Water resources status to global changes in the Taznakht plain, Draa basin, Morocco.

Tilila AIT JEDDI¹, Mohammed HSSAISOUNE¹,², *, Aicha SAAD³, Zine El Abidine EL MORJANI³, Mouad MAAZIZ¹, Mohamed BERAOUZ¹ & Lhoussaine BOUCHAOU¹,⁴

¹1. Applied Geology and Geo-Environment Laboratory, Faculty of Science, Ibn Zohr University, P.Box. 8106, Dakhla city, 80000 Agadir, Morocco
²2. Faculty of Applied Sciences, Ibn Zohr University, B.O. 6146 Azrou district, 86153 – Ait Melloul, Morocco.
³3. Exploration and Management of Natural and Environmental Resources Team (EGERNE), Polydisciplinary Faculty Taroudant, Ibn Zohr University, Hay El Mouhammadi- B.O. 271- 83000, Taroudant, Morocco.
⁴4Mohammed VI Polytechnic University (UM6P), International Water Research Institute (IWRI, Lot 660, Hay Moulay Rachid Ben Guerir, 43150, Morocco.

Abstract. The Taznakht area, located in the central part of southeastern Morocco, belongs to an arid zone. It has an extreme scarcity of water resources. The water resources are mainly drawn from groundwater using wells and traditional irrigation systems (Khettara). This study analyzes how climate and anthropic factors have impacted the state of water resources in the Taznakht plain throughout the last decades (1985-2015). We conducted a statistical analysis using climate data to identify climate trends in the area. With remote sensing, we tracked the diachronic evolution of vegetation into the plain to observe the impact of the resulting trends. Then, we established Khettara distribution all over the plain, and their state of functioning was related to the evolution of agricultural fields. The results showed a clear impact of drought phases on vegetation throughout the 30-year study, implying a vulnerable water state. Taking one particular village as an example, we found that the disappearance of Khettaras due to climate change, extensive pumping, lack of maintenance by the inhabitants, and reliance on less environmentally friendly irrigation systems has contributed to the disappearance of agricultural fields. This situation indicates that global warming and climate change are severe problems for water management in Taznakht region. Therefore, we discussed that after 2005, due to the Green Morocco Plan (GMP), these climate and anthropic impacts did not affect vegetation as much as in previous years. Nevertheless, these impacts affect the Taznakht plain ecosystem, and the socio-economic situation of its population, so continuing with applying similar GMP strategies and encouraging the process of Khettaras renovation and recovery is the right path for a well-balanced lifestyle in the area.

Key words: global changes; water resources; gis & remote sensing; khettara system, taznakht plain

1. Introduction
Morocco is a semi-arid Mediterranean country with limited and irregular precipitation (SCHILLING et al. 2012). Surface water and groundwater are important for its socio-economic development, where 80% to 95% of water resources are used in agriculture, with at least 40% originating from groundwater (SCHILLING et al. 2020). Climate change has significantly impacted the water situation, inducing a dramatic decline (from 20 to 65m) in groundwater levels over the last 30 years (HSSAISOUNE et al. 2020). It creates a lingering imbalance between groundwater extraction and recharges in many basins (HEIDECHE & HECKELEI 2010; HSSAISOUNE et al. 2017; KLOSE et al. 2008; WARNER et al. 2013). The Draa basin was most affected and has been underwater stress in recent years (HSSAISOUNE et al. 2020; CARRILLO-RIVERA et al. 2013; QUYSSE et al. 2015). The groundwater resources in Drâa basin, located in the southern part of Morocco, are strongly impacted by climate variability and anthropogenic activity (HSSAISOUNE et al. 2020; CARRILLO-RIVERA et al. 2013). The low precipitations in the Draa basin have affected water resources highly and, therefore, socio-economic activities in the area (HEIDECHE & HECKELEI 2010; HEIDECHE & KUHN 2007; SCHULZ et al. 2007). Evapotranspiration increases

* Corresponding Author:
E-mail address: m.hssaisoune@uiz.ac.ma
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and induces a decline in surface water resources (dropped and stored by dams) in different climate scenarios projected by TRAMBLAY et al. (2018). As predicted by MILANO et al. (2012), apart from the trends in water supply, an escalation in water stress did happen because of a sharp rise in water demand due to population growth and economic development.

In Ouarzazate province, the water demand increased from 2.3 million cubic meter (MCM) in 2010 and was expected to reach 4.1 MCM in 2030, which is a remarkable increase compared to Zagora and Agdez cities that is from 1.4 MCM to 2.5 MCM, and 0.3 MCM to 0.6 MCM, respectively in the same period (KARMAOUI et al. 2019; JOHANNSEN et al. 2016). Taznakht village, not far from Ouarzazate city, shows the same situation. It is a region containing Khettaras, which are subterranean channels draining perched shallow aquifers that helped favor agriculture crops which is one of the potentials generating income activities in the area (MESSOULI et al. 2008). However, since the decreasing economic role of agriculture, the collective maintenance of Khettaras systems has declined and turned useless due to different factors (LIGHTFOOT 1996; FAIZ & RUF 2009). Therefore, the degradation of the Khettaras network, among other impacts, could be a relevant indicator of global changes in the area. According to several authors (PENG et al. 2015; MORAWITZ et al. 2006; SEABROOK et al. 2007), geographical information system (GIS) and remote sensing are important tools to study the vegetation dynamics, change in plant cover, and the analysis of global changes impact on water resources.

This paper aims to assess the impact of human activities and climate change on water resource depletion in Taznakht and on Khettara’s system degradation. The particular contribution of this study is to use the statistical trends, remote sensing, and geographic information systems to assess the impact of global change on groundwater resources in arid areas.

2. Study area

Taznakht is part of the Ouarzazate province, itself part of the large region of Draa-Tafilalet (Fig. 1). Administratively, Taznakht is subdivided into five communes: rural (Ouislsate, Iznaguene, Siroua, Khzama) and one urban (Taznakht). The latter is the center of the administrative complex (AIT ELHAI; & BOUÑAR 2016). The total area of Taznakht is 4,405 km² with an estimated population of 45,225 inhabitants, spread over 7,140 households (HAUT-COMMISSariat AU PLAN 2014).

Taznakht is an integral part of Drâa basin, characterized by an arid to semi-arid climate with a bimodal precipitation distribution (i.e., dry summers and winters with erratic precipitation events (DE JONG et al. 2008; SCHULZ & DE JONG 2004)). According to Köppen-Geiger climate system, the study area is classified as Arid Desert hot “BWh” climate type (see Table 1 in PEEL et al. 2007). This classification indicates a warm Mediterranean climate with a dry summer. The average temperature in Taznakht is 19.5 ° C, and the average rainfall is 161.9 mm. The high evaporation rate can exceed 3000 mm/yr (KLOSE et al. 2008; AIT LAMQadem et al. 2019). The hydrological system depends to an extent on water runoff from the Anti-Atlas Mountains range surrounding the Tznakhte plain. However, the quasi-absence of surface water supplies in the area results in high dependence on groundwater extraction, which, increased in the last decade due to the Moroccan Green Plan.

The Taznakht area, part of the Precambrian Zenaga Buttonhole, is located about 80 km southeast of Ouarzazate in the central Anti-Atlas, on the northern edge of the West African Craton (WAC). This buttonhole consists of a Paleoproterozoic basement, composed of schists, micaschists, and granites (CHEVALLIER et al. 2001). The northern slope includes non-metamorphic sub-vertical outcrops of the Neoproterozoic age (Fig. 2). They are composed of quartzites and conglomerates, overlain unconformably by two slightly deformed Late Proterozoic and Terminal Proterozoic units (SAIDI et al. 2019). The first unit is a low-acid Precambrian III volcanic unit composed of an orogenic sequence of calc-alkaline affinity. The second unit corresponds to an upper Adoudouian carbonate sequence (SAIDI et al. 2019). Note finally that, IKENNE et al. (2017) noticed the presence of Mesoproterozoic overlying materials,
represented by limestones and quartzites that they attribute to the Taghdout group.

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In Taznakht, the useful agricultural area counts for 193400 ha where 2780 ha is dry and 1880 ha is irrigated, the rest (more than 97% of the total area) is mostly uncultivated spaces used as rangelands. The practice of Saffron cultivation spreads over an area of 80 ha in four rural communes: 30 ha in Siroua, 25 ha in Iznaguene, 15 ha in Ousselsate, 10 ha in Khouzama. The total number of Saffron producers in Taznakht is estimated to be 1025, with an average area of 959 m² of saffron per producer. Water resources are limited and irrigation is practiced around water sources, Wadis, and private wells. Besides saffron, agriculture is based on cereals, horticulture, forage crops, and arboriculture. This plant production system is associated with extensive breeding of mainly sheep and goats (ABOUDRARE et al. 2014). The region of Taznakht is widely known for the quality of its Berber carpets, which usually require women of the area often weave several months of work. Subsistence farming, extensive breeding, and traditional carpet weaving crafts are the primary sources of income for the Taznakht people.

![Figure 2: Schematic geological map, illustrating (a) the geological structures in Morocco and (b) the Anti-Atlas domain (THOMAS et al. 2002), and (c) the major rock materials in Zenaga inlier.](image-url)
3. Data and Methodology

3.1. Data

This study used the rainfall and temperature data, remote sensing images and field trips investigations, and inventory and social survey of Khettara systems.

3.1.1. Rainfall and temperature data

Rainfall and temperature records from Assaka meteorological station, as outlet points of the Taznakht plain, were used in this study. Data series from Assaka station were provided by the Draa Oued Noun Hydraulic Basin Agency (ABHDON).

The meteorological data used in this study are annual precipitations, monthly precipitations, monthly average temperatures, monthly maximum temperatures, and monthly minimum temperatures, from the year 1985 to the year 2015, recorded in the station of Assaka.

In addition to in-situ measured temperatures, monthly average estimated temperatures are extracted from the “climate change knowledge world-bank” for 12 points into the plain.

3.1.2. Remote sensing data

Seven multispectral image sets from Landsat 4-5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) were downloaded freely online from the U.S. Geological Survey platform (https://earth explorer.usgs.gov/). The selected period is from the 20th of April to the end of May, except for 2020 where the most recent image was acquired on the 30th of March. We chose this period to avoid confusion with the annual vegetation and agricultural periods, using the radiometric resolutions for the Landsat MSS and TM sensors were 8 bits. In comparison, the radiometric resolution of the Landsat OLI sensor was 16 bits. Table 1 presents the main characteristics of the used images.

3.2. Methodology

The adopted methodology in this work is divided into three fundamental phases, as presented in Fig. 3. The first phase concerns the collection and statistical analysis of climate data. The second phase starts with the Landsat images collection and pre-processing and ends with the study of the vegetation evolution to evaluate the impact of climate and anthropic factors on the water resource condition and the vegetation change (Fig. 3). Finally, we dedicate the third phase to Khettaras inventory and spatiotemporal change detection of rural agricultural fields.

Therefore, we combined the data and results obtained with the change detection output into an integrated analysis and discussion, providing a better understanding of the spatiotemporal dynamics of vegetation and impacts on groundwater resources.

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<th>Satellite</th>
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<td>Landsat 8</td>
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3.2.1. Statistical treatment of climate data

Two statistical methods were used in this study: The Standardized Precipitation Index (SPI) and the moving average.

The SPI, developed by MCKEE et al. (1993), is a powerful tool for drought studies and is classified as a green index thanks to its simplicity and ease of use. It is the standard index for tracking and monitoring meteorological drought. SPI is performed from the following equation (1):

$$SPI = \frac{(Pi - Pm)}{\sigma}$$  \hspace{1cm} (1)

Where:
- $Pi$: Total rainfall for the year $i$;
- $Pm$: Mean annual rainfall of the time series;
- $\sigma$: Standard rainfall deviation of the time series.

The moving average is the most apparent data smoothing over a specified period. It is a calculation that analyzes data points by creating a series of averages of different subsets of the full data set, which helps smooth out short-term fluctuations and highlight longer-term trends or cycles.

The monthly average temperature extracted from the climate change portal of the World Bank for 12 points within the plain is interpolated using inverse distance weight (IDW) to visualize the spatiotemporal distribution of temperature.

3.2.2. Vegetation index

The Normalized Difference Vegetation Index (NDVI) quantifies vegetation by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs) using the equation below (WEIER & HERRING 2000):

$$NDVI = \frac{(\text{Near infrared} - \text{Red})}{(\text{Near infrared} + \text{Red})}$$  \hspace{1cm} (2)

This index varies from -1 to +1.

Varying between -1 and +1, NDVI was computed for all the plains extracted from the satellite images using the same remote sensing and image processing software. Then, they were reclassified into two classes: a vegetation cover, and a non-vegetation cover, using a geospatial processing program.

Finally, we converted each image into a percentage to define the vegetation cover and analyze its evolution over the years. We then deduce a graph to verify the existence of a trend.

3.2.3. Khettaras Inventory

Using Google earth and field trips inventory, Khettaras were digitized throughout the Taznakht plain and documented according to their number.
and location in a GIS database. Some their characteristics are extracted such as wells number, length of every system, current status of in addition to the total length of all the Khettaras in the Taznakht plain.

4. Results
4.1. The Standardized Precipitation Index and rainfall trend

With equation (1), we calculate the SPI to determine the wet and dry phases in the climate of Taznakht plain, using the annual mean of rainfall data from 1985 to 2015. Figure 4a displays that the 30-year study starts with a lightly dry year heading for a moderately dry one by the end of 1986, and directly after 1987, an extremely wet phase started and kept going until the end of 1989. A variation of dry and wet steps began from 1990 to 1993, followed by a continuous wet phase until 1995. We divided this wet phase into a moderate one in 1994 and a light one in 1995.

From 1996, precipitation kept decreasing until the end of 2000, so this whole period was marked a lightly dry one but 2000, which was a moderately dry year. In 2001, precipitation went up again keeping an SPI of only 0.09 but making it at least a lightly wet year. However, it started falling again, marking a lightly dry phase from 2002 to 2007 with one moderate dry year; 2004. From 2008 to 2010, another wet phase started, followed by a dry one that lasted from 2011 to 2014, with the two years 2011 and 2013 moderately dry. The year 2014 increased directly after, marking the highest SPI since 1989. Finally, we noted that over the 30-year study period, we counted 17 dry years and 12 wet years.

![Figure 4](image.png)

**Figure 4.** Statistical treatment of rainfall data, (a) SPI results for the period 1985-2015, (b) Moving average of annual rainfall (1985-2015)

We calculated the moving average of annual precipitation to confirm the predominance of dry phases throughout the years. For this purpose, we used groups of 5 years to see the precipitation trend during the global period 1985-2015. Figure 4b shows a remarkable decrease in rainfall throughout the years, with huge variations, especially from 1985 to 1998. This period witnessed the most substantial precipitation in 1989, with 198.58 mm of rain. Furthermore, we noted an evident decline in rainfall from 1995 to 2000 to the end of the time series. As a result, we demonstrated a widespread rain was decreasing trend in the area, reducing around 70 mm during the studied period.

4.2. Spatiotemporal evolution of temperatures in the Taznakht basin

Using groups of 5 years, we calculated the moving average of the maximum and minimum temperatures (Fig. 5) to understand better the impact of temperature on the plain of Taznakht.
In Figure 5a, the trend declines very softly throughout the years, as the first and last maximum temperatures are very close; they are both limited between 28 °C and 29 °C. On the other hand (Fig. 5b), an evident increasing trend in minimum temperatures with a variation of 3.36°C was noted. Therefore, we detected that temperature is building up in the new millennium as it exceeds 8°C, contrary to the decades before where it never passed 6°C, which influenced the trend to increase even more.

In Figure 6, the elaborated maps using estimated satellite climate data and validated by in-situ measured data (Fig. 7) show that temperatures have increased over the Taznakht plain during the 30-years period.

The lowest temperatures are recorded in the northern part of the plain, while the highest temperatures are in the southern region and the same distribution list for the whole period. We noted that the temperature decreased in the upper half of the plain from 1980 to 1995. It rises again before the year 2000 and then decreases again from 2005 to 2010 and finally increases again until 2015.
4.3. Evolution of plant cover

The application of the NDVI on every satellite image allowed us to obtain the vegetation maps that show the evolution of the plant cover from 1985 to 2015 (Fig. 8). In this studied period, there was a slight change in the plant cover in the NE of the plain where it has gotten stronger with the emergence of a green field in the SW. From 1985 to 2000, a general decline of the plant cover all over the plain was recognized where vegetation looks less strong, specifically mentioning the disappearance of two fields in the NE of the plain. From 2000 to 2015, a very remarkable vegetation growth was noted, as it appears stronger and more intense throughout the whole plain in 2015 compared to 2000, along with the emergence of many green fields in the north and in the south parts of the plain.

In the study of the evolution of vegetation in the plain of Taznakht, we calculated the percentage of vegetation cover and then compared it to the non-vegetation surface. We gathered our results in the
graph of Figure 9. From 1985 to 1995 we noticed that the percentage of plant cover growing by 0.77%, and then reduced until 2005 by 1.07%. After 2010, the plant cover exceeds 2%.

![Figure 8. Spatiotemporal evolution of vegetation in the plain of Taznakht from 1985 to 2015](image)

![Figure 9. Vegetation percentage evolution during the period 1985 to 2015](image)

4.4. Agricultural field distribution according to the Khettaras conditions

After the field inventory and the digitizing of all the Khettaras around the plain of Taznakht using Google Earth, data were exported, then projected over a satellite image of the year 2020 as shown in the map below (Fig. 10). We noticed that Khettaras are distributed all over the plain and are mostly localized close to water streams. Almost every village or Douar has its own and sometimes multiple Khettara series, depending on the size of irrigated fields. There is 11.48 km of the Khettara series across the whole plain.

Most of the Khettaras in the Taznakht plain are not functioning, which impacts vegetation reduction, proven in the example of the small Douar Ait Alioun. The NDVI results in figure 11 show the distribution of vegetation by green color. Generally, the surface occupied by irrigated fields is reduced from 1995 to 2005. According to field observations and social surveys, this reduction is quite remarkable. For example, in the 2005 map, an entire agricultural field disappeared compared to the 1995 map, rounded by the red circle in figure 11.
5. Discussion

We conducted the climate analysis using statistical and GIS interpolation methods that revealed that during the period 1985-2015, the climate of Taznakht experienced a variety of wet and dry phases. The results of the standard precipitation index allowed us to observe a variety of precipitation statuses in Taznakht, as they showed a climate that experiences different phases ranging...
from extreme wetness to moderate drought over the 30 years (1985-2015). Taznakht experienced the last intense wet phase in 1987-1989, with the highest amounts of precipitation record, ranging from 185.4 mm to 281.3 mm. Indeed, after 1983, we never had such a high precipitation rate, but after a dry phase, an occasional increase occurred from time to time.

Figure 11. Example of agricultural field losing in the study area. NDVI maps of year 1995 (a) and year 2005 (b)
Comparing the period 2000-2015 to 1985-2000, we noticed that the precipitation rate decreased. The moving averages of precipitation and temperature showed correlative results. Precipitation showed, according to the standard index results, a decreasing trend. Maximum temperatures presented a decreasing trend, as the change is hardly recognizable. In contrast, minimum temperatures increased since 1985; this trend continued from the new millennium until the end of the time series. We can thus conclude that it was not as cold as before because the temperature is constantly increasing in Taznakht, especially since the decrease in precipitation did not help.

Furthermore, the increasing frequency and intensity of drought in Taznakht are related to global climate change. Therefore, the resulting trends will likely be more evident in the future. In this case, reduced precipitation and increased temperatures in the Taznakht plain will drastically reduce water resources. This reduction will impact the irrigation of agricultural fields, and only groundwater will be available to alleviate the water stress in this plain.

In 1985, the vegetation cover only counted for 1.18% of the whole area of Taznakht plain. The plain being can explain this small percentage at its early recovery from the light drought it experienced between 1982 and 1983. The vegetation cover in Taznakht plain kept going up until 2000. After that, it started declining drastically, especially in 2005, when it reached the lowest amount of vegetation cover during the whole time series of 30 years due to climate change's impact on the plain. However, 2005 had a modest amount of precipitation; for example, the Assaka station recorded only 108.3 mm, which we explain by unseasonal rainfall.

A notable increase in vegetation cover occurred in 2010 when it reached the highest percentage in the 30-year time series due to increased rainfall and the adoption in 2008 of the Green Morocco Plan, which aims to improve vegetation cover. This plan has allowed a substantial increase in the production of saffron, in parallel with market demands. Subsequently, thanks to this plan, the vegetation remained abundant, despite the 50% decrease in rainfall compared to 2010.

Furthermore, analysis of the NDVI maps of Douar Ait Alioun shows that the change in vegetation cover appears negative due to the decrease in agricultural fields between 1995 and 2005. According to our survey, it seems that the series of Khettaras in this Douar was inactive after the year 1995, which caused the disappearance of some fields, usually directly irrigated by this system. Therefore, it is clear that the disappearance of the Khettara system has impacted the distribution of agricultural fields and has led to erosion and a decrease in vegetation cover.

Finally, we noted that the decline in the performance of this system is mainly due to the orientation of the inhabitants towards more modern irrigation systems through boreholes, even if they are more expensive. Unfortunately, a prolonged period of intense drilling and pumping will undoubtedly lead to a general disturbance of the aquifer, sometimes resulting in a lowering of the water table and drying up of the Khettaras.

6. Conclusion

The plain of Taznakht experiences severe drought proven by rainfall reduction (with almost 50%) during the observed 30-years (1985-2015) with more dry phases than wet ones, increasing temperatures accompanied by high evapotranspiration rates, and dry inactive Khettaras; which impacts the economic and social situation of its population. The evolution of vegetation cover was studied using Landsat images and the vegetation index to clarify the impact of climate change on water resources in the plain.

This study demonstrated a reduction in vegetation cover of 45% since the beginning of the new millennium, showing a correlation with the climate tendency. However, after 2005 the state of vegetation reached the highest area in 2010 (2894 ha). This cover extension coincides with Green Morocco Plan, launched in 2008 and supported an agriculture process in the country including the Taznakht area. During 2015, the vegetation cover observes a similar extension of 2738 ha than 2010, despite the high temperature and low rainfall. The main water supply was from groundwater, causing overexploitation of the aquifer. We highlighted
this human impact by distributing agricultural fields and Khettaras state over the plain using the NDVI results. These Traditional techniques used to collect water for drinking and agriculture purposes are in continuous degradation, in the area, letting place to the boreholes which the government supports. This local turning from traditional Khettara systems to more modern techniques of drillings because they need a high cost of maintenance to exacerbate the water crisis in the area.

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