

## Mapping Favorable Groundwater Potential Recharge Areas Using a GIS-Based Analytical Hierarchical Process – A Case Study of Ferkla Oasis, Morocco

Ait Lahssaine Ismail<sup>1,4\*</sup>, Kabiri Lahcen<sup>1</sup>, Messaoudi Badre<sup>1</sup>, Essafraoui Badre<sup>1</sup>, El Ouali Mohamed<sup>1</sup>, Ouali Lamy<sup>1</sup>, Albergel Jean<sup>3</sup>, El Amraoui Meryem<sup>1</sup>, Kassou Amina<sup>1</sup>, Ali Essahlaoui<sup>2</sup>

<sup>1</sup> Geo-Resource Geo-Environment Geological and Oasis Heritage Research Team, Department of Geosciences, Faculty of Sciences and Techniques, Moulay Ismail University, Errachidia, Morocco

<sup>2</sup> Geoengineering and Environment Laboratory, Research Group “Water Sciences and Environment Engineering”, Sciences Faculty of Meknes, Moulay Ismail University, Morocco

<sup>3</sup> Montpellier SupAgro, IRD, University of Montpellier, Montpellier, France

<sup>4</sup> Center of Applied Research, Karlsruhe University of Applied Sciences, 76133 Karlsruhe, Germany

\* Corresponding author’s e-mail: [i.aitlahssaine@edu.umi.ac.ma](mailto:i.aitlahssaine@edu.umi.ac.ma)

### ABSTRACT

In the Ferkla Oasis, much like in numerous other oases across the southeastern region of Morocco, a range of socio-economic and environmental challenges are intricately linked to the inadequate management of water resources. One proposed remedy to address these concerns is the implementation of artificial aquifer recharge, which stands as an alternative strategy to safeguard the crucial oasis ecosystems. Thus, to evaluate the viability of this method in promoting sustainable water resource usage, it becomes imperative to delineate groundwater recharge potential zones (GRPZs). This study aims to achieve this objective by mapping GRPZs within the Ferkla Oasis, employing a fusion of the analytical hierarchy process (AHP), geospatial information derived from remote sensing (RS), and geographic information system (GIS) technologies. In pursuit of this goal, an array of geological, topographical, pedological, hydrological, and climatic criteria have been meticulously selected, classified, and assigned weights following their relevance to water infiltration suitability. This comprehensive approach culminates in the generation of seven thematic maps: slope, lineament density, lithology, soil type, drainage density, land use/land cover, and rainfall distribution. Through the integration of these aforementioned maps, a tripartite classification of potential GRPZs emerges, comprising low, medium, and high categories. The findings underscore the distribution: 30% of the total study area exhibits a low potential for GRPZs, 50% of the total land area is characterized as having medium potential GRPZs, while the remaining 20% is designated as high potential GRPZs. These outcomes have been substantiated through validation against piezometric levels, which have been ascertained through recent field surveys. Consequently, these results stand as a testament to the efficacy of the presented approach as a robust decision-making tool. The approach effectively facilitates the establishment of conditions conducive to viable artificial recharge, thereby offering a means to safeguard the groundwater reservoirs that sustain the fragile oasis environments.

**Keywords:** groundwater reservoirs, safeguard, artificial recharge, remote sensing, Ferkla Oasis, Morocco.

### INTRODUCTION

Water is a crucial natural resource for life, and is needed for the majority of economic activities. In addition, quite, it is getting increasingly hard to

find its accessibility differs significantly over both space and time. This resource is extremely sensitive to the detrimental consequences of human activities, which are becoming increasingly severe as economic and industrial demands increase

(Moody and Brown, 2013; Madani *et al.*, 2014). Water scarcity stands out as a paramount concern afflicting oasis regions. This challenge assumes a pivotal role in shaping the trajectory of long-term advancement, elevating the quality of life, and safeguarding the harmony of human civilization.

In the Rheris watershed, particularly in the Ferkla Oasis, access to water is a vital element in economic development and a requirement for the improvement of the population's living standards. Within this region, water resources primarily find utilization in the domains of irrigation and drinking purposes. Several temporary watercourses (wadis) contribute to surface water resources. The highest annual flow (25 Mm<sup>3</sup>/year) occurs at the Oued Tanguerfa, while the Oued Ferkla and Oued Satt can contribute only lower water amounts with 10 million m<sup>3</sup>/year and 6 million m<sup>3</sup>/year, respectively (DRPE, 2007). Simultaneously, the oasis regime shows shallow flows throughout the year and very violent floods of short duration likely in Autumn. These strong fluctuations of the Wadis water flow between wet and dry seasons limit the availability of the resource water. Given the inadequacy of available surface water to meet the demands of both palm grove irrigation and the local population's domestic requirements, there has been a growing inclination toward tapping into groundwater resources. In the context of the Ferkla Oasis, the extraction of groundwater hinges predominantly on groundwater pumping. This practice has gained momentum, particularly as surface water resources have progressively diminished (Bakki *et al.*, 2015). Consequently, intensive irrigation practices contribute to the depletion of the quaternary aquifer's water reserves, potentially leading to overexploitation if a sustainable method of artificial recharge is not implemented. Additionally, in certain oasis regions, deep water extraction is facilitated through a network of channels and well systems known as "Khettaras" (Lightfoot, 1996).

Identification of groundwater recharge potential zone (GRPZ) is essential to plane artificial groundwater recharge. The GRPZ map serves as a valuable tool in enhancing groundwater management through its ability to provide more precise forecasts regarding the distribution of recharge from precipitation. Groundwater and surface water resources can be estimated using a geographic information system (GIS) and remote sensing (Jothiprakash *et al.*, 2003; Selvarani *et al.*, 2017; Kumar *et al.*, 2020; Ouali *et al.*, 2023a; Badi *et al.*, 2023). A range of methods has been used to

identify GWPZ (Rajasekhar *et al.*, 2019; Arshad *et al.*, 2020). Analytical hierarchy process (AHP) and multi-influencing factors (MIF) methods are used as a multi-criteria decision-making (MCDM) technique to calculate spatial relationships between two different variables by using a scoring system (Abimbola *et al.*, 2020). These scores are based on significant key elements that affect the GRPZ (Meena *et al.*, 2019). Recent studies show the possibility to use a rapid, precise, and by greatly decreasing the mathematical complexity of decision-making through the combination of a systematic professional evaluation, and long-term examination of groundwater recharge potential (Mallick *et al.*, 2019; Abijith *et al.*, 2020). AHP is an MCDM approach for the pairwise evaluation of geographical attributes that assigns weights based on expert opinion and makes it possible to save time and plan artificial recharge in a large area with limited data (Jothibasur *et al.*, 2016).

In the Ferkla Oasis, the GRPZ are found by considering the most important factors that affect the groundwater recharge process (Díaz-Alcaide and Martínez-Santos, 2019). The main factors considered are the lithology, soil types, land cover, slope, lineament density, rainfall, and drainage density (Krishnamurthy *et al.*, 1996; Shaban, *et al.*, 2006; Sener *et al.*, 2005; Hsin-Fu *et al.*, 2009; Aouragh *et al.*, 2017; Murmu *et al.*, 2019; Mallick *et al.*, 2019; Abijith *et al.*, 2020 Patil and Lad, 2021). In order to ensure sustainability while taking into account current challenges of water scarcity, the objective of this study is to identify artificial recharge thresholds for recharging the groundwater in the context of oases across the southeastern region of Morocco using this combined approach for the first time.

## STUDY AREA

The Ferkla Oasis is located within the Rheris watershed in southeastern Morocco (Figure 1). It's located between 31° 27' 0" N and 31° 37' 30" N, and 5° 10' 30" W and 5° 0' 0" W and determined with a total area of 28 km<sup>2</sup>, the elevation varies between 900 m and 1300 m. This Rheris watershed is of national and international interest. It's part of the UNESCO South Moroccan Oasis Biosphere Reserve (United Nations Educational, Scientific, and Cultural Organization) declared on 10 November 2000. It is also part of the Ramsar zone of Tafilat.

Unless significant measures are undertaken, this oasis faces the looming threat of extinction.

According to the 2014 General Population Census, the Ferkla oasis has a total population of 43,980 with 7,189 households (6.4 people per household). For 36% of the population, agriculture is the main source of income. Thus, it is the primary income sector and employs the majority of the working population. Since this is where the majority of people work, it promotes the expansion of the local economy. The majority of farming is done on irrigated areas in the plains as well as on river terraces (El Amraoui *et al.*, 2022). In general, the climate in the Ferkla region is characterized by low and irregular annual precipitation, which is less than 150 mm and decreases from north to south. The maximum average temperature is recorded in August (41.59 °C), and the minimum temperature (7.88 °C) is recorded in January (ABH GZR, 2021). This region contains groundwater reservoirs of relevance as a water resource. The water mainly flows in the Quaternary geological

formations composed of consolidated gravels, lacustrine limestone, and sands. Furthermore, groundwater can also be found in the sandstones and marls of the Infra-Cenomanian. According to Margat *et al.* (1962) and Kabiri (2004), the shales and limestones of the Primary in the Anti-Atlas could be connected to the Jurassic aquifer.

The permeability levels of the Quaternary formations vary depending on the lithology of the aquifer levels. Generally, a high permeability ( $K = 1 \text{ to } 3 \cdot 10^{-3} \text{ m/s}$ ) is found in sandy-gravelly alluviums, a medium permeability ( $10^{-5} \text{ m/s} < k < 5 \cdot 10^{-4} \text{ m/s}$ ) characterize conglomerates and fractured lacustrine limestone, and low permeability ( $10^{-6} \text{ m/s} < k < 10^{-5} \text{ m/s}$ ) for lacustrine marls, compact limestone, and clays. The transmissivity of the Quaternary overburden varies between  $2.5 \cdot 10^{-4}$  and  $3 \cdot 10^{-2}$  m/s, whereas the thickness is known to be between 1 and 40 m (Margat *et al.*, 1962; Messaoudi *et al.*, 2023; Ait Said *et al.*, 2023). From a structural and geological point of view, the Ferkla Oasis is bounded to the south by

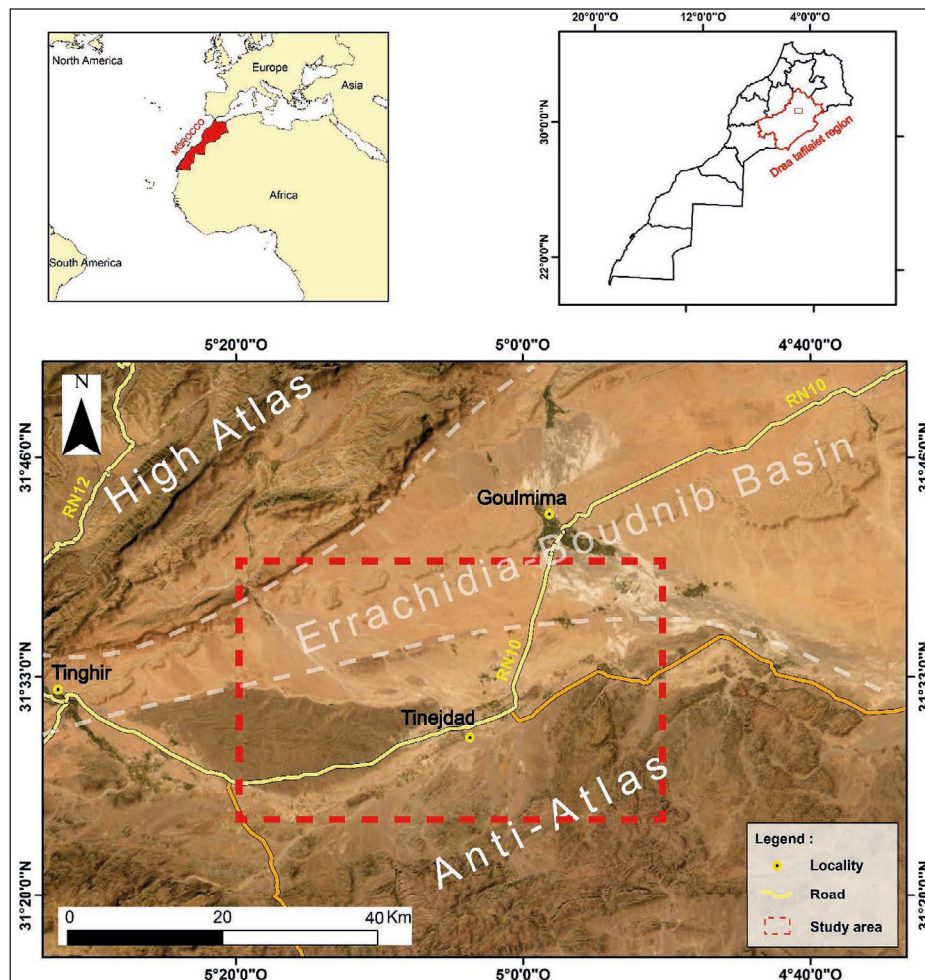


Figure 1. Localization of the study area

the Anti-Atlas Atlas Domain, to the east by the Rheris Plain, to the north by the Central High Atlas (Ifgh-Aghbalou N’Kerdous), and to the west by the Ghalil plain (Figure 2). The Ferkla Oasis comprises strata ranging in age from the Paleozoic to the Quaternary. The Paleozoic corresponds to a sedimentary series that extends from the Lower Cambrian to the Carboniferous (Figure 2). At the beginning of this Era, part of the Eastern Anti-Atlas was a proximal zone not affected by the Terminal Neoproterozoic-Lower Cambrian carbonate and dolomitic deposits of the Central and Western Anti-Atlas (Destombes *et al.*, 1986).

Cretaceous deposits are composed of sandstones from the Ifezouane Formation and an alternation of marls, clays, gypsum, and limestone from the Aoufous Formation (Essafroui, 2014; El Ouali *et al.*, 2021). All these deposits are related to the Infra-Cenomanian. The last part of the Cretaceous period is made up of marine limestone that makes up the decametric Cenomanian-Turonian Beds of the Akrabou Formation (Essafroui, 2014; Chaou *et al.*, 2022). The Quaternary formations, which for the most part cover Paleozoic formations, include Pleistocene and Holocene formations with travertine. This fact leads to the assumption of the existence of a paleo-lake in the area. The quaternary deposits consist of alluvial deposit areas that are terraced and exposed to erosion (Margat *et al.*, 1962; Boudad *et al.*, 2003).

## MATERIAL AND METHODS

In the Ferkla Oasis, GRPZ was mapped by taking into account the key factors that affect the

recharge process. These factors include lithology, soil type, land cover, slope, lineament density, rainfall, and drainage density (Krishnamurthy *et al.*, 1996; Sener *et al.*, 2005; Shaban *et al.*, 2006; Hsin-Fu *et al.*, 2009; Ahmed and Mansor, 2018; Kumar *et al.*, 2020). In this regard, a variety of data sources, including remotely sensed data and pre-existing maps (Figure 3, Table 1) were used to characterize the research area. Thematic maps were then developed, described, and then categorized based on their appropriateness for infiltration. To examine the interactions between the various categories, an MCDM study based on the AHP approach (Saaty, 1977) was used.

Designated weights were used to reclassify the thematic layers after being converted to a raster format. Each influence factor and its criteria were given the appropriate weights and ranks within thematic levels. According to previous literature assessments, professional judgment, the adequacy of the groundwater storage, flow, and different influencing aspects, these weights were assigned. High GPRZ are represented by higher weights or rankings according to the weights of each thematic layer’s criteria (Figure 3), while low groundwater recharge potentials are indicated by lower weights (Kumar *et al.*, 2014; Rahmati *et al.*, 2015). The integration of all thematic layers and their weights is performed using the weighted sum and product analysis in the GIS environment (Swetha *et al.*, 2017; Harini *et al.*, 2018). The probability that the decisions within the matrix were formulated and indicated is assessed using a metric known as the consistency ratio (CR). If the CR value is less than or equal to 10%, the consistency is acceptable; if the CR is greater than 10%,

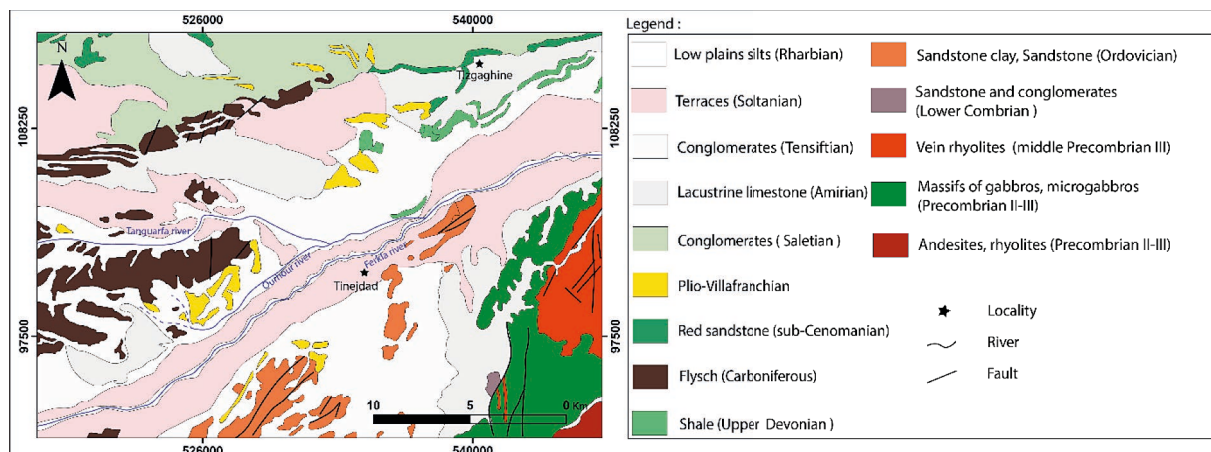
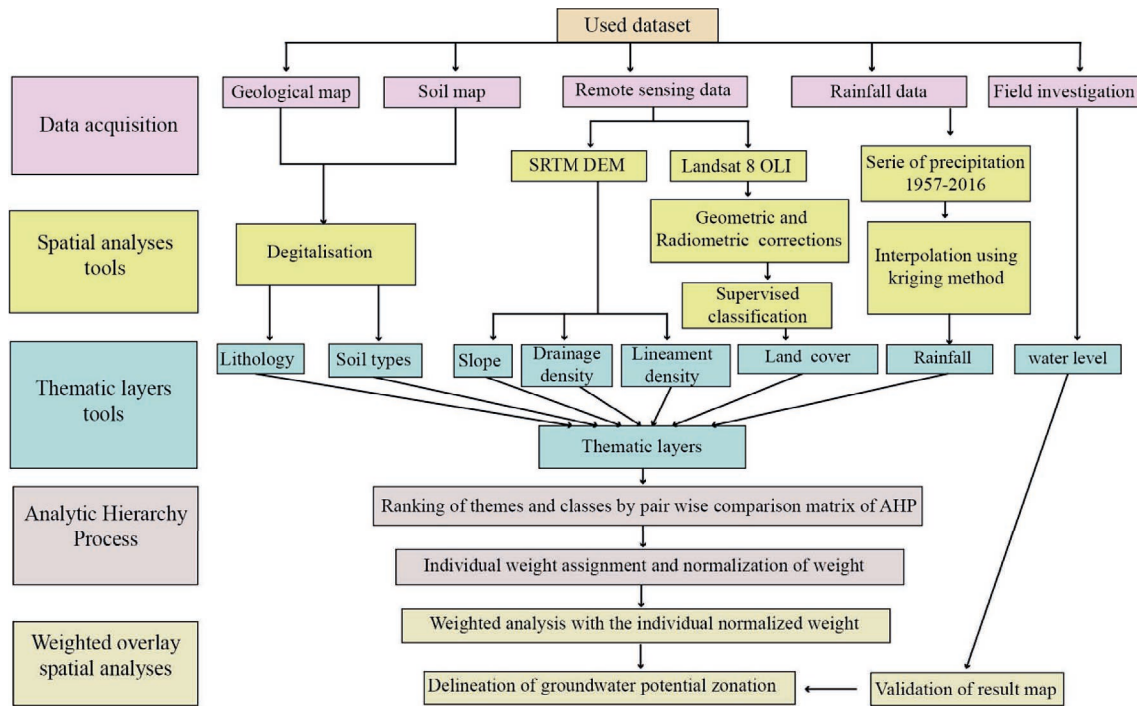


Figure 2. Geological map of the Ferkla Oasis (extracted from the geological map of Tinjdad 1:100,000, Hadri *et al.*, 1997)



**Figure 3.** Methodology adopted

the consistency is unacceptable (Figure 3). By the described procedure, the developed map of GRPZ was validated with 60 piezometric level observations of existing wells in the Ferkla Oasis between 07 and 19 August 2021. The interpolation of the piezometric level was done using The Kriging method as a geo-statistical approach that utilizes a semivariogram to model the spatial correlation to interpolate the piezometric level of a given area.

**Input database**

The data used in this work was collected from multiple sources (Table 1), including field data, remote sensing data, and data collected from the Guir, Ziz, Rheris Hydraulic Basin Agency (ABH

GZR), and the Regional Office for Agricultural Development of Tafilalet. The types, sources, and applications of data are listed in Table 1.

The lineament map was generated from Landsat OLI-8 image using supervised classifications, which were then manually validated using the 1:100000 geological map of Tinjdad (Hadri *et al.*, 1997). Lithology was digitalized from the previously mentioned geological map. The land cover map was derived from a Landsat 8 satellite image and underwent processing through supervised classification, employing the maximum likelihood algorithm within the realm of remote sensing. Topographical and hydrological factors derived from DEM data were processed using terrain analysis tools, (Drainage density and Slope). Simultaneously, the

**Table 1.** Type, source and abbreviation of the various datasets, that were used in the groundwater recharge analysis

Data type	Source	Abbreviation
Digital elevation model (DEM)	Shuttle radar topography mission data (USGS)	DEM
Drainage density	Shuttle radar topography mission data (USGS)	DD
Rainfall	Annual rainfall data (1957–2016)	RF
Land cover	Prepared from Landsat 8 OLI	LULC
Slope	Shuttle radar topography mission data (USGS)	SLO
Lineament density	SRTM (DEM) data (USGS)	LD
Lithology	Geological map of Tinjdad 1:100,000 (Hadri <i>et al.</i> , 1997)	LI
Soil type	Soil map of Draa Tafilalet (ORMVA TF, 2012)	SL
Piezometric level	Field investigation	PL

precipitation map was derived by generating value contour lines utilizing point data amassed from designated rainfall stations situated within the Guir, Ziz, Rheris, and Maider basins. This data span encompasses the period from 1957 to 2016 and has been supplied by ABH-GZR, employing the kriging method approach. Finally, the soil types present in the Ferkla region were digitalized using the soil map of the Ferkla oasis from the Regional Agricultural Development Office of Tafilalet.

**Analytic hierarchy process**

Thematic maps play a pivotal role in analyzing the components that contribute to the identification of potential groundwater recharge potential zones. Initially, an internal relative classification is conducted for each individual factor. Subsequently, a weight is assigned to each unit or criterion within the range of 1 to 10, predicated on hydrogeological interpretations or the suitability of infiltration associated with the respective unit or criterion. The AHP approach is used in the second phase to assign each element a coefficient based on its relative importance to the other factors (Table 2). This approach accounts for the fact, that some of the studied factors have a stronger influence on groundwater recharge than others (Krishnamurthy and Srinivas, 1995; Krishnamurthy *et al.*, 1996; Saraf and Choudhury, 1998; Sener *et al.*, 2005). Subsequently, the groundwater recharge potential

index is calculated from all thematic layers that are integrated into a GIS environment using the Equation 1 with a spatial resolution of 30 m.

$$GRPI (total\ weight) = \sum_{i=0}^n Wi * Xi \quad (1)$$

where: *GRPI* – groundwater recharge potential index, *n* – total number of used factors, *Wi* – normalized weight of the factor, *Xi* – weight of the criteria.

The potential recharge zones were determined by classifying the total weight into five criteria.

*Matrix of pairwise comparisons*

Based on the ratings from the previous step, the hierarchy of the factors is determined based on a pairwise comparison. In this study, lithology, slope, and soil types are the factors with the highest importance for groundwater recharge (Table 3, Figure 4).

*Verification of the matrix coherence*

The coherence of the matrix was verified based on the coherence index (CI – Eq. 2), and coherence ratio (CR – Eq. 5) (Mageshkumar *et al.*, 2019):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

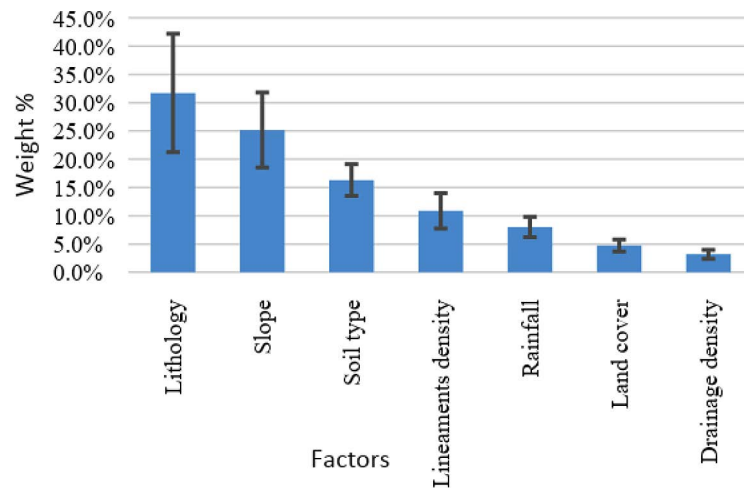
$$CR = \frac{CI}{RI'} \quad (3)$$

**Table 2.** Analytic hierarchy process relative class rate scale according to Saaty (1977)

Importance	Equal	Weak	Moderate	Moderate plus	Strong	Strong plus	Very strong	Very, very strong	Extreme
Scale	1	2	3	4	5	6	7	8	9
	1/9	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9
← Less important					More important →				

**Table 3.** Pairwise comparison matrix of the used factors

Matrix	Lithology	Slope	Soil type	Lineament density	Rainfall	Land cover	Drainage density
	1	2	3	4	5	6	7
Lithology	1	1	2	2	3	5	7
Slope	2	1	2	3	4	5	6
Soil type	3	1/2	1	2	2	4	5
Lineament density	4	1/4	1/3	1	2	3	4
Rainfall	5	1/3	1/4	1/3	1	2	3
Land cover	6	1/5	1/5	1/4	1/3	1	2
Drainage density	7	1/7	1/6	1/5	1/4	1/3	1



**Figure 4.** The relative importance of each of the factors in the hierarchy

where:  $CI$  – coherence index,  $\lambda_{max}$  – maximum value of the matrix,  $n$  – number of factors,  $CR$  – coherence ratio,  $RI'$  – the value of hazard index depending on a number of factors.

The achieved  $CR$  of 0.025 (Eq. 3), demonstrates the validity of the weights ( $X$ ) assigned to the thematic layers. The weights of the seven thematic layers (Eq. 4) were finally used to create a map of GRPZ. This was done by calculating the GRPZ Index as the sum of all layer values.

$$GWRZ\ Index = (0.31 \times LI) + (0.047 \times LC) + (0.25 \times SLO) + (0.10 \times LD) + (0.079 \times RN) + (0.031 \times DD) + (0.16 \times ST) \quad (4)$$

where:  $LI$  – lithology,  $LC$  – land cover,  $SLO$  – slope,  $LD$  – lineaments density,  $RN$  – rainfall,  $DD$  – drainage density,  $ST$  – soil type.

## RESULTS AND DISCUSSION

### Assessment of groundwater recharge controlling factors

Final normalized weights of the studied factors are calculated, an explanation of each factor can be found in the following sections.

#### Slope

According to the analysis carried out, the slope has the second highest influence on the recharge potential of the seven investigated factors (relative weight of 0.25). It is inversely related to the recharge potential of an aquifer. High slopes

accelerated water runoff, considerably resulting in a significant reduction of the available water amount for percolation. In contrast, low slopes are favorable for water accumulation and infiltration (Satapathy and Syed, 2015). In the study area, the steepest slopes are observed in the northern (High Atlas) and southern parts (Anti-Atlas; Figure 5a).

#### Lineament density

Lineament i.e. faults, cracks, and joints within lithological units facilitate groundwater recharge. Therefore, the GRPZ is expected to increase in areas with higher lineament density (Al-Ruzouq *et al.*, 2019). Consequently, mapping these areas is particularly important for locating GRPZ in fractured basement settings (Krishnamurthy *et al.*, 1996; Sener *et al.*, 2005). The lineament density map of the Ferkla oasis (Figure 5b) shows that highly fractured zones consist of the Precambrian bedrock, Ordovician deposits, Tisssdafine Carboniferous deposits, and the northern Jurassic deposits. These results can be explained by the fact that the geological formations in the study area have undergone several deformation phases related to deferent orogenesis e.g. the Pan-African orogeny in the Precambrian basement (Hadri *et al.*, 1997).

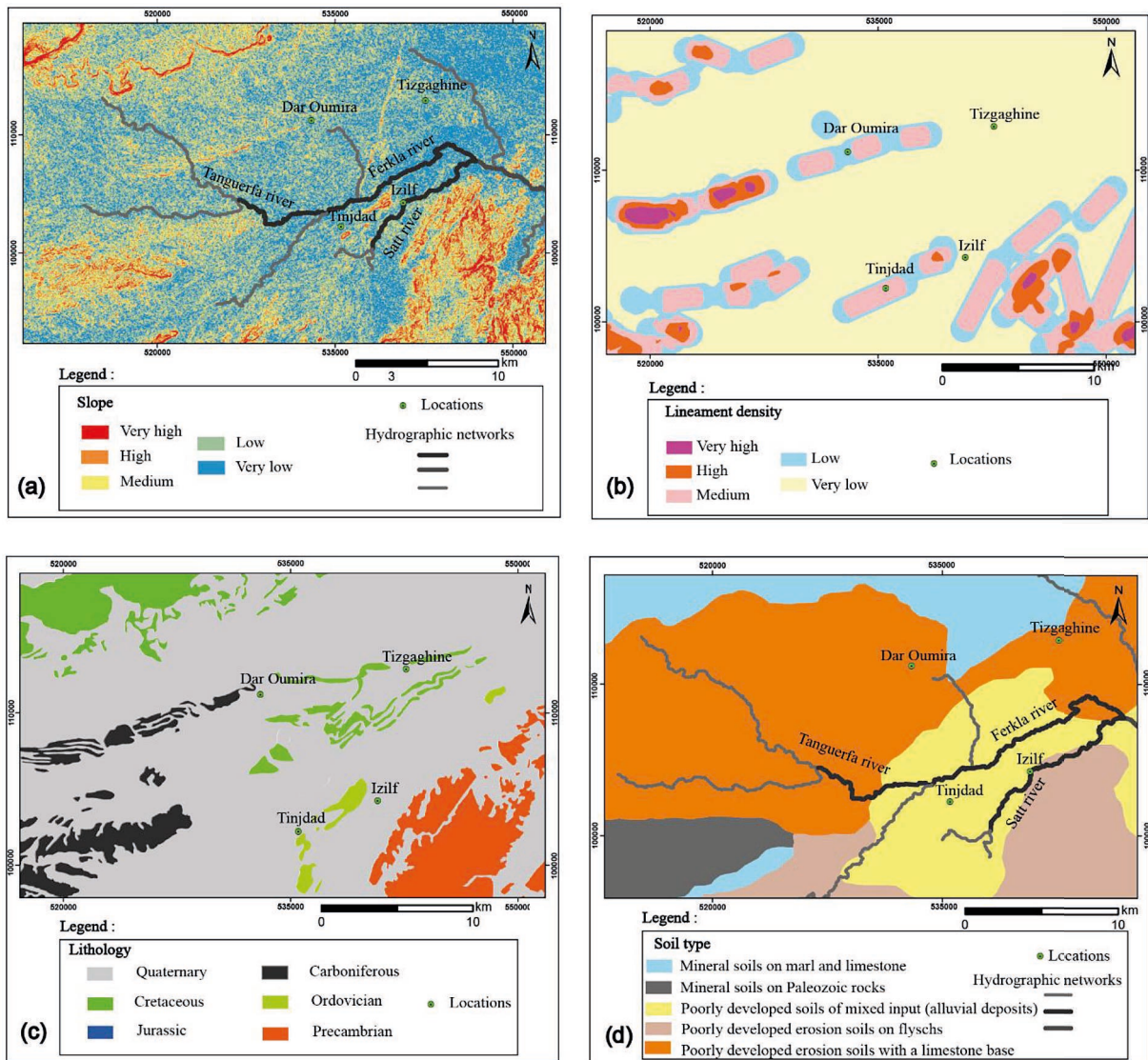
#### Lithology

The compaction and weathering of rocks, as well as the presence of cracks and joints on subsurface and surface rocks, are lithological properties that determine the possibility for water to infiltrate (percolate through) these geological formations. Thus, these physical properties provide important information about the recharge process of

aquifers. This importance is also reflected by this factor’s high relative weight of 0.31. It is therefore the factor with the highest influence on the aquifer recharge potential of the area (Rahmati *et al.*, 2015; Rajasekhar *et al.*, 2019). The lithology of the Ferkla Oasis is divided into seven main geological units (Figure 5c): The highest value is designated to the unit of Quaternary alluvium, conglomerates, and lacustrine limestones (55.2%). The units of “Devonian limestones and shales, Cretaceous sandstones, clays, marls, and limestones” as well as “Volcanic and subvolcanic rocks” show already far lower values with 13.08% and 15.6%, respectively. The lowest values are Ordovician shales and quartzite sandstones (10%), Carboniferous fly shales (alternate sandstones and sandstone marls, 10%), and Jurassic limestones (1%).

### Soil type

Soil characteristics influence groundwater recharge by controlling the penetration and transmission of surface water into aquifers through traits such as porosity, structure, stickiness, and uniformity (Souissi *et al.*, 2018). With a relative weight of 0.16, the soil type is ranked third after Lithology and Slope regarding the relevance of influencing the overall aquifer recharge. In the study area, soils are largely undeveloped, with stony or saline soil being common. The region’s historical climatic circumstances, which hardly allowed pedogenetic activity, explain the widespread occurrence of Leptosol (Kabiri, 2003). Frequently found soils in the study area are shallow alluvial sedimentary deposits with reduced



**Figure 5.** Maps representing the thematic layers used in MCDM tools to map groundwater recharge potential: (a) slope; (b) lineament density; (c) lithology; and (d) soil types



soil fertility that have been formed by floods in valley bottoms and river beds (Figure 5d).

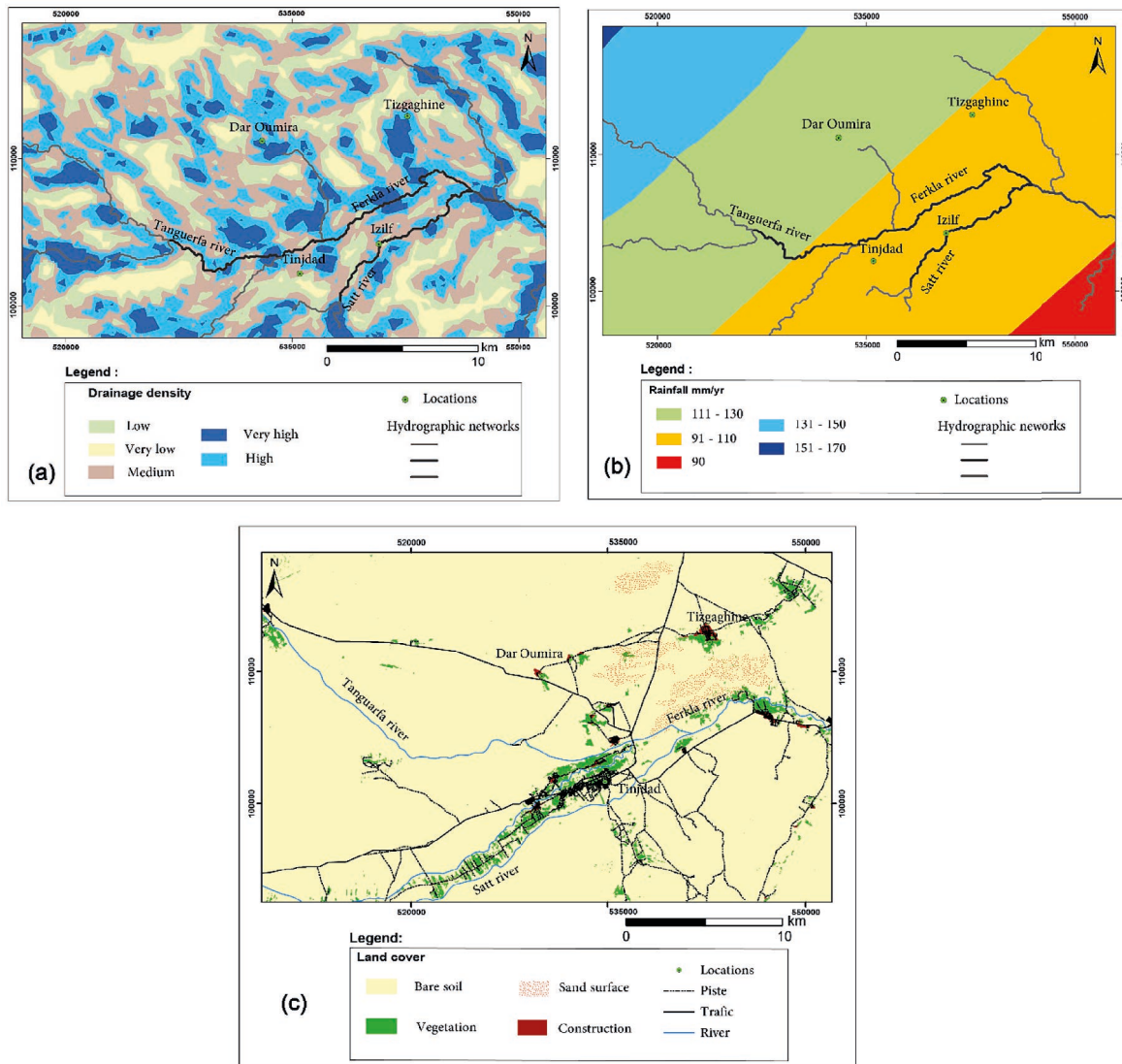
*Drainage density*

The density of a drainage network is known to affect the recharge potential in an area. The common perception is a higher drainage network density guides to an increased water flow, and thus the amount of water available for the recharge of the aquifer decreases. Nevertheless, in the calculation of the GWPZ index, the Drainage density (DD) has a comparatively low relevance with a normalized weight of 0.03. That may be because under some circumstances. Based on a density analysis that is connected to permeability, the hydrogeological factors of a drainage network

can be evaluated. This was done for the study area with mapping and visualization was carried out with an adequate GIS environment (Figure 6a). Identified areas were classified as very low, low, medium, high, and very high drainage density. The drainage density in the Ferkla Oasis favors water infiltration at the Precambrian basement and runoff in other places (Figure 6a).

*Land cover*

The LC significantly influences groundwater recharge. In Ferkla Oasis five types of land cover have been identified (Figure 6c): vegetation, bare soil, sand surfaces, and buildings. The term LC refers to a broad spectrum of variables on the ground’s surface. The majority of the study area



**Figure 6.** Maps representing the thematic layers used in the MCDM tools to map groundwater recharge potential areas: (a) drainage density; (b) rainfall; and (c) land cover

(69.01%) is made up of bare soil, followed by sand surfaces (21.3%), vegetation (8.3%), and rural or urban buildings (1.3%). The widespread occurrence of bare soil, which makes up more than 70 % of the study area, maybe a reason for the limited significance of the LC factor in influencing the recharge process.

**Rainfall**

Obviously, rainfall quantities play a key role in the aquifer recharge process, as they are the main water source for this recharge. The precipitation patterns in the research area follow the orographic structures of the region and are characterized by a strong gradient with high rainfall quantities in the northwest to low rainfall in the southeast (Figure 6b). The analysis of the area’s rainfall series shows that a mean yearly precipitation of 170 mm in the elevated mountain areas (High Atlas) in the North West. The lowest mean yearly precipitation values with 90 mm are found in lowlands with desert influence.

**Groundwater potential recharge area**

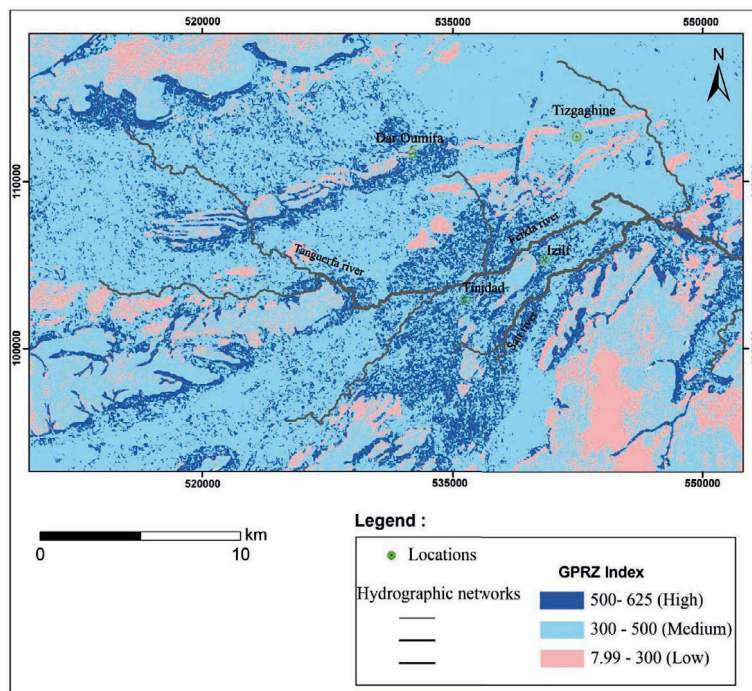
Results of the analysis for GRPZ are shown in Figure 7. The present approach led to the identification of three categories of potential recharge areas. Based on the classification in Zghibi *et al.*, 2020, the first category has a high recharge

(GWPZ index: 500–625) and represents about 20 % of the entire area. Its spatial distribution is not homogeneous. 30% of the area is in the second category, which has very low and low recharge (GWPZ index: 8-300) and is found in the north and southeast. Finally, the third category is moderate (GWPZ index: 300–500) and covers about 50% of the area.

The sites deemed suitable for recharge are primarily situated within the Middle and Recent Quaternary strata, characterized by lacustrine limestone, conglomerates, silts, and gravelly alluvium. Additionally, the Carboniferous piedmonts are also identified as favorable zones for groundwater recharge, owing to their structural configuration. (Figure 7).

**Validation of groundwater potential recharge areas map**

Validation is an important phase in evaluating the performance of all models by finding the link between GRPZ classes and piezometric observations (Janizadeh *et al.*, 2019). The GRPZ map has been validated in several ways, including assessing well performance during field visits and performing a comparative between 60 water level observations made in August 2021 and the GRPZ map (Jaafari *et al.*, 2019).



**Figure 7.** Groundwater recharge areas of the Ferkla Oasis

In the validation phase, the piezometric levels of 60 pre-existing wells within the Ferkla Oasis were ascertained during the period from 07 to 19 August 2021. The validation procedure concentrated specifically on the quaternary aquifer, given its significance and the pressing concern of over-pumping. Notably, all 60 data points were situated within the confines of the identical aquifer. The resultant map (Figure 8) presents an irregular distribution of piezometric levels. The contour lines' configuration suggests a directional flow from the southwest to the northeast. The configuration of the piezometric levels unveils

promising sectors suitable for groundwater replenishment, with water reserves centrally positioned within the study area. Notably, the areas featuring the greatest piezometric level depths align with potential zones for groundwater recharge. On the map (Figure 8), the yellow circles denote designated locations earmarked for the implementation of artificial recharge mechanisms along the segments of three rivers: Tanguerfa, Satt, and Ferkla. The establishment of these mechanisms is aimed at regulating water flow in the rivers, thereby ensuring a sustainable utilization of water resources. This approach not only safeguards the environment

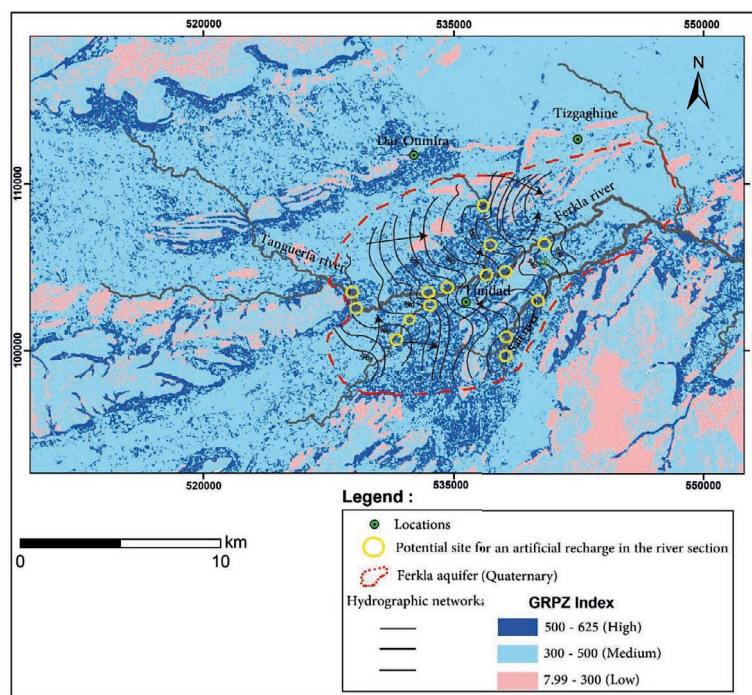


Figure 8. Validation of the groundwater zone map with the piezometric level

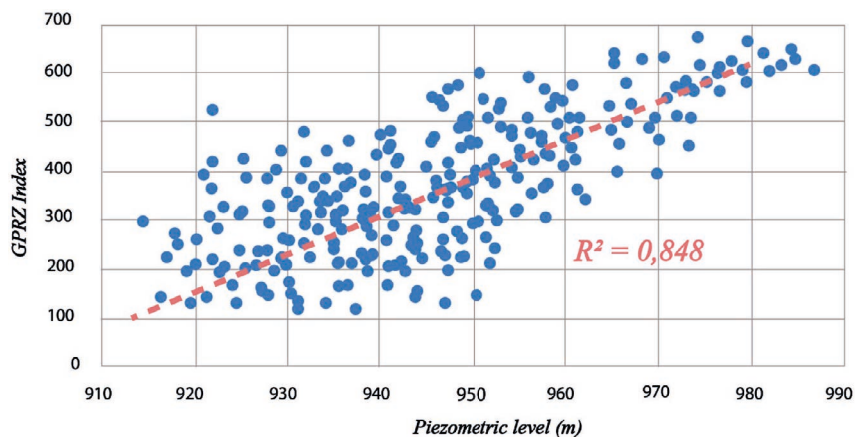


Figure 9. Correlation between the measured piezometric level and the potential groundwater recharge index (GWPZ index) derived from the GWPZ map

but also guarantees a consistent water supply to the quaternary aquifer. Values were obtained by calculating the spatial correlation of two rasters (GPRZ and piezometric level) using an appropriate GIS environment to obtain the statistical linear correspondence of variation between these two variables (Figure 9). The High groundwater potential zones produced for the study area clearly correspond with bore-well data. The high value for  $R^2$  of 0.848 shows a good correlation between piezometric level data and GWPZ index, 80% of the piezometric level points are highly correlated with GPRZ.

## CONCLUSIONS

To delineate the groundwater recharge potential zones within the Ferkla aquifer in southern Morocco, a comprehensive approach combining the analytical hierarchy process and geospatial analytical techniques was employed. Factors including lithology, land cover, slope, lineament density, rainfall, drainage density, and soil type were identified as influential in determining the aquifer's recharge potential. As a result, a geospatial map of the research area was generated, categorizing aquifer recharge potential into three distinct groups: very low, medium, and high. These categories respectively cover 30%, 50%, and 20% of the total surface area of the Ferkla Oasis. These outcomes hold promise in enhancing groundwater management strategies and facilitating artificial recharge planning. Validation of the GWPZ map was conducted using piezometric data from 60 wells, yielding a strong correlation with an  $R^2$  value of 0.848. This case study underscores the effectiveness of harnessing AHP, GIS, and remote sensing techniques to analyze groundwater recharge potential, thereby promoting sustainable groundwater management practices.

The aquifer's replenishment primarily occurs through rainwater infiltration, supplemented by the re-infiltration of irrigation water within the aquifer's central region. The installation of artificial recharge thresholds along sections of the Tanguarfa and Toudgha-Ferkla rivers, intersecting the Ferkla Oasis from southeast to northwest, holds considerable significance. These findings offer a pivotal decision-making tool, ensuring the effective replenishment and preservation of the Ferkla Oasis's groundwater resources. The methodological framework presented in this study emerges as a potent approach for optimizing water resource

protection and management plans within arid oasis regions. Furthermore, its adaptability to analogous contexts in other global oases enhances its applicability. The integration of predictive models based on machine learning algorithms could further amplify the effectiveness of this methodology. To further enhance and complete the scope of this work, several additional studies could be undertaken to identify the optimal points for recharging the water table using surplus floodwater from the wadis. Here are some potential areas of study:

1. Hydrological modeling: Conduct detailed hydrological modeling of the Oueds in the study area to understand their flow patterns, peak discharge, and flooding dynamics. This modeling can help identify areas prone to flooding and potential points for water recharge.
2. Flood risk assessment: Perform a flood risk assessment to determine the areas most susceptible to flood events. This assessment could include factors such as historical flood data, topography, and land use patterns.
3. Water quality analysis: Evaluate the quality of surplus floodwater from the wadis, assessing parameters such as sediment load, pollutants, and contaminants. Understanding water quality is crucial before considering it for groundwater recharge.
4. Groundwater quality assessment: Investigate the quality of the groundwater in the recharge zones to ensure that the floodwater will not negatively impact the existing aquifer's water quality.
5. Aquifer storage and recovery (ASR) feasibility: Explore the feasibility of implementing ASR systems. ASR involves intentionally recharging an aquifer during times of surplus water and then recovering it during times of scarcity.
6. Social and economic impact assessment: Evaluate the potential social and economic impacts of diverting surplus flood water for groundwater recharge. This assessment should consider the implications for local communities, agriculture, and the environment.
7. Infrastructure design: Develop detailed engineering designs for the infrastructure required to divert and manage floodwater for recharge. This includes constructing diversion channels, recharge basins, and monitoring systems.
8. Climate change considerations: Account for potential changes in precipitation patterns and flood frequency due to climate change. Ensure

that the recharge strategy remains viable under changing conditions.

9. Stakeholder engagement: Involve local communities, water authorities, and other stakeholders in the decision-making process. Their input can provide valuable insights and ensure the success of the recharge strategy.

By addressing these additional studies, a comprehensive and robust plan for recharging the water table using surplus flood water from the wadis. This integrated approach will help ensure the sustainability and effectiveness of the groundwater recharge strategy while considering various environmental, hydrological, and societal factors.

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### REFERENCES

1. ABH-GZR. 2021. Étude d'actualisation du plan directeur d'aménagement intégré des ressources en eau des bassins hydrauliques du Guir-Ziz-Rheris et Maider. Errachidia.
2. Abijith, D., Saravanan, S., Singh, L., Jennifer, J., Saranya, T., Parthasarathy, K. 2020. GIS-based multi-criteria analysis for identification of potential groundwater recharge zones A case study from Ponnaniyaru watershed, Tamil Nadu, India. *HydroResearch*, 3, 1–14. <https://doi.org/10.1016/j.hydres.2020.02.002>
3. Abimbola, H., Bolanle, A., Ojokoh Adebayo, O. 2020. Performance analysis of fuzzy analytic hierarchy process multi-criteria decision support models for contractor selection, *Scientific African*, 9, e00471, <https://doi.org/10.1016/j.sciaf.2020.e00471>.
4. Ahmed, J.B., Mansor, S. 2018. Overview of the application of geospatial technology to groundwater potential mapping in Nigeria. *Arab J Geosci* 11, 504. <https://doi.org/10.1007/s12517-018-3852-4>
5. Ait Said, B., Mili, E.M., El Faleh, E.M., Mehdoui, R., Mahboub, A., Hamid, F.E., El Fakir, R. 2023. Hydrochemical evolution and groundwater quality assessment of the Tinejdad-Touroug quaternary aquifer, South-East Morocco. *Front. Ecol. Evol*, 11, 1201748. <https://doi.org/10.3389/fevo.2023.1201748>
6. Al-Ruzouq, R., Shanableh, A., Yilmaz, A.G., Idris, A., Mukherjee, S., Khalil, M.A., Gibril, M.B.A. 2019. Dam site suitability mapping and analysis using an integrated GIS and machine learning approach. *Water*, 11(9), 1880
7. Aouragh, M.H., Essahlaoui, A., El ouali, A., El hmadi, A., Kamel, S. 2017. Groundwater potential of Middle Atlas plateaus, Morocco, using fuzzy logic approach, GIS and remote sensing, *Geomatics, Natural Hazards and Risk*, 8(2), 194-206, DOI: 10.1080/19475705.2016.1181676
8. Arshad, A., Zhang, Z., Zhang, W., Dilawar, A. 2020. Mapping favorable groundwater potential recharge zones using a GIS-based analytical hierarchical process and probability frequency ratio model: A case study from an agro-urban region of Pakistan. *Geosci. Front.* <https://doi.org/10.1016/j.gsf.2019.12.013>.
9. Badi, I., Pamučar, D., Stević, Ž., Muhammad, L.J. 2023. Wind farm site selection using BWM-AHP-MARCOS method: A case study of Libya. *Scientific African*, 19, e01511.
10. Boudad, L., Kabiri, L., Weisrock, A., Wengler, L., Fontugne, M., El Maatoui, M., Makayssi, A., Vernet, J.L. 2003. Les formations fluviatiles du Pléistocène supérieur et de l'Holocène dans la «plaine» de Tazoughmit (Oued Rhéris, piémont sud-atlasique de Goulmina, Maroc), *Quaternaire*, 14(3), 139-154. <https://hal.archives-ouvertes.fr/hal-02504318>
11. Chaaou, I., Kabiri, L., Essafroui, B., Charroud, A., Si Mhamdi, H., Abioui, M., Abdelrahman, K., Neto, C., Fnais, S. 2022. Lithostratigraphic, paleoenvironmental characterization and correlations of the Albian–Turonian deposits of the Errachidia–Boudnib–Erfoud basin (southeast Morocco). *Applied Sciences*, 12(21), 11048. <https://doi.org/10.3390/app122111048>
12. Destombes, J., Hollard, H. 1986. Carte géologique du Maroc au 1/200 000, feuille Tafilalt-Taouz. *Notes Mém. Serv. Géol. du Maroc*, 244.
13. Díaz-Alcaide, S., Martínez-Santos, P. 2019. Advances in groundwater potential mapping. *Hydrogeology Journal*, 27(7), 2307-2324.
14. DRPE. 2007. Direction de la Recherche et de la Planification de l'Eau : état de la qualité des ressources en eau au Maroc année 2007-2008, 110.
15. El Amraoui, M., Kabiri, L., Kassou, A., Ouali, L., Nutz, A. 2022. Diachronic Study of the Vegetation Covers Spatiotemporal Change Using GIS and Remote Sensing in the Ferkla Oasis: Case Study, Bour El Khourbat, Tinejdad, Morocco. *Journal of Geoscience and Environment Protection*, 10, 173-188. [10.4236/gep.2022.101012](https://doi.org/10.4236/gep.2022.101012)
16. El Ouali, M., Kabiri, L., Essafroui, B., Kabiri, L., Charroud, A., Krencker, F.N., Bodin, S. 2021. Stratigraphic and geodynamic characterization of Jurassic-Cretaceous “red beds” on the Errachidia-Msemrir transect (Central High Atlas, Morocco). *Journal of African Earth Sciences*, 183. <https://doi.org/10.1016/j.jafrearsci.2021.104330>

17. Essafraoui, B. 2014. Enregistrement séquentiel du Cénomanien-Turonien des bassins sudatlasiques sur la transversale Agadir-Goulmima (Maroc). Thesis. Ibn Zohr University of Agadir, p. 178.
18. Hadri, M. 1997. Carte Géologique du Maroc 1: 100.000. TINEJDAD. Notes et Mémoires du Service Géologique du Maroc.
19. Harini, P., Sahadevan, D.K., Das, I.C., Manikyamba, C., Durgaprasad, M., Nandan, M.J. 2018. Regional groundwater assessment of Krishna River Basin using integrated GIS approach. *Journal of the Indian Society of Remote Sensing*, 46(9), 1365–1377. <https://doi.org/10.1007/s12524-018-0780-4>
20. Hsin-Fu, Y., Lee, C., Hsu, K., Po-Sun, C. 2009. GIS for assessment of groundwater recharge potential zone. *Environ Geol.* 58, 185–195. <https://doi.org/10.1007/s00254-008-1504-9>
21. Jaafari, A., Zenner, E.K., Panahi, M., Shahabi, H. 2019. Hybrid artificial intelligence models based on a neuro-fuzzy system and metaheuristic optimization algorithms for spatial prediction of wildfire probability. *Agricultural and forest meteorology*, 266, 198–207.
22. Janizadeh, S., Avand, M., Jaafari, A., Phong, T.V., Bayat, M., Ahmadisharaf, E., Lee, S. 2019. Prediction success of machine learning methods for flash flood susceptibility mapping in the Tafresh watershed, Iran. *Sustainability*, 11(19), 5426. <https://doi.org/10.3390/su11195426>
23. Jothibas, A., Anbazhagan, S. 2016. Modeling groundwater probability index in Ponnaiyar River basin of South India using analytic hierarchy process. *Model. Earth Syst. Environ.* 2, 109. <https://doi.org/10.1007/s40808-016-0174-y>
24. Jothiprakash, V., Marimuthu, G., Muralidharan, R., Senthilkumar, N. 2003. Delineation of potential zones for artificial recharge using GIS. *Journal of the Indian Society of Remote Sensing*, 31, 37–47. <https://doi.org/10.1007/BF03030750>
25. Kabiri, L. 2003. Impact des changements climatiques et anthropiques sur les ressources en eau dans l'Oasis de Ferkla. MAB, UNESCO, p. 52.
26. Kabiri, L. 2004. Contribution à la connaissance, la préservation et la valorisation des Oasis du Sud marocain : cas de Tafilalt. Thèse d'habilitation universitaire, Facultés des Sciences et Techniques, Errachidia, Université My Ismaïl, Maroc, p. 280.
27. Krishnamurthy, J., Srinivas, G. 1995. Role of geological and geomorphological features in groundwater exploration: A study using IRS LISS data. *International Journal of Remote Sensing*, 16(14), 2595–2618. <https://doi.org/10.1080/01431169508954579>
28. Krishnamurthy, J., Venkatesa Kumar, N., Jayaraman, V., Manivel, M. 1996. An approach to demarcate groundwater potential zones through remote sensing and a geographical information system. *Int J Remote Sensing*, 7, 1867–1884.
29. Kumar, T., Gautam, A.K., Kumar, T. 2014. Appraising the accuracy of GIS-based multi-criteria decision-making technique for delineation of groundwater potential zones. *Water Resources Management*, 28(13), 4449–4466. <https://doi.org/10.1007/s11269-014-0663-6>
30. Kumar, V.A., Mondal, N.C., Ahmed, S. 2020. Identification of Groundwater Potential Zones Using RS, GIS and AHP Techniques: A Case Study in a Part of Deccan Volcanic Province (DVP), Maharashtra, India. *J. Indian Soc. Remote Sens.* 48, 497–511. <https://doi.org/10.1007/s12524-019-01086-3>
31. Lightfoot, D.R. 1996. Moroccan khettara: traditional irrigation and progressive desiccation. *Geoforum*, 27(2), 261–273. [https://doi.org/10.1016/0016-7185\(96\)00008-5](https://doi.org/10.1016/0016-7185(96)00008-5)
32. Madani, K., Guégan, M., Uvo, C.B. 2014. Climate change impacts on high-elevation hydroelectricity in California. *J. Hydrol.* 510, 153–163. <https://doi.org/10.1016/j.jhydrol.2013.12.001>
33. Mageshkumar, P., Subbaiyan, A., Lakshmanan, E., Thirumoorthy, P. 2019. Application of geospatial techniques in delineating groundwater potential zones: a case study from South India. *Arabian Journal of Geosciences*, 12, 1–15. <https://doi.org/10.1007/s12517-019-4289-0>
34. Mallick, J., Khan, R.A., Ahmed, M., Alqadhi, S.D., Alsubih, M., Falqi, I., Hasan, M.A. 2019. Modeling Groundwater Potential Zone in a Semi-Arid Region of Aseer Using Fuzzy-AHP and Geoinformation Techniques. *Water*, 11, 2656. <https://doi.org/10.3390/w11122656>
35. Margat, J., Destombes, J., Hollard, H. 1962. Mémoire explicatif de la carte hydrogéologique au 1/50000 de la plaine du Tafilalt. Notes Mém. Serv. Géol. du Maroc, n°150 bis.
36. Meena, S.R., Mishra, B., Piralilou, S.T. 2019. Hybrid Spatial Multi-Criteria Evaluation Method for Mapping Landslide Susceptible Areas in Kullu Valley, Himalayas. *Geosciences*, 9, 156. <https://doi.org/10.3390/geosciences9040156>
37. Messaoudi, B., Kabiri, L., Ait Lahssaine, I., et al. 2023. Groundwater resources management using Hydrodynamic modelling in southeastern Moroccan oases: case of Ferkla Oasis. <https://doi.org/10.21203/rs.3.rs-3044585/v1>
38. Moody, P., Brown, C. 2013. Robustness indicators for evaluation under climate change: Application to the upper Great Lakes: Robustness Indicators for Climate Change on Lakes. *Water Resour. Res.*, 49, 3576–3588. <https://doi.org/10.1002/wrcr.20228>
39. Murmu, P., Kumar, M., Lal, D., Sonker, I., Singh, S.K. 2019. Delineation of groundwater potential zones using geospatial techniques and analytical

- hierarchy process in Dumka district, Jharkhand, India. *Groundw. Sustain. Dev.*, 9, 100239. <https://doi.org/10.1016/j.gsd.2019.100239>
40. Ouali, L., kabiri, L., Essafraoui, B., et al. 2023. Spatial modeling of water erosion vulnerability and mapping potential sites of control measures using GIS and MCDM: A case study from the drylands of southeastern Morocco. *Model. Earth Syst. Environ.*, 9, 3473–3482. <https://doi.org/10.1007/s40808-023-01720-7>
  41. Patil, S.G, Lad, R.K. 2021. Evaluation of spatio-temporal dynamics of groundwater recharge and locating artificial recharge structures for watershed in Upper Bhima Basin, Pune, India. *Journal of the Indian Society of Remote Sensing*, 49, 2467-2488. <https://doi.org/10.1007/s12524-021-01400-y>
  42. Rahmati, O, Samani, A.N., Mahdavi, M., Pourghasemi, H.R., Zeinivand, H. 2015. Groundwater potential mapping at Kurdistan region of Iran using the analytic hierarchy process and GIS. *Arabian Journal of Geosciences*, 8(9), 7059–7071. <https://doi.org/10.1007/s12517-014-1668-4>
  43. Rajasekhar, M., Raju, G.S., Sreenivasulu, Y., Raju R.S. 2019. Delineation of groundwater potential zones in semi-arid region of Jilledubanderu river basin, Anantapur District, Andhra Pradesh, India using fuzzy logic, AHP and integrated fuzzy-AHP approaches. *HydroResearch.*, 2, 97–108. <https://doi.org/10.1016/j.hydres.2019.11.006>
  44. Saaty, T.L., Bennett, J.P. 1977. A theory of analytical hierarchies applied to political candidacy. *Behavioral Science*, 22(4), 237-245.
  45. Saraf, A.K, Choudhury, P.R. 1998. Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites. *International journal of Remote sensing*, 19(10), 1825-1841.
  46. Satapathy, I., Syed, T.H. 2015. Characterization of groundwater potential and artificial recharge sites in Bokaro District, Jharkhand (India), using remote sensing and GIS-based techniques. *Environ Earth Sci*, 74, 4215–4232. <https://doi.org/10.1007/s12665-015-4474-8>
  47. Selvarani, A.G., Maheswaran, G., Elangovan, K. 2017. Identification of artificial recharge sites for Noyyal River Basin using GIS and remote sensing. *Journal of the Indian Society of Remote Sensing*, 45, 67-77. <https://doi.org/10.1007/s12524-015-0542-5>
  48. Sener, E., Davraz, A., Ozcelik, M. 2005. An integration of GIS and remote sensing in groundwater investigations: a case study in Burdur, Turkey. *Southeastern Nigeria. Hydrogeology J.*, 6, 394–404. <https://doi.org/10.1007/s10040-004-0378-5>
  49. Shaban, A., Khawlie, M., Abdallah, C. 2006. Use of remote sensing and GIS to determine recharge potential zones: the case of Occidental Lebanon. *Hydrogeology Journal*, 14, 433-443. <https://doi.org/10.1007/s10040-005-0437-6>
  50. Souissi, D., Msaddek, M.H., Zouhri, L., Chenini, I., May, M., Dlala, M. 2018. Mapping groundwater recharge potential zones in arid region using GIS and Landsat approaches, southeast Tunisia. *Hydrol. Sci. J.*, 63, 251–268. <https://doi.org/10.1080/02626667.2017.1414383>
  51. Swetha, T.V., Gopinath, G., Thirvikramji, K.P., Jesiya, N.P. 2017. Geospatial and MCDM tool mix for identification of potential groundwater prospects in a tropical river basin, Kerala. *Environ Earth Sci* 76, 428. <https://doi.org/10.1007/s12665-017-6749-8>
  52. Zghibi, A., Mirchi, A., Msaddek, M.H., et al. 2020. Using analytical hierarchy process and multi-influencing factors to map groundwater recharge zones in a semi-arid Mediterranean coastal aquifer. *Water*, 12(9), 2525. <https://doi.org/10.3390/w12092525>