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# Mapping natural groundwater potential recharge zones using GIS-AHP in the Upper Cheliff alluvial aquifer, Algeria

## *Identificazione delle zone di ricarica potenziale delle acque sotterranee mediante GIS-AHP nell'acquifero alluvionale della Piana del Cheliff Superiore, Algeria*

**MEROUCHI H.**[a] ✉ , **BOUDERBALA A.**[b], **ELMEDDAHI Y.**[a]

[a] Vegetal Chemistry-Water-Energy Laboratory (LCV2E). Department of Hydraulics, Faculty of Civil Engineering and Architecture, University Hassiba Ben Bouali of Chlef, Algeria - email ✉ : *h.merouchi@univ-chlef.dz*

[b] PRAVDURN Laboratory. Department of Earth Sciences, Faculty of SNV-ST. University Djilali Bounâama of Khemis Miliana, Algeria email: *a.bouderbala@univ-dbkm.dz*

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**Correspondence to:**
**Merouchi H** ✉
*h.merouchi@univ-chlef.dz*

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### Riassunto

La scarsità d'acqua è una problematica rilevante in regioni aride e semi-aride. La sfida è particolarmente evidente nella Piana del Cheliff Superiore in Algeria, dove l'acquifero alluvionale gioca un ruolo vitale nel supportare la fornitura idrica per scopi potabili e irrigazione. L'acquifero è soggetto a un'alta richiesta e a problematiche di qualità. In questo contesto è stato condotto uno studio mediante l'utilizzo di un approccio cartografico per valutare la ricarica potenziale delle acque sotterranee dalle precipitazioni. L'obiettivo del presente studio è di identificare le zone di ricarica potenziale naturale delle acque sotterranee utilizzando l'Analytic Hierarchy Process (AHP) integrato a Sistemi Informativi Geografici (GIS) e combinando diversi fattori che possono influenzare la ricarica, ad esempio: precipitazioni, tipologia di suolo, pendenza dei versanti, uso e copertura del suolo, zona insatura, soggiacenza e Curve Number.

La carta risultante dalle analisi mostra che solamente il 22% dell'area di studio ricade nella classe a bassa o molto bassa ricarica potenziale, il 35% ricade nella classe a media potenzialità di ricarica e il 43% presenta una ricarica potenziale alta o molto alta. La zona orientale dell'area di studio, tra le città di Djendel e Ain Soltane, presenta zone a ricarica potenziale da moderata ad alta. Ciò è legato alla ricarica naturale per le precipitazioni e per infiltrazione dai corsi d'acqua superficiali durante il rilascio di acque dalle dighe presenti a monte, agli eccessi irrigui e alla ricarica laterale dalla formazione arenacea miocenica a diretto contatto con l'acquifero.

E' stata eseguita una procedura di validazione utilizzando i dati di 66 pozzi distribuiti nella piana ed è emerso che 48 pozzi mostrano un buon accordo con la carta risultante, mentre 18 pozzi mostrano leggere deviazioni. I risultati mostrano un accordo del 72.72% tra il numero di pozzi attesi e quelli esistenti, confermando un buon risultato predittivo della metodologia AHP.

### *Abstract*

*Water scarcity is a big issue in arid and semi-arid regions. This challenge is particularly evident in the Upper Cheliff plain in Algeria, where the alluvial aquifer plays a vital role in drinking water supply and supporting irrigation. This aquifer faces high demand and quality issues.*

*A study was conducted in this context, employing a cartographic approach to assess potential groundwater recharge from precipitation into the alluvial aquifer. The current study aimed at mapping zones with potential natural groundwater recharge zones by applying the Analytic Hierarchy Process (AHP) integrated within a Geographic Information System (GIS) environment, combining various factors that can influence recharge, such as rainfall, surface soil type, slope degree, land use and land cover, unsaturated zone, groundwater depth, and curve number.*

*The map resulting from the analysis indicates that only 22% of the assessed area covers zones with very low and low potential recharge, 35% with moderate potential recharge zones, and 43% with high and very high potential recharge zones. This map reveals that the eastern region of the plain, from the cities of Djendel to Ain Soltane, is moderately to highly favorable for recharge. This is due to the natural recharge from rainfall and watercourse infiltration during dam release periods, excess irrigation water, and recharge from the Miocene sandstone aquifer in areas with direct aquifer contact.*

*A validation process was performed using data from 66 wells distributed in this plain and it indicated that 48 wells exhibited good agreement with the resulting map, while 18 wells showed slight deviations. The results indicate an agreement of 72.72% between expected and exist number value of wells which confirming the good prediction of the AHP technique.*

## Introduction

Groundwater is a precious and indispensable resource for life because it is the most stable source of water supply (Arunbose et al., 2021). Moreover, groundwater is mostly not vulnerable to contamination if there is an impermeable layer covering the aquifer (Maizi et al., 2020; Rao et al., 2018). Nevertheless, industrial development, population growth, and the expansion of irrigated areas have caused intensive exploitation of this resource and have aggravated the quantitative and qualitative degradation of groundwater for many aquifers (Ali Rahmani & Chibane, 2022 ; Bouderbala, 2015; Santacruz et al., 2017). Therefore, the importance of the evaluation of groundwater regulating reserves is essential for a good management of groundwater resources, hence it is important to estimate the natural recharge rate of an aquifer (Scanlon et al., 2002; Tilahun & Merkel, 2009).

Natural groundwater recharge is influenced by many components, such as vegetation cover, type and composition of the soil, topography (i.e., slope degree), geologic nature (Zarate et al., 2021), and depth to the water table, and other parameters (Richard et al., 2015; Rukundo and Doˇgan, 2019). The spatial variation of each component, the interaction of these factors with each other, and the extent of their influence on water percolation process through the unsaturated zone (UZ) must be well represented to identify the preferential groundwater recharge zones.

Remote sensing (RS) allows systematic analysis of hydrogeomorphic units/landforms/adequate lineaments, while their interaction is best represented by the use of Geographic Information System (GIS) tools thanks to their ability to manage large and complex spatial data. Indeed, the development of information technologies, in terms of database management, satellite monitoring and the spatial processing of satellite images, allowed the appearance of new geospatial techniques for assessing the natural groundwater recharge potential zone and therefore the planning and sustainable management of water resources (Scanlon et al., 2012).

The geospatial techniques have been used in many cases to avoid the difficulty of finding data and field surveys. Application of GIS techniques can be used to quantify the rate of groundwater recharge. Moreover, the GIS analysis coupled with Multi-Criteria Decision Analysis (MCDA) can increase the accuracy of results and offer a systematic spatiotemporal depiction of productive areas and accurate predictions of groundwater recharge (Hayat et al., 2021; Jha & Chowdary, 2007). In addition, effective use of MCDA is very effective for water management and for solving decision problems (Biswas et al., 2020; Makonyo & Msabi, 2021). The Analytic Hierarchy Process (AHP), as a part of the MCDA, is used for complex decision-making in groundwater management, where it simplifies the attribution of a priority influence to several decision alternatives, such as, the case of the unequal influence of the factors which govern the natural groundwater recharge, while an analysis by coupling MCDA and GIS provided usefulness in geospatial modeling (Al Farajat et al., 2015; Arunbose et al., 2021 ; Rahmati et al., 2015; Souissi et al., 2018).

The aims of the present study are to understand the processes that control groundwater recharge by using a classification of thematic layers based on a weighted overlay analysis of the AHP technique in a GIS environment and to precisely map the natural groundwater potential recharge zones within the Upper Cheliff alluvial aquifer, located in Algeria, using an advanced GIS-MCDA analysis approach.

## Material and methods

### *Study area*

#### *Climate and geomorphology*

The Upper Cheliff alluvial plain is located about 120 km southwest of Algiers (Algeria). The study area is situated between 36° 6'N and 36° 18'N latitude and from 2° 00'E to 2° 27'E longitude. It covers an area of 348.4 km², its northern boundary is defined by Zaccar massif, eastern by the Djendel threshold, on the south by the Ouarsenis chain, and on the west by the Aribs threshold and Doui massif. The surface elevation ranges between 203 m (MSL) and 490 m (MSL), with an average of 286 m (MSL) (Fig. 1). The Upper plain of Cheliff has an agricultural vocation with several towns, and groundwater is a principal source for domestic use, drinking purposes, and agricultural irrigation.

A semi-arid climate prevails in this region with an average annual cumulative precipitation of 395.5 mm (2008-2018) and an irregular intra-annual distribution. The annual average air temperature is 19.2°C (2008-2018). The structure of the hydrographic network shows an average drainage density due to low topography; it includes the mainstream, wadi Cheliff, which is part of the Cheliff Zehraz basin. The stream crosses the plain from east to west and receives tributaries (affluent tributaries) on its left and right banks, including Deurdeur, Massine, Harreza, Boutane, Talbanet, and Rayhane. Most of the hydrographic network is dry throughout the year, except during the rainy season.

#### *Soil and vegetation cover*

In Upper Cheliff, Algeria, the study area exhibits two major soil groups:

Group 1: Border associations with varying degrees of soil erosion and parent rock alteration, transitioning from Miocene and Pliocene limestone to sandstone or marl. This results in young soils, occasionally found in the siliceous bedrock of the Doui massif.

Group 2: The central salt group includes six soil classes. Notably, unevolved alluvial soils dominate the primary bed along wadi Cheliff, while alluvial soils have evolved in recent terraces. Smaller areas are covered by unevolved alluvial soils along wadi Cheliff and its tributaries. Over 34% of the plain is characterized by colluvial soils and alluvial soils from minor tributaries, featuring young soils with light to medium sandy loam and silt, and sometimes clayey properties. Highly evolved soils, characterized by silt and clayey silt texture and limestone nodules at depth, cover extensive areas. Hydromorphic soils appear sporadically due to surface

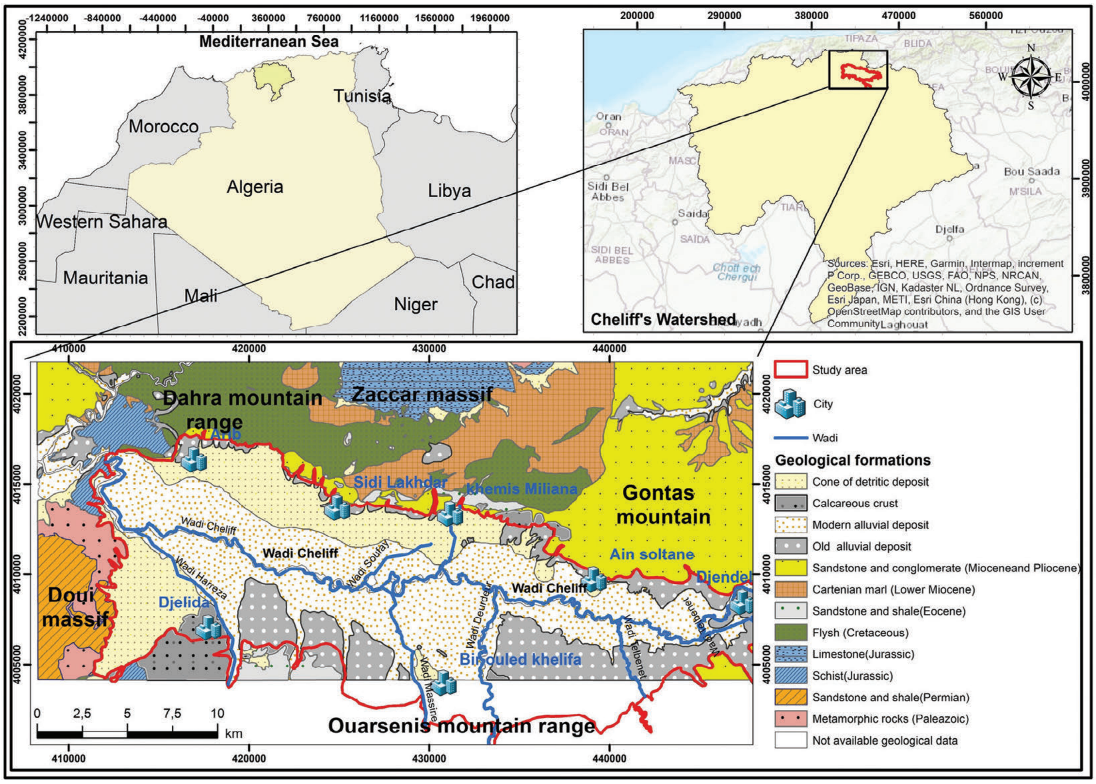

*Fig. 1 - Geographic location and geological formations map of Upper Cheliff plain. Perrodon (1957), modified. Coordinate Reference System: WGS84 UTM Zone 31N (EPSG:32631).*

Fig. 1 - Ubicazione dell'area di studio e carta geologica della Piana del Cheliff Superiore. Modificato da Perrodon (1957). Sistema di Coordinate di Riferimento: WGS84 UTM Zone 31N (EPSG:32631).

water flow networks, temporary water cover, and non-saline groundwater. Calcic soils are found in small southern areas, featuring differentiated soils with limestone accumulations. Upper Cheliff's soils are primarily used for agriculture and urban development, with herbaceous crops and permanent crops like vineyards, olive trees, and fruit plantations being common. Fruit cultivation occupies a significant portion of the agricultural surface more than 23 %.

## Geology and hydrogeology context

The lithostratigraphy of the study area (Fig. 1), as described by Mattauer (1958) and Perrodon (1957), consists of primary land on the Zaccar and Doui massifs, which are formed by alternating layers of black schist, quartzite, and clay. The Triassic period is represented by three solid masses: Zacca, Doui, and Ouarsenis. In the latter, it is characterized by formations of dolomite and gypsum, as well as carbonate rocks. Jurassic formations are well-developed and comprise limestone and marly limestone at the base, conglomerates, sandstone, sand, and marl at the top. The Quaternary is made up of alluvial deposits, spring travertines, and scree. Topographically, the Doui massifs are characterized by Jurassic dolomitic limestone that is 1000 m thick, while Zaccar consists of dolomite and other carbonate rocks. Neocomian shale clays, Albian flysch facies, and Cretaceous marls outcrop on the side edges of the plain. The central part of the plain is formed by accumulations of Miocene, Pliocene, and Quaternary sediments, with the Lower Miocene consisting of clay and marl, followed by the Miocene of middle age, which includes marl and clay, and some passages of conglomerate or sandstone, forming a layer that is 300 m thick. The Pliocene, which is 100 m thick, is formed by clays and conglomerates and is known as Gontas. The continental quaternary, as described by Glangeaud (1955) and Perrodon (1957), is made up of sands, gravels, and clay interlayers. To the south of the plain, the coarse alluvium of the early Quaternary is mounted on whitish limestone tuffs covered with beds of clay or silt, most of which are covered by thin organic soils.

The hydrogeological framework of this plain is characterized by a multilayered aquifer system. Hydraulic continuity between the Quaternary alluvial and Mio-Pliocene aquifers is solely established at the plain peripheries (Mania & Djeda, 1990), where direct contact occurs without an impermeable layer between them. However, a significant clay layer is present between the two aquifers within the central plain. It's crucial to clarify that our emphasis is solely on the Quaternary alluvial aquifer. Groundwater within this alluvial aquifer predominantly flows towards the central region, aligning with the primary drainage axis, wadi Cheliff. The principal flow direction is from the east to the west. Water table depths exhibit variation, with measurements ranging from approximately 5 meters in the western zone (near Djelida and Arib cities) to around 30 meters in the eastern zone (adjacent to Djendel city). In the central portion of the plain, water table depths average around 10 meters.

## Material and methods

In this study, multiple analysis of parameters that govern natural recharge distribution was performed using the AHP technique (Saaty, 1990, a) in a GIS environment (Mitina et al., 2023), to obtain a potential recharge map. Eight spatial parameters, namely rainfall, surface soil type, land use/ land cover (LULC), slope, geological characteristics of the unsaturated zone (UZ), drainage density, depth to water table, and curve number (USDA, 1986), were analyzed using the AHP approach, which involved calculating the geometric mean and normalized weights to explore the potential groundwater recharge zone.

## Data collected

A total of eight spatial parameters were used for the preparation of the geospatial database (Fig. 2). A preprocessing analysis of remote sensing data and geographic information of the Upper Cheliff alluvial aquifer was carried out using ArcGIS 10.4 software (ESRI, 2016).

The average annual rainfall was calculated by summing mean monthly rainfall amounts and converting them into a map layer. This comprehensive dataset was obtained from the National Agency for Water Resources (ANRH) and covers the period from 2008 to 2018. It encompasses data collected from seven (7) rainfall stations located across the plain. The data were converted into a thematic layer using the interpolation tool of inverse distance weighted (IDW) (Shepard, 1968) in ArcGIS environment. The thematic soil type layer was prepared from the soil map drawn by Boulaine (1957), using digitization techniques in the ArcGIS environment. The Landsat 08 image of September 15th, 2021 resolution 30 m, (USGS, 2024) was used to prepare the LULC map using the supervised classification method in ArcGIS 10.4 software, Imagery date selection is based on clear sky conditions to minimize cloud cover. Additionally, we aimed to align the chosen date with recent data used to elaborate other layers to ensure dataset compatibility and coherence. The slope and drainage density layers were generated from the digital elevation model (DEM) data with a resolution of 90 m downloaded from USGS website (USGS, 2024).

The map of the average groundwater depth was prepared using the method of IDW interpolation using seasonal point data of piezometric levels collected by ANRH. Noted that depth to water table is obtained by subtracting the elevation of the water table from the elevation of the ground surface at the same point. The curve number, which is defined in hydrology as the empirical parameter that can use to predict direct runoff or infiltration due to excess precipitation, was calculated by introducing the concept of soil hydrological groups (SHG), and the LULC data of the study area (Hawkins et al., 2008). The curve number map was obtained in ArcGIS by combining the two maps (SHG and LULC) using the Join Data function based on the Technical Release 55 (TR-55) procedure described in USDA (1986).

The UZ map visualizes the nature of the layers extending between the surface and the upper limit of the alluvial aquifer. In this study, the nature of these layers was presented by a single equivalent layer. It was identified based on two

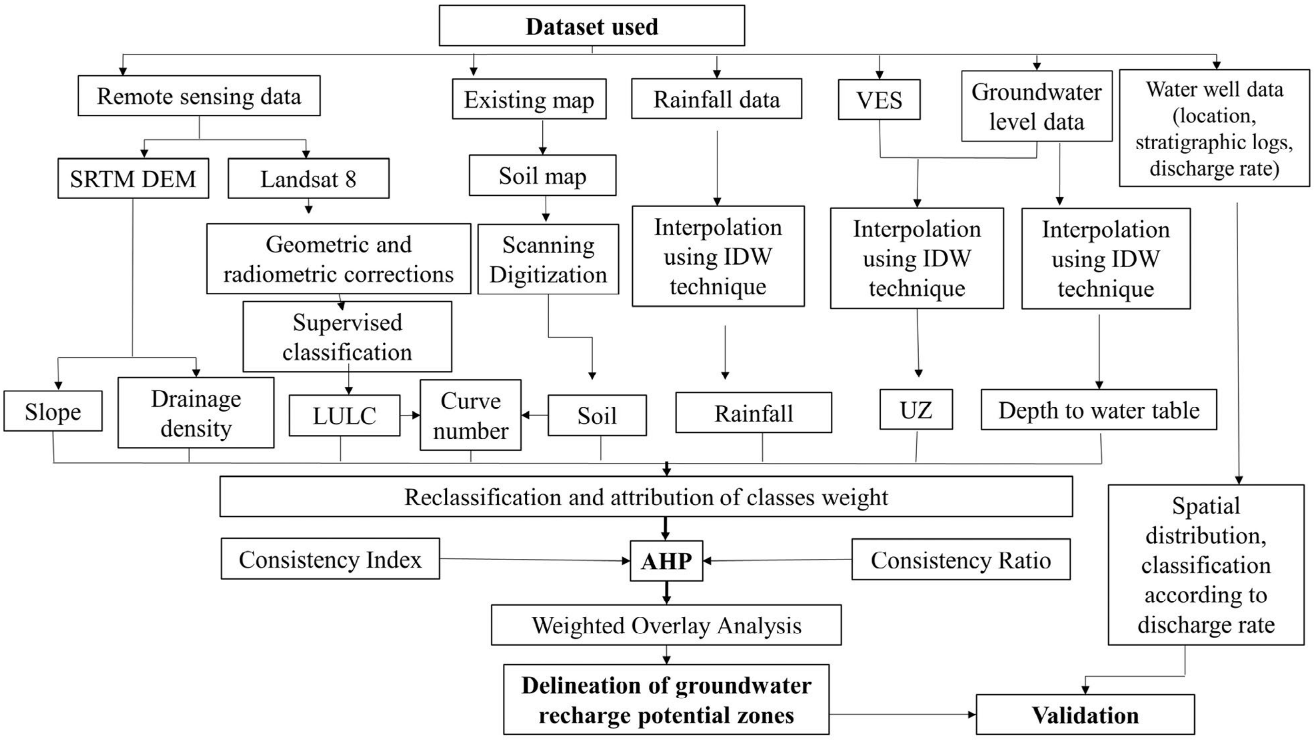

*Fig. 2 - General flowchart of study methodology.*

Fig. 2 - Schema di flusso della metodologia utilizzata nello studio.

main pieces of information: the unsaturated zone thickness according to the piezometry of the aquifer and the lithological nature of this zone, which was determined using geophysics (geo-electric soundings and the true resistivity values of the geological formations). Equivalent resistivity values were obtained from 74 vertical electric soundings (VES).

For a measurement point, the thickness of the unsaturated zone ($e$) is

$$e = e_1+e_2+...+e_n \qquad (1)$$

Where:

- $e_1$: Thickness of the first layer with true resistivity $R_1$
- $e_2$: Thickness of the second layer with true resistivity $R_2$
- $e_n$: Thickness of the second layer with true resistivity $R_n$

The equivalent resistivity at this measurement point will therefore be equal to:

$$R_{eq} = \frac{R_1 \cdot e_1 + R_2 \cdot e_2 + ... + R_n \cdot e_n}{e_1 + e_2 + ... + e_n} \qquad (2)$$

Based on the equivalent resistivity $R_{eq}$ of all soundings (Fig. 3.a), the map of spatial variation of equivalent resistivity was established using IDW tool in the ArcGIS environment (Fig. 3.b). An unsaturated zone variation map was generated using the corresponding resistivity based on the soil type resistivity scale (Fig. 3.c).

The common coordinate system of WGS84 UTM Zone 31N (EPSG:32631) and a similar cell size of 100 m × 100 m resolution were used for all thematic layers.

## Groundwater Recharge mapping method

### Analytic Hierarchy process

The AHP is a systematic technique that organizes and prioritizes information hierarchically by employing a pairwise comparison matrix (Saaty, 1990, a). It is very useful as a decision-making aid and has become one of the most widely researched topics for various decision analysis questions across different disciplines, such as the field of commerce and economics (Elsheikh, 2022), solid waste disposal (Siejka, 2020), as well as for natural risk management and floods (Akindele & Todome, 2021; Zine, 2018), erosion fire exposure zones (Arfa & Alatou, 2019; Taibi et al., 2020). Similarly, AHP is widely used in delineating potential groundwater zones and groundwater recharge potential zones (Charan et al., 2020; Kumar & Krishna, 2016). In order to determine the potential zones of natural groundwater recharge in the alluvial aquifer of the Upper Cheliff, the AHP technique was followed through four principal steps: (1) Selection of factors that govern the recharge process (Data collection section), (2) Creation of the matrix of pairwise comparison, (3) Eigenvectors and calculation of relative weights, (4) Evaluation of the consistency of matrix by calculating the Consistency Index (CI) parameter.

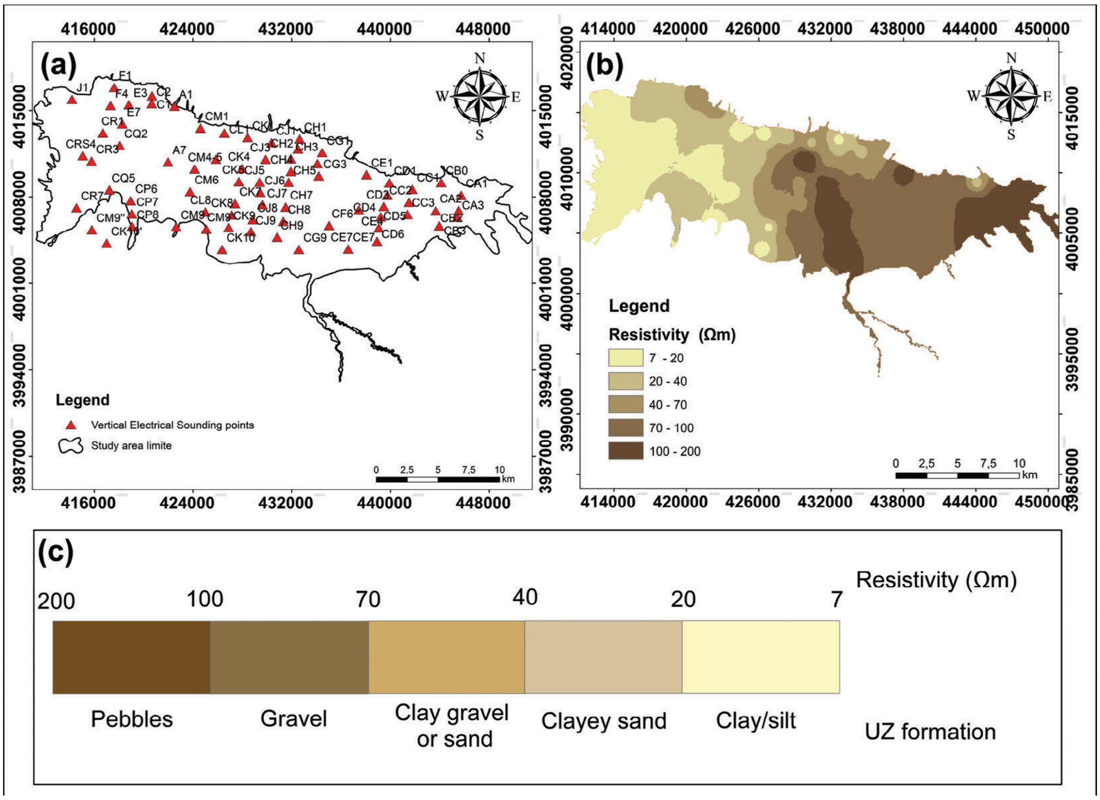

*Fig. 3 - (a) Vertical Electrical Sounding (VES) used to determine equivalent resistivity of the UZ, (b) spatial variation of equivalent resistivity of the UZ, (c) Resistivity Scale of dominant geological layers in the UZ.*

Fig. 3 - (a) Ubicazione dei Sondaggi Elettrici Verticali (SEV) utilizzati per calcolare la resistività equivalente della zona insatura, (b) distribuzione spaziale della resistività equivalente della zona insatura, (c) scala di resistività associata ai livelli geologici della zona insatura.

### *Construction of pairwise comparison matrix*

The pairwise comparison matrix, A (n*n) = $a_{ij}$ (Table 1) as a positive and reciprocal matrix ($a_{ii}$=1 and $a_{ji}$=1/$a_{jij}$), was constructed based on the input factors that govern recharge (Saaty, 1994) where n is the number of parameters involved in the study. These factors were presented as thematic layers and reclassified according to their degree of influence on the recharge process, where the highly influential factor was listed first, followed by lower influencing factors.

Rainfall, as main source of groundwater in arid and semi-arid regions, strongly controls recharge (Owor et al., 2009; Kotchoni et al., 2018), was selected as the first parameter, appearing in row 1 and column 1 of matrix A. Rainfall water fallen on the Earth's surface is faced with two possibilities: i) to infiltrate and percolate through the unsaturated zone and recharge the saturated zone, ii) to remain stuck in the upper layer of the soil and return to the atmosphere by evaporation or transpiration. In this case the type of soil, land use and land cover, slope and drainage density have a decreasing impact on the fate of these waters (Gee 1987; Owuor et al., 2016). Indeed, the type and characteristics of soil that covers an area determine the infiltration capacity and permeability of precipitation water in depth, the soil type factor was therefore selected in second order of importance after precipitation.

The use and cover of the soil also reflect the capacity of the space occupied to allow water to infiltrate. Agricultural land presents areas with high recharge where the plant cover plays the role of obstacles by slowing down the flow on the soil surface, slows down runoff and promotes infiltration, instead urbanized areas represent impermeable land. LULC was considered as a parameter of order three in the matrix A.

The slope reflects the ability of surface water to run off and infiltrate at depth. Indeed, a steep slope implies rapid runoff and consequently low infiltration of groundwater, whereas a low slope takes more time for water to infiltrate into the first layer of soil. Thus, the slope parameter was placed in the fourth position in the matrix. The drainage density (DD) is directly proportional to the runoff rate and therefore inversely proportional to infiltration and recharge. The DD was classified in the sixth row and column of the matrix.

The UZ parameter gives an overview of the nature of the formations of the soil layers in depth, the impermeable and thick formation builds a barrier against water percolating from surface soils, and on the other hand, the porous UZ promote infiltration and present a bridge transition of surface soil water to the underground water reservoir. The UZ parameter was ranked fifth in order of importance. Whereas, the thickness of this zone, i.e. the depth of the water table, which determines the time taken by the infiltration waters to reach the water table, was ranked in the seventh order.

The curve number (CN) is an essential quantitative interpretation for predicting runoff as well as water infiltration: a high CN characterizes areas with high runoff, a low CN characterizes areas with low runoff and therefore high recharge. The CN parameter was classified in eighth position because of its dependence on the parameters already classified previously.

In the pairwise comparison matrix, each entry represents the influence of the row factor relative to the column factor. The influences of the factor on others were determined based on previous field experiences (Gaolatlhe & Loago, 2020) as well as the opinion of groundwater experts and are structured on a scale from 1 to 9 points (Table 2). For example, the pair "Rainfall/Soil type" was assigned a coefficient of 2 because the importance of precipitation as a source of recharge is almost equal to that of the soil type which presents the first barrier passed in front of the surface waters, it is obvious that a coefficient of 1/2 is what to use in position "Soil type/Rainfall". Then the "Rainfall/LULC", "Rainfall/Slope", "Rainfall/UZ, "Rainfall/DD" pairs were assigned a coefficient of 5 because rainfall is essential for the development of the soil cover and the creation of slope in the terrain.

In addition, the rainy sectors have a significant effect on the depth of the water table, and on the CN curve number. Coefficients of 7 and 8 were assigned respectively for "Rainfall/Depth to water table" and "Rainfall/CN". The value of one was assigned to parameters of equal importance.

*Tab. 1 - Pairwise comparison matrix for AHP.*

Tab. 1 - Matrice di confronto a coppie utilizzata nell'Analytic Hierarchy Process (AHP).

| Recharge | A | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Rainfall | Soil type | LULC | Slope | UZ | DD | Aquifer depth | CN |
| Rainfall | 1.00 | 2.00 | 5.00 | 5.00 | 5.00 | 5.00 | 7.00 | 8.00 |
| Soil type | 1/2 | 1.00 | 2.00 | 4.00 | 3.00 | 5.00 | 8.00 | 5.00 |
| LULC | 1/5 | 1/2 | 1.00 | 2.00 | 2.00 | 3.00 | 5.00 | 5.00 |
| Slope | 1/5 | 1/4 | 1/2 | 1.00 | 3.00 | 4.00 | 8.00 | 3.00 |
| UZ | 1/5 | 1/3 | 1/2 | 1/3 | 1.00 | 5.00 | 5.00 | 5.00 |
| DD | 1/5 | 1/5 | 1/3 | 1/4 | 1/5 | 1.00 | 3.00 | 2.00 |
| Depth to water table | 1/7 | 1/8 | 1/5 | 1/8 | 1/5 | 1/3 | 1.00 | 3.00 |
| CN | 1/8 | 1/5 | 1/5 | 1/3 | 1/5 | 1/2 | 1/3 | 1.00 |

*Tab. 2 - The fundamental scale (Saaty, 1994).*

Tab. 2 - La "scala fondamentale" (Saaty, 1994).

| Degree of significance measured on an objective scale | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two factors contribute equally to the groundwater recharge processes. |
| 3 | Moderate importance of one factor over another | The judgment of an expert moderately favors one factor over another. |
| 5 | Strong importance | The judgment of an expert strongly favors one factor over another. |
| 7 | Very strong importance | A factor is strongly favored and its dominance |
| 9 | Extreme importance | The evidence favoring one factor over another is the highest possible order of affirmation. |
| 2,4,6,8 | Intermediate values between the previous and the next judgments | |

### Eigenvectors and calculation of relative weights

The eigenvector shows the order of influence of the factors on recharge by assigning and calculating the relative weights $W_i$ of each parameter towards recharge (Brunneli, 2015).

The eigenvector $W_i$ is calculated using the Rows Geometric Mean Method (RGMM) for the n*n pairwise comparison matrix $A=a_{ij}$ (Escobar et al., 2004).

In calculation the geometric mean $r_i$:

$$r_i = \left( \prod_{i=1}^{n} a_{ij} \right)^{1/n} \tag{3}$$

In eigenvector $W_i$:

$$W_i = \frac{r_i}{\sum_{j=1}^{n} r_j} \tag{4}$$

### Main eigenvalue (λmax)

The degree of consistency in the AHP matrix is measured by $\lambda_{\max}$ parameter, it is calculated using equation (5). The validity of pairwise comparison matrix is in relation with the value of $\lambda_{\max}$ ($\lambda_{\max} \geq$ number of parameters involved in the study); otherwise, a new matrix is required (Saaty, 1994). In our case, the principal eigenvalue for an 8*8 matrix is $\lambda_{\max}=8.91$, which allowed us to proceed to calculate the Consistency Index (CI).

$$\lambda_{max} = \frac{1}{n} \sum_{i}^{n} \frac{(AW)_i}{W_i} \tag{5}$$

Where: AW represents the multiplication of matrix A by the eigenvector $W_i$

### Assessment of matrix consistency

Matrix consistency is verified by determining the Consistency Index (CI), and the Consistency Ratio (CR) using equation 6 and 7. These indices are determined to evaluate the fairness of the judgment made during the construction of the comparison matrix, in other words, to what extent the given order of influence of one parameter over another with respect to recharge is acceptable and true.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{6}$$

$$CR = \frac{CI}{RCI} \tag{7}$$

Where:

*n*: Number of parameters comprising the matrix

*RCI*: Value of the random consistency index, which is given by Saaty's norm (Table 3); it depends on the matrix size.

The CR should be less than or equal to 10 %. If it exceeds 10%, the assessments may become somewhat random and might require revisions to identify and rectify inconsistencies (Saaty, 1990, b). A CR of 0% indicates a meaningful comparison or perfect consistency. The threshold value of 10% signifies that the judgment matrix is reasonably consistent.

In our case:

$$CI = \frac{8.91-8}{8-1} = 0.13$$

$CR = \frac{0.13}{1.4} = 0.09 = 9\% < 10\%$ ; The matrix coherence is there therefore acceptable, and the integration of the eight thematic factors as layers along with their normalized weights in ArcGIS software has become possible.

*Tab. 3 - Saaty's Random Consistency Index (RCI) value (Makonyo & Msabi, 2021).*

Tab. 3 - Valori del Random Consistency Index (RCI) di Saaty (Makonyo & Msabi, 2021).

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RCI | 0.0 | 0.0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

### Mapping potential recharge and calculating rates

The reclassified layers of rainfall, soil type, LULC, slope, geological characteristics of the unsaturated zone, drainage density, depth to the water table, and curve number, along with their percentage of influence on the recharge process, have been integrated to produce a map depicting the spatial distribution of natural groundwater recharge zones in the Upper Cheliff alluvial plain using the weighted overlay tool in ArcGIS software.

Input raster layers were categorized into 5 subclasses, using the reclassify by individual values tool in ArcGIS: the subclasses were reclassified in order 1, 2, 3, 4, 5 according to their high ability of recharge, very high, high, moderate, low, and very low (Table 4). Then these layers were multiplied by the weights obtained through the AHP technique as in Eq. (8) (Fig.2) and the final distribution map of the recharge zones was obtained.

$$GWRZ= R_L\, R_W + ST_L\, ST_W + LULC_L\, LULC_W + S_L\, S_W + UZ_L\, UZ_W + DD_L + DD_W + GWD_L GWD_W + CN_L CN_W$$

Where:

$GWRZ$ = Groundwater Recharge Zone, $R$ = Rainfall, $ST$ = Soil type, $LULC$ = Land Use and Land Cover, $S$ = Slope, $UZ$ = Unsaturated Zone, $DD$ = drainage density, $GWD$ = depth to water table, $CN$ = curve number; the index "$L$" and "$W$" designate the terms Layer (column 1 of Table 4) and Weight (column 5 of Table 4).

### Validation

The validation of the results aims to verify how much the classification of regions in terms of potential recharge extracted from the final output map is correct, based on data from wellfield in the alluvial aquifer. These wells provide crucial information, including stratigraphic logs and extraction flow rates. This information is essential for validating the resulting groundwater potential recharge zone map. Effectively, possible zones for groundwater boreholes can serve as a proxy for potential zones for groundwater recharge (Asfaw Kebede et al., 2023; Lentswe & Molwalefhe, 2020; Tolche, 2021; Zghibi et al., 2020). Indeed, data on extraction rates, such as the discharge flow rate from the wells, is indispensable for achieving an accurate estimation and prediction of natural groundwater potential recharge. A total of 66 wells were utilized for validation, primarily distributed across the plain. The exploited wells exhibited flow rates ranging from 2 to 45 L/s and were categorized into five classes, from very weak flow to very high flow.

## Results and discussion

### Suitability analysis of reclassified factors

The recharge influencing factors are reclassified and scaled from very high to very low potential recharge. Weights are assigned to represent their relative importance with respect to groundwater recharge.

### Rainfall (R)

Rainfall as a main source of natural groundwater recharge regulates the amount of water available for infiltration into the groundwater system. Rainfall thematic layer was generated based on the annual rainfall rushing over seven hydrologic stations for 10 hydrological years (2008-2018). Five classes of rainfall characterize the upper Cheliff plain: > 416; 416 - 405; 405 – 395; 395– 382 and 382– 352 mm/year (Fig. 4). Rainfall map shows heavy rainfall in the northeast region (Djendel), Ain Soltane and Khemis Miliana, compared to the central parts which record a moderate rainfall. Whereas, in the south of the plain, around Bir Ouled Khalifa region, a low amount of rainfall is recorded mainly due to the influence of the Zaccar Mountain.

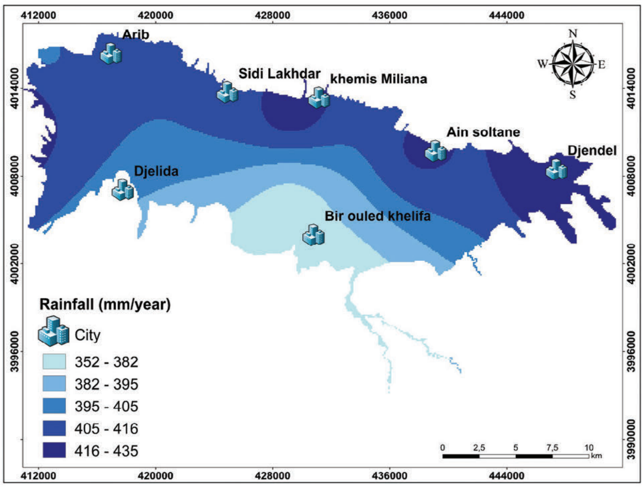

*Fig. 4 - Rainfall distribution map.*

Fig. 4 - Distribuzione delle precipitazioni.

### Soil (ST)

The type of soil mainly reflects its texture, which plays a key role in the process of groundwater recharge. It controls the ingress of surface water into the aquifer system. A detailed analysis of the soil map reveals that the study area can be categorized into five soil groups (Fig. 5):

(1) Soils covering the wadi bed (5.41%) consist mainly of alluvium with a coarse texture, facilitating rainwater infiltration, especially during floods. (2) Limestone shell formations are concentrated primarily in the eastern and western edges of the plain (5.15%) and are characterized by high infiltration capacity. (3) The major portion of the study area (34.98%) comprises fine sands, slightly less sandy silts, and occasional clayey silts with some sand content. (4) Fine-textured formations such as silts, clayey silts, alluvium from the small shales wadi, and calcareous shell covered by thin silts (22.01%) are also present. (5) The central part of the plain is dominated by clayey to very clayey soils, silts, and clayey silts (32.44%).

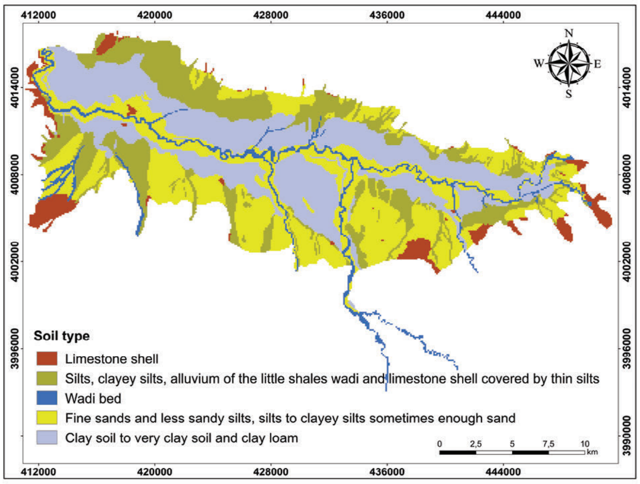

*Fig. 5 - Soil type map.*

Fig. 5 - Tipologie di suolo.

### *Land Use and Land Cover (LULC)*

LULC determines the rate of infiltration and surface runoff as well as evaporation and soil moisture, and consequently groundwater recharge. In this study, the LULC map (Fig. 6) shows the presence of the following land covers: (1) water bodies (wadi, accumulation of precipitation water, etc.), (2) Vaste agriculture areas (market gardening, wheat fields, fodder crops, etc.), (3) Perennial crop (Shrub land), (4) bare land and (5) urbanized areas and road network (Built Up). The first-class water bodies have a high potential for groundwater recharge and are the main components of groundwater aquifer recharge, especially during the winter seasons. Vast agricultural areas and shrub lands have high to moderate recharge potentials because they tend to impede surface runoff, with infiltration weights of 4 and 3 respectively assigned to these classes. Bare lands are characterized by a high rate of runoff and evaporation, which reduces their capacity for deep infiltration; a weight of 2 is assigned to this class. Urbanized sectors present places with lower recharge potential. In fact, concrete prevents infiltration and promotes runoff, consequently assigning the least importance to this class.

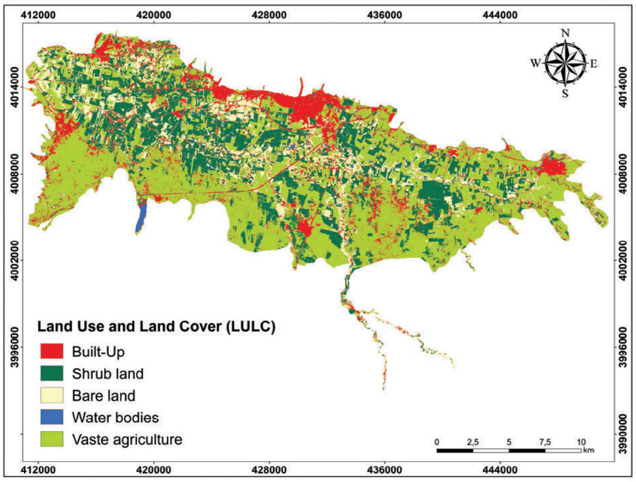

*Fig. 6 - Land use and land cover map.*

Fig. 6 - Uso e copertura del suolo.

### *Slope (S)*

Upper Cheliff plain is characterized by a low slope. The slope map shows slight variation in slope from 0 to 30.6% (Fig. 7). For the allocation of weights, the interval has been divided into five classes, viz. 0–1.6%, 1.6–3.2%, 3.2–5.8%, 5.8–10%, and 10–30.6%. Classes with a lower slope percentage due to the flat terrain, which provides more time for precipitation water to stagnate on the ground surface and infiltrate to depth thereafter, received a higher ranking. On the opposite, steeper slopes were given a lower rank (Table 4).

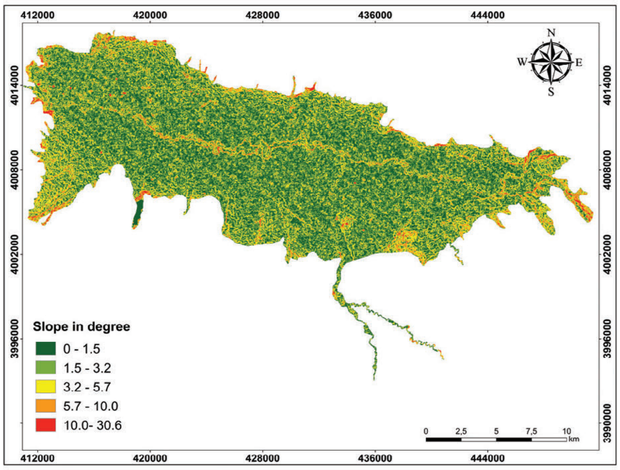

*Fig. 7 - Slopes map.*

Fig. 7 - Carta delle pendenze.

### *Geological characteristics of unsaturated zone (UZ)*

The map of the unsaturated zone illustrates the geological characteristics of the unsaturated zones in the Upper Cheliff alluvial plain (Fig. 8). In the eastern region of the plain, formations of (1) pebbles and (2) gravels facilitate the percolation of water from the soil surface to the aquifer, promoting natural groundwater recharge. In the central part of the plain, the unsaturated zone is primarily composed of (3) clayey gravels and (4) clayey sands, resulting in moderately low recharge rates compared to the eastern sector. In the western sector, clay and silt formations (5) predominate, resulting in very low natural recharge.

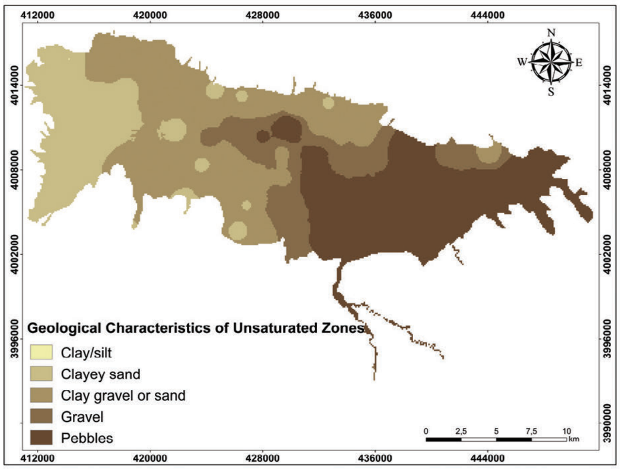

*Fig. 8 - Unsaturated zones map .*

Fig. 8 - Caratteristiche geologiche della zona insatura.

### ***Drainage density (DD)***

Based on the drainage density value, the territory of the plain was classified into five groups: 3.3–4.4, 2.6–3.3, 2.0–2.6, 1.3–2.02 and 0.2–1.3 km/km$^2$ (Fig. 9). As drainage density is an inverse function of water infiltration, high values indicate areas of low recharge and high runoff and the opposite is true for low values of drainage density, explaining areas favorable for recharge.

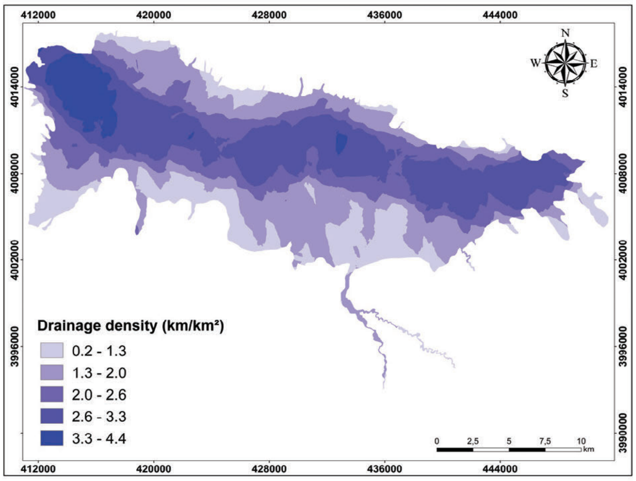

*Fig. 9 - Drainage density map.*

Fig. 9 - Densità di drenaggio.

### ***Depth to water table (GWD)***

The spatial distribution map of depth to water table (Fig. 10) reveals that groundwater table depths in the study area range from 4.9 to 35.1 meters below ground surface (m b.g.s.). In the major part of the area, depths range from 11.9 to 16.3 m b.g.s. In the eastern part of the plain, the deepest levels are observed, varying from 21.3 to 35.0 m b.g.s. The depth of the aquifer significantly impacts recharge; it recharges more effectively when the groundwater depth is shallow. Conversely, in deeper aquifers, natural recharge from rainfall takes a longer time to reach the aquifer, with a substantial portion of this water evaporating. Therefore, higher weights are assigned to shallow depths.

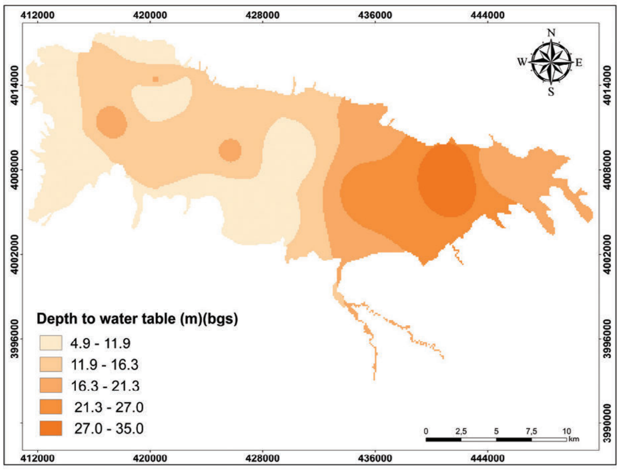

*Fig. 10 - Groundwater depth map.*

Fig. 10 - Soggiacenza.

### ***Curve number (CN)***

Empirical curve number parameter calculation is based on the soil hydrological group of the area, as well as the soil use, the values obtained vary from 66 to 100, and they are reclassified into 5 classes presented on the map (Fig. 11). The high CN reflects a low infiltration capacity and a high runoff rate, a low weight has been associated for these values and vice versa.

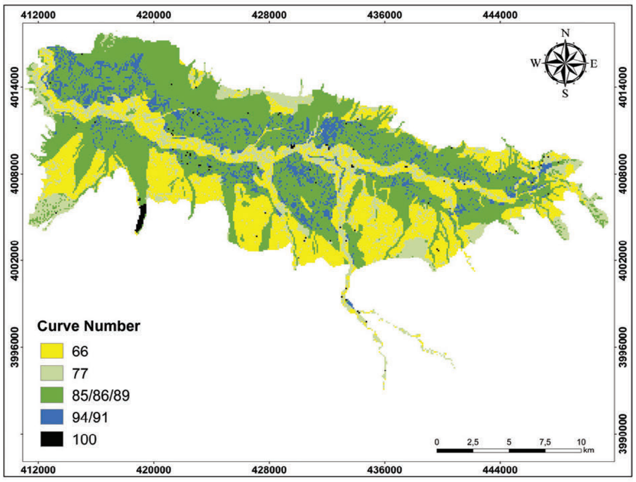

*Fig. 11 - Curve number map.*

Fig. 11 - Curve Number.

Table 4 illustrates factors's assigned weights of subclasses, thereby by normalized weights $W_i$ in percentage attributed to the eight factors, predicated on their influence on groundwater recharge.

### ***Resulting groundwater recharge potential map***

The groundwater recharge potential distribution map (Fig. 12) for the Upper Cheliff alluvial plain is derived by applying Eq. 8, that is multiplying each reclassified factor map (Fig. 3 to 10) with its corresponding percentage weight (Column 5 of Table 4) and then adding up the resulting maps. This map classifies groundwater recharge potential into five classes using equal interval reclassification method (Osaragi, 2008) ranging from very high to very low.

In the map, areas with very high recharge potential are prominently marked in red, while orange regions represent high recharge potential zones. Yellow areas indicate moderate potential for recharge, and green shading indicates low and very low recharge zones. An initial analysis reveals a predominant recharge pattern on the eastern side and the right bank of wadi Cheliff compared to the left bank. Specifically, the zone with very high recharge potential extends along the eastern border of the study area, characterized by limestone shell layers with excellent permeability. In the Djendal region, where sandy and silty soils dominate and heavy rainfall (ranging from 416 to 435 mm/year) occurs, the potential for recharge is notably high. Additionally, the Mio-Pliocene formation, known for its high permeability and direct connection with the alluvial

*Tab. 4 - Assigned weight and normalized weights of respective classes of factors influencing potential groundwater recharge zones.*

Tab. 4 - Pesi assegnati e pesi normalizzati delle rispettive classi dei fattori che influenzano le zone di ricarica potenziale delle acque sotterranee.

| Factors | Classes | Assigned weight | Influence on groundwater recharge | Factor's normalized weights $W_i$(%) |
|---|---|---|---|---|
| Rainfall | 352 - 382 | 1 | Very low | 34.66 |
| | 382 - 395 | 2 | Low | |
| | 395 - 405 | 3 | Moderate | |
| | 405 - 416 | 4 | High | |
| | 416 - 435 | 5 | Very high | |
| Soil type | Clay soil to very clay soil and clay loam | 1 | Very low | 22.73 |
| | Silts, clayey silts, alluvium of the little shales wadi and limestone shell covered by thin silts | 2 | Low | |
| | Fine sands and less sandy silts, silts to clayey silts sometimes enough sand | 3 | Moderate | |
| | Limestone shell | 4 | High | |
| | Wadi bed | 5 | Very high | |
| LULC | Built-Up | 1 | Very low | 13.15 |
| | Bare land | 2 | Low | |
| | Shrub land | 3 | Moderate | |
| | Vaste agriculture | 4 | High | |
| | Water bodies | 5 | Very high | |
| Slope | 10.0 - 30.6 | 1 | Very low | 11.00 |
| | 5.7 - 10.0 | 2 | Low | |
| | 3.2 - 5.7 | 3 | Moderate | |
| | 1.5 - 3.2 | 4 | High | |
| | 0 - 1.56 | 5 | Very high | |
| UZ | Clay/silt | 1 | Very low | 8.95 |
| | Clayey sand | 2 | Low | |
| | Clay gravel or sand | 3 | Moderate | |
| | Gravel | 4 | High | |
| | Pebbles | 5 | Very high | |
| DD | 3.3 - 4.4 | 1 | Very low | 4.31 |
| | 2.6 - 3.3 | 2 | Low | |
| | 2.0 - 2.6 | 3 | Moderate | |
| | 1.3- 2.0 | 4 | High | |
| | 0.2- 1.3 | 5 | Very high | |
| Depth to water table | 27.0 - 35.0 | 1 | Very low | 2.68 |
| | 21.3 - 27.0 | 2 | Low | |
| | 16.3 - 21.3 | 3 | Moderate | |
| | 11.9 - 16.3 | 4 | High | |
| | 4.9 - 11.9 | 5 | Very high | |
| CN | 100 | 1 | Very low | 2.52 |
| | 91/94 | 2 | Low | |
| | 85/86/89 | 3 | Moderate | |
| | 77 | 4 | High | |
| | 66 | 5 | Very high | |

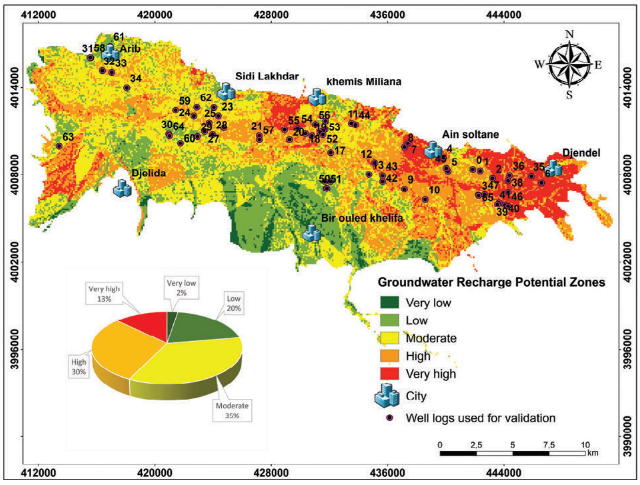

*Fig. 12 - Results of the Natural Groundwater Recharge Potential Map using the AHP approach and validation with well location.*

Fig. 12 - Carta delle aree di ricarica potenziale delle acque sotterranee ottenuta col metodo AHP e validazione mediante l'ubicazione dei pozzi.

aquifer, ensures greater recharge in the Ain Soltane area, classified as a very high-class recharge category. A remarkable area approximately 9 kilometers long, between the junctions of wadi Cheliff and wadi Ouassane, exhibits consistently high recharge potential. This aligns with the findings of Mania & Djeda (1990) and can be attributed to several factors. The alluvial nature of wadi Cheliff, characterized by a wide major bed and coarse alluvium, sometimes reaching up to 280 meters in width, plays a significant role. Additionally, this area receives significant rainfall (ranging from 435 to 405 mm/year) and has a relatively gentle slope. These regions feature an unsaturated zone composed of pebbles and gravels, facilitating water percolation into the aquifer. Certain sporadic areas west of Khemis Maliana to Sidi Lakhdar and in the south of Djelida city exhibit substantial recharge potential. The strip along the banks of tributaries like Ouassane, Telbenet, Massine, Harreza, and wadi Boutane is highly favorable for recharge zones. Collectively, these high recharge potential areas cover a 43.72 km² area, representing approximately 30% of the plain's total surface area. Regions displaying high potential of recharge are notably concentrated in the central and eastern areas. Furthermore, the area extending from east to west around wadi Cheliff exhibits a substantial recharge capacity. These regions are characterized by fine sands, occasionally less sandy silts, and silts with clayey content, often with the presence of sand. They receive annual rainfall between 416 and 395 mm/year, primarily used for agricultural purposes. Below the surface, there is an unsaturated zone consisting of pebbles, gravels, and sometimes clay or sand. This sector with high recharge potential encompasses an area of 29.82 km². In contrast, the zone with moderate recharge potential is located in the western region on both banks of wadi Cheliff, covering areas between Khamis Miliana and Ain Soltane cities, as well as between Ain Soltane and Djendel cities. The presence of a thick surface clay formation, as indicated by well logs, hinders direct infiltration of water into deeper layers. These areas receive annual precipitation ranging from 341 to 417 mm/year and are primarily used for cultivation. This category covers the largest area, spanning 119.03 km², accounting for nearly 35% of the plain's total surface area. Areas with low and very low potential recharge are predominantly concentrated in the southern regions of the plain, near Bir Ouled Khelifa, the sector between wadi Deurdeur and Massine, and near Djelida city. These areas are characterized by clay soils, relatively low precipitation rates, high curve numbers, and low permeability in the geological unsaturated zone. These combined factors significantly inhibit natural recharge processes, categorizing these regions as low and very low potential recharge zones. Specifically, these two distinct classes cover an area of 67.45 km² and 8.84 km², respectively, representing the low and very low potential recharge categories.

## Validation

With the aim of validate the resulting map by elucidate the extent to which information extracted from the final map on potential groundwater recharge aligns with the flow information provided by wells drilled in the same area, we observed a strong agreement between the flow rate categories of the existing wells and the predicted potential groundwater zone categories (representing potential natural recharge) derived from the resulting map. Notably, the flow rate categories obtained from 48 wells closely matched those obtained from the resulting map of groundwater potential recharge zones, with only 19 wells showing a slight deviation from the predicted category (Table 5). Most of the disagreements involved wells with high-flow rates compared to those with lower flow rates. This uncertainty may be attributed to additional sources of recharge that contribute to the improvement of well flow. The precision of the prediction can be calculated using the well discharge flow rate, which aligns with the predicted map. Out of the 66 well rates used in this validation, 48 corresponded with the predicted values. The compatibility obtained between existing and expected wells number is approximately 72.72%, indicating that the procedure employed for the present analysis is reasonably accurate (Rajasekhar et al., 2020).

## Conclusions

The Upper Cheliff plain in north of Algeria faces the challenges of a semi-arid climate with annual precipitation of less than 400 mm. Groundwater serves various essential purposes here, including domestic, industrial, and, most significantly, irrigation needs. Efficiently managing these groundwater resources is imperative, considering factors such as water quantity, recharge sources, and preferential recharge zones. To address these challenges, our study focused on delineating potential groundwater recharge zones within the Upper Cheliff alluvial plain. We considered eight critical factors that influence recharge: rainfall, soil type, LULC, slope, geological characteristics of the unsaturated zone, drainage density, water table depth, and curve number.

*Tab. 5 - Validation of natural groundwater potential recharge zone considering the discharge flow rate of 66 wells located in the study area.*

Tab. 5 - Validazione delle aree di ricarica potenziale mediante l'uso della portata estratta in 66 pozzi ubicati nell'area di studio.

| Total Wells | Range discharge flow rate (L/s) | Classes Description | N of well in classes | N well in predicted classes | Agreement* | |
|---|---|---|---|---|---|---|
| | | | | | Agree | Disagree |
| 66 | < 2 | Very low | 1 | - | 0 | 1 |
| | 2 - 5 | Low | - | - | - | - |
| | 5 - 15 | Moderate | 22 | 29 | 19 | 3 |
| | 15 - 25 | High | 21 | 19 | 16 | 5 |
| | > 25 | Very high | 22 | 18 | 13 | 9 |
| Total | | | 66 | 66 | 48 | 18 |
| **Agreement between existing well category and predicted recharge category* | | | | | | |

Using GIS environment, we developed a comprehensive map depicting natural potential groundwater recharge. Among these factors, rainfall and soil type were the most significant contributors, with influence coefficients of 34.65% and 22.73%, respectively. LULC (13.15%), slope (11%), and geological characteristics of unsaturated zones (8.95%) played moderate roles, while aquifer depth and Curve Number were considered less influential (22.68% and 2.53% respectively).

Our analysis classified Upper Cheliff alluvial plain into five distinct groundwater recharge potential zones: very high and high recharge zones were primarily concentrated in the eastern and right bank of wadi Cheliff, covering 145.31 km². These regions receive substantial precipitation, consist largely of agricultural land, and feature permeable lithology, including sandy soils with gravel-rich unsaturated zones. In contrast, the moderate recharge class was more widespread across the plain, covering 35% of its surface, primarily in the western regions with loamy and clayey soils, often used for cultivation. Areas with low and very low recharge potential were predominantly situated in the southernmost part of the study area. These zones accounted for 19.8% and 2.59% of the total area, respectively. They were characterized by the lowest precipitation and clayey soils inhibiting surface infiltration. The resulting map was validated: effectively a comparison with 66 existing wells showed strong agreement (72.72%) with areas of good to very good recharge potential. This underscores the map's significance in delineating potential groundwater recharge zones in the Upper Cheliff alluvial plain. These regions are a favorable site for future artificial recharge projects, but they are sensitive areas which must be protected from contamination coming from factories discharge and urban planning on the one hand, and the excessive use of agricultural fertilizers in the surrounding lands on the other. As a field of research, mapping areas with potential groundwater recharge is a step which precedes the launch of a detailed study for the quantification of volume that annually reaches the groundwater table, and then control the amount that can be safely pumped annually without causing further overexploitation.

In conclusion, effective groundwater management, particularly in high-recharge areas, provides valuable insights into recharge mechanisms and groundwater conditions. However, further research is needed to quantify combined recharge from various sources. Our findings offer a robust foundation for effective management of groundwater resource in similar regions, emphasizing the importance of protecting these vital water sources.

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## Competing interest

All authors, declare no competing interests.

## Author contributions

Hanane Merouchi led the conceptualization, methodology, and supervision of the project. Abdelkader Bouderbala, serving as the supervisor, meticulously reviewed and proofread the manuscript. Both Hanane Merouchi and Abdelkader were actively involved in the collection of samples, analysis of data, and interpretation of results. Yamina Elmeddahi provided valuable input through her thorough review and approval of the final manuscript. All authors contributed to and approved the final version of the manuscript.

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