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Mapping Groundwater Potential Zones with GIS-RS-AHP Under Climate Change – Case of Mostaganem Plateau, Northwest Algeria

Cherifa Hanene Kamelia Chemirik[1*], Djelloul Baahmed[1], Rachid Nedjai[2], Djamel Boudjemline[3], Ikram Mahcer[1]

[1] Civil and Environmental Engineering Laboratory, University of Djillali Liabes, BP 89. DZ- 22000. Sidi Bel Abbés, Algeria

[2] CEDETE Laboratory EA 1210, University of Orleans, 10 Rue de Tours, 45069 Orléans, France

[3] Laboratory of Management and Water Treatment, Faculty of Architecture and Civil Engineering, University of Science and Technology of Oran-Mohamed Boudiaf, BP 1505, El M'Naouer, Oran 31000, Algeria

* Corresponding author's e-mail: chemirikcamelia@gmail.com

ABSTRACT

In arid regions with increasing water needs due to growing populations and agriculture, heightened by climate change, groundwater arises as a crucial asset. This research evaluated climate change influence on groundwater potential zones (GPZs) during 2000 and 2014, within the Mostaganem plateau's alluvial aquifer in Algeria, using a methodology that integrates analytical hierarchy process (AHP), remote sensing (RS) and geographic information system (GIS). Forecasts for 2030 and 2050 were conducted using the QGIS MOLUSCE plugin. Findings reveal a (30.29%) decrease in zones of moderate potential, the vanishing of high potential sectors, alongside a (7.53%) and a (22.1%) rise in fair potential and low potential, respectively, from 2000 to 2014. Between 2014 and 2030, fair and moderate potential decrease by 6.62% and 0.48%, while low potential zones see a 7.47% increase. These shifts are linked to changes in rainfall distribution, and land use land cover (LULC), notably intensive agriculture of herbaceous crops. Slight changes are anticipated between 2030 and 2050, possibly due to the onset of a resilience equilibrium from 2030 onwards. These findings are crucial as a preliminary investigation, highlighting the necessity of optimal groundwater management.

Keywords: analytical hierarchy process, groundwater potential, climate change, remote sensing, GIS, MOLUSCE.

INTRODUCTION

One of the most important natural resources on Earth is groundwater. Stored in subsurface geological formations, it serves as a vital resource for both agriculture and human activities (Arulbalaji et al., 2019; Raihan et al., 2022). Its role in mitigating climate change-induced fluctuations in water availability underscores its significance (Hellwig et al., 2020). In the current epoch of Anthropocene, groundwater reserves and sustainability are under tremendous strain from climatic and anthropogenic stressors (Aslam et al., 2018). Groundwater is vital to sustaining stream flow during periods when there is no or minimal rain, especially in semi-arid regions. However, due to over abstraction through unsustainable activities, most groundwater resources are being gradually depleted, notwithstanding their immense contributions to ecosystems and human health (Aslam et al., 2018). This situation is exacerbated by climate change, which alters the patterns and quantity of groundwater recharge (Aslam et al., 2018; Taylor et al., 2013). Climate variation plays a significant part in influencing the hydrological cycle, exerting pressure on groundwater resources (Kanema and Gumindoga, 2022; Kundzewicz, 2008). Indicators of climate change can take many forms, such as drought. It is characterized by a shortage of precipitation and reduced groundwater levels (Hellwig et al., 2020).

Drought and groundwater depletion are a major concern in developing countries (Balacco et al., 2022). Currently, half the global population is living under a water stress state, particularly in semi-arid region such as Asia, Middle East, North Africa and the Mediterranean basin (Ashraf et al., 2021; Chandrasekara et al., 2021; Oxford Analytica, 2023). The majority of these regions rely on groundwater due to the seasonality or total absence of surface water. As water demand is concentrated for agriculture in North Africa (85% of water is used for irrigation) (Hejazi et al., 2023), groundwater availability and food security are interlinked to a national and regional scale.

Given the hidden aspect of groundwater, the assessment of its potentiality requires the consideration of multiple factors that influence its occurrence (Boitt et al., 2023; Kanema and Gumindoga, 2022). According to studies by (Arulbalaji et al., 2019; Dar et al., 2021; Mallick et al., 2019; Pande et al., 2021), these factors can be topographical, geological, or hydrological. Geographical information system (GIS) and remote sensing (RS) technologies are widely used in mapping groundwater potential zones (GPZ) due to their capacity to generate spatial and temporal data, crucial for modelling and forecasting (Moharir et al., 2023). Recently, researchers used these tools in conjunction with fuzzy logical analysis (Shao et al., 2020), and analytical hierarchy process (AHP) (Morgan et al., 2022). Among of all the methods mentioned, AHP has gained wide acceptance in scientific decision-making due to its minimal bias, simplicity and effectiveness (Baghel et al., 2023; Murmu et al., 2019).

Several studies have documented the application of geospatial techniques and AHP in GPZs delineation around the world (Sapkota et al., 2021). Many researchers have investigated GPZ using the same techniques in Africa (Ait Lahssaine et al., 2024; Moodley et al., 2022; Owolabi et al., 2020; Ozegin et al., 2024; Siziba and Chifamba, 2023). Many investigations on GPZs have been conducted in Algeria using GIS, RS and AHP (Aissaoui et al., 2023; Boufekane et al., 2020; Maizi et al., 2023; Nemer et al., 2023). These methods were used to delineate recharge areas, define groundwater potential zones as well as monitor groundwater levels, and were found to be effective in the semi-arid climate of Algeria. Algeria has been struggling with reduced rainfall and increased evapotranspiration, attributed to rising temperatures, in the past few years (Bouznad et al., 2020). Spinoni et al. (2014) highlight that climate change contributes to a widespread reduction in groundwater reserves, exacerbated by the severity of droughts across the Mediterranean basin. Over the last thirty years, Algeria's water demand has surged, fuelled by human development (Derdour et al., 2022). Consequently, changes occurred in land use and cover (LULC) distribution, notably the expansion of artificial and agricultural zones, which diminish infiltration rates and lead to over-extraction (Basset et al., 2023; Touitou and Abul Quasem, 2018). Moreover, lack of awareness and knowledge on sustainable consumption has resulted in the widespread unauthorized creation of wells, particularly in Northern Algeria, specifically in Mostaganem Plateau (Baiche et al., 2015). The government's enactment of water resources protection legislation and the adoption of regulated irrigation systems have delayed the depletion of groundwater resources, compared with other neighbouring countries, where agriculture has drastically depleted reserves. However, despite these preventive measures, population growth and the intensification of agriculture have seriously altered the country's water capital. This situation underscores the urgency to assess the impact of changing climate on GPZ, making it essential to ensure water security and sustainable development. The purpose of this research was to analyze the evolution of GPZ, considering both temporal and spatial changes, in the Mostaganem plateau. This aquifer is one the most exploited in northwest Algeria but still lacks comprehensive exploration of its potential, considering that previous studies made in this region omitted to consider the influence of changes in rainfall and LULC on GPZ as well as their development. The study applied a combination of GIS, RS, and AHP, considering seven factors: soil, drainage density, lineament density, slope, geology, rainfall, and LULC, for 2000 and 2014. Forecasts of GPZ with the QGIS Plugin MOLUSCE, are made for 2030 and 2050. This research introduces an innovative approach in GPZs predictions, employing AHP and MOLUSCE plugin methodology. While the synergy of AHP and MOLUSCE has been explored in various environmental applications, its application for GPZ forecasting is novel, and unprecedently used in the Mostaganem Plateau. The objective of this study was to assess the effect of changing climate on GPZs, for suitable planning, sustainable consumption and management of groundwater resources.

STUDY ZONE

Geographical and meteorological overview

The study area lies within the Mostaganem department in north-western Algeria (Figure 1). It spans from approximately 35° 45' 58.5" to 36° 0' 49.5" N in latitude and from 0° 0' 14.49" to 0° 26' 34.5" E in longitude. The dominant activity and land use within the 600 km^2 of the Mostaganem Plateau is agriculture. It is limited by the Plain Bordjias and Beni Chougrane massif to the south, the Mediterranean Sea to the west, the Cheliff river to the north and the Bouguirat syncline to the east. The topography gradually declines from the east to the west, exposing distinct ripple patterns that are oriented in a northeast-southwest direction. They have a crucial impact on water management within the area. Summers are typically hot and dry, while winters are mild and wet due to the strong influence of Mediterranean Sea on the regional climate. Summers are hot and dry, while winters are mild and wet.

Nevertheless, since 1990, the region has encountered climatic challenges as a result of increased aridity associated with global climate change. The mean annual temperature between 1990 and 2015 was 19.4 °C, with an average annual rainfall of 281 mm (Benfetta and Ouadja, 2020).

Geological setting

The Calabrian Sandstone layer is the main aquifer of the plateau. Its thickness varies between 100 and 200 m, decreasing from east to west (Algerian National Water Resources – ANRH). The aquifer is composed of marl, clay, sand and sandstone (Baiche et al., 2015; Guermoud, 2021). The recharge process is supported by rainfall and the aquifer supports more than 200 wells, 50 springs, and 16 borehole piezometers (Bahri and Saibi, 2010; Guermoud, 2021).

MATERIALS AND METHODS

Data acquisition and initial processing

Two GPZs maps were generated for the study area in 2000 and 2014, with the following factors: LULC, and rainfall (for both years), geology, lineament density, soil, slope, and drainage density. The study periods were selected based on the surge of population growth in 2000 after a long period of slow growth, the launching and application of the National Agricultural Development Program (PNDA), which aimed to modernize, intensify and expand the agricultural sector along with irrigation capacities to reach food security (Laoubi and Yamao, 2012), and the intensification and persistence of drought over northern Algeria in 2000 (Haied et al., 2023). The year 2014 was selected because of the lack piezometric monitoring past this year for the study region.

The Algerian National Water Resources provided rainfall data, well locations, and geology. Soil was sourced from Food and Agriculture Organization (FAO). The spatial distribution of rainfall was achieved with the inverse distance weighted (IDW) in QGIS. The LULC data is acquired through the European Space Agency (ESA). It offers 300 m resolution maps of the world land cover. Delimitation of the study region, slope, lineaments and drainage density

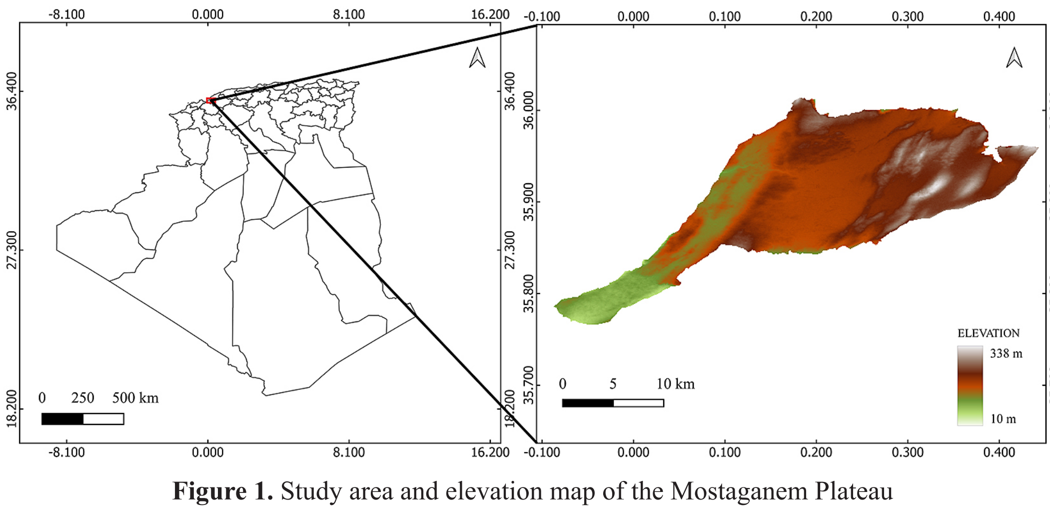

Figure 1. Study area and elevation map of the Mostaganem Plateau

were extracted from the digital elevation model (DEM), relying on spatial tools of QGIS. The automatic lineament extraction and the drainage density are done on the SRTM with the density analysis tool. The raster files are resampled, and have the same geographic reference system. Detailed descriptions of all the input are presented in (Table 1).

Evaluating climate change impact on GPZs using AHP and weighted overlay analysis

To assess the impact of climate change on GPZs, the research applied a combined modelling technique of GIS-RS and AHP. This method is efficient and cost-effective, making it appropriate for developing countries and regions with limited data availability. It entails transforming geographical data (input) into decision output. Using Saaty's scale, a pair comparison matrix is created to convert qualitative data on particular themes and attributes into quantitative values (Baghel et al., 2023; Saaty, 1990). Thematic layers with their sub-criteria are evaluated by field experts using Saaty's scale, ranging from 1 to 9. This evaluation is based on the impact of these layers on groundwater occurrence, as well as the variability of LULC and rainfall. The flowchart of the followed methodology is in (Figure 2). The paired assessment of parameters in the AHP method often results in some inconsistencies. For this purpose, the consistency ratio (*CR*) is calculated. It is ascertained using the comparison matrix eigenvalues and the random index scale. It is calculated as the ratio of the consistency index (*CI*) to the random consistency index (*RI*).

$$CR = CI/RI \tag{1}$$

where: *CI* = consistency index, *RI* = random consistency index

$$CI = -\frac{\lambda\max - f}{f-1} \tag{2}$$

where: f the number of criteria being compared.

Weighted overlay analysis is performed on the reclassified thematic layers with ArcGIS. This approach simplifies the assessment of GPZs by taking into account multiple inputs. Reclassified raster maps are combined using the weighted overlay analysis tool, which uses weights derived from the AHP pairwise comparison matrix. Thereafter, every score of input raster cell is multiplied by the matching weighted values from every raster layer.

$$GPZ = \sum Wi \times Xi \tag{3}$$

where: *GPZ* is the overall score, *wi* the weight of the criteria, *xi* is the score of the sub-criteria.

Forecasting 2030 and 2050 GPZs

QGIS plugin MOLUSCE is considered to be one the best tools for prediction estimation for LULC, and in this research, it is used to forecast the GPZ scenarios for 2030 and 2050. As per (El-Tantawi et al., 2019; Muhammad et al., 2022), the MOLUSCE plugin employs the CA-ANN technique for predictions, given its perceived efficiency over linear regression. The forecasting process relies on dependent and independent variables, GPZs and thematic maps, respectively (Edan et al., 2021). The model estimated 2014 GPZs using 2000 and 2010 GPZs, which were then compared to the actual GPZ for the same year. The accuracy of the model for the 2014 GPZ was evaluated using the MOLUSCE plugin kappa statistics, which includes the overall kappa coefficient and the percentage of correctness. Upon reaching satisfactory levels of accuracy, the model can be applied for projections. The ANN learning process involved a learning rate of 0.001, a neighborhood size of 1x1 pixel 1000 iterations, 10 hidden layers, and a momentum of 0.05 for the predictions.

The combined methodological framework of AHP and MOLUSCE Plugin for the purpose of spatial and temporal prediction of GPZs represents a novel insight in groundwater potential mapping. The duo AHP-MOLUSCE plugin was used by (Gantumur et al., 2022) in the estimation of urban development suitability area. The adaptability of the MOLUSCE plugin was demonstrated by its combined use with the DRASTIC method in prediction of GPZs for 2042 by (Boitt et al., 2023) after it was previously employed to forecast changes in Land Surface Temperature (Mahcer et al., 2024; Rahman and Rahman, 2023).

RESULT AND DISCUSSION

Thematic maps development

Creating thematic maps is an essential part of building a model. The evaluation of climate change on GPZs entails analyzing the impact of variations in precipitation and LULC changes from 2000 to 2014 along with the other factors. Table 2 represents the

Table 1. Input parameters of the study

Factor	Data resolution	Year	Source
LULC		2000/2014	www.esa-landcover-cci.org
Geology	30 m	1986	Algerian Agency of water
Rainfall	30 m	2000/2014	
Drainage density	30 m	2013	http://www.earthexplorer.usgs.Gov
Slope			
Lineament density			
Soil	1/5.000.000	1986	FAO

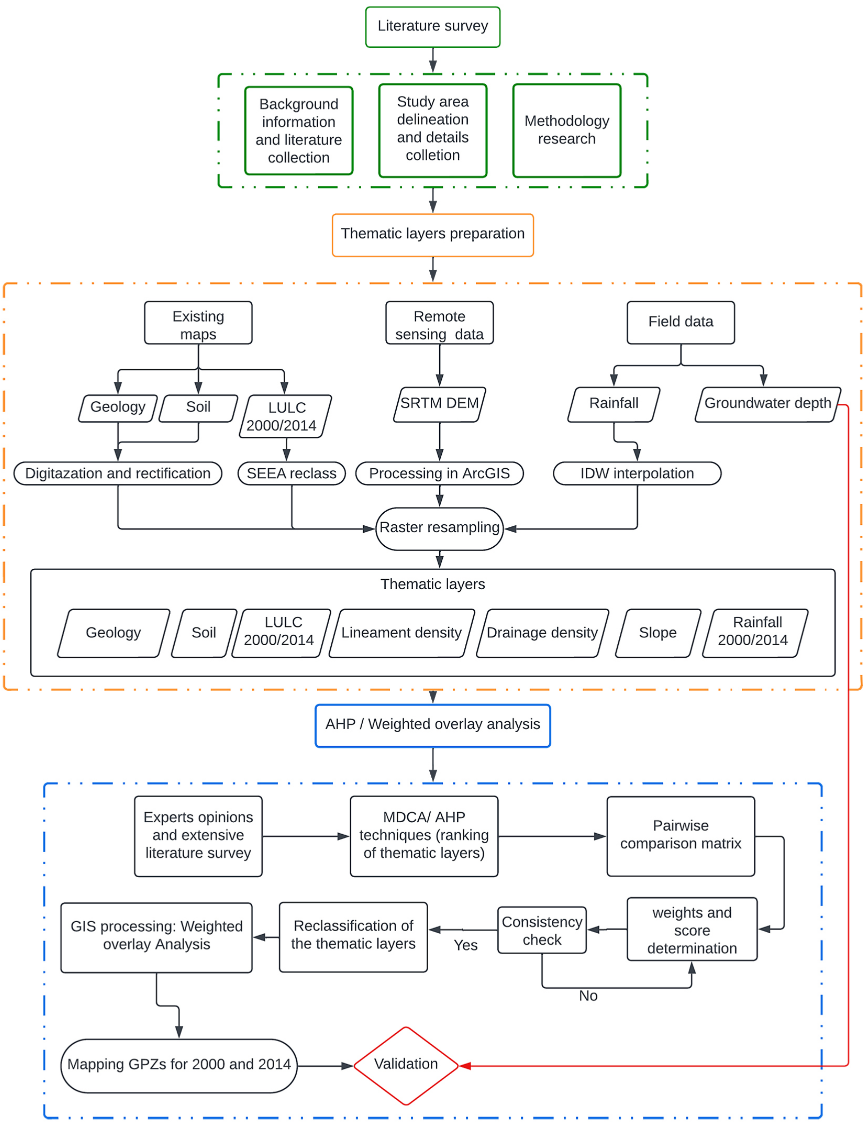

Figure 2. Flowchart of the applied methodology

specific weights assigned to the thematic maps and their corresponding classes.

Geology

GPZs delineation is significantly dominated by geology (Mallick et al., 2019). On the basis of their relative importance and influence on GPZ, four geological classes are shown to dominate the study area in (Figure 3). These geological classes are alluvium, marls, sandstone and sand. The marls exhibit extremely low permeability, establishing an impermeable boundary stretching from

Table 2. Overview of thematic maps assigned weights

Factors	Classes	Influence (%)	Assigned weight
Drainage density	0.25–0.5 km/km^2	7	3
	0.5–1 km/km^2		2
	1–2 km/km^2		1
Slope	3–4%	10	1
	2–3%		3
	0–2%		5
Rainfall	< 350 mm	4	1
	350–400 mm		2
	400–450 mm		3
	450–470 mm		5
LULC	Artificial surface	5	1
	Terrestrial baren land		4
	Multiple or layered crops		3
	Tree cover		1
	Sparsely natural vegetation		5
	Shrub cover area		4
	Herbaceous crops		5
Geology	Sand	35	5
	Marls		1
	Sandstone		4
	Alluvium		5
Lineament density	0.75–1 km/km^2	23	7
	0.5–0.75km/km^2		2
	0.15–0.5km/km^2		2
	0–0.15 km/km^2		1
Soil	Reddish clay sandstone	16	7
	Sand, sandstone		1
	Calcareous sandstone		3

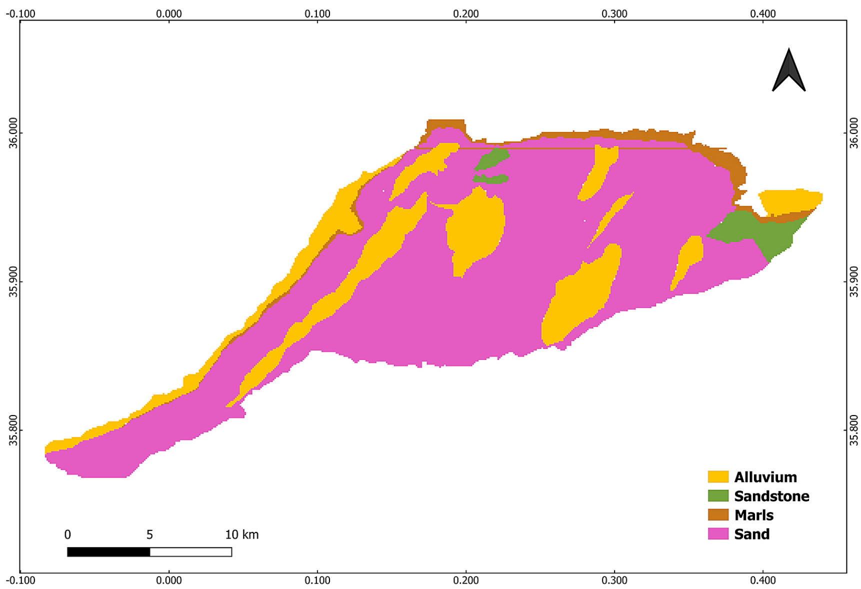

Figure 3. Geological setting of the aquifer based on the geological map from the general government of Algeria 1951–1952

Oued Kheir to Stidia. The high permeability of alluvium contributes significantly in groundwater storage. It is present in the central, easternmost, and northwestern regions of the plateau. The plateau is predominantly covered by sand, which is highly permeable and allows for effective recharge of the alluvial aquifer.

Lineament density

Lineaments are discernible structural characteristics on satellite images, distinguished by variations in tone relative to surrounding terrain features (Pande et al., 2021). Lineaments tend to occur in hard rock formations, although linear features can also be present in alluvial formations which enhances permeability (Khodaei and Nassery, 2013). The density of lineaments is greater in the central region of the plateau (Figure 4), ranging from 0.5 to 1 km/km^2 and aligned along the NE-NW axis. Their disposition corresponds to the occurrence of the alluvium formation, which is a strong indicator of an area with high potential for groundwater (Arulbalaji et al., 2019). The results of lineaments from SRTM data are consistent with the results of earlier research by (Bahri and Saibi, 2010; Bellal et al., 2020). These studies reveal that the region has undulations aligned in the NE-SW direction, forming small basins that enhance water retention and encourages percolation.

Soil

Soil has a significant impact on porosity, permeability, and infiltration capacity (Arulbalaji et al., 2019). (Figure **5**) represents the predominant soil type of the area. It primarily consists of clayey sandstone soils with a reddish hue, characterized by a porosity level ranging from low to medium (Al-Kharra'a et al., 2023). Southwestern and eastern regions of the plateau are classified as either sand-sandstone or calcareous sandstone. The first formation has favorable permeability, while the second one demonstrates low permeability. In general, the region's soils, combined to lineament density, create an environment that is favorable for the occurrence of groundwater.

Slope

Slope affects surface water infiltration, which makes it a significant factor in the occurrence of GPZs. The study area exhibits gentle slopes, which promote increased percolation time for water. (Figure 6) represents the slope and show a variation between 0 and 4%. Globally, the plateau has a mild slope ranging from 0.05 to 0.5 km/km^2.

Drainage density

Drainage density is inversely proportional to permeability, as it is influenced by a highly developed drainage system that enhances runoff and reduces infiltration (Chowdhury et al., 2008; Kanema and Gumindoga, 2022). The region has a poor drainage system. The majority of the plateau presents a notably low drainage density, as illustrated in Figure 7. Low to moderate drainage density is seen in the coastal region and southern area. Both the increased urbanization near the coast and the southern region's proximity to the

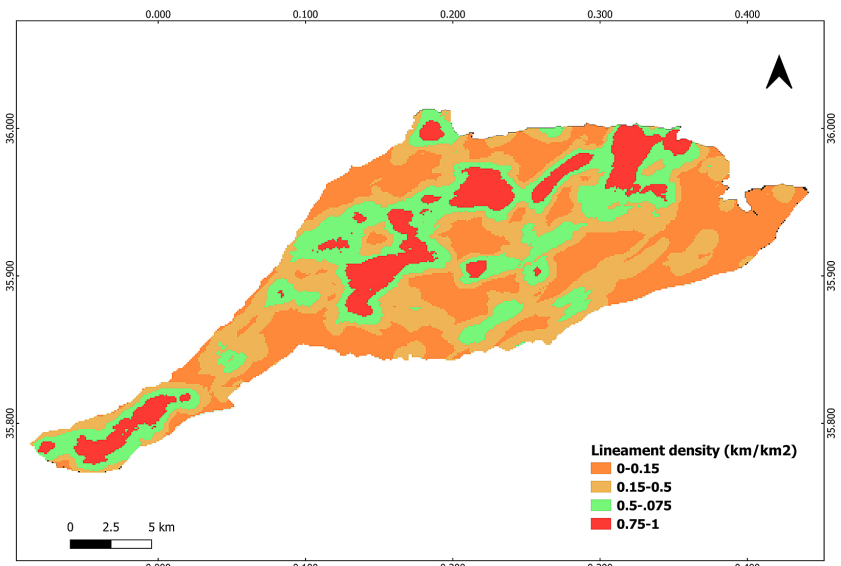

Figure 4. Map of lineaments of the study area

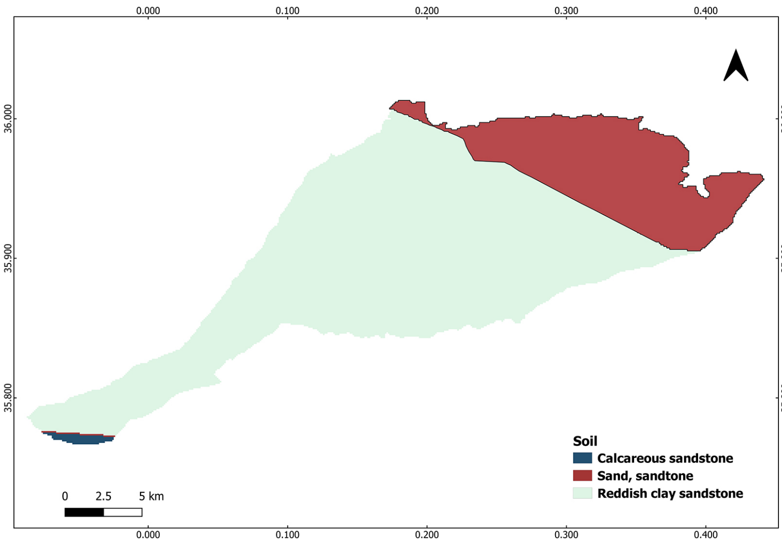

Figure 5. Soil composition of the study area

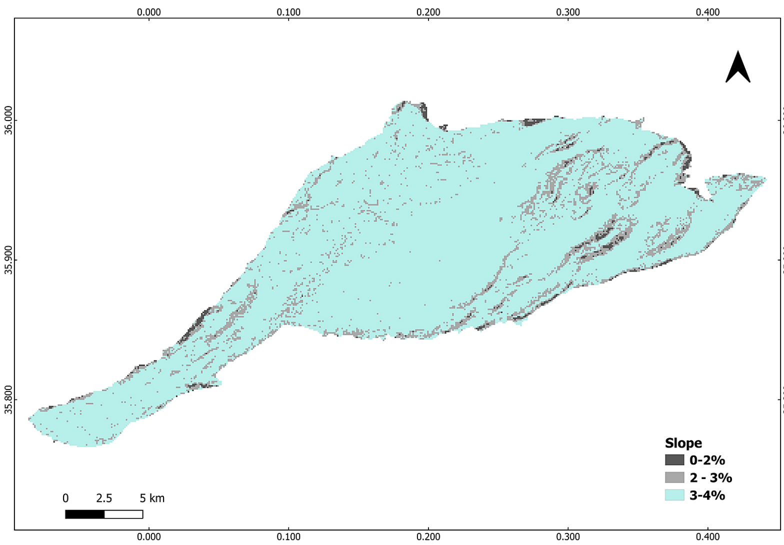

Figure 6. Map illustrating the slope of the study area

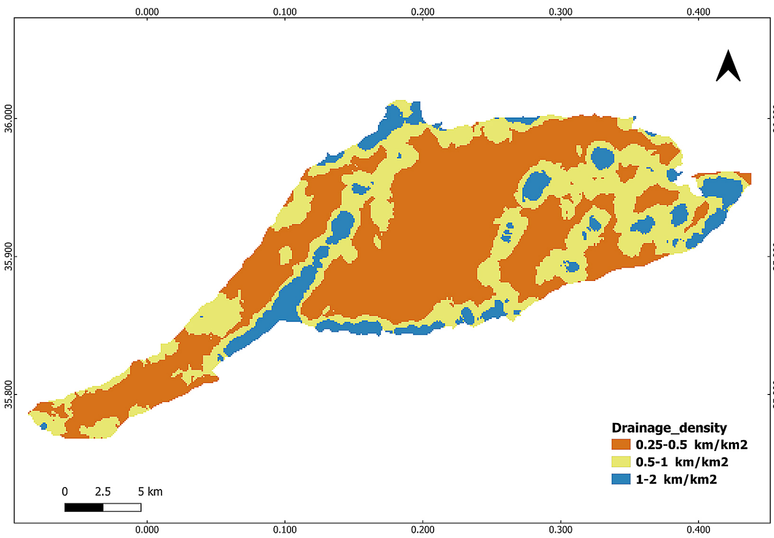

Figure 7. Map of the drainage density

mountain foothills can be responsible for the variations. This low drainage density serves as an excellent factor of groundwater potential existence (Chowdhury et al., 2008).

Variation of rainfall

Climate change impacts the distribution and frequency of rainfall, which in turn affects the replenishment of groundwater. To estimate the impact of climate change on groundwater potentiality during 2000 and 2014 (Figure 8), two rainfall maps are established. For alluvial aquifers, like the one mentioned here, the process of recharge is significantly impacted by precipitation. Meaning the regions characterized by high precipitation rates are more likely to experience high levels of GPZ. The lowest rate was assigned to low rainfall class and vice-versa (Table 2). As per Figure 8, from 2000 to 2014, rainfall amount decreased and shifted substantially. The maximum rainfall dropped from 527 mm to 422 mm. These results are in accordance with those of (Camarasa-Belmonte et al., 2020), who found that there is a general trend of decreasing rainfall in Spain and in the Mediterranean basin, from 1989 to 2016, mostly due to climate change. While there is some disagreement among studies regarding the decrease in yearly rainfall, there is a consensus that climate change is causing a change in the distribution of precipitation (Mensah et al., 2022). The Mediterranean region is highly susceptible to climate change, with the potential for significant shifts in temperature and precipitation patterns due to increased moisture divergence within the average atmospheric circulation (Seager et al., 2014; Tuel and Eltahir, 2020). Emissions of greenhouse gases may also be responsible for changes in rainfall patterns and their decrease. By indirectly influencing cloud properties, they contribute to changes in rainfall patterns and intensity.

Variation of land use land cover

LULC maps were used to assess how their variation affects GPZs. The 2000 and 2014 maps show the studied area groundwater usage by depicting the earth natural and human-induced features. This feature was selected for the delineation of GPZ because shifts in land use can significantly impact hydrological dynamics, thereby disturbing recharge capabilities (Wakode et al., 2018). The major land use and land cover (LULC) classes observed in this region consist of herbaceous crops, artificial surfaces, terrestrial barren land, multiple or layered crops, shrub cover area, tree cover and sparsely natural vegetation (Figure 9). The highest score of 5 was given to herbaceous crops and sparsely vegetated areas among all land use and land cover (LULC) classifications. This is due to the fact that their roots have the ability to loosen the soil and they have lesser runoff capacities compared to artificial surfaces. On the basis of their ability to transmit and retain water, artificial surfaces and terrestrial barren land received a moderate to low score of 1 and 4, respectively. In 2000, the dominant LULC pattern consisted of herbaceous crops (62.82%), followed by multiple or layered crops (16.04%), sparsely natural vegetation (8.54%), shrub cover (7.29%), artificial surfaces (4.08%), terrestrial barren land (0.75%), and tree cover (0.46%). Table 3 indicates that in 2014, there were changes in all land uses, with the exception of tree and shrub cover areas.

Artificial surface increased significantly by 2.71% between 2000 and 2014. The herbaceous

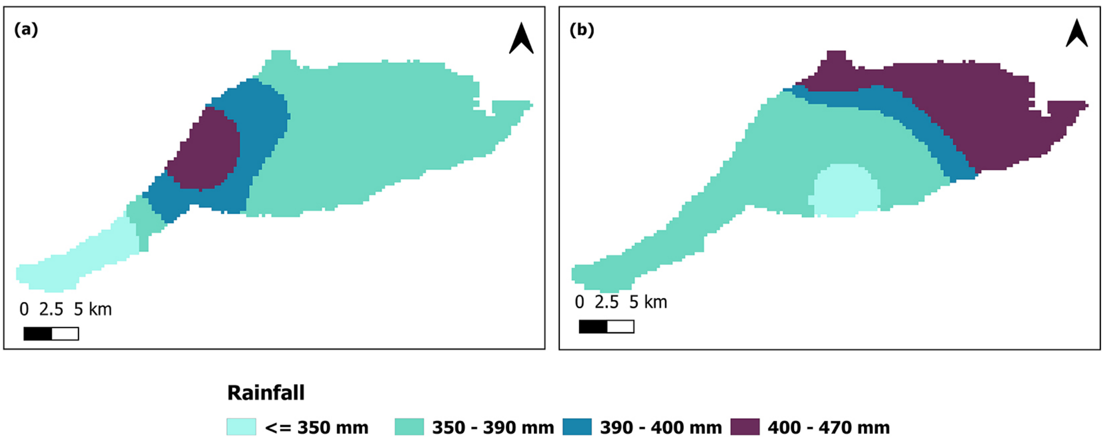

Figure 8. Comparative rainfall maps: (a) 2000 and (b) 2014

Table 3. LULC classes and area and change detection for 2000 and 2014

Classes	2000		2014		2014–2000
	Surface (km²)	%	Surface (km²)	%	Change (%)
Herbaceous crops	377	62.83	373	62.17	-0.73
Terrestrial baren land	4.5	0.75	1.25	0.21	-0.54
Artificial surface	24.5	4.08	40.75	6.79	+ 2.71
Multiple or layered cropS	96.25	16.04	92.25	15.38	-0.66
Tree cover	2.75	0.46	2.75	0.46	0
Shrub cover area	43.75	7.29	43.75	7.29	0
Sparsely natural vegetation	51.25	8.54	46.25	7.71	-0.83

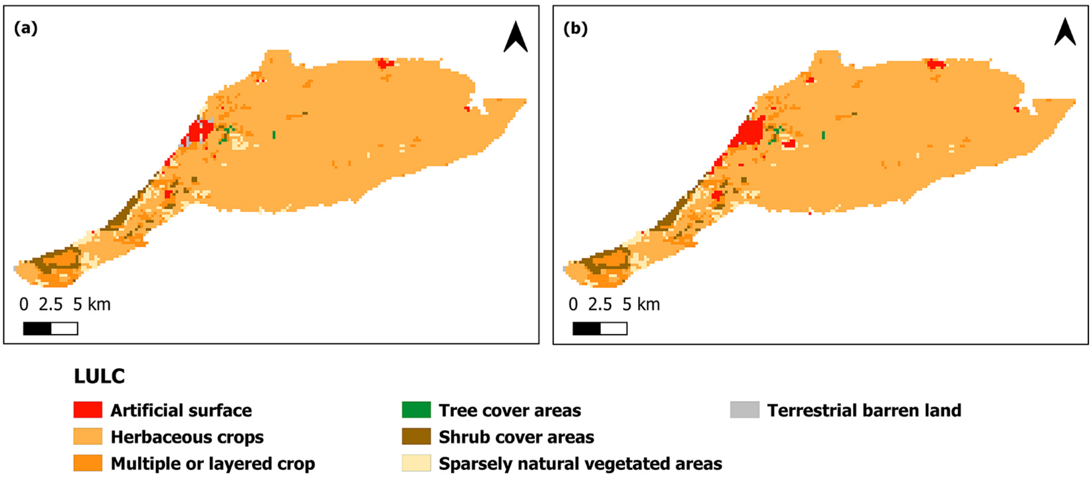

Figure 9. LULC maps for (a) 2000 and (b) 2014

crops experienced a decrease of -0.73%, while the multiple or layered crops saw a decrease of -0.66%. Sparsely natural vegetation and barren land decreased both 0.83% and 0.54%. Artificial surface class exhibits the greatest change. As depicted in (Figure 9), there is a clear transformation of barren land into artificial surfaces, resulting in the growth of urban regions. Similar results were discussed by (Somvanshi et al., 2020), in the district Gautam Budh Nagar, India, a region where built-up is strictly close to perennial agricultural land, they observed an increase of built up area and a small decrease in cropland between 2001 and 2016.

Delineation of GPZs

Groundwater potential zones were mapped for 2000 and 2014 according to the Pairwise Comparison Matrix (Table 4). The values found for the consistency ratio (CR) and the consistency index (CI) were 0.03% and 0.05%, respectively. These results fall below 0.10%, which is an acceptable estimate of inconsistency (Castillo et al., 2022). According to (Table 2), the findings show that geology has the greatest impact on groundwater potential (35%), followed by lineament density (23%), soil (16%), slope (10%), and drainage density (7%). The dominance of geology in GPZs occurrence in alluvial area is confirmed by (Karmakar et al., 2021). High and moderate potential are promoted by the NE-SW lineament network, which sits on the alluvium and sand formations in the plateau's center (Figure 10a). The fluctuations in GPZs primarily stem from the shifting rainfall patterns and variations in LULC, as these are the sole variable factors. According to (Figure 10), there was a decline in GPZs between 2000 and 2014. Most of the plateau had moderate potential in 2000. The northwestern, northeastern, and central regions exhibited a significant capacity for groundwater resources. In contrast, the eastern region of the plateau exhibits a progression from fair potential to very low potential. For most of the region, groundwater potential decreased significantly in 2014. In the southwest and central areas of the plateau, there is a significant decline

Table 4. AHP pairwise comparison matrix

Features	Geology	Lineament density	Soil	Slope	Drainage density	Rainfall	LULC
Geology	1	2	3	4	5	6	6
Lineament density	0.5	1	2	3	3	5	5
Soil	0.33	0.5	1	2	3	4	4
Slope	0.25	0.33	0.5	1	2	3	3
Drainage density	0.2	0.33	0.33	0.5	1	2	2
Rainfall	0.16	0.2	0.25	0.33	0.5	1	0.5
LULC	0.16	0.2	0.25	0.33	0.5	2	1

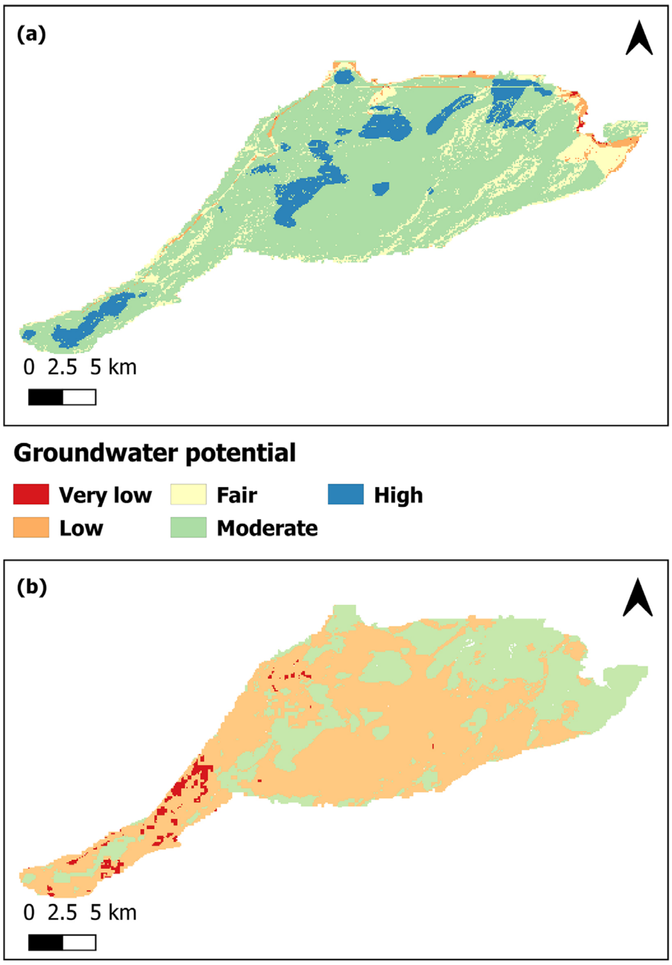

Figure 10. Groundwater potential zone maps for (a) 2000 and (b) 2014

to very low and low potential. The moderate potential was only maintained in the northwest and north regions. The north and northwestern part remained with a moderate potential.

As indicated by the change detection analysis (Table 6), in 2014, low potential zones experienced an increase of 22.1%, a decrease of 30.29% in moderate potential, and high potential areas vanished completely. The results are close to those of (Kanema and Gumindoga, 2022) who found that zones of high and moderate potential are decreasing under decreasing precipitation rates in 2015. In addition to the persistence of agricultural activity shown by LULC maps, the decrease in GPZs can be ascribed to the shift and decrease in rainfall. The rainfall patterns of 2014 are consistent with the GPZs, which is due to rainfall being the aquifer's primary source of recharge (Bellal et al., 2020). Also, the cultivation of herbaceous crops has a significant impact on the shift in rainfall patterns due to the release of greenhouse gases and their large water requirements (Vandecasteele et al., 2016). For intensive agriculture in the Mediterranean Basin, this kind of crop contributes significantly to greenhouse emissions (Aguilera et al., 2015).

Despite the decline in agricultural lands, the region is still acknowledged as a perennial agricultural area (Belguesmia et al., 2021), and the intensity of the activity impacts the physical as well as hydrological soil properties, such as porosity. In addition, plowing disturbs the connectivity of macropores in the plough layer by altering the structure, porosity, and pore size distribution of the soil (Owuor et al., 2016). This modification lowers the rate at which soil infiltration occurs, which in turn decreases groundwater recharge and increases runoff. Additionally, the agricultural fields with insufficient drainage systems, excessive pumping for human activity and irrigation, and other factors can cause groundwater depletion (Kaur et al., 2020). Following agriculture, urbanization is the second influential factor on GPZs, resulting in a 2.71% increase. Mensah et al. (2022) highlighted that urban surface significantly affects the recharge process. In fact, Patra et al. (2018) found that there is a strong negative correlation between urban growth and groundwater level. Combining fast demographic growth, increased shortage of water, variability of LULC and climate change is redesigning the hydrological patterns in various regions, which in turn affects recharge process. These effects are intensified by urbanization, which reduces infiltration rates and increases impermeable surfaces (Ávila-Carrasco et al., 2023; Zomlot et al., 2017).

Validation of groundwater potential zones

Due to the lack of prior research identifying GPZs in the area, the GPZs could not be independently verified against any other studies conducted in the field. The validation procedure made use of the groundwater depth for twelve monitoring wells. A decrease in water level is observed throughout the region, which is consistent with the GPZs of the study years, according to a comparison of potentiality maps and depth to groundwater (Table 5). The northeast region experiences a decline ranging from 3 to 6.62 m. The central area of the plateau exhibits a decrease in elevation ranging from 6 to 10.3 m, while the northwestern region experiences a decrease between 3 to 6 m. The groundwater capacity in specific areas is accurately represented by the values employed for validating the GPZs maps. The validation results indicate that approximately 83% of the wells accurately align with the zonation of the groundwater potential map.

Groundwater potential zones forecasting and evolution

The novel approach of coupling AHP and MOLUSCE plugin enabled to forecast GPZs for 2030 and 2050 (Figure 11). The predictions were

Table 5. Groundwater potential zones validation

No	Latitude	Longitude	Depth to groundwater (m)			Location of well on GPZ map		Agree/disagree
			2000	2014	Drawdown	2000	2014	
1	0.10498062	35.88554825	20.08	26	6.08	Moderate	Moderate	Disagree
2	0.27473114	35.9825554	5.87	12.49	6.62	Moderate	Low	Agree
3	0.10998287	35.91924564	23	26	3	Moderate	Low	Agree
4	0.3151474	35.89893654	16.88	20.95	4.07	Moderate	Fair	Partially agree
5	-0.0631262	35.77986716	25.22	-	-	Moderate	Low	Disagree
6	0.38612506	35.94552129	17.39	21.56	4.17	Fair	Low	Agree
7	0.02955096	35.82165734	22.48	–	–	Fair	Very low	Agree
8	0.35719434	35.97642211	10.91	14.06	3.15	Moderate	Fair	Partially agree
9	0.16295333	35.97878204	31.22	35.15	3.93	Fair	Low	Agree
10	0.13467905	35.92677311	25.15	32.10	6.95	High	Low	Agree
11	0.23140154	35.90084719	19.64	29.94	10.30	Moderate	Low	Agree
12	0.24921261	35.88047011	23.91	30.56	6.65	Moderate	Low	Agree

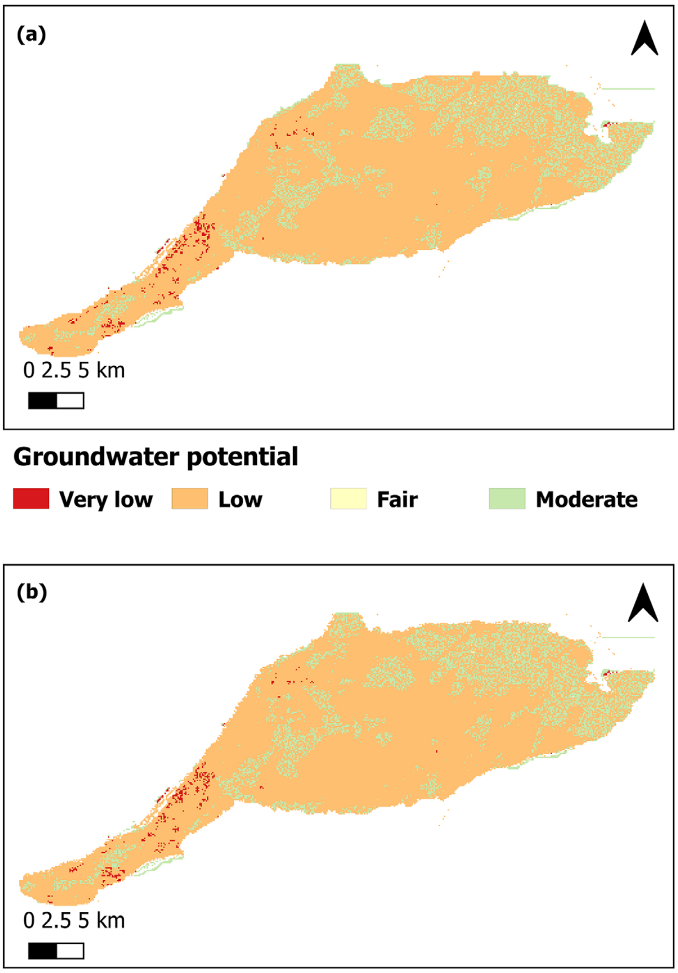

Figure 11. (a) 2030 and (b) 2050 groundwater potential zone forecasts

determined based on the results of the MOLUSCE plugin, which indicated a correctness rate of 89.05%, an overall kappa value of 79.10%, a histo kappa value of 94.92%, and a loc kappa value of 83.33%. According to (McHugh, 2012), kappa values above 0.75 are acceptable and reflect the model's strength and the precision of its predictions (Santamouris, 2020; Zhang et al., 2021). Aquifer potential ranges from very low to moderate, according to the estimated GPZs for 2030 and 2050 (Figure 11). While there will be low and very potential zones in the center and south, respectively, the east will have sporadic patches of moderate potential. From 2014 to 2030 (Table 6), there was a 7.47% increase in low potential zones and a 6.62% decrease in fair potential zones. These changes can be attributed to the ongoing decrease in rainfall and the persistence of intensive agriculture. Accordingly, Sahabi-Abed (2022), Tarín-Carrasco et al. (2024) estimate that there will be a drastic decrease in rainfall in the northwest of Algeria. The prediction results also corroborate with those of (Boitt et al., 2023) who used a modified DRASTIC model in conjunction with MOLUSCE, to demonstrate that GPZs are predicted to significantly reduce by 2042 in Kenya, due to changes in climate conditions and increased urbanization. It is noteworthy to acknowledge that the reduction in GPZs shown by Boitt et al., (2023) is comparatively less severe than the decline reported in Mostaganem Plateau, owing to the significantly lower precipitation rates in the studied region. From 2030 to 2050, there are minimal fluctuations observed in GPZs. The stability of the aquifer can be ascribed to its inherent resilience mechanism, which allows it to achieve equilibrium in the face of fluctuating climate conditions (Hera-Portillo et al., 2021; Wu et al., 2020).

According to (Lapworth et al., 2013; Wu et al., 2020), aquifers can assimilate shocks and return to a state of equilibrium or transition to a new equilibria in response to stresses such as intense pumping and changes in rainfall amounts

Table 6. Variation evaluation of GPZs in percentage

Variation evaluation of GPZs					
Years	Very low	Low	Fair	Moderate	High
2000–2014	0.66%	22.1%	7.53%	-30.29%	-100%
2014–2030	-0.36%	7.47%	-6.62%	-0.48%	-
2030–2050	-0.04%	0.24%	-0.18%	-0.01%	-

and patterns. This indicates the possibility of a balanced state of resilience that will begin in 2030, allowing the aquifer to efficiently tackle challenges presented by climate change and human activities. This new equilibrium state may represent a significantly altered condition from the original state of the aquifer, with diminished capacity and function (Jasechko et al., 2024).

Moreover, the MOLUSCE plugin is based on Markovian approach for the creation of transition matrix, before using the CA-ANN combination for the forecasting (Muhammad et al., 2022). Markov chain assumes that the probability distribution of future states depends only on the current state of the studied element (Püts et al., 2020). Therefore, the forecasts do not take into account the laws and measures adopted by the Algerian authorities. The linear aspect of Markov chain could also explain the minimal fluctuations between the forecasted GPZs.

CONCLUSIONS

This study highlights the development of GPZs in the Mostaganem plateau with regard to the impact of climate change, specifically changes in LULC and precipitation. This research used a GIS-RS and AHP approach to delineate GPZs between 2000 and 2014. In addition, the study applied an unprecedented use of the AHP-MOLUSCE plugin combination for groundwater potential zones forecasts for the years 2030 and 2050. The results demonstrated a significant decline in groundwater potentiality, high GPZs were eliminated and shifted toward lower potential in different areas, underscoring the crucial role that anthropogenic and meteorological factors have. These changes have been primarily attributed to the persistence of intensive agricultural practices and changes in rainfall patterns. The perennial agriculture practices in the region and the specific types of crops grown have a disruptive effect on the physical properties of the soil and also influence the pattern of rainfall through the emission of greenhouse gases. The proliferation of urban areas over barren lands, combined to demographic expansion, shortage of water, and the subsequent decline of recharge, aggravate the issue. The forecasts of 2030 and 2050 offered significant knowledge of future aquifer dynamics. The forecasting displays a consistent decrease in GPZs until 2030, with minor fluctuations anticipated from 2030 to 2050. The ability of the aquifer to create a new equilibrium in response to continuous climate and human-induced pressures is attributed to the resilience mechanism. The validation of the results confirmed that the integrated methodology and the MOLUCSE CA-ANN model exhibited satisfactory reliability.

These results may be representative of the behavior of numerous alluvial aquifers in semi-arid climates that are subjected to human activity and intensive agriculture. This novel approach can enhance the understanding of the aquifer's behavior. This preliminary study on managing groundwater resources is of great importance. However, it has certain limitations that can be addressed by incorporating the analysis of groundwater quality, evapotranspiration losses and soil moisture that can be influenced by LULC. Additional investigation into the mechanisms of resilience is also necessary. In light of both climatic and anthropogenic challenges, this study emphasizes the critical importance of implementing appropriate land and water resource management practices.

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