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Hydro-agricultural zoning of Southern Tlemcen steppe using GIS and *k*-means clustering

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Hihglights
- Insufficient groundwater agriculture in steppe region and anthropozoic pression.
- The 119 groundwater points analysed using field data and GIS integration.
- Results support efficient resource planning aligned with water SDG.
- GIS and machine learning enabled zoning for sustainable hydro-agricultural planning.

Abstract: The Algerian steppe rangelands especially located in the southern region of Tlemcen province, the primary areas for extensive sheep farming, play a crucial role in the national agricultural economy. However, the inadequate management of water resources for the country's development is frequently neglected by local authorities. It is essential to quantify and manage this resource as rigorously as possible. The study area, covering approximately 3200 km^2, includes five municipalities (Sebdou, Sidi Djilali, El Gor, El Bouihi, El Aricha) in the southern region of Tlemcen province (Algeria). The main objective of this study is to locate (georeferencing) all existing water points managed by the government (boreholes, wells, springs, etc.) and characterise their flow rate, depth, etc., in order to insure a sustainable management of the water resource. Over 119 water points have been identified, located and integrated into a database within a geographic information system (GIS) to create a georeferenced database. Moreover, the results (the database) are used for further spatial analysis using the *k*-means clustering algorithm. By applying this unsupervised classification method, the study successfully delineates clusters of water points that require similar management strategies. The resulting maps are intended to support local decision-makers in implementing more effective and sustainable water resource management practices tailored to the specific characteristics of each zone.

Keywords: Algeria, GIS, *k*-means, steppe, sustainable development, water

INTRODUCTION

In Algeria, the degradation of natural environments in arid and semi-arid zones has dramatically increased in recent years due to rapid population growth, socio-economic changes, and the transformation of natural resource exploitation systems (Haddouche *et al.*, 2008). Increasing anthropogenic and climatic pressures have led to sometimes irreversible desertification phenomena (Haddouche and Saidi, 2014). For several decades, the natural resources of the steppe ecosystem (water, soil, vegetation, etc.) have suffered severe degradation.

The hydrographic network is heavily influenced by seasonal and interannual variations in rainfall and the steppe's topography (Khelil, 1997). Most steppe wadis are irregular, dry in summer, but with violent floods typically occurring at the beginning and the end of winter, and occasionally in summer. These floods cause significant land erosion and considerable loss of livestock. In steppe regions, water resources are scarce, poorly renewable, and unevenly distributed.

Water resources consist of surface water from storm rainfall, representing an annual volume of 40 bn m^3, and groundwater, with an estimated potential of 1.4 bn m^3, which is the only reliable resource used for human needs, livestock watering, and crop irrigation (MADR, 2008). This resource is understudied, except in the Oued Touil and Hodna perimeters, and is often exploited anarchically, as evidenced by the large number of wells that have become non-functional due to the declining levels of alluvial and phreatic aquifers caused by excessive drilling.

As water resources become scarcer, very cautious management is required to minimise loss and non-productive water uses. New regulations are needed to safeguard water resources for sustainable development. The use of statistical analysis and GIS tools remains essential and offer the best tools for managing water resources and other related issues like drought and flood risk (Yahya, Ahmed and Saeed, 2023).

This study addresses the sustainable use of water resources in agricultural development, with the aim of optimising water conservation, reducing time investment, and minimising financial costs.

MATERIALS AND METHODS

STUDY AREA PRESENTATION

The study area, located in the southern part of the Tlemcen province, is an arid and semi-arid steppe region with an average altitude of 1,170 m, administratively composed of five municipalities (Sebdou, Sidi Djilali, El Gor, El Bouihi, El Aricha). It covers a total area of 3,268.4 km^2 (Fig. 1).

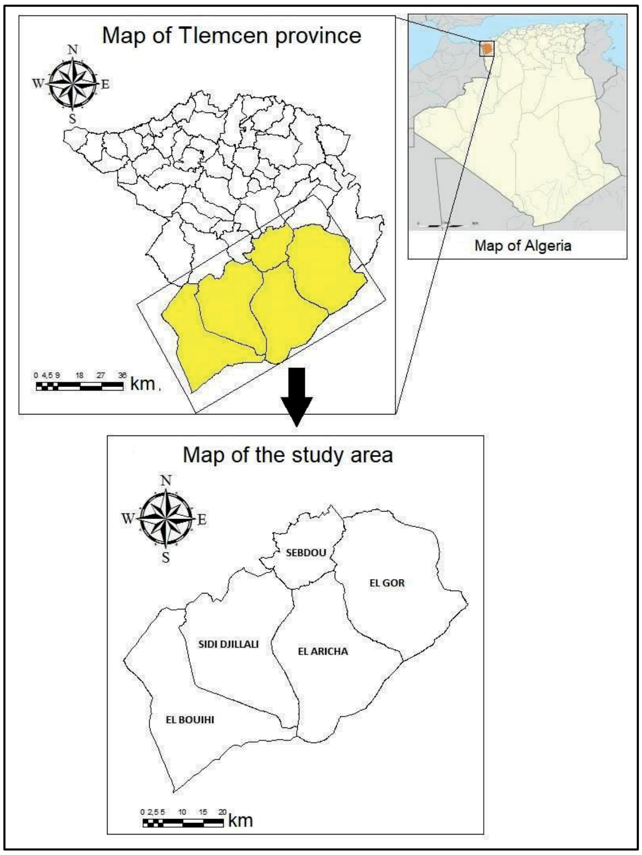

Fig. 1. Location of the study area; source: own elaboration

According to the National Agency for Water Resources (ANRH, 2005), three distinct geographical features can be identified.

- To the north, a mountain range runs southwest to northeast, more rugged in the west than in the east. The topography gradually descends from west to east (from 1,300 to 900 m, with a drop of about 400 m).
- The centre, small hills and depressions and the incisions caused by a non-hierarchical hydrographic network give the terrain a wavy appearance with a 1,000 m of altitude.
- To the south of the Tlemcen Mountains lies a plain where the Djebel Sidi El Abed, Djebel Makaïdou, and Djebel En Necheb rise (average altitude of 1,200 m).

The study area is fed by three major watersheds according to the hydrological units of Algeria: the Tafna watershed, the Chott Echergui watershed, and the Macta watershed.

Climatically and according to the National Office of Meteorology, the data collected from 2016 to 2022 demonstrate that the annual rainfall in this area is around 345.8 $mm \cdot y^{-1}$, and the temperature range is between 3.9 and 32°C. The steppe vegetation has been the subject of numerous phytosociological and ecological studies. Most have concluded that the vegetative cover is in an alarming state due to the combined effects of climatic and anthropogenic factors (Djebaili *et al.*, 1982; Bouazza, 1995; Le Houérou, 1995; Nedjraoui, 2003; Bensaid, 2006; Hirche, Boughani and Salamani, 2007; Haddouche, 2009; Nedjimi and Guit, 2012; Bellahcene, 2017). According to Bellahcene, Haddouche and Khalid (2014), the vegetation in the study area consists mainly of open, sparse formations: alfa grass steppes (*Stipa tenacissima*), white wormwood steppes (*Artemisia herba-alba*), as well as Aleppo pine reforestations (*Pinus halepensis*) and shrublands.

As locally recognised, the southern Tlemcen's steppe region is undergoing notable socio-economic shifts, driven by modest population growth and a largely agro-pastoral livelihood. Among the localities, Sebdou emerges with relatively high population density and strong agricultural output, particularly in olive cultivation and market gardening. Livestock rearing – mainly sheep – remains central to the local economy, while cattle farming has seen significant gains, bolstered by public support programs. Despite these developments, the area continues to face structural challenges that limit its full rural development potential.

The interaction of environmental factors (morphology, lithology, slope, vegetation, climate, and human activity) influences soil evolution. According to Haddouche *et al.* (2008), steppe soils, adapted to arid climates, are generally underdeveloped, shallow, and sometimes absent. The steppe landscape of the Tlemcen region is a mix of plains and depressions where, according to Bellahcene, Haddouche and Khalid (2014), soils are shallow, with a base of limestone layers susceptible to water and wind erosion.

FIELD SURVEY AND INSTITUTIONAL COLLABORATION

Field surveys were conducted to an exhaustive list of water points (wells, springs, boreholes) was compiled with the assistance of various institutions, including the hydrology service, the forest department, the High Commission for Steppe Development (Fr.: Le Haut-Commissariat du Développement de la Steppe – HCSD), the National Agency for Water Resources (Fr.: l'Agence Nationale des Bassin Versant – NAWR), the Water Basin Agency (Fr.: Agence des Bassins Hydrographiques – WBA), and the Agricultural Services Directorate (Fr.: La Direction des Services Agricoles – ASD). Fieldwork, conducted in the five municipalities, was based on auxiliary maps available at these institutions to compare and update our results.

From the United States Geological Survey official website (USGS, no date), the digital elevation model (DEM) with a 30-meter resolution was used to create thematic maps (slope, aspect, etc.). Data analysis was conducted using specialised GIS software. The land use map was produced through unsupervised classification of Landsat-7 satellite imagery acquired on May 12, 2014, obtained from the same source previously cited.

The water point list was verified and confirmed by the institutions (GPS coordinates, flow rate, depth, static level, etc.) and was entered into a database. Each water point, created in the database, was supplemented with useful data (location, flow rate, depth, etc.) and the rest of the data issued from GIS analysis (lithology, slope, aspect, hydrographic network, and land use) data was assigned to each water point.

The recent studies by Hilal *et al.* (2024) and Chemirik *et al.* (2024) are conducted to define the groundwater potential zones using thematic layers (lithology, rainfall, land use, drainage and lineament density, slope, and distance to rivers). Otherwise, the use of statistical analysis (*k*-means) is essential to strengthen our research referring to Marín Celestino *et al.* (2018) who mentioned that the *k*-means is a robust tool for underground water management. However the *k*-means clustering plays a key role in our research. All data were categorised numerically (e.g.: 0–6) to standardise and ensure compatibility with statistical analysis (*k*-means).

STATISTICAL ANALYSIS USING *K*-MEANS CLUSTERING

The principal objective of the k-means clustering algorithm is to partition an unlabelled dataset into k clusters (groups or categories), represented by centroids (Hancer and Karaboga, 2017). In this research, we use the *k*-means clustering (Fig. 2) which is an unsupervised machine learning algorithm that partitions a dataset into *k* distinct, non-overlapping clusters.

The algorithm iteratively assigns each data point to the nearest cluster centroid (mean) and updates the centroids based on the current cluster memberships. The objective is to minimise the within-cluster sum of squares.

$$E = \sum_{i=1}^{k} \sum_{x \in C_i} |x - \overline{x_i}|^2 \tag{1}$$

where: E = the sum of squared error of the data set of all objects, x = the point in the place, a given data object, x_i = the average value of cluster C_i (x and C_i are multi-dimensional). The role of this criterion is to make the generative clusters as compact and independent as possible (Yang and Deng, 2010).

Data preprocessing included correction of anomalies and normalisation strategy selection using whisker plot analysis, which is one such representation technique for visualising and analysing the distribution of data, which provides a graphical representation of the five-number summary of a dataset, including the minimum, maximum, median, and quartiles (Majaw and Ahmed, 2023). The box and whisker plot will allow our data to choose between normalisation and *z*-standardisation for outlier-affected features (e.g., flow rates). The *k*-means clustering (using MATLAB) was iteratively applied, with optimal cluster count (k) determined by maximising mean silhouette scores across k. Silhouette score is used to evaluate the quality of clusters created using clustering algorithms.

The silhouette score is calculated by comparing the average distance between a point and all other points in the same cluster (a) with the average distance between all points in the nearest neighbouring cluster (b). The score (s) is given by the formula:

$$s = (b - a)/\max(a, b) \tag{2}$$

RESULTS AND DISCUSSION

INITIAL RESULTS

Before reaching the final result concerning the hydrogeological potential clustering of the study area, auxiliary results were obtained, including thematic maps created from digital elevation model (DEM) using geographic information system (GIS) software.

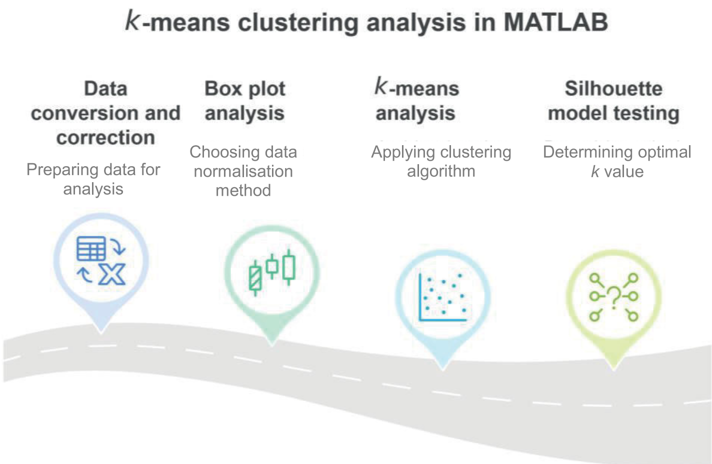

Fig. 2. Preprocessing and k-means clustering evaluation; source: own elaboration

During field, a total of 119 water points (springs, wells, boreholes) were identified, georeferenced, and confirmed (Fig. 3).

It should be noted that the lithological map has been recoloured based on a source lithological map (Tounkob, 2016).

Using the thematic maps (slope, hydrographic network, land use, lithology, and aspect), we extracted site-specific characteristics for each water point (Fig. 3). These variables provided the environmental context necessary for the spatial interpretation and clustering analysis.

The total water obtained from the five municipalities is 650.4 $dm^3 \cdot s^{-1}$, with 588.5 $dm^3 \cdot s^{-1}$ from boreholes, 27.9 $dm^3 \cdot s^{-1}$ from wells, and 34 $dm^3 \cdot s^{-1}$ from springs.

The raw data of all water points and all extracted data are from thematic maps.

The box and whisker plot result of the huge water point database shows clearly that the flow of our dataset contains very high outlier values varying from 0 to 30 (case Demmam water point 30 $dm^3 \cdot s^{-1}$). The z-standardisation method has been chosen to address the sensitivity of k-means clustering (Euclidean distance). It should be noted that all inventoried water points are state-owned. The first result is a map that combines all the data with georeferenced water points.

Silhouette analysis confirms k = 6 as the optimal cluster number for characterising groundwater potential in the western Algerian steppe study area). This classification effectively distinguishes hydrogeological units based on yield, lithology, and terrain characteristics, providing actionable insights for water resource management shown in Table 1.

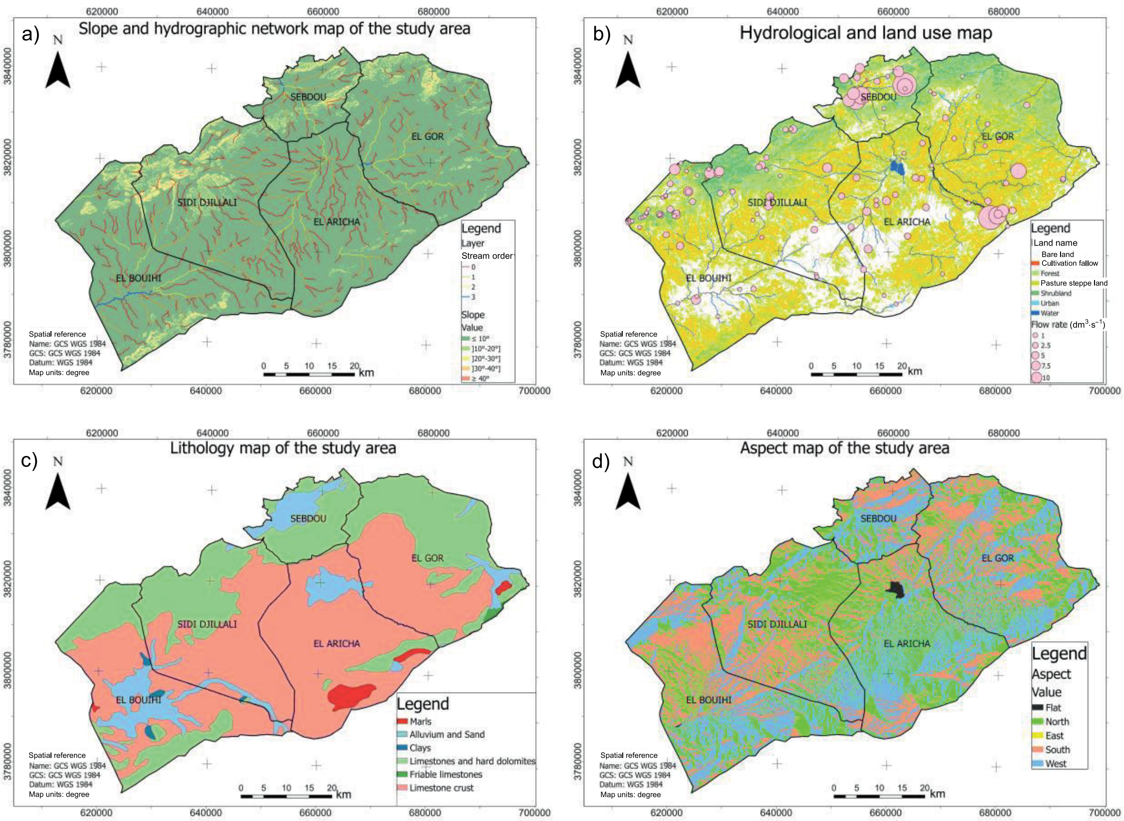

Fig. 3. Maps of study area: a) slope and hydrographic network, b) hydrological, c) lithology, d) aspect; source: own study

Table 1. Summary parameters for each k

Cluster	Flow	Lithology	Slope	Aspect	Land use	Revised interpretation
1	low	limestone crust	<10°	south	bare/pasture	very poor: worst aspect + impermeable crust
2	low	mixed	<10°	south/south east	bare/pasture	poor
3	moderate high	hard limestone	20–40°	north east/east	shrub/forest	good: optimal aspect + fractures
4	high	hard limestone/ alluvium	10–20°	various	bare/forest	excellent: where north/east aspects
5	moderate	hard limestone	10–20°	south east / north east / east	pasture/shrub	very good: best aspects + recharge
6	none	hard limestone	<10°	north	bare/pasture	paradox: good aspect but no flow

Source: own study.

The table of the cluster classification of the study area shows that cluster 1 represents the least favourable conditions with impermeable limestone crusts, low slopes, poor southern aspects, and a minimal groundwater flow. Cluster 2 remains poor, but slightly better due to mixed lithology.

Cluster 3 and cluster 4 have high to excellent potential, due to the hard limestone, steeper slopes, and favourable north-east aspects which particularly where vegetation supports recharge.

Cluster 5 also has a moderate potential, combining moderate flow with optimal aspect and land use.

Cluster 6, however, presents the deficiency despite having good slope and aspect, it shows no flow, likely due to subsurface geological barriers. This reinforces the importance of integrating both surface and subsurface data in hydro-agricultural planning.

The spatial distribution of the clustered water points, along with their corresponding geographic mapping, is illustrated in the figure (Fig. 4). This visualisation provides insight into the spatial patterns and regional differentiation revealed by the clustering analysis.

The Fig. 4 shows a distinct spatial pattern in groundwater potentialities availability with clusters grouped into three primary hydro-agricultural potential zones.

– The cluster 01 and 06 (respectively poor low-yield and dry-impermeable mentioned in the legend) are concentrated in the south, feature low groundwater yield due to impermeable limestone crust and dry conditions, restricting use to limited rainfed agriculture or pastoralism.
– The high yield points in the cluster 3 and 4 (respectively moderate-high and high alluvial) are primarily in the north, feature fractured limestone and alluvial deposits capable of sustaining intensive irrigation for high-value crops.
– The cluster 2 and 5 (low-moderate and moderate karstic) feature moderate potential or need a site-specific verification, dominate the north area and need careful water management.

SIMPLIFIED HYDRO-AGRICULTURAL POTENTIAL CLASSIFICATION

For a clear interpretation, the original six clusters have been consolidated into three distinct zones based on water availability (Fig. 5).

The hydro-agricultural suitability analysis, as presented in Fig. 5, reveals a clear spatial difference within the study area. The study area is clearly segmented into northern and southern zones, with the latter being predominantly characterised by limited potential for agricultural development. This is indicated by the concentration of zones of very low hydro-agricultural potential, forming a contiguous, belt-like pattern across the southern region of the study area. Such spatial clustering in red aligns closely with arid steppe conditions and may reflect the limitation of soil quality and groundwater availability.

One of the most important results of this clustering is the noticeable status of the Sebdou municipality, which is entirely out of the red belt, offering an area of high hydro-agricultural potential. Also Sebdou municipality hosts the Demmam water point, identified as the highest-yielding source in the dataset. This combination of favourable factors make Sebdou the best municipality for future agricultural planning and resource allocation within the region.

In comparison, in El Aricha, which is the largest area in our study area, there have been no high-yielding groundwater sources shown. The absence of such critical infrastructure in El Aricha may reflect underlying hydrogeological constraints or the lack of investment in water point development.

The observed spatial distribution of suitability classes (potentialities) shows that the *k*-means clustering algorithm offers valuable results of how environmental and infrastructural factors converge to determine agricultural potential. These results highlight the need for targeted interventions especially in the south of the study area to enhance water accessibility or adapt land-use planning to environmental realities.

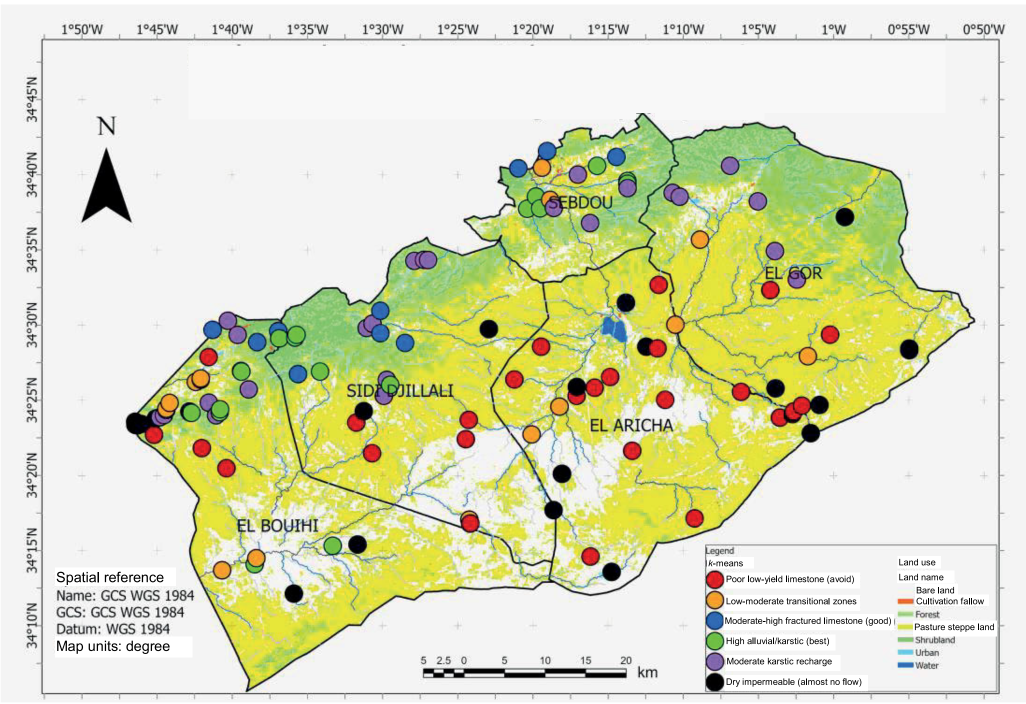

Fig. 4. Hydrological potential zones of the study area $k = 6$; source: own study

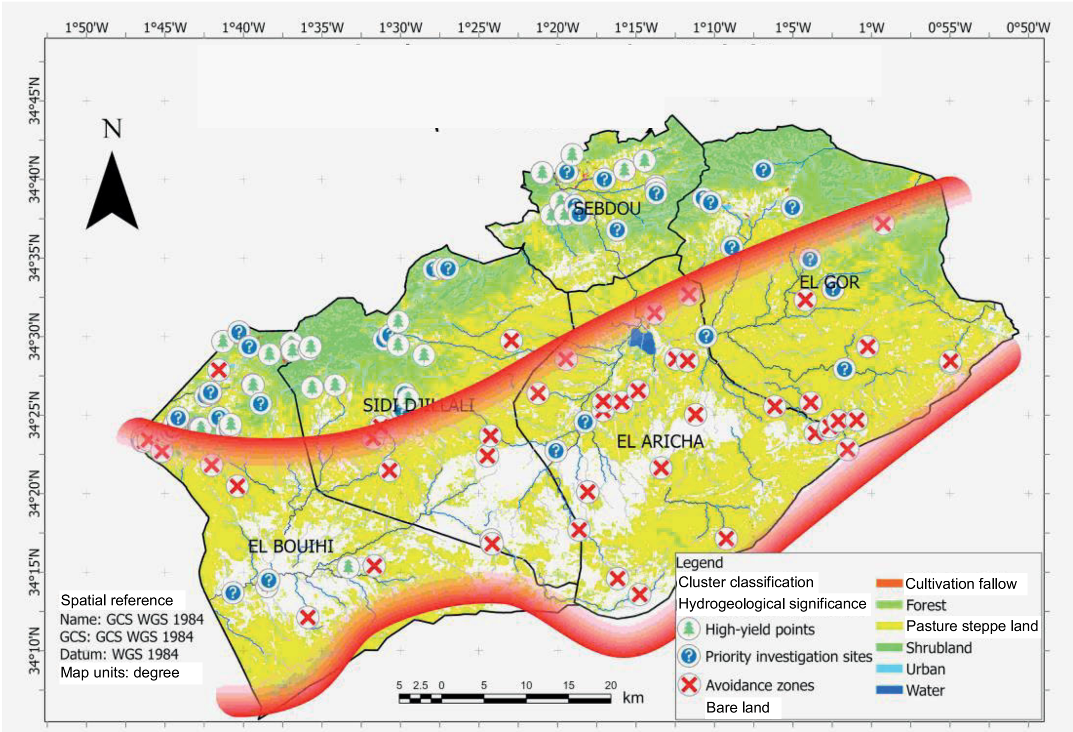

Fig. 5. The *k*-means hydro agricultural suitability map (k = 6 clusters); source: own study

Finally, the study reaffirms the use of GIS and the statistical analysis (*k*-means clustering) techniques for zoning complex, climate-sensitive ecosystems like the southern Tlemcen steppe. It provides a robust framework for guiding investment (sustainable development) and decision making, and a balanced resource strategy underscores the critical role of efficient water resource management.

CONCLUSIONS

This study highlights the effectiveness of combining unsupervised classification techniques, particularly *k*-means, with multi-layered spatial datasets to assess hydro-agricultural potential in a semi-arid and predominantly pastoral environment. In addition to hydrogeological parameters, the integration of land use data, as illustrated in the land use map, allowed for a more accurate delineation of favourable and unfavourable zones for agricultural development while accounting for environmental constraints and anthropogenic pressures.

The results reveal a clear geographical divide: the northern part of the study area, particularly around Sebdou, is home to the majority of high-yield water points. Conversely, the southern sector forms a very distinct low water source belt, affecting municipalities such as El Aricha, El Gor, Sidi Djilali, and El Bouihi. The clustering approach offers a significant gain in time and cost efficiency for agricultural planning and decision-making, particularly in semi-arid regions where pastoral pressures and land degradation are prevalent.

Finally, the study reaffirms the use of GIS and the statistical analysis (*k*-means clustering) techniques for zoning complex, climate-sensitive ecosystems like the southern Tlemcen steppe. It provides a robust framework for guiding investment (sustainable development) and decision making, a balanced resource strategy.

This study makes a contribution to several sustainable development goals (SDG), SDG 6 (clean water and sanitation) and SDG 15 (life on land). It directly supports target 6.4 "progress on water-use efficiency" and target 15.3 "combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world". In this context, our study provides not only a precise territorial diagnosis but also a valuable decision-support tool for promoting sustainable agricultural strategies and the water-use efficiency to local environmental constraints emphasising the need for careful land use and restoration efforts. These insights are essential for guiding practical, site-specific planning in steppe environments under pressure.

Building on these findings, future work could involve the inclusion of temporal data such as seasonal flow variations and groundwater levels, as well as socio-economic factors like land tenure and agricultural practices. Advanced techniques in machine learning (e.g., fuzzy clustering, neural networks) could further refine the classification. Additionally, integrating remote sensing, hydrological modelling, and participatory mapping may provide a more holistic and actionable framework for sustainable land and water resource management in arid and vulnerable regions.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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