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SPATIAL AND TEMPORAL ANALYSIS OF ARIDITY TRENDS USING THE DE MARTONNE INDEX: A GIS-BASED STUDY OF THE TIMGAD BASIN, ALGERIA

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ABSTRACT

Knowledge of drought conditions is necessary for the rational use of water resources, the prevention of the dangers resulting from them, and for explaining landscape and ecology characteristics. To analyze annual, seasonal and monthly aridity trends in the Timgad Basin, North-East Algeria, climate data from 07 meteorological stations within the 1975-2009 period were used. After computing the De Martonne aridity index at each station, a geographic information system (GIS) was utilized to maps this index throughout the region and specify drought trends, visualizing detected annual, seasonal and monthly tendencies. On an annual scale, the De Marton Drought Index shows a semi-arid climate in the entire Timgad Basin. On a seasonal scale, the winter season shows a dry semi-humid climate - from Mediterranean to semi-humid conditions, and the climate of the region in autumn and spring is semi-arid except for some eastern areas, which are characterized by a dry semi-humid climate - from Mediterranean conditions in spring. In contrast, summer shows from very dry to dry. The period extending from May to October is characterized by a semi-arid to dry climate; December and January reveal humid conditions, while November, February, March and April belong to a semi-arid to Mediterranean climate.

KEYWORDS

De Martonne Index, Drought Analysis, GIS, Timgad Basin

CITATION

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1. Introduction.

Aridity, an important end member in the continuum of climates, was first elucidated by suggesting that understanding the concept of climatic aridity would be beneficial and broad-reaching (Liu et al., 2023). A thorough understanding of aridity is important, as it forms the basis of desertification studies and soil degradation, as well as for environmental and urban planning (AbdelRahman, 2023). Droughts have become a recurrent phenomenon in many regions of the world affecting more and more ecosystems and society. Therefore, climate indices become a good indicator for analyzing climate change (Abbass et al., 2022)). Aridity can unite different scientific disciplines, providing possibilities for integrated research and resource evaluations (Begizew, 2021); (Isukuru et al., 2024). The Aridity Index is one of a succession of formulas developed to describe the climatic dryness of a given location, derived from a simple ratio of the annual precipitation accumulated and the mean annual temperature (Meng et al., 2021); (Bešťáková et al., 2023). The De Martonne Aridity Index is an essential geographical climatic index used to understand, assess, and grade the climatic environmental conditions relating to aridity. Aridity indices are undergoing massive studies in contemporary climate series for environmental change studies ((Derdous et al., 2021). This provides a correlation between temperature and rainfall values. The base of the aridic changes in various climates from place to place can be observed on a map of a more significant area as well (Araya-Osses et al., 2020).

There are a number of aridity indices around the world (Balmaceda-Huarte et al., 2021), but the De Martonne formula remains highly significant due to its ability to measure climate aridity accurately and makes it possible for these indicators to be compared with each other (Dunn et al., 2020); (Abbas & Mayo, 2021); (Balmaceda-Huarte et al., 2021).

This study aims to evaluate the drought of seven stations located in the study area, both temporally and spatially. It then uses geographic information systems (GIS) to represent these phenomenon in maps according to seasons and months, thereby assessing the water status of the region and determining the extent of the impact of rainfall deficiency on water and environmental resources from 1974 to 2009.

In Algeria, drought and desertification are one of the main research topics for many climate experts, against the backdrop of climate change and exceptional fluctuations in rainfall and temperature. Drought is more severe in the interior regions of Algeria, which correspond mainly to the steppe, plateau, and desert areas. Most studies indicate an increase in drought in these regions due to a decrease in rainfall, in addition to a continuous increase in temperatures and evaporation. Drought was highlighted and analyzed by (Derdous et al., 2021) for the northern regions of Algeria, where he relied on 31 climatic stations, where he concluded that the climate is very spatially diverse and is dominated by a semi-arid climate. (Taibi et al., 2017), after analyzing the drought in northern Algeria from 1936 to 2010, concluded that the western and central highlands regions experienced severe drought during the seventies and eighties, resulting in a critical deficit. (Mrad et al., 2020) relied on multivariate analysis of annual rainfall in northeastern Algeria during the period 1970–2012 and revealed large interannual fluctuations in rainfall amounts, resulting in relatively long alternating wet and dry cycles. The research paper (REGAD Nora & TATAR Hafiza, 2019) provides a comprehensive analysis of rainfall trends in a semi-arid region, highlighting the major shifts in climate patterns and the effectiveness of statistical methods in detecting these changes.

This study aims to assess drought temporally and spatially using the De Marton Index (DMI) at seven stations located in the study area and to present a GIS-based modeling approach that integrates climate indices with interpolation and thus analyzes the water situation in the region and determines the impact of rainfall deficits on water and environmental resources from 1974 to 2009.

2. Materials and Methods.

2.1 Study area

The Timgad watershed is located in the northeastern part of Batna city, in eastern Algeria (Fig. 1). between 35°19′25″ and 35°37′04″ north latitude and between 6°14′29″ and 6°35′33″ east longitude. It covers almost an area of 546 Km² and contains at its output the Koudiat Medouar Dam, which has a capacity of 62 million cubic meters.

The Timgad watershed experiences a semi-arid climate, with cold, wet winters and hot, dry summers, and receives annual rainfall between 300 and 450 mm (Tiri et al., 2015). The average annual temperature ranges from 14 to 16°C, with August being the warmest month and January the coldest. The mountainous area includes peaks like El Mahmel (2,231 m) and Rass Errih (1,916 m), while in the east, there are the Djebels Timagoult (1,875 m), Lizoures (1,746 m), and Jebel Aslef (1,606 m). To the northwest, the watershed boundary is formed by the Bouarif mountain range, extending from the southwest to the northeast, following the general orientation of the Saharan Atlas. The foothills serve as a transition zone between the mountains and the plain, stretching from west to east at the southern base of Djebel Bouarif and northwestward into rolling hills of colluvial deposits that gently slope down to the plain (Vila JM, 1980).

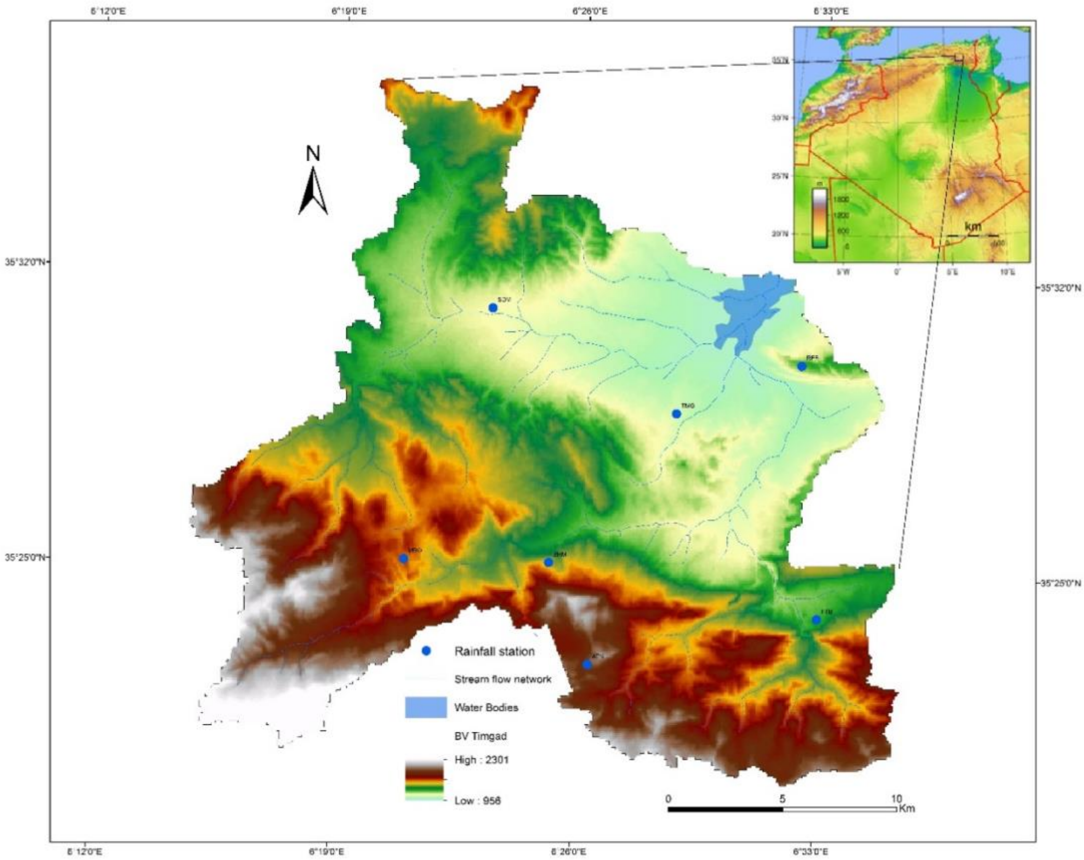

Fig. 1. Location of Timgad Basin and distribution of studied stations

2.2 Data description

The data used in the present study are temperature and precipitation 1975–2009 records from 07 rainfall stations managed by the National Agency for Hydraulic Resources (ANRH) and meteorological station managed by the National Meteorological Office (ONM). Geographic coordinates, elevations, and the main statistical characteristics of rainfall and temperature data series of the selected meteorological stations are presented in (Table. 1), while the spatial distribution of the selected stations is shown in (Fig. 1).

Table 1. Coordinates of the selected stations

Station	Code	Longitude	Latitude	Altitude
Foum Toub (FTB)	70406	6.48	35.48	1160
M. Baiou (MBO)	70407	6.54	35.497	1510
Bouahmar (BHM)	70408	6.39	35.52	1275
Timgad (TMG)	70409	6.346	35.42	1000
Sidi Mançar (SDM)	70410	6.55	35.4	1112
Reboa (REB)	70403	6.42	35.42	1002
Ain Tinn (ATN)	70405	6.44	35.378	1650

2.3 Methodology

2.3.1 The De Martonne aridity index

The De Martonne index (de Martonne, 1925) is extensively utilised globally and has demonstrated considerable efficacy in characterising drought conditions, yielding valid results applicable in many analyses ((Jafarpour et al., 2023); (Jahangir & Danehkar, 2022). IDM was employed to categorise the predominant climatic type at each station included in the analysis (Burić et al., 2023); (Miloud, 2024). Consequently, all assessments were conducted based on results obtained from IDM concerning the conditions of the relevant stations (Tianqi Wei et al., 2024) ((Hashemi et al., 2024). This index, derived from precipitation and temperature, can be computed as follows.

2.3.1.1 Annual index

The De Martonne yearly index is determined using the formula:

$$IDMa = \frac{P}{10+T} \quad (1)$$

P represents the annual precipitation total in millimetres; T is the annual mean temperature in degrees Celsius; IDMa refers to the De Martonne annual index.

2.3.1.2 Seasonal index

The formulas for calculating De Martonne monthly or seasonal indices are as follows:

$$IDMs = \frac{4*P}{10+T} \quad (2)$$

P represents the total precipitation over three seasonal months in millimetres, T is the average temperature for the same three months in degrees Celsius, and IDMs refers to the De Martonne seasonal index.

2.3.1.3 Monthly Index

$$IDMm = \frac{12*P}{10+T} \quad (3)$$

Let P represent the monthly precipitation total in millimetres, T denote the monthly average temperature in degrees Celsius, and IDMm signify the De Martonne monthly index.

Table 2 allows us to translate the results and classify the climate by months, seasons and years (Jahangir & Danehkar, 2022) (Vlăduţ & Licurici, 2020).

Table 2 The De Martonne aridity index classification

Climate	Values of IDM
Arid	IDM < 10
Semi-arid	10 ≤ IDM < 20
Mediterranean	20 ≤ IDM < 24
Semi-humid	24 ≤ IDM < 28
Humid	28 ≤ IDM < 35
Very humid	35 ≤ IDM < 55
Extremely humid	IDM ≥ 55

2.4 Interpolation method

The processing and spatial representation of the analyzed index were conducted in a GIS system. Numerous interpolation algorithms exist for this purpose. The quantity of samples (observations) is crucial in selecting the optimal technique. Due to the limited number of stations (seven stations), we have selected the inverse distance weighting (IDW) method (Masoudi, 2021). Additionally, this approach has other advantages. This method is recognized as one of the most prevalent and effective strategies among interpolation methods. It is rapid, simple to execute, and readily adaptable to certain specifications. This method facilitates anisotropy in the data (Sluiter R, 2009).

The inverse distance weighting (IDW) method calculates cell values by averaging nearby sample data points for each processing cell. It posits that each measured site exerts a local influence that diminishes with distance ((Rabiei-Dastjerdi et al., 2022); (Chen & Liu, 2012). The points nearest the prediction location are assigned greater weight, with weights diminishing as distance increases.

3 Results and Discussion.

The spatial distribution of annual IDMa reveals that the entire study area has a semi-arid climate during the studied period (1975-2009) (tab. 2), the same classification that researchers reached in their studies in the studied area or neighboring areas (REGAD Nora & TATAR Hafiza, 2019) (Derdous et al., 2020).

Table 3. Annual of the De Martonne aridity index in the Timgad bassin (1975–2009)

Station	*IDM*a	Climate
TMG	14.89	Semiarid
REB	17.81	Semiarid
SDM	14.20	Semiarid
MBO	11.50	Semiarid
FTB	13.62	Semiarid
BHM	11.08	Semiarid
ATN	14.98	Semiarid

3.1 Seasonal Variability and Climate Classification in the Timgad Basin

The De Martonne aridity index's spatial distribution throughout the spring, summer, fall, and winter is displayed in Figure 2 and 3. Although there is a noticeable seasonal variation in this index, the geographical variations are greater in the spring and winter and lower in the autumn and summer.

During autumn, the spatial distribution of IDM is very similar to the annual pattern of semi-arid climate over the entire study area. During winter, the basin shifts to a semi-humid climate in the east and northeast of the study area by 57% and similar to the Mediterranean climate in the western areas by 26%, while the rest of the percentage is distributed between semi-arid by 9% and humid by 7% (Figure 4), reflecting an increase in IDM values due to seasonal rainfall. This seasonal shift is consistent with (Huang et al., 2019), who found that winter moisture plays a crucial role in supporting ecosystems in Mediterranean and semi-arid climates.

Spring represents a return to semi-arid conditions in most of the Timgad basin by more than 88%, with semi-humid areas persisting only in the local northern areas. According to (Gao et al., 2021), the seasonal decrease in soil moisture during spring increases the need for irrigation to support agriculture, especially as temperatures begin to rise.

The summer season is dominated by arid conditions in the east and northeast (57.19%), while the rest of the region is characterized by a very arid climate (about 43%)(Figure 4). This season is very dry in the Timgad Basin, with very high temperatures and usually no rainfall. Most studies, including (Zarei & Mahmoudi, 2022), suggest that rising temperatures and declining rainfall in recent decades have intensified drought risks in semi-arid regions, making summer the most challenging season for water management.

Areas with higher elevations, denser vegetation, or favorable soil conditions retain more moisture, resulting in slightly higher IDM readings even during the driest seasons. Research by (Huang et al., 2019) supports this finding, emphasizing the importance of local environmental factors in shaping aridity levels within a single watershed.

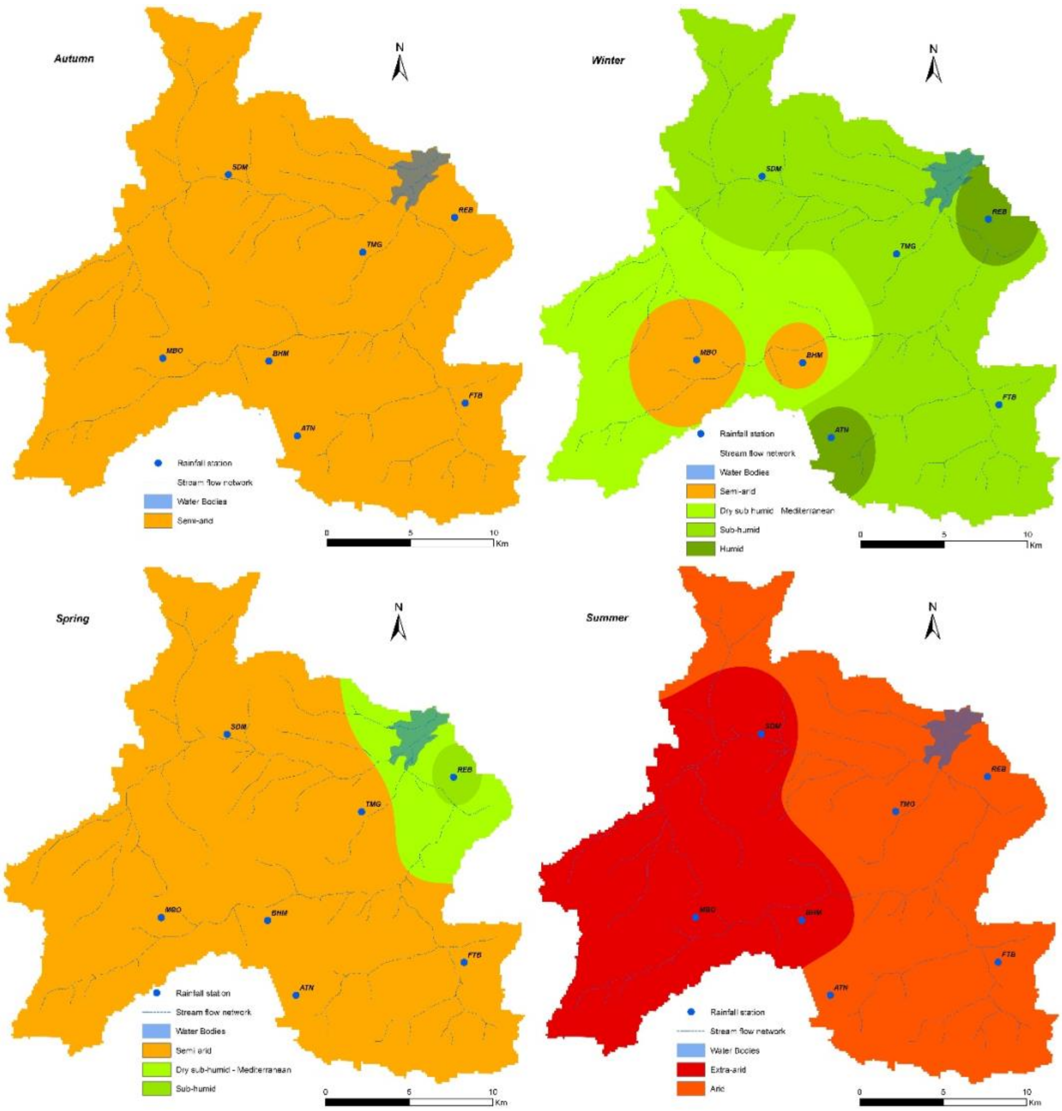

Fig. 2. Seasonal spatial distribution of the De Martonne aridity index in the Timgad bassin (1975–2009)

During transitional seasons like autumn and spring, IDM values reflect a moderate level of aridity, indicating a partial dependence on irrigation. However, the winter's higher IDM levels suggest that rainfall alone may be sufficient to sustain certain crops, reducing the need for additional water input.

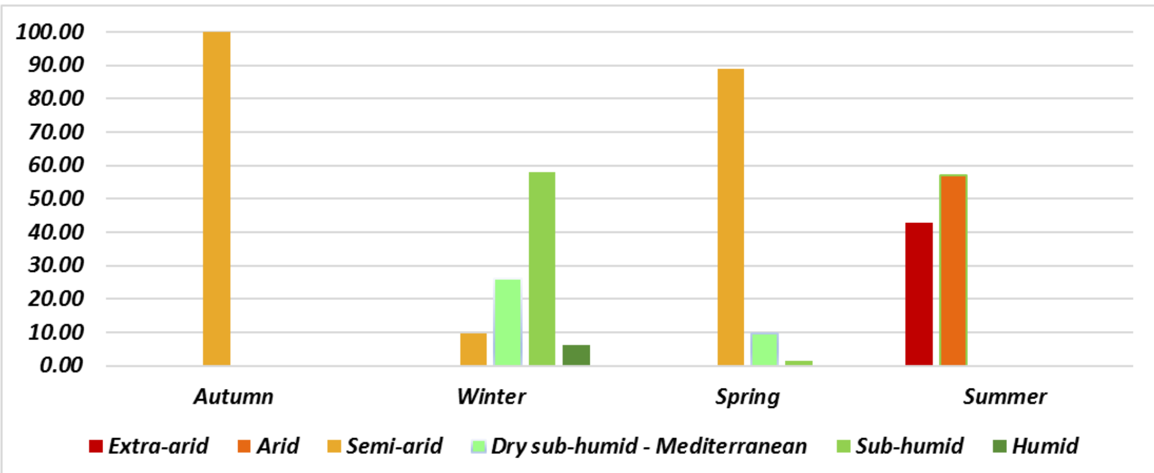

Fig. 3. Percent changes seasonal in De Martonne aridity index in the Timgad bassin (1975–2009)

3.2 Monthly Variability and Climate Classification in the Timgad Basin

The Timgad Basin demonstrates clear seasonal shifts from humid to arid conditions, as indicated by the De Martonne Index (IDM) maps. The monthly variations in climate categories offer vital information regarding the region's aridity levels and water requirements, which are crucial for agricultural and water management strategies.

In September and October, the basin shifts from the dry summer to early fall, with a significant portion of the territory categorized as semi-arid to arid in September. By October, minor enhancements in IDM values are noted, when specific regions transition to semi-arid or dry sub-humid conditions. Notwithstanding restricted water resources, this phase signifies the onset of precipitation, facilitating the restoration of soil moisture following the summer drought (Feng et al., 2021).

November marks a notable shift as heightened precipitation raises a substantial portion of the basin, particularly in the northern areas, to dry sub-humid to sub-humid classifications. This precipitation restores soil moisture and signifies the beginning of the wetter winter season, essential for groundwater replenishment and the maintenance of natural vegetation. Late fall precipitation is essential for the stabilization of semi-arid ecosystems (Huang et al., 2019).

From December to February, the basin has its most precipitation-intensive phase, primarily classified as sub-humid, with several areas nearing humid conditions. This phase, influenced by winter precipitation, is essential for water retention and ecosystem vitality. Winter precipitation decreases reliance on irrigation by naturally satisfying agricultural water needs (Gao et al., 2021).

During March and April, IDM values progressively decrease as the basin reverts to semi-arid conditions. By April, the majority of regions revert to semi-arid classifications, with only a few isolated locations maintaining elevated humidity levels. This transition highlights the transient effect of winter precipitation, as elevated temperatures necessitate enhanced irrigation to offset the swift decline in natural moisture (Gao et al., 2021).

By May, the basin is predominantly semi-arid, signifying the conclusion of spring. The decreasing IDM values underscore the increasing need for irrigation to sustain agriculture, rendering this month crucial for the preparation of water resources before to the dry summer. Studies (Zarei & Mahmoudi, 2022) underscore the importance of effective planning for summer water needs during this period.

The summer months, spanning June to August, are characterized by severe dryness, with extensive classifications of extra-arid and arid conditions. July and August demonstrate significant water deficits, as natural water supplies are inadequate for agricultural and ecological requirements. Irrigation is essential during this time, since climate change intensifies summer aridification, increasing drought risks in semi-arid areas such as North Africa (Zarei & Mahmoudi, 2022).

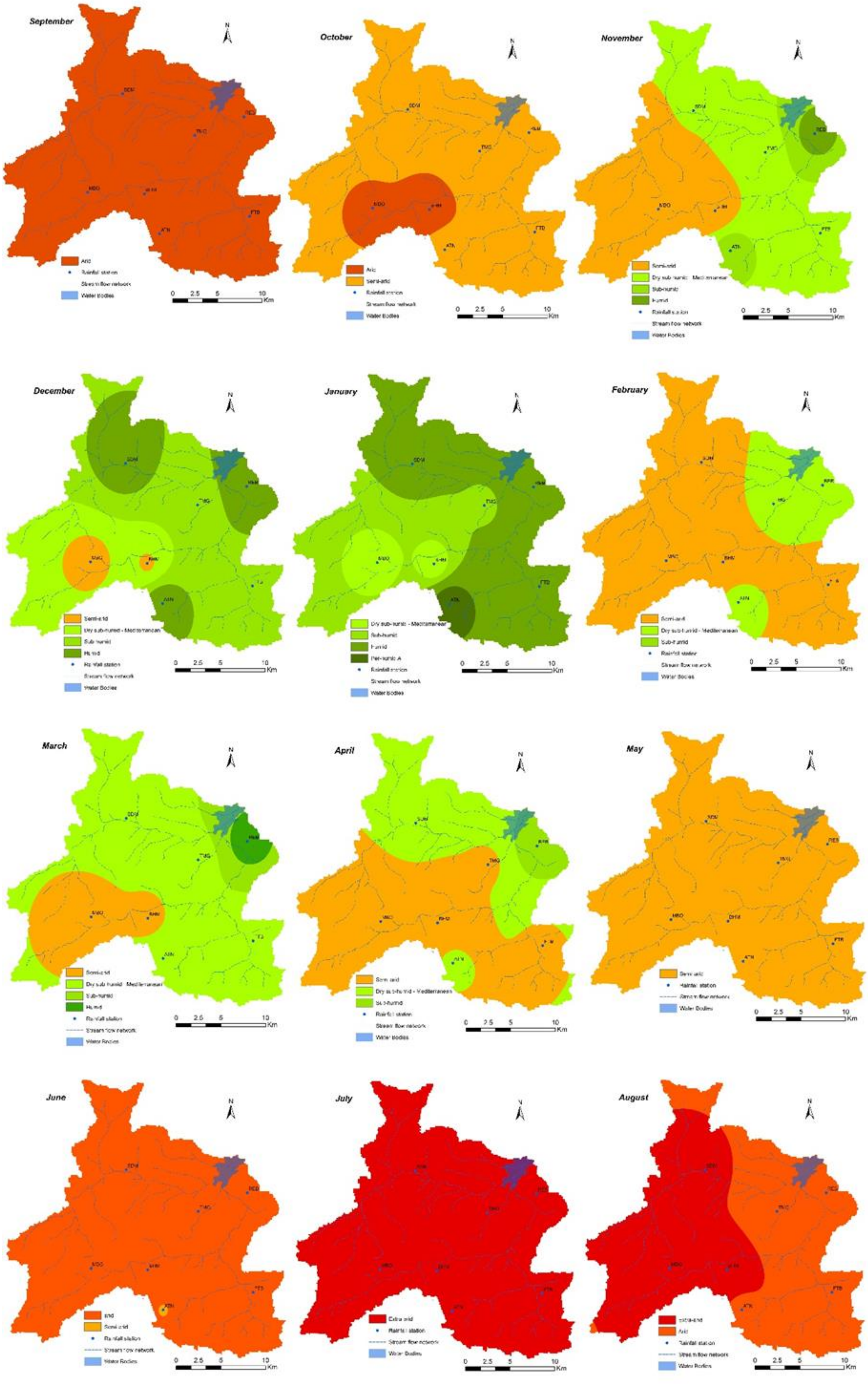

Fig. 4. Monthly spatial distribution of the De Martonne aridity index in the Timgad bassin (1975–2009)

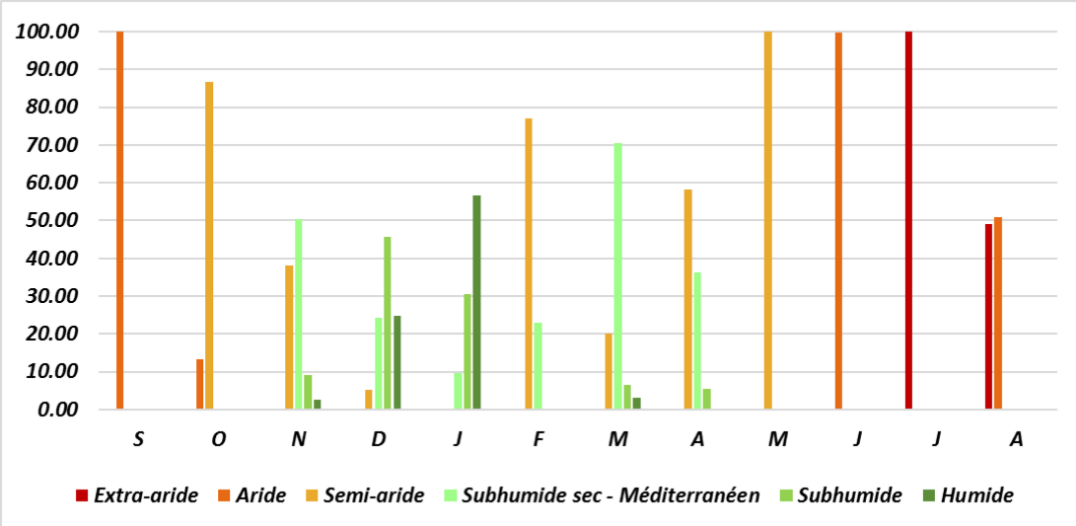

Fig. 5. Percent changes monthly in De Martonne aridity index in the Timgad bassin (1975–2009)

4. Conclusions

This study examines drought changes in the Timgad Basin, North-East Algeria, from 1975 to 2009, employing the De Martonne Aridity Index and Geographic Information Systems (GIS). The findings suggest that the region generally endures a semi-arid environment each year, characterized by considerable seasonal and monthly fluctuations. In winter, the climate transitions to semi-humid and Mediterranean conditions in some regions, resulting in augmented precipitation. Conversely, summer is marked by intense aridity and elevated heat, requiring substantial dependence on irrigation. Transitional seasons like spring and fall demonstrate considerable dryness, with specific semi-humid zones in northern latitudes. The research emphasizes geographical variability, indicating that elevated terrains and richer flora exhibit reduced aridity. These findings underscore the vital significance of irrigation during arid intervals, particularly in summer, and utilizing winter precipitation to alleviate water stress. The research offers a significant foundation for educated water management methods, agricultural planning, and climate change adaptation in semi-arid areas.

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