced the traditional irrigation system to almost no-function, as the foggara was only sustainable to a limited extent. We essentially replaced the foggara with deep wells, resulting in the greater depletion of groundwater due to over-extraction. In order to better assess this deterioration of vegetation cover in oasis, we used aerial pictures from two distinct periods (2000 and 2022) to detect some distinct changes in vegetation density and even patterns of spatial distribution.

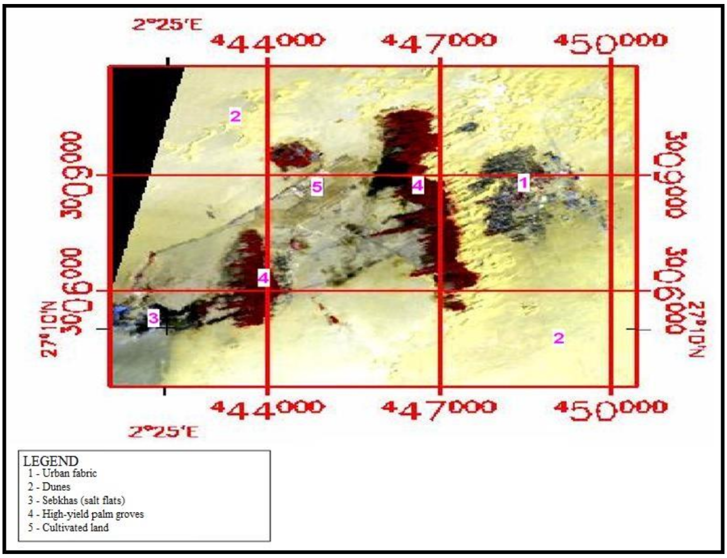

Fig. 8. The visual interpretations of the TM 2000 images reflect the real

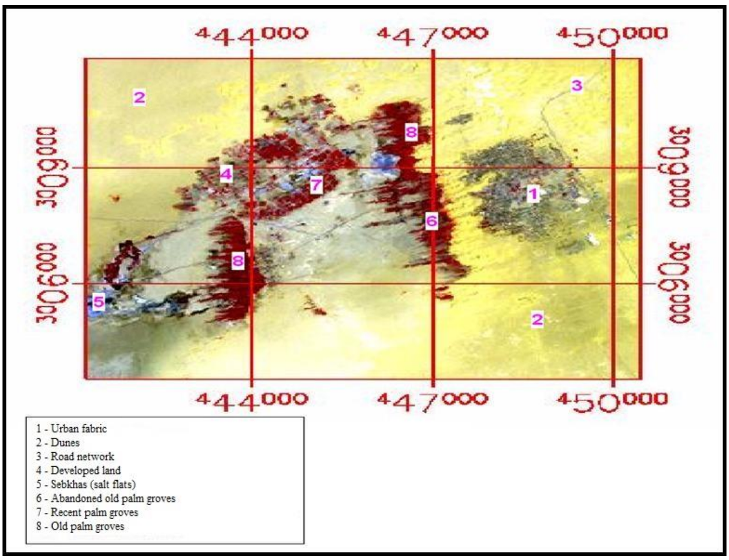

Fig. 9. The visual interpretations of the ETM+ 2022 images reflect the real

By analyzing images 08 and 09, we can observe significant spatial transformations in the study area, particularly concerning palm oases and desert agriculture. Traditional agricultural zones have visibly deteriorated, even as new agricultural areas have emerged beyond the historical boundaries of the oases. This decline is primarily the result of ownership of land in oases being common property, which has normally resulted in ignoring and breaking up the land by inheritance practices, while at the same time, urban expansion caused by intense demographic pressure has encroached upon and reduced agricultural lands as well.

Recent drought waves have not only accelerated the depletion of water resources but have also undermined the structural integrity of traditional agricultural systems. The continued drop in the groundwater table - primarily due to the over-abstraction of water for irrigation - has precipitated the collapse of traditional water management methods such as the foggara. While attempts have been made to extend cultivated areas horizontally through expansions of the oasis, these efforts have not offset this trajectory.

Modern agricultural practices have been brought to bear on the situation, but they have no chance of success given poor water management policies, a scarcity of infrastructure, increased population demands, and encroaching urbanization, all of which finely disturb the delicate ecological balance that exists in the oasis.

e- Natural disasters resulting from climatic drought:

The Tidekilte region endures an intense heatwave lasting approximately six months each year, from May to September. During this period, temperatures frequently exceed 50°C, contributing to heightened drought conditions and a surge in natural disasters—most notably recurring fires in palm groves during the summer months (Remini, 2018). According to the Civil Protection Directorate of the Wilaya of In Salah, which includes the study area, interventions aimed at mitigating natural risks—particularly drought—have become a routine necessity across various parts of the region. The increasing frequency and severity of these disasters are directly linked to the ongoing wave of climatic drought, a phenomenon that has acquired geostrategic implications due to its wide-ranging environmental, economic, and social impacts.

Fig. 10. Fires in the Tidekilte Palm Oases: Causes and Effects. Source: Directorate of Civil Protection of In Salah State, Fire and Natural Disaster Control Authority, March 2023.

Discussion

Our research contributes to and confirms a lot of previous research regarding the effects of climatic drought on the vulnerability of arid landscapes on the Saharan continent especially in Tidekilte. In line with Cissokho et al. (2019) , we confirm the soil degradation and consequent salinization and loss of soil fertility. The potential evaporation, and low ion exchange capacity (≤ 12.5 mg 100g-1) of the soils will also be reported on based on our fieldwork as well as El-Rawy et al. (2023) will show the vulnerability of the soils in Tidekilte. The salinity of the soil compounds the low groundwater table and high summer temperatures near 60°C enabling salt to capillary rise then evaporate and return to the surface of the soil.

Wind erosion is yet another factor that supports Salih et al. (2021), Salih et al. linked consistent wind and sandy soils to a greater land degradation process. Our meteorological data indicated wind speeds over 5 m/s for 56% of the time in our study site, with the result of wind erosion filling irrigation channels with sand and blowing over palm trees. These disturbances disrupt agriculture and intensify desertification, as described by (Benmedjahed et al., 2015). The phenomenon of "widowhood" or the abandonment of farmland due to sand encroachment and soil decline is increasingly common.

Agricultural productivity is declining as a result of these soil and climate stresses, mirroring Smati (2007) observations regarding yield reductions in desert regions following extended droughts. High salinity, weak soil structure, and frequent sandstorms compromise the viability of oasis agriculture, long essential to local livelihoods. These effects are worsened by a persistent water deficit; our data record a summer water balance shortfall of up to 500 mm, consistent with observations in arid Algerian areas by (Agnew & Anderson, 2024; Saidou et al., 2022). This deficit, driven by high evapotranspiration and low rainfall, persists year-round.

The Foggara, one of the oldest technologies of sustainable water management in the Saharan desert, is in serious decline. Our findings corroborate (Benmedjahed et al., 2015; Remini, 2018), both of which identified falling groundwater levels, and diminishing Foggara efficiency at the time of their research, and both identified the current drought conditions in the region . The move to deep wells in the 1980s has exacerbated overdraft and overuse of the aquifers, and accelerated environmental degradation that threatens agricultural sustainability.

Social and economic consequences are also considerable, as land degradation and loss of water supplies have sent rural communities fleeing from the land (Dufumier, 2004) and into a dependency upon external aid. Loss of farmland and traditional methods of farming restrict food supplies and creates poverty (e.g. loss of livelihoods, generations of cultural capital), both individually and as a community. These trends follow larger studies on climate change in Algeria (Rouibah, 2022; Rouibah & Belabbas, 2022; Tatar, 2013), and suggest that arid regions have increased biophysical vulnerability.

Addressing them requires multiple intervention pathways. Our research highlights the imperative for sustainable land and water management through rehabilitating degraded soils, transitioning to salt-resilient crops, and upgrading irrigation through renewable energy consumption, as outlined in the Plan National Sécheresse Algérie (2019). Application of local knowledge combined with innovative technologies, and the establishment of future drought and wind erosion early warning systems, is fundamental for improving resilience.

Development of rural infrastructure, solar energy and water management irrigation programs can address the socio-economic impacts of drought, while promoting sustainable development, in Tidekilte, and other comparable Saharan areas.

Our study thus updates and extends previous studies through providing localised datasets and generating insights on climatic and environmental, and socio-economic interactions in Tidekilte. As well as demonstrating the different rationale behind an integrated adaptive approach to access and resource management to protect sensitive ecological systems and vulnerable livelihoods.

In addition to soil and water effects, Tidekilte's ecosystems are under increasing threat from the additional effects of drought Saidou et al. (2022) discovered a significant decrease in the health of oases which were once important a keystone for biodiversity and agrarian practices.Designative factors of prolonged drought, evaporation and heat lead to less recharge and a lower water table, endangering the practices of traditional farmed systems and putting native flora and/or fauna at risk (Rouabhi et al., 2016). As vegetation follows, erosion increases and desertification happens rapidly as we have seen on some of the landscapes in the Algerian Sahara (Mohammed & Al-Amin, 2018)

There is spatial variety in the effect of the drought between basins in the biological region. Low-lying basins that are associated with saline groundwater and a sandy soi attribute, are sunk to salinization and likely wind erosion: as observed by Côte (2005), the area's geomorphological makeup enhances the effects of wind and inherent risks due to buried infrastructure and incessant sand encroachment. This means that each micro-environment needs their own adaptation strategy (Voinot, 1994).

Declining oasis agriculture and limitations of 'traditional' systems like the Foggara have diminished yields, and calls into question income stability (Remini, 2018), resulting in increased rural-to-urban migration, especially among youth. Erosion of local knowledge, as well as weakened social networks, provide further constraints on adaptive capacity (Nichane & Khelil, 2015). There is evidence of localized innovation and adaptation. Fieldwork has established that some communities are taking up drought tolerant crops, improving both irrigation and windbreaks. Indigenous ecological knowledge that embeds modern innovations suggests fruitful avenues towards resilience (UNDP, 2009).

National and global initiatives, such as the Plan National Sécheresse Algérie (2019), and the recommendations of the IPCC (2007)have called for multi-scalar governance of drought that incorporates participatory elements combining research, policy and grassroots activities. The case of Tidekilte illustrates the immediate and pressing need for spatially and locally explicit, and endorsed, research on drought impacts in the Algerian Sahara. However, as Giorgi (2006) states, only through a 'nuanced' understanding of local realities, will actions be implemented to minimize vulnerability, and develop pathways for adaptive capacity and long-term sustainability. Therefore, to preserve the ecological and cultural legacies of Tidekilte, continued support for climate change monitoring, land and water management, and community driven

In addition, climate projections indicate that extreme events are anticipated as increasing in frequency and severity, particularly heatwaves and extended dry periods which could compound soil degradation and water stress (IPCC, 2007). Models for North Africa predict a reduction in precipitation and a significant rise of more than 2.5°C in average temperatures within the next thirty years. These observations highlight an urgent requirement to adapt technologies such as remote sensing and early warning systems along with solar-powered drip irrigation systems (FAO 2020. Local measures implementing these technologies collectively could significantly improve the adaptive capacity of communities to climate change in the Saharan region, in order to protect, enhance and rationalise the use of heritage, natural and cultural resources and preserve them for future generations and the stability of their populations (Benferhat & Bouder, 2024).

Conclusion

Climate drought in the region of Tidekilte represents another substantial hindrance to development, and climate drought is also considered the primary representation of desertification, affecting social, economic, and environmental aspects of life. The environment is the primary commodity needed for human sustenance and alternatives must be searched and adaptation must be made to deal with the environmental and water shortfall. While the situation is challenging, it is not hopeless. It is now time to shoulder the responsibilities and to explore viable solutions that would adequately address climate and environmental problems. Despite the extreme environmental challenges of living in a desert climate, into which people have settled, desert communities in Tidekilte have been able to overcome climatic and environmental droughts to establish [partial] ecosystems capable of sustaining life and development since humanity's early arrival to the region. Climate appropriately, the oasis at the El-Fouggara irrigation system is adequately reflective of this resilience, as a partial adaptation to the brutality and drought to the climate providing communities with a sense of place to exist despite inhabiting what seemed like an extreme place to live.

To confront the effects of climate drought in the Tidekilte region, several practical solutions and proposals can be implemented. First, improving the region's water collection is crucial. This can be achieved by creating water sources that secure water reserves during drought periods. There are great underground water resources in the region and they are going to be used in an advanced way using groundwater dams for farming irrigation and other commercial business. Secondly, modern technical irrigation options are needed. For instance, pivot sprinklers for large crop areas and drip irrigation for palm trees will limit groundwater waste and mining. A plan for recycling used water will limit water losses and be used for treatment of the human body.

Thirdly, methods suitable for dry areas are essential. This includes plowing, fertilizing, seeding rates, planting dates, and weed control. A switch from subsistence agriculture to commercial agriculture (such as harm of early fruiting) must be developed. This is especially important as there are low fertility soils available, which can be improved. Also, continue to work on research into drought tolerant varieties of wheat, barley, and other agricultural products. Rational use of nature will also help to develop an environmental balance, so that we develop fully sustainable exploitation of the fragile desert ecosystem.

To safeguard the soil and stop it from degenerating due to wind erosion, we need to increase the pace of afforestation, especially in areas subject to wind erosion, to cut back the sand incursion into urban and agricultural land. Finally, establishing climate centers/stations to study climate fluctuations and their impacts in dry desert areas is essential, as they could tackle scientific studies and research on drought and desertification as two principal obstacles to development in such areas.

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