

Assessment of the impact of climate change on soil moisture using remote sensing and Geographic Information Systems (GIS)

M. Meghraoui¹ and M. Regagba²

⁽¹⁾National Institute of Forestry Research, ,
BP 88, Mansourah, Tlemcen, Algeria
Email : meghraoui_forestier@yahoo.fr

⁽²⁾National Institute of Forestry Research, ,
BP 88, Mansourah, Tlemcen, Algeria
Email : regmoha13@gmail.com

ABSTRACT

Studying the relationship between the Soil Moisture Index (SMI) and climate change is crucial, as it provides insights into the impacts of changing climatic conditions on soil moisture dynamics and hydrological processes. Our main objective in this study is to evaluate soil moisture variations in the El Mefrouche watershed in northwestern Algeria, based on changes in climatic parameters such as precipitation and temperature over a period of five years. To achieve this objective, we will use Landsat 8 satellite images for each year of the study period. The study uses a Soil Moisture Index (SMI) to analyze satellite images taken on five different dates. The results show that on 02/01/2019, the soil moisture was very high (SMI from 0.8 to 1) covering an area of 309.67 hectares, whereas on 12/30/2017, the soil moisture was very low (SMI from 0.8 to 1) covering only an area of 65.46 hectares. The driest SMI values (0 to 0.2) were recorded on 12/30/2017, covering the largest area of 1809.37 hectares, indicating that the soil was very dry in a large part of the watershed. What is really confirmed after analyzing the climatic data for the cited period

Keywords: SMI, Remote sensing, Landsat8, climate, El Mefrouche.

Mathematics Subject Classification Number: 62P12

1. INTRODUCTION

The Soil Moisture Index (SMI) is an index that allows the measurement of soil moisture content in a watershed. It is generally calculated from satellite data and allows the evaluation of soil moisture over a large area at a given time (Arnab et al. 2019 ;Yiping et al. 2018 ; Mohamed et al. 2019). The importance of SMI in watersheds lies in the numerous advantages it offers for water resource management and hydrological analysis , the SMI allows for the tracking of variations in soil moisture at the watershed scale, which can help predict hydrological phenomena such as floods or droughts (Nitu 2021). It can also be used to monitor the effects of climate change on water resources and ecosystems (Arnab et al. 2019).

There have been several studies that have used satellite imagery to evaluate the Soil Moisture Index (SMI). (Mishra and Singh 2012 ; Anderson et al. 2007 ; Njoku and Entekhabi 1996 ; Carlson and Ripley 1997) used different types of satellite images and sensors to evaluate soil moisture using the Soil Moisture Index (SMI). The methods used in these studies include the use of thermal imaging, passive microwave remote sensing, and the relationship between the NDVI (Normalized Difference Vegetation Index), fractional vegetation cover, and the Soil Moisture Index. These studies have shown that satellite imagery is useful for evaluating soil moisture at different spatial and temporal scales.

The annual monitoring of soil moisture is important to assess the effect of changes in climatic parameters. By tracking soil moisture over time, it is possible to identify patterns and trends that may be related to changes in precipitation, temperature, or other climatic factors (Mimeau et al. 2021). This information can be used to better understand the impacts of climate change on soil moisture and to inform land management decisions (Nitu 2021). Remote sensing tools, such as satellite imagery, can be particularly useful for monitoring soil moisture over large areas and over time. By combining remote sensing data with ground-based measurements and models, researchers can gain a more comprehensive understanding of how soil moisture is changing and what the implications of those changes may be (Roman et al. 2020).

2. STUDY AREA AND DATA USED

The El Mefrouche watershed is located in the Tlemcen region, in the northwest of Algeria, between the following geographical coordinates: Longitude $x_1 = 123$ km, $x_2 = 139$ km and Latitude $Y_1 = 170$ km, $Y_2 = 180.5$ km (fig.1). It covers an area of 86 km², with a perimeter of 46.3 km. It is a region of mountains and hills with an altitude ranging from 1100 to 1450 meters, covered with vegetation typical of the Mediterranean region.

The climate of the region is Mediterranean, characterized by hot and dry summers and mild and rainy winters. Average annual precipitation is around 600 mm, with significant variations from year to year.

The watershed is crossed by several watercourses, the main ones being the Tafna and Mefrouche rivers. These watercourses are vital for the region, as they provide water for irrigation and human consumption.

The substrate is mainly composed of sandstone and limestone from the Secondary period. To the north, the substrate consists of Miocene marls, in which very hard yellowish sandstone beds are intercalated, and to the south, of Jurassic sandstone and limestone (Ghenim and Meghounif 2013).

To achieve the objectives of this study, we used digital data in the form of Landsat 8 satellite images downloaded from the USGS GloVis website for the following dates:

Landsat 8 Image 1 of 30/12/2017

Landsat 8 Image 2 of 02/01/2019

Landsat 8 Image 3 of 05/01/2020

Landsat 8 Image 4 of 22/12/2020

Landsat 8 Image 1 of 10/01/2022

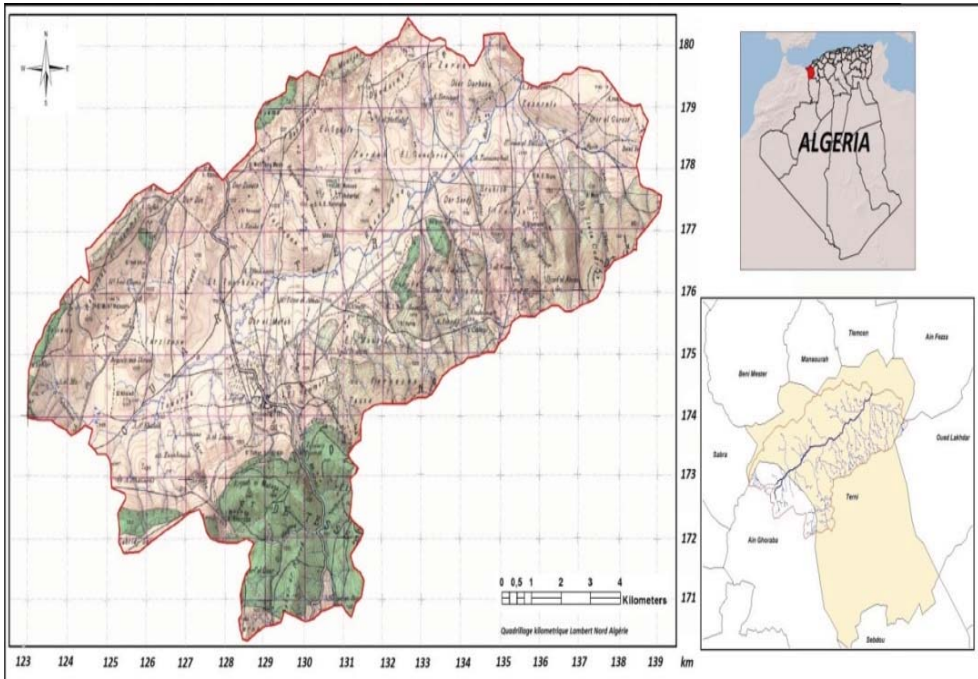


Figure 1. Map of the location of the El Mefrouche watershed

3. METHODOLOGY

Our methodological approach is summarized in the organizational chart presented in Figure 2. This figure schematically illustrates the different stages of our methodology. We used this approach to conduct our study, following the different steps described in the organizational chart. It is important to note that this methodology was designed to ensure a rigorous and consistent approach throughout the study.

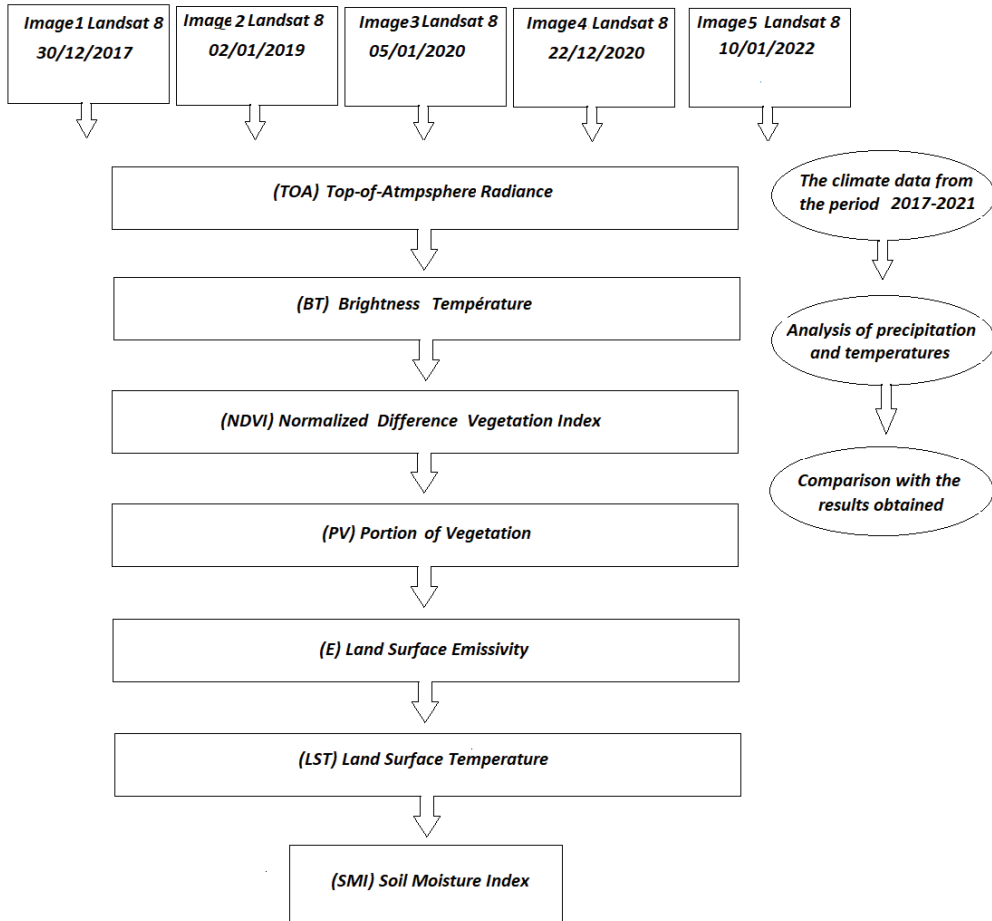


Figure 2. Evolution of the ratio R_p^2 / R_0^2 according

3.1. Top of Atmpsphere Radiance (TOA)

The TOA radiance can be calculated by multiplying the radiance multiplier by the digital counts from the satellite sensor, adding an additive offset, and subtracting the atmospheric contribution (Kowalik 1983).

$$L(\lambda) = ML \times \text{Band 10} + AL - O_i$$

$$\text{TOA} = 0.0003342 \times \text{Band 10} + 0.1 - 0.29$$

Where : $L(\lambda)$: TOA spectral radiance

ML : Radiance multiplicative band (from information of satellite image)

AL : Radiance add band 10 (from information of satellite image)

O_i : Correction value of band 10

3.2. Brightness Temperature (BT)

Brightness Temperature (BT) is a measure of the thermal radiation emitted by an object in the microwave spectrum. It is expressed in units of temperature (usually Kelvin or Celsius) and is used to estimate the temperature of the object emitting the radiation, The BT values can be used to derive other geophysical parameters, such as soil moisture, snow depth, and vegetation water content, among others (Zhou and Cheng 2020).

$$BT = K2 / \ln (K1 / L(\lambda) + 1) - 273.15$$

$$BT = (1321.0789 / \ln(774.885 / L(\lambda) + 1)) - 273.5$$

Where : BT : Top of Atmosphere brightness temperature °C

L(λ) : TOA spectral radiance

K1 : Constant for band 10 (from information of satellite image)

K2 : Constant for band 10 (from information of satellite image)

3.3. Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a simple, yet powerful remote sensing index that is commonly used to assess the health and vigor of vegetation. It is calculated from the reflectance values of two bands of light - one in the red region of the spectrum and the other in the near-infrared (NIR) region (Tucker 1979).

$$NDVI = (\text{Near-infrared} - \text{RED}) / (\text{Near-infrared} + \text{RED})$$

$$NDVI = (\text{Band 5} - \text{Band 4}) / (\text{Band 5} + \text{Band 4})$$

3.4. Portion of vegetation (PV)

The Portion of Vegetation (PV) is a parameter commonly used in remote sensing to quantify the amount of vegetation cover in a particular area. It is calculated as the fraction of the ground covered by vegetation, and is typically expressed as a percentage (Liu et al. 2018).

$$PV = ((NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min}))^2$$

Where: PV: Portion of vegetation

NDVI: values of NDVI image

NDVI_{max/min}: Max & Min values of NDVI image

3.5. Land surface Emissivity

Land surface emissivity (E) is a measure of how effectively a surface emits thermal radiation, which is an important parameter in remote sensing and climate modeling (Zhou and Cheng 2020).

$$E = 0.004 \times PV + 0.986$$

Where: E: Land Surface Emissivity
PV: Portion of vegetation

3.6. Land Surface Temperature

Land Surface Temperature (LST) refers to the temperature of the Earth's land surface, typically measured in degrees Celsius or Fahrenheit. It is an important parameter in climate studies, as it can affect energy and water exchanges between the land surface and the atmosphere, which in turn can impact weather patterns and the Earth's climate (do Nascimento et al. 2022).

$$LST = BT / (1 + (\lambda \times BT / C2) \times \ln(E))$$

$$LST = BT / (1 + (10.8 \times BT / 14388) \times \ln(E))$$

Where : BT : Top of Atmosphere brightness temperature °C
 λ : Wave length of emitted radiance (for Landsat 8 band 10 $\lambda = 10.8$)
 $C2 : h \times C / S$ $C2 = 14388$ (h : Plank's constant = 6.626×10^{-34}), (S : Boltzmann Constant = 1.38×10^{-23} JK), (C = velocity of light = 2.998×10^8 m/s).

3.7. Soil Moisture Index

The SMI (Soil Moisture Index) is an index that allows to assess soil moisture. It can be calculated from the LST (Land Surface Temperature), which is the temperature of the earth's surface measured by satellite sensors (Potic et al. 2017).

$$SMI = (LST_{max} - LST) / (LST_{max} - LST_{min})$$

Where: SMI: Soil Moisture Index
 LSTMax/Min: Max & Min values of Land Surface Temperature image
 LST: values of LST image.

4. RESULTS

4.1. Normalized Difference Vegetation Index (NDVI)

The values of NDVI have a direct impact on the SMI. These values generally range from -0.10 to 0.47, and can vary from year to year. High values of NDVI indicate strong chlorophyll activity and a dense vegetation cover, while low values may indicate weak chlorophyll activity or a lower density of vegetation (fig.3).

Comparing the data from 2018 to 2022, we can see that 2019 recorded higher NDVI values, with a precipitation of 695 mm, compared to only 296.2 mm in 2018. This difference in precipitation directly

influenced the vegetation density, which explains the higher NDVI values in 2019 compared to 2018. These annual variations can be useful for understanding the effects of climate change on vegetation and for making decisions regarding land management.

4.2. Land Surface Temperature

There is a direct relationship between Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI). We observed that where LST values are low, vegetation density is also less significant, and may even decrease to a minimum value of 0.96 for the year 2020. Conversely, when LST values are high, vegetation density increases, reaching a maximum value of 16.94 for the year 2019 (fig.4).

4.3. Soil Moisture Index (SMI)

Table 1: The Soil Moisture Index surfaces per hectare

SMI	30/12/2017	02/01/2019	05/01/2020	22/12/2020	10/01/2022
0 - 0,2	1809,37	116,87	424,43	431,50	415,62
0,2 - 0,4	5708,32	1710,77	3193,75	3838,35	2397,22
0,4 - 0,6	750,63	4332,47	3236,81	2962,86	3737,64
0,6 - 0,8	174,71	2038,71	1501,53	1146,97	1755,48
0,8 - 1	65,46	309,67	151,94	128,81	202,44

The results of the soil moisture index (Table.1) (Fig.5) show that soil moisture is very important in the Mefrouche watershed for the image of 02/01/2019. The SMI interval from 0.8 to 1, which is considered high moisture, covers an area of 309.67 hectares. This indicates that the soil was very moist on this date in this area of the watershed.

In contrast, for the image of 30/12/2017, a very low SMI value was recorded for the interval of 0.8 to 1, covering only an area of 65.46 hectares. This indicates that the soil was very dry on this date in this area of the watershed.

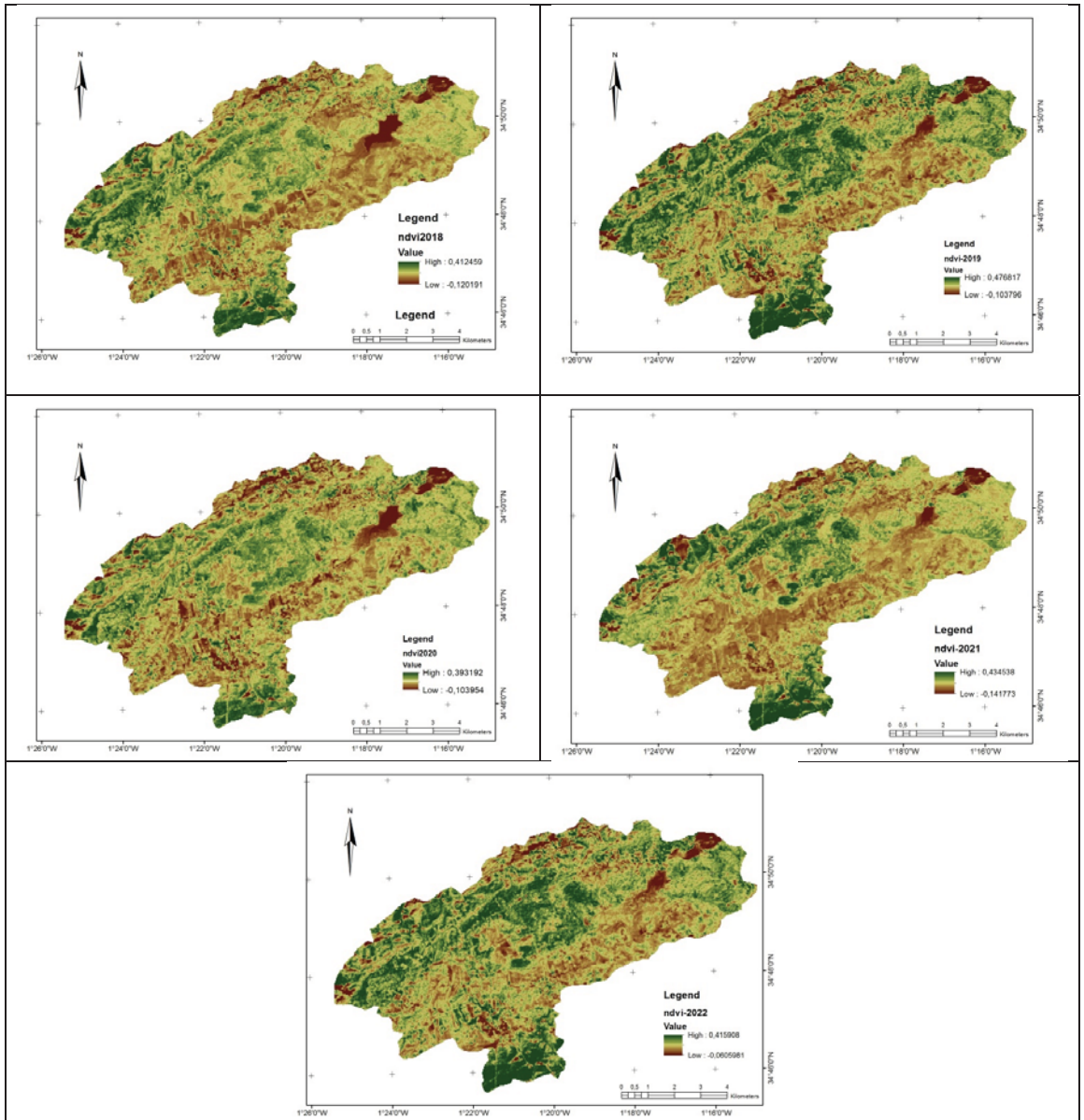


Figure 3. The Normalized Difference Vegetation Index (NDVI) of the El Mefrouche Watershed, period of 2018-2022

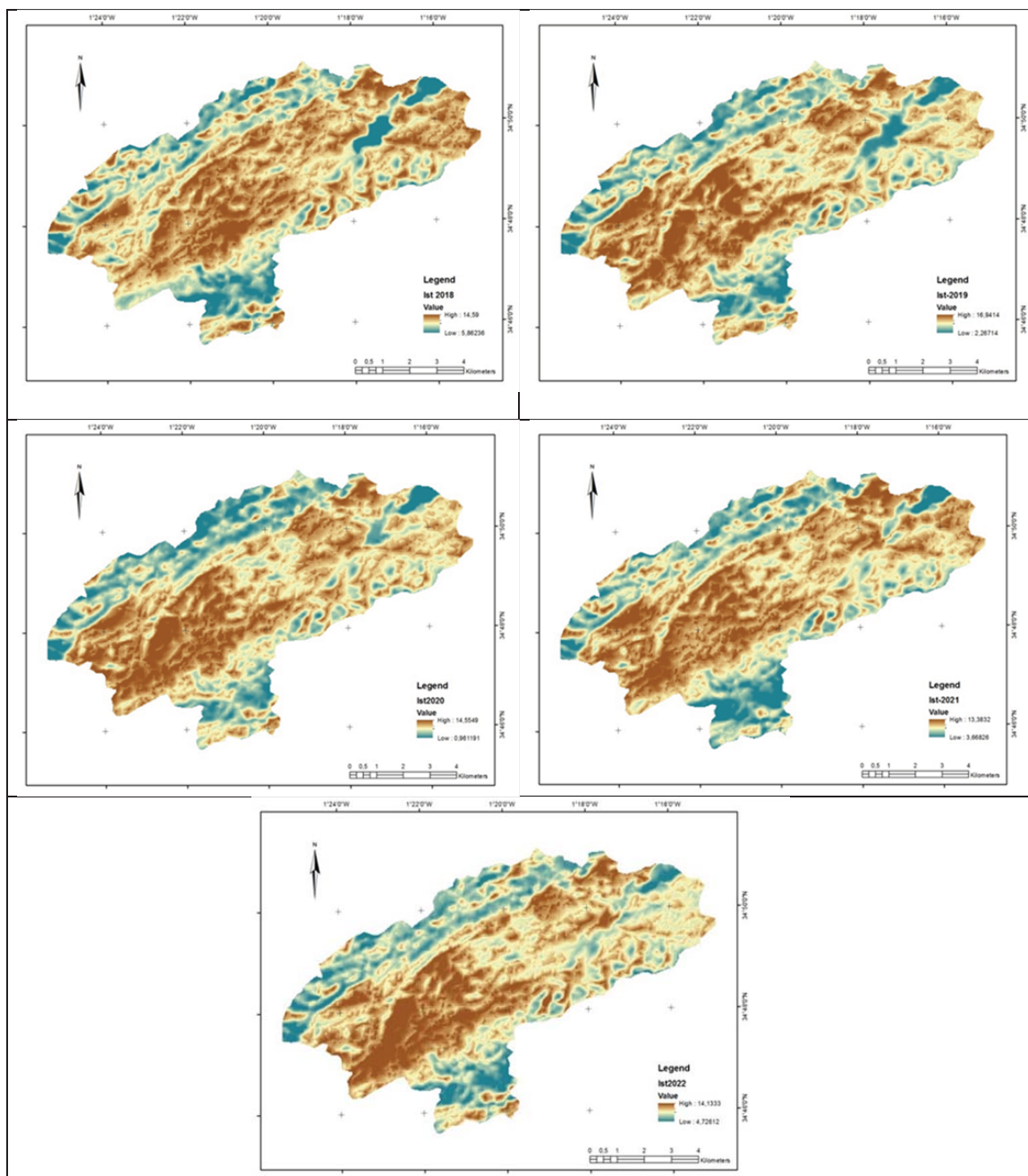


Figure 4. The Land Surface Temperature (LST) of the El Mefrouche Watershed, period of 2018-2022

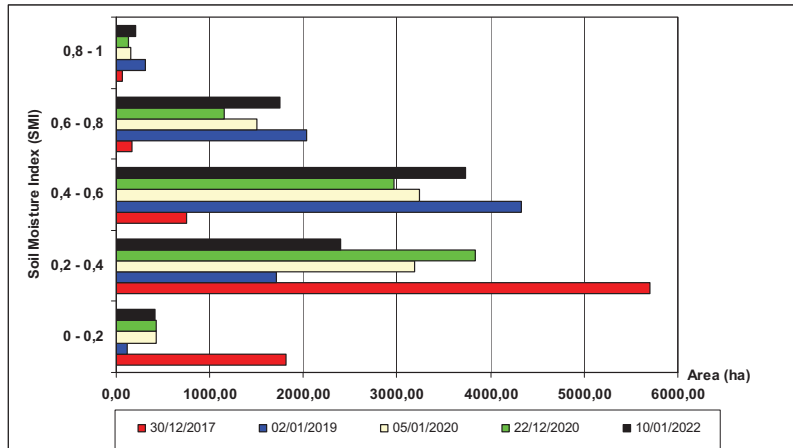


Figure 5. The Soil Moisture Index surfaces per hectare of the El Mefrouche Watershed

When looking at the driest SMI values, from 0 to 0.2, the image of 12/30/2017 recorded the largest area of 1809.37 hectares. This indicates that the soil was very dry in a large part of this area of the watershed on this date. In contrast, the image of 02/01/2019 recorded the smallest area for this same category, with only 116.87 hectares, which indicates that the soil was relatively moist on this date in this area(fig.6).

4.4. The impact of climate change on soil moisture

Table 2: Climatic data of the El Mefrouche Watershed (2017-2021)

Year	2017	2018	2019	2020	2021
Rain (mm)	296,2	695,4	280,2	283,2	290,5
Temp(°c)	17,58	15,96	16,24	17,42	17,37

To evaluate the impact of climate change on soil moisture and confirm the reliability of previous results, we examined the climatic data for the period from 2017 to 2021 (Table 2). We found that the wettest year was 2018 with 695.4 mm, and a low average temperature preceding the image of 02/01/2019, which showed a higher SMI (Soil Moisture Index). On the other hand, in 2017, although it did not record the highest value with 17.58 °c , the average temperatures were higher. Since temperatures play a very important role in soil evaporation and drying, this could explain these differences (fig.7). These results confirm the reliability of our study.

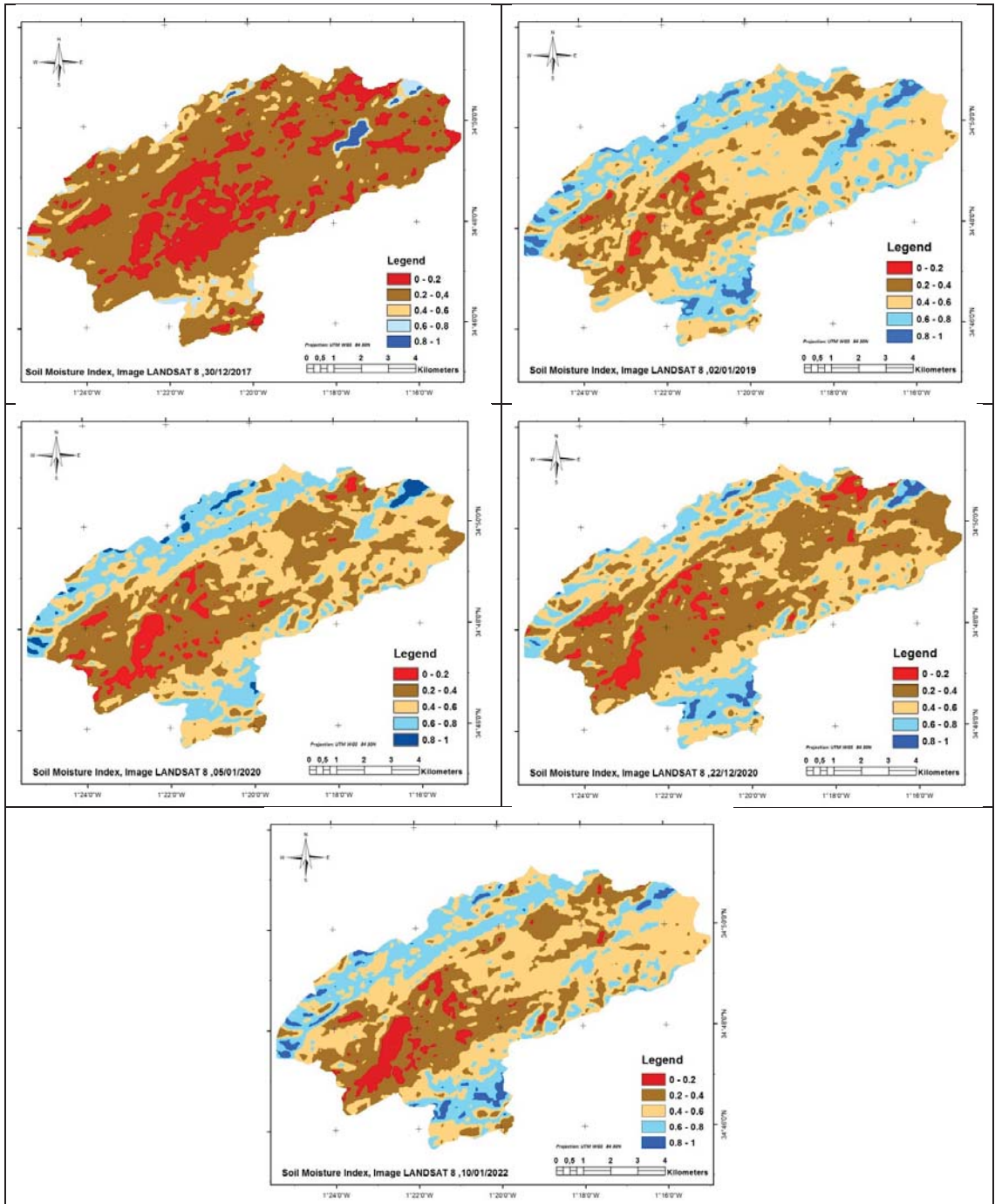


Figure 6. The Soil Moisture Index (SMI) of the El Mefrouche Watershed, period of 2018-2022

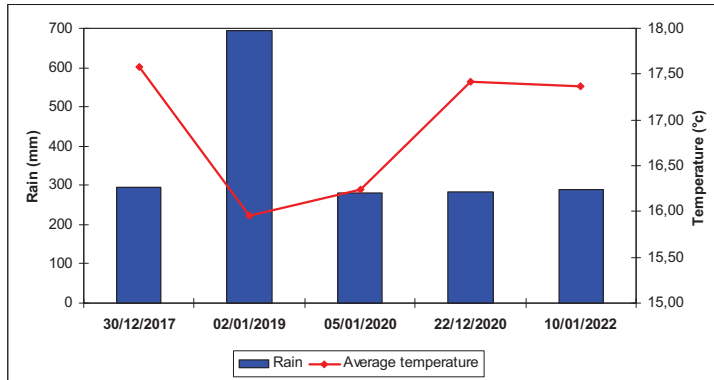


Figure 7. Temperature and precipitation in the El Mefrouche Watershed.(2017-2021)

If we compare our study with that of other authors, several have examined the relationship between soil moisture and climatic data. Seneviratne et al. 2010 examined the interactions between soil moisture and climate in the context of climate change. The authors reviewed previous studies on the subject and discussed methods for modeling these interactions. Taylor et al. 2012 studied the relationship between soil moisture and precipitation was highlighted, with the suggestion that afternoon rains are more frequent on drier soils. Zeng et al. 2001, researchers studied the response of soil hydrology to climate warming using general circulation models. The results suggest an increase in soil evaporation and a decrease in soil moisture in response to warming.

In summary, the work of these authors aims to explore the relationships between soil moisture and climate at different spatial and temporal scales using a variety of approaches.

5. CONCLUSION

The findings of the study clearly demonstrate the impact of climate change on soil moisture dynamics and provide valuable insights into the mechanisms involved in this relationship. By examining the climatic data from 2017 to 2021, the study identified significant differences in soil moisture levels between different years, with the wettest year being 2018 and the driest being 2017. The results also showed that average temperatures played a crucial role in soil evaporation and drying, which could explain the observed differences in soil moisture levels. These results provide further evidence of the importance of monitoring and researching the relationship between climate change and soil moisture dynamics using remote sensing and geographic information systems . It is clear that ongoing changes in climate patterns will continue to have a significant impact on soil moisture levels, with potential consequences for agriculture, natural ecosystems, and water resources. Therefore, it is crucial to continue studying this relationship and developing strategies to mitigate the impacts of climate change on soil moisture dynamics.

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