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Mapping groundwater recharge potential zones in a semi-arid, anthropogenically modified mountainous basin

Abderrahman El Farchouni^{a,*}, Abdessamad Hadri^a, Younes Fakir^{b,c}, Mohamed Ouarani^a, Mohamed Azaroual^d, Azzouz Kchikach^{e,f}

^a International Water Research Institute (IWRD), Mohammed VI Polytechnic University, 43150 Ben Guerir, Morocco

^b Center for Remote Sensing Application (CRSA), Mohammed VI Polytechnic University, 43150 Ben Guerir, Morocco

^c Department of Geology, Faculty of Sciences Semlalia, Cadi Ayyad University, 40001 Marrakech, Morocco

^d BRGM (French Geological Survey), France

^e Geology and Sustainable Mining Institute (GSMD), Mohammed VI Polytechnic University, Morocco

^f Georesources, Geoenvironment & Civil Engineering, Cadi Ayyad University, Morocco

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ABSTRACT

Mapping groundwater recharge potential zones (GRPZ) is essential for predicting recharge distribution and supporting aquifer management in large basins. However, previous studies have mainly relied on multiparameter approaches without validation using multiple lines of evidence. Stable isotopes, which are effective tracers of recharge sources and altitudes, have rarely been applied in semi-arid anthropized basins. Delineating GRPZ remains challenging in these regions due to limited observational data, spatial heterogeneity of recharge mechanisms, and increasing anthropogenic impacts such as urbanization and irrigation. To address these challenges, this study adopted a multi-factorial approach integrating several factors controlling water sources and infiltration processes. Land Use and Land Cover (LULC) was emphasized as a pivotal recharge factor in (semi)arid anthropized basins, reflecting the effects of urbanization, irrigation, and surface water bodies. GRPZ in the Tensift basin (Morocco) were delineated using remote sensing (Google Earth Engine), GIS, Analytical Hierarchy Process (AHP) and stable isotopes. Six recharge factors were used: rainfall (TerraClimate), LULC, lithology, lineament density, slope, and drainage density. Validation was done using stable isotopes ($\delta^{18}O$ and δ^2H) for groundwater samples and Local Altitudinal Line (LAL) to determine Altitudes of Groundwater recharge and sources. The findings indicated that mountains and piedmonts represent the most favorable recharge zones, consistent with previous studies. These areas receive high precipitation and seasonal snowfall, while the plains are dominated by moderate recharge potential, with localized high recharge beneath irrigated areas and low recharge beneath urban zones. The study provides a transferable framework for guiding groundwater resources management and Managed Aquifer Recharge MAR in semi-arid regions and contributes to advancing sustainable water use and climate resilience in line with the Sustainable Development Goals.

* Corresponding author.

E-mail address: Abderrahman.ELFARCHO@um6p.ma (A.E. Farchouni).

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Introduction

Many anthropized semi-arid and arid basins face a situation of low rainfall, high rates of evaporation and transpiration, and reduced groundwater recharge [26]. Consequently, their aquifers are at high risk of rapid depletion because of limited surface water availability and excessive groundwater abstraction. This situation intensifies on the one hand the challenge of meeting water demands and on the other hand the need for management practices that preserve groundwater sustainability. In this framework, understanding and assessing groundwater recharge (GwR) are critical information for management strategies. GwR is indispensable for calculating water budgets, evaluating groundwater availability, constructing regional hydrological and hydrogeological models, analyzing contaminant transport, and augmenting aquifer replenishment by managed aquifer recharge (MAR). Nevertheless, assessing GwR over large basins is challenging, as it stands as one of the most intricate and heterogeneous components of the water cycle [10]. The challenge is especially pronounced in arid and semi-arid regions, where recharge rates are typically low and exhibit considerable temporal variability.

The identification and delineation of potential zones of GwR could be an essential and useful step in understanding, assessing and managing recharge over large basins. Numerous studies have mapped groundwater recharge potential zones (GRPZs) around the world using GIS and remote sensing techniques [11,20]. Groundwater recharge occurs in zones where water from precipitation or other sources infiltrates the ground surface, percolates downward through the unsaturated zone and reaches the saturated zone of aquifers. Consequently, when mapping GRPZs, several factors that control the sources of water, as well as the processes of infiltration and percolation, must be taken into consideration. The primary factors related to this process include precipitation, geology, and topography [20]. Precipitation is a primary source of recharge in humid regions. In (semi)arid regions, high-elevation mountains may receive substantial amounts of rainfall and seasonal snow, which can supply recharge. Geology encompasses the study of rock and sediment composition, as well as the distribution of lineaments (geological discontinuities). Topographic factors include the slope of the land surface that influences runoff speed and the drainage density that determines the runoff capacity.

Consequently, mapping GRPZs requires consideration of multiple factors that influence both the sources of water and the processes of infiltration and percolation. The key controlling parameters include precipitation, geology, and topography [36]. In humid regions, precipitation represents the dominant source of recharge.

In arid to semiarid regions, it is well documented that GwR can majorly result from streamflow losses [32], from percolation across the alluvial sediment [8] or loss to stream banks or floodplains. Natural or artificial lakes, as open water bodies, could also provide GwR during high flow conditions [6]. In anthropized basins, GwR could be influenced by human activities, such as agriculture and urbanization. Agricultural regions have the potential to generate GwR as returns from surface water irrigation [2]. Conversely, GwR could be reduced by urban areas generally due to impervious surface coverings such as buildings, roads, pavements, which prevent the natural infiltration of rainwater and increase the surface runoff [19,33]. Therefore, the processes associated with the influence of water bodies (streams, lakes) and human activities (agriculture and urbanization) on recharge must be considered when mapping the GRPZs in arid and semiarid anthropized basins. Land use and land cover (LULC) map, which are valuable source information about the Earth's surface components and activities, can serve as a proxy for considering the effects of those processes. Indeed, LULC maps indicate areas with surface water bodies that could be a source of water for infiltration and GwR, such as surface streams, natural lakes and artificial reservoirs. Furthermore, they could help in identifying zones with varying degrees of water infiltration potential, encompassing both natural vegetation and irrigated areas with high potential, and urbanized areas with low potential.

While previous studies have commonly used physical parameters such as rainfall, slope, and lithology for mapping GRPZ, few have explicitly incorporated LULC to represent both natural and man-made recharge mechanisms. Our approach expands upon existing frameworks integrating irrigated regions, artificial lakes, and urban surfaces, allowing for a more comprehensive delineation of recharge regimes. Additionally, employing an integrated workflow in Google Earth Engine enhances computational efficiency, reproducibility, and scalability, facilitating effective GRPZ mapping in heavily anthropized basins.

In the present study, the GRPZs were delineated over a large anthropized basin (approximately 22,000 km²) in the southern Mediterranean. The basin encompasses mountains and several agricultural plains where groundwater is extensively exploited. The delineation of the GRPZs was conducted using six key recharge factors, which were categorized according to their rank in the recharge process. The six factors cited in order of their rank are as follows: rainfall, land use and land cover (LULC), lithology, lineament density, slope, and drainage density. The data, except for lithology, are inferred from remote sensing, TerraClimate data and Google Earth Engine. The Analytical Hierarchy Process (AHP) is applied to determine the relative importance and assign weights to each factor. By overlapping factors with a Geographic Information System (GIS), a spatial distribution map of zones with high, medium, and low GwR potential is elaborated. This distribution is examined in light of extant research works on GwR in our basin and used to discuss possible GwR processes that require further field investigations. Insights and issues from mapping GRPZ over large anthropized basins are highlighted.

Groundwater is mostly an invisible resource, mapping this potential recharge zone can be challenging. In addition, many (semi)arid regions, data on key factors such as rainfall, soil moisture, and groundwater levels are scarce or inconsistent [18]. These constraints make the delineation of groundwater recharge potential zones (GRPZ) particularly difficult in large, anthropized basins where recharge mechanisms are complex and spatially heterogeneous. Traditional methods frequently overlook the effects of anthropogenic pressures such as urbanization, irrigation, and artificial water bodies, which can significantly influence recharge patterns.

Materials and methods

Study area

The study area lays majorly over the Tensift basin and over the western part of the Oum Er Rabiaa basin to include the entire Plioquaternary alluvial aquifer (Fig.1). The Tensift Basin is located in central Morocco (Fig.1). It encompasses several agricultural plains, surrounded by the Paleozoic massif of Jebilet in the north and the High-Atlas mountains in the south peaking at 4167 m (Jbel Toubkal). The basin has an arid to subhumid climate, with mean annual precipitation ranging from <200 mm in the plains to >500 mm in the High-Atlas Mountains, considered as the water tower that provides several ephemerals to intermittent streams. The study area is highly anthropized, encompassing urban zones (e.g. Marrakech city) and large irrigation zones. The main irrigated zone is the Haouz plain, which lies over 6500 km². In the center of the plain, modern irrigation lands have expanded since the 1990s, supplied by dams and groundwater withdrawals. In the piedmont, traditional irrigation is practiced, using diverted streamflow from the High-Atlas Mountains. The main crops are olive trees, citrus and wheat.

Geology is more homogenous over the plains than the High-Atlas Mountains and Jebilet Massif. The plains are dominated by Plioquaternary alluvial deposits (alluvial cones, fluvial deposits). Cenozoic and Mesozoic sedimentary carbonate (limestone, phosphates, and marl-limestone) cover the western part. The High-Atlas mountains exhibit a diverse geology including pre-Cambrian and Paleozoic eruptive and metamorphic rocks, Triassic formed of red beds, evaporites, basaltic lava, Jurassic and Cretaceous formed of carbonate sedimentary layers [21]. The massif of the Jebilet consist of folded Paleozoic rock of schists and flysches intruded by acidic and basic intrusions as well as by granitoid plutons.

The largest aquifer of the study area is the Plioquaternary aquifer formed mainly of Plioquaternary alluvial deposits of the Haouz plain. Its basement is composed of Miocene marls, which often include intercalated lacustrine limestones and conglomerates [34]. Groundwater that flows from south to north (Fig. 1), is extensively exploited for irrigation, thus experiencing depletion during the last decades [25]. Groundwater occurs also in limestone aquifers in the western part of the basin.

Input data for the thematic layers

In order to produce a comprehensive dataset for the assessment of GRPZ in the study area, geodata sets from GIS and satellite

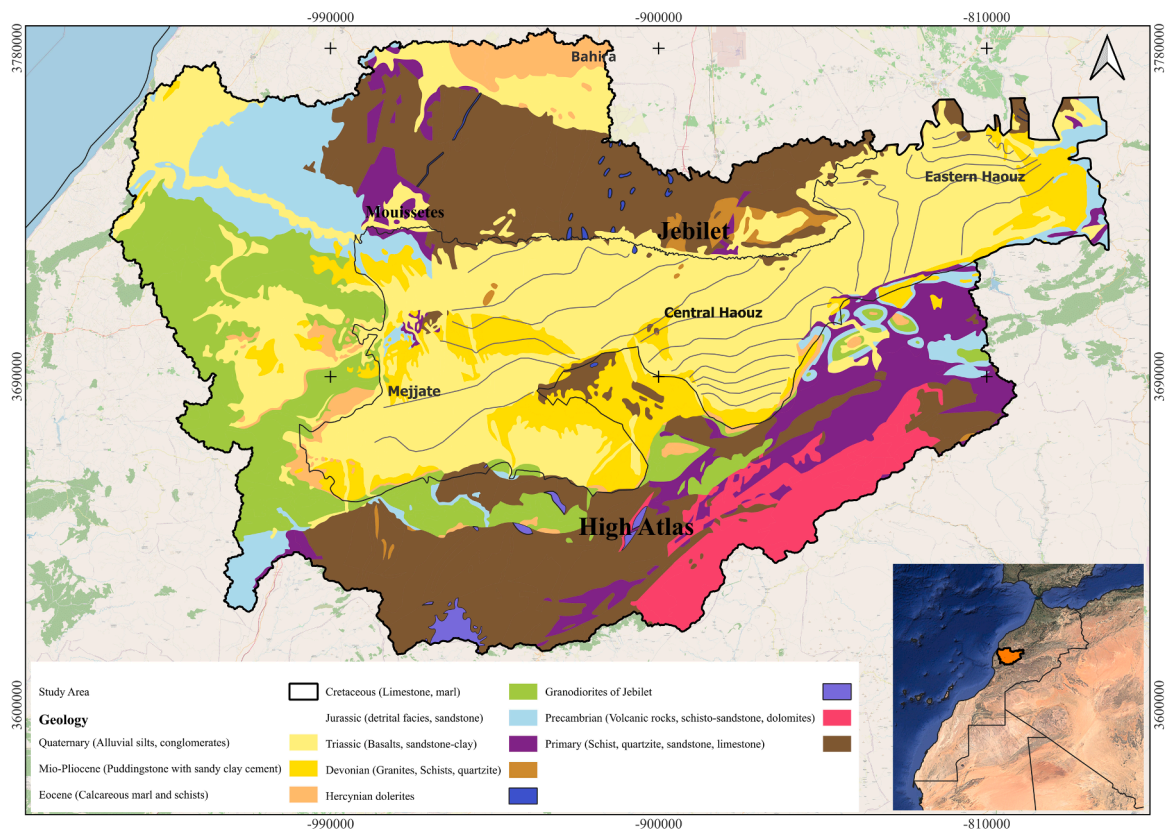


Fig. 1. Study area showing the largest plain of the Haouz, the High-Atlas mountains and the Jebilet massif. The Plioquaternary alluvial aquifer is extensively exploited in the Haouz plains. Cretaceous carbonate aquifers are exploited in the western basin.

sources have been combined and preprocessed to elaborate the thematic layers corresponding to the key recharge factors (Fig. 2). For overlapping, layers must exhibit similar cartographic characteristics, including consistent resolution, geographical extent, units of measurement, and projection systems. Adhering to these standards is essential to ensure that calculations are performed on a uniform matrix or mesh size, thereby enhancing the accuracy and reliability of the analysis.

Precipitation:

Precipitation patterns strongly influence the groundwater recharge. Arid zones with low precipitation have low recharge and humid zones have higher recharge [9]. In mountain catchments, snowmelt contributes significantly to groundwater recharge. Accurate rainfall data can be challenging to obtain, especially in areas with sparse rain gauge networks or complex topography [15]. Our study area is characterized by a complex rainfall pattern resulting from variations in topography and climate. Additionally, the number and distribution of weather stations are inadequate both spatially and temporally. To overcome these limitations, we used TerraClimate precipitation data, which was recently assessed of good accuracy and consistency in the Tensift basin [15]. These data served to elaborate the precipitation map for the period 1980–2022 (42 years), which describe the distribution of precipitation amounts over the whole basin.

Lithology:

Lithology of rock and sediments, through permeability, play a critical role in groundwater recharge. It could control surface water infiltration in case the considered geological formations are outcropping, as well as water percolation towards the water-table. According to [31], rock types can strongly influence the availability and recharge of groundwater. For our study, lithological information was derived from the geological maps of Marrakech (1:500,000) and the Oriental Haouz, which were digitized for analysis.

Land use / Land cover:

Physical-geographical factors, such as topography, geological composition, and climate, alongside human activities like land clearing and agricultural practices shape the landscape and determine how land is utilized and classified. Analysis of different LULC categories, using machine learning approaches, can be performed in Earth Engine using remote sensing datasets. Google Earth Engine is a platform that integrates high-performance computer services with remote sensing data, or satellite images from various sources, to simplify and expedite the processing of satellite imagery [39].

A supervised classification was conducted using a Random Forest (RF) classifier to map the land use and land cover (LULC) of our study area based on remotely sensed data from Sentinel 2 imagery. The methodology followed a structured approach utilizing Google Earth Engine for data acquisition and processing. Initially, Sentinel 2 satellite imagery was obtained and subjected to cloud filtering to ensure data quality. We then calculated vegetation indices, specifically the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI), to enhance the detection of vegetation and water features. An image composite was created from this processed data to provide a comprehensive view of the study area. In preparation for classification, representative samples of different LULC classes were collected to train the Random Forest classifier. The RF classification process involved testing and comparing different values for a key parameter: the number of trees (ntree) in the forest. This optimization step was crucial for improving the classification accuracy. The RF model was then trained on sample regions representing various LULC classes before being applied to the entire study area to generate the final LULC map. To evaluate the performance of our classification model, we conducted a rigorous accuracy assessment.

Lineaments density:

Lineament density reflects the presence and intensity of fractures, faults and any structural discontinuities at the surface. Higher lineament density areas are associated with increased groundwater recharge potential due to improved infiltration and percolation pathways and enhanced permeability [37]. The occurrence and movement of groundwater resources are strongly influenced by the connectivity, length, and spatial organization of fractures.

The lineaments are linear or curvilinear discontinuities in direct connection with the faults and the composite fractures. They may be studied and analyzed using satellite imaging. Radiometric calibration, panchromatic sharpening, and atmospheric correction are among the crucial pre-processing procedures that are applied to Landsat 8 OLI (Operational Land Imager) images in order to improve their quality and interpretability.

We employed the LINE algorithm in PCI GEOMATICA software for automatic lineament extraction, leveraging edge detection techniques that enhance the pixels at the edges of an image. Lineament density (Ld) is calculated based on the following equation (Eq.1) (where $\sum_{i=1}^{i=n} Li$ denotes the length of lineament lines, and A denotes the area):

$$Ld = \frac{\sum_{i=1}^{i=n} Li}{A} \quad (1)$$

Slope:

Slope is a significant factor in groundwater recharge particularly in mountainous catchments [40]. The slope gradient directly influences the infiltration of rainfall. Steeper slopes lead to rapid runoff, reducing the time available for water to infiltrate the soil and recharge the saturated zone. Areas with gentle slopes tend to have higher recharge rates. In this study, we utilized the slope analysis function in GIS to assess slope variations within the study basin, using data derived from the ASTER Digital Terrain Model database.

Drainage density:

Drainage density D_d is defined as the total length of streams in a unit area, as follows (Eq.2).

$$D_d = \frac{\sum_{i=1}^{i=n} S_i}{A} \quad (2)$$

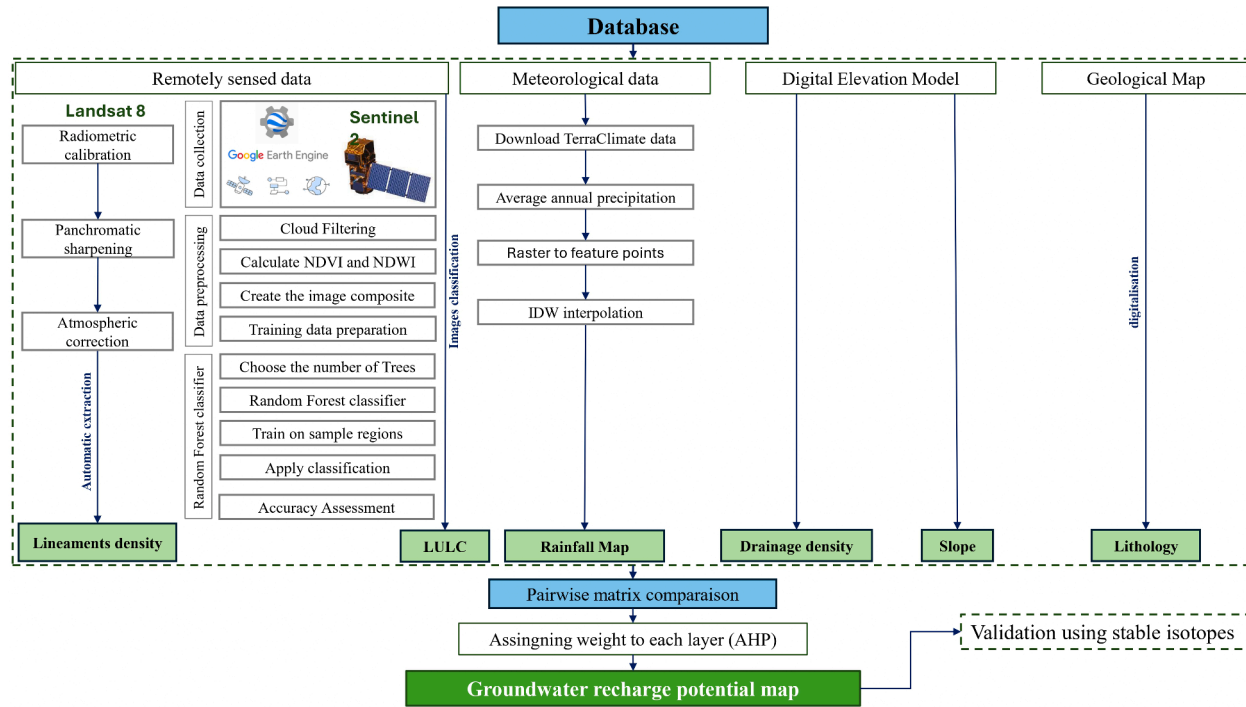


Fig. 2. A Multi-Source Data Integration Framework for Groundwater Recharge Potential Mapping Using Remote Sensing, GIS, and Analytical Hierarchy Process (AHP).

where $\sum_{i=1}^{i=n} S_i$ denotes the total length of streams [L] and A the surface in [L²].

Drainage density of streams controls the interception of rainwater and its flow off rather than its infiltration. Therefore, higher drainage density could lead to lower infiltration and recharge. In our study, the streams network is determined using the ASTER digital elevation model before calculating the raster of drainage density (D_d). Analyzing the structural characteristics of a drainage network aids in determining features of groundwater recharge zones [40]. The ratio of total stream length to drainage area defines drainage density. Higher drainage density generally leads to increased surface runoff, limiting infiltration and groundwater recharge [37].

Establishing ranks and weights using AHP

Developed by Thomas L. Saaty [28], the Analytical Hierarchy Process (AHP) is a well-established multi-criteria decision-making technique tool. This technique that has been widely used for identifying groundwater recharge potential zones [16]. It relies on 2-to-2 comparisons of recharge factors, organized into comparison tables at each hierarchical level. According to [1], there are four basic steps in AHP: (1) standardizing the evaluation factors; (2) creating a pairwise comparison matrix; (3) confirming that the created criteria are inconsistent; and (4) aggregating the weighted findings. Through this procedure, the thematic layers of each recharge factor as input data, are converted into numerical scores and then transformed into judgments for elaborating the map of GRPZ.

Pairwise Comparison Matrix (PCM):

A statistical method called the Pairwise Comparison Method establishes the relative significance of every element in the decision-making process. The Saaty’s score is employed for the construction of a PCM [29].

One statistical method for figuring out how important each component is in the decision-making process is the Pairwise Comparison Method (Table SM3). Pairwise factor comparisons are made, square matrices are generated, and the weighting coefficients are computed using the eigenvectors of these matrices. This methodology guarantees a systematic approach to the decision-making process by providing an objective determination of the weights or weighting coefficients. The significance of every parameter in the groundwater potential characterization was taken into consideration while determining the weights of each parameter. Tables SM1 and SM2 of Saaty’s [28] 1–9 scale served as the foundation for this comparison.

Assessing Matrix Consistency:

In the hierarchical classification approach of the Analytic Hierarchy Process (AHP), it is crucial to verify the consistency of the pairwise comparison matrix. The consistency check ensures that the judgments made in the pairwise comparisons are reliable and can be used for further analysis. This assessment is performed using the Consistency Index (CI) and Consistency Ratio (CR).

Consistency Index (CI): The Consistency Index (CI) is a measure that helps to determine the degree of consistency in the pairwise comparison matrix. It is calculated using the principal eigenvalue (λ_{max}) and the number of parameters (n) involved. The formula (Eq.3) for CI is:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

Where : λ_{max} is the maximum eigenvalue of the matrix, n is the number of parameters.

The CI provides an indication of how much the judgments deviate from a perfectly consistent matrix. A lower CI value indicates a higher degree of consistency.

Principal Eigenvalue Calculation:

The principal eigenvalue (λ_{max}) is calculated by adding the products of the sum of the columns of parameters and the eigenvectors of the comparison matrix (Table SM2). This step is essential to derive the CI accurately.²

In our case λ_{max} =6.435 for six parameters ($n = 6$), the CI can be calculated as (Eq.4) :

$$CI = \frac{6.435 - 6}{6 - 1} = 0.087 \tag{4}$$

The Consistency Ratio (CR) is derived by comparing the CI to a Random Index (RI), which is an average CI of a large number of randomly generated matrices. The formula CR is calculated using (Eq.5), as described by:

$$CR = \frac{CI}{RI} \tag{5}$$

where RI is obtained from established tables based on the number of parameters (Table SM4). For six parameters, RI is 1,24. Therefore, CR is : $CR = \frac{0.087}{1.24} = 0.07 = 7\%$. The obtained CR of 7 % is eligible to overlay weighted parameters for GWPZ mapping. The CR value should be lower than 0.1 to confirm that the pairwise comparison judgments are compatible. However, if the CR value is higher than 0.1, the coefficients of the matrix are inconsistent and are not usable for further processing [38].

Geometric Consistency Index (GCI):

The Geometric Consistency Index (GCI) was introduced as a method to evaluate the consistency of the pairwise comparison matrix in the AHP model. The GCI uses the geometric mean of the elements in each row of the pairwise comparison matrix to determine the priority vector.

The i th element w_i of the priority vector w (normalized priority vector) is calculated using the geometric mean of the elements of the i th row of the pairwise comparison matrix $A = [a_{ij}]$, as follows (Eq.6):

$$w_i = \left(\prod_{j=1}^n a_{ij} \right)^{1/n} \div \sum_{i=1}^n \left(\prod_{j=1}^n a_{ij} \right)^{1/n} \tag{6}$$

The error term e_{ij} associated with each entry a_{ij} of the matrix A is given by (Eq.7):

$$e_{ij} = a_{ij} \cdot \frac{w_j}{w_i} \tag{7}$$

If the matrix is consistent, then $a_{ij} = \frac{w_j}{w_i}$, and hence, for a consistent matrix, $e_{ij} = 1$.

The GCI is found by evaluating the distance from a specific consistent matrix using the formula (Eq.8):

$$GCI = \frac{2}{(N-2)(n-1)} \sum_{i < j} (ne_{ij})^2 \tag{8}$$

For our analysis, the Geometric Consistency Index (GCI) was determined to be 0.17, which suggests a reasonable level of consistency within the pairwise comparison matrix. Given that threshold values for acceptable consistency depend on the number of criteria, a low GCI value ensures reliable decision-making while allowing some flexibility for expert judgment variations.

Assessing the accuracy of the AHP method:

The Receiver Operating Characteristic (ROC) curve approach and area under the curve (AUC) was utilized to assess the accuracy of the AHP method which have been used in several study [20]. However, their application often relies on binary validation data derived from the locations of wells, boreholes, or springs. This approach assumes that the presence of a water point implies high recharge potential, which can be misleading in arid to semi-arid anthropized regions. Boreholes are commonly placed based on human needs, not hydrogeological criteria, and may exploit stored or fossil water or be influenced by lateral flows. Given these limitations, we have chosen not to rely on ROC-AUC validation. Instead, we evaluated the GRPZ map using hydrogeological reasoning and field-supported environmental tracers, including stable isotopes $\delta^{18}O$ and δ^2H , which offer more direct insight into recharge processes and recharge areas or altitudes. Several studies in our basin [2–4] have shown that mountain recharge signatures can be clearly distinguished in plains aquifers using isotopic gradients. These isotopic signals, along with the distribution of historical springs and piezometric trends, support the delineation of recharge zones identified in this study. Thus, our approach favors a process-based validation framework that is more appropriate for complex and data-scarce basins like Tensift.

Results

Factors controlling groundwater recharge

Precipitation:

Precipitation is the key parameter for groundwater recharge and other hydrological processes. The analysis of long-term precipitation data becomes very important in the delineation of groundwater recharge potential zones, as it helps in understanding the variability of water availability and its impact on hydrological processes. TerraClimate data allowed to elaborate a gridded map of average annual precipitation from 1980 to 2022 (Fig. SM1).

To harmonize the precipitation data with other thematic layers divided from the SRTM DEM (slope, drainage density) and Landsat8 (Lineaments) with 30 m of Resolution, the TerraClimate precipitation Raster (Fig. SM1) for the Average annual precipitation converted to 1437 points features which each point represents the centroid of a grid cell over the basin and its boundaries. The aim of using the precipitation parameter in this study is not to predict the exact amount of precipitation at specific places, but to find the spatial trend

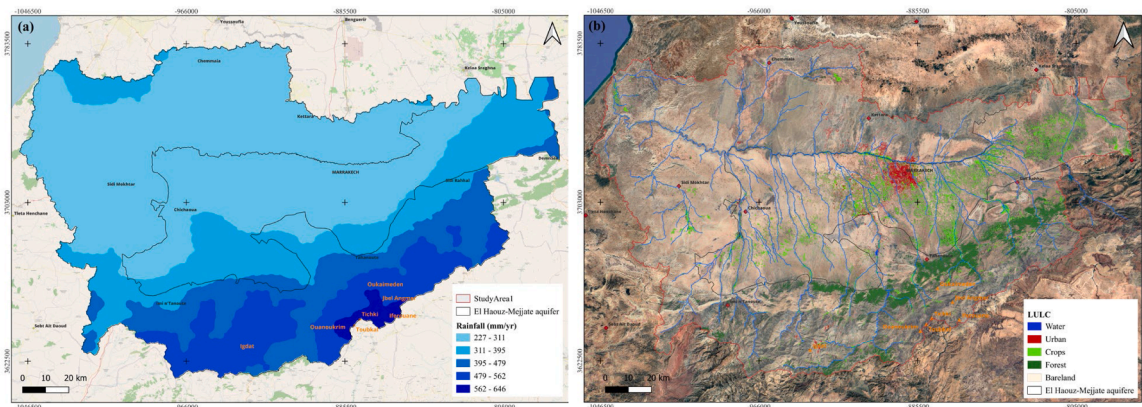


Fig. 3. (a) Rainfall Map Interpolated Using the Inverse Distance Weighting (IDW) Method for the Period 1980–2022; (b) Land Use/Land Cover (LULC) Classification Map of the Tensift Basin and the Haouz Plain Derived from Remote Sensing Data.

and rainfall distribution by identifying areas of relatively higher and lower precipitation (Fig. 3). For this purpose, the Inverse Distance Weighting (IDW) method was applied.

The inverse distance weighting (IDW) method, a deterministic spatial interpolation model, is one of the most widely utilized techniques by geoscientists and geographers, and it has been integrated into numerous GIS software packages. The fundamental premise of this method is that the attribute values of any specified pair of points are interrelated, with their similarity being inversely proportional to the distance separating the two locations [22]. Its computational simplicity and independence from semivariogram modeling. Previous applications in semi-arid and mountainous basins have demonstrated that IDW provides accurate estimates of rainfall patterns, while preserving spatial variability across heterogeneous terrains.

To ensure the robustness of the interpolation, different power parameters were tested (from 1 to 13) using cross-validation between measured and predicted values. The optimal performance was obtained at a power value of 12, which yielded a high coefficient of determination ($R^2 = 0.98$) and a low prediction error, with Root Mean Square Error (RMSE) of 12.87, and a Mean Absolute Error (MAE) of 8.04.

The elaborated map (Fig. 3) presents the spatial variability of the average annual precipitation from 1980 to 2022. The precipitation range is from 220 mm/year in the plains to over 500 mm/year in the High-Atlas Mountains. The spatial variability of rainfall underscores the importance of the High-Atlas Mountains as the water tower of the Tensift is basin [13].

Land use land cover LULC:

The systematic approach allowed us to optimize the classification process and improve the accuracy of the LULC mapping, as illustrated in fig. SM3.

The classification model achieved an overall accuracy of 99.48 %, indicating that nearly all LULC classes in the study area were correctly classified. This high accuracy demonstrates the model’s effectiveness in distinguishing between different LULC types, such as Urban, Crops, Forest, Bareland, and Water, with minimal misclassification errors.

The resulting LULC map (Fig. 4) presents the spatial distribution of urban areas, agriculture, water bodies (streams and dams) and natural vegetation. The major human activities are concentrated in the Haouz plain. Urban areas consist mainly of the city of Marrakech and its surroundings. Agriculture is widely practiced in the Haouz plain, supplied by modern irrigation in the center and traditional irrigation in the piedmont. Forests, predominantly comprised of sparse trees, occupy the low and medium-altitude mountain terrains.

Lithology:

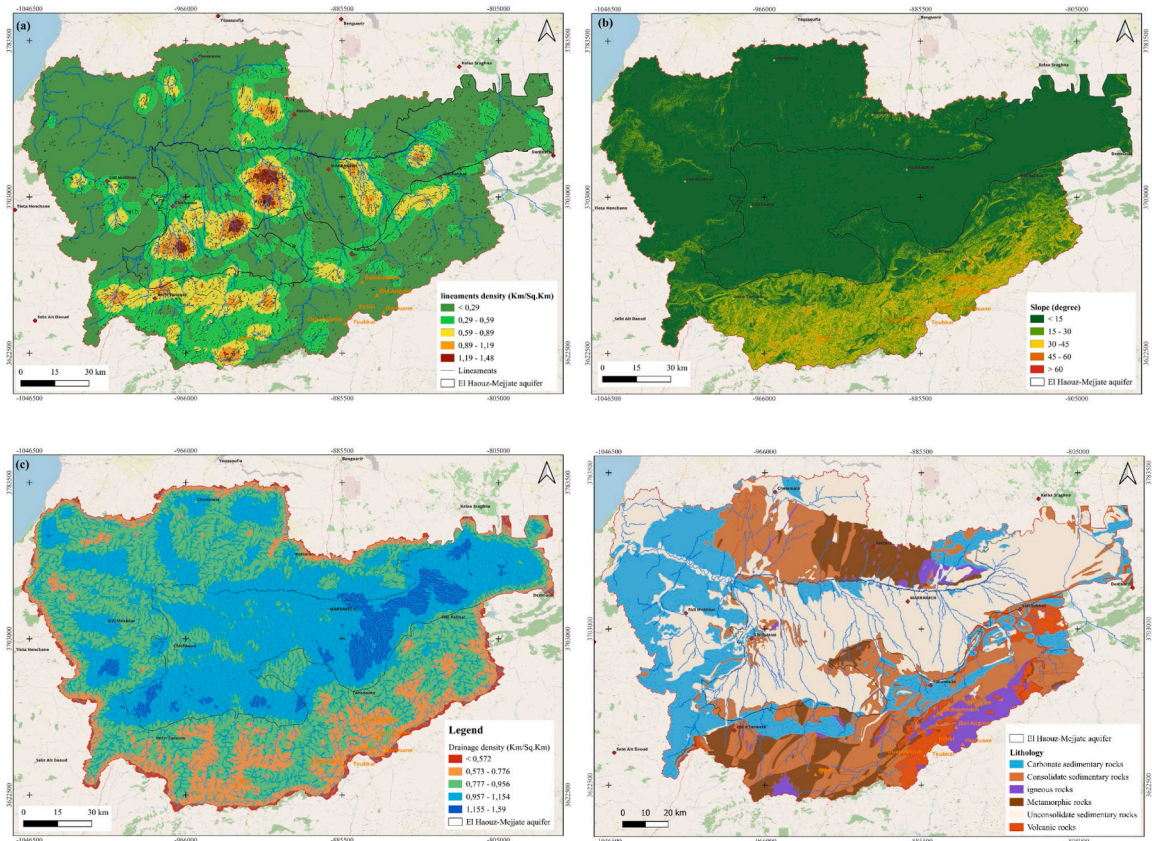


Fig. 4. parameters maps, (a) lineaments density, (b) slope, (c) drainage density, (d) lithology.

The lithological thematic map is prepared using the geological data (Fig. 1), which is summarized into six classes of rocks: unconsolidated sedimentary (alluvial deposits), consolidated sedimentary (conglomerates, sandstones), carbonate sedimentary (limestone, phosphates, and marl-limestone), igneous (granite, granodiorites), volcanic (basalt), and metamorphic (schists). The class of unconsolidated sedimentary deposits is the most prevalent, followed by carbonate sedimentary rocks outcropping in the West of the basin and in the lower part of the High-Atlas mountains. Consolidated sedimentary rocks are largely extended over the High-Atlas (Fig. 5.d).

Lineaments density, slope, drainage density:

The lineament density map (Fig. 4a) is classified into five classes, ranging from 0.29 to 1.48. High lineament density over the mountains coincides with the extended outcrops of fractured Mesozoic carbonate rocks. In the Haouz plain, the variation of lineament density could be explained by effects on the surface terrains of fractures and structural discontinuities of the Paleozoic basement of the plain [12], which uplifts Northwards and largely outcrops in the Jebilet massif. The slope map (Fig. 4b) illustrates that the steepest slopes are predominantly located in the High Atlas mountains, which are a young range mostly built during the Neogene [35]. The drainage density map (Fig. 4c) provides valuable insights into the distribution and intensity of surface drainage across the study area.

Delineation of groundwater recharge potential zones

To delineate GRPZ in the Tensift Basin, thematic layers corresponding to the above described factors were reclassified based on their impact on Gwr. The Analytical Hierarchy Process (AHP) was used to assign weights to these layers. The final weights assigned to the factors influencing GRPZ were determined through the AHP process and are presented in (Table SM5). These weights reflect the relative importance of each parameter in identifying and delineating groundwater recharge zones. A weighted overlay analysis was applied within a geographic information system (GIS) environment to generate the GRPZ map (Fig. 5).

The resulting GRPZ map (Fig. 5) classifies the study area into five groundwater recharge potential categories: Very Low, Low, Moderate, High, and Very High. The moderate GRPZ is the most extensive, covering approximately 82.5 % of the area (17,832.7 km²). It is followed by high recharge zones (7.6 %; 1636.1 km²). Low recharge zones (9.8 %; 2126.7 km²) and very low recharge zones (0.1 %; 17.4 km²) cover smaller portions of the area. The very high recharge zones account for only 0.001 % (0.3 km²), indicating a minimal presence.

The High-Atlas mountains and the piedmont comprise the majority of the high potential zones of Gwr. In the mountains, high

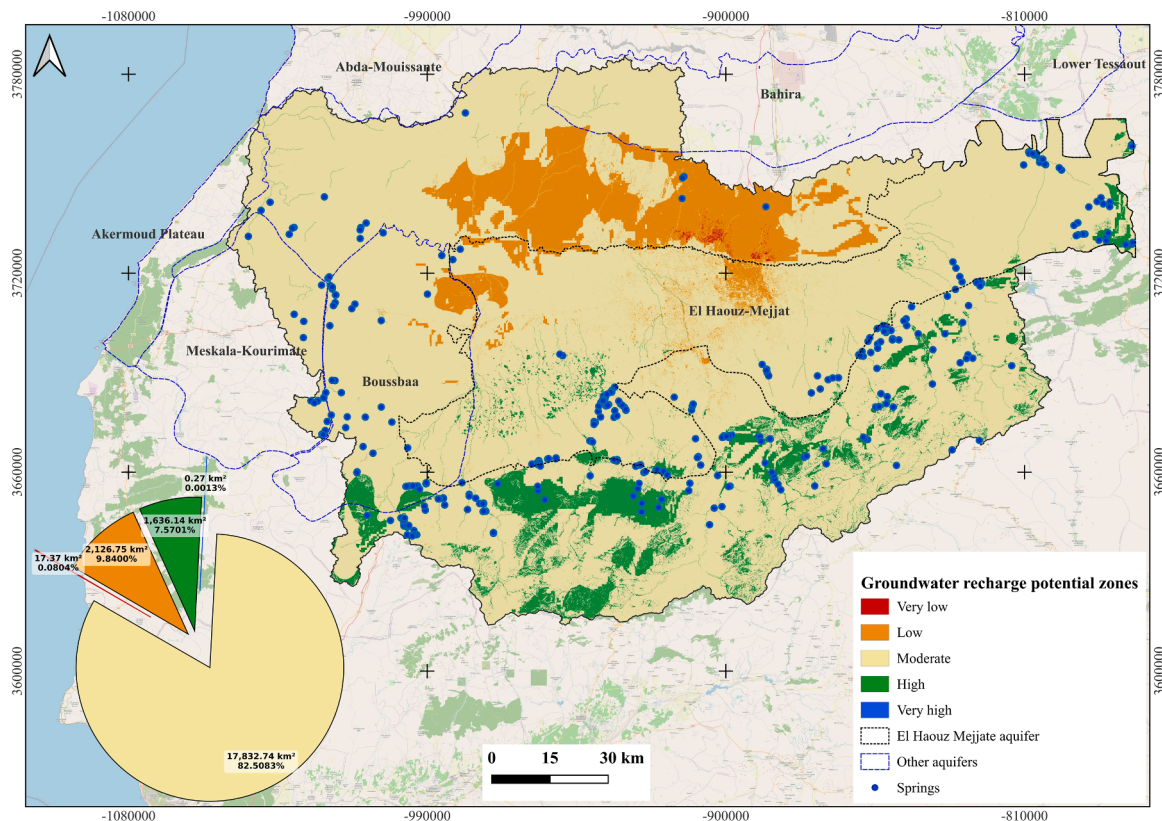


Fig. 5. Groundwater Recharge Potential Zones and Spring Locations. The map illustrates groundwater recharge potential categorized from very low to high. Blue dots represent the locations of current and historical springs within the basin. The pie chart shows the areal distribution of groundwater recharge potential zones, categorized from very low to very high.

precipitation amounts and significant snowmelt at high altitudes [13] would play a pivotal role in sustaining recharge. In the piedmont, the presence of streams and traditional irrigation that relies on streamflow diversion are the dominant factors of high recharge potential. The moderate recharge potential prevails in the plains, both over the alluvial and carbonate aquifers. Despite the good permeability of alluvial and carbonate deposits, the low rainfall is certainly reducing the possibilities for supplying GwR. Exiting urbanized areas further alter this potential, particularly beneath Marrakech city and its surroundings. Low recharge potential characterizes the Paleozoic massif of Jebilet. This part of the basin has unfavorable recharge conditions, including the lowest rainfall and the prevalence of low permeability metamorphic terrains.

Validation using stable isotope signatures and recharge altitude gradient

To complement the qualitative validation of the GRPZ map and overcome the limitations of binary well-based validation methods in semi-arid and anthropized basins, we adopted a process-based approach using environmental tracers. Stable isotopes of oxygen ($\delta^{18}\text{O}$) and hydrogen ($\delta^2\text{H}$) serve as effective indicators of groundwater recharge sources, altitudinal gradients, and mechanisms. The isotopic composition of precipitation varies systematically with altitude, allowing us to infer the recharge elevation of sampled groundwater. In the Tensift basin, this relationship has been well established by [27] using $\delta^{18}\text{O}$ values of rain and snow samples collected across a range of elevations. The resulting Local Altitudinal Line (LAL) indicated a depletion rate of about 0.32 ‰ in $\delta^{18}\text{O}$ per 100 m of elevation gain, providing a reliable basis for estimating the recharge altitude of groundwater based on its isotopic composition.

Additionally, the same authors developed a Local Meteoric Water Line (LMWL: $\delta^2\text{H} = 8 \delta^{18}\text{O} + 13.5\text{‰}$), exhibiting a deuterium excess of 13.5 ‰ and a slope similar to the Global Meteoric Water Line (GMWL; $\delta^2\text{H} = 8 \delta^{18}\text{O} + 10 \text{‰}$), which reflects the regional isotopic signature of meteoric water. In this study, we compared groundwater isotopic data to both the LMWL and GMWL using datasets from [2,4]. These comparisons were used to validate the recharge altitudes and sources inferred from our GRPZ map, particularly highlighting the role of high-altitude recharge from the High Atlas Mountains. The most depleted isotopic signatures, aligned with high-elevation precipitation, correspond well to zones classified as having high to very high recharge potential in the mountainous southern fringe of the basin, reinforcing the physical reliability of the GRPZ delineation.

The isotopic data from [4], plotted relative to both the GMWL and the LMWL (Fig. 6a), provide compelling evidence for the meteoric origin of groundwater across the Haouz plain and its southern piedmont. Most samples align closely with the LMWL, while a few show slight enrichment in heavier isotopes, indicating limited evaporative influence. Notably, the most depleted $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values are associated with recharge from high elevations in the High Atlas Mountains. These findings support the classification of “high” and “very high” recharge potential zones in the mountainous southern sector of our GRPZ map. Moreover, the stable isotope composition suggests that groundwater recharge is primarily governed by infiltration of high-altitude precipitation, which is subsequently conveyed toward the plains via ephemeral rivers and wadis flowing from south to north. This hydrological transfer mechanism reinforces the idea that much of the plain’s groundwater is sustained by indirect recharge originating from the High Atlas, thereby confirming the validity of our spatial recharge potential delineation.

The relationship between $\delta^{18}\text{O}$ and elevation, illustrated in Fig. 6b, further supports the GRPZ map’s validity. Using the Local Altitudinal Line (LAL) as a reference, the main recharge elevation for the sampled springs falls within the range of approximately 1800 to 2800 m above sea level (m.a.s.l.). These isotopically depleted samples follow the expected altitudinal gradient of $\delta^{18}\text{O}$ depletion (0.32 ‰ per 100 m), confirming that recharge occurs primarily at higher elevations in the High Atlas. In contrast, well samples from the plains exhibit more enriched $\delta^{18}\text{O}$ values, consistent with either local low-elevation recharge or indirect recharge via flow paths from the mountains. The clear altitudinal signal observed in spring samples aligns with the spatial pattern of high recharge potential zones in

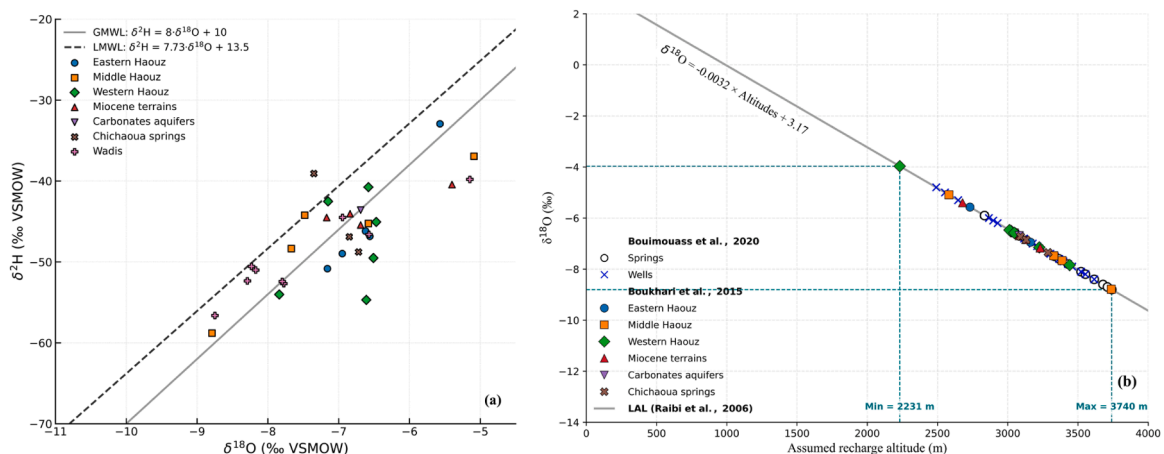


Fig. 6. Isotopic Validation of Groundwater Recharge in the Tensift Basin. (a) $\delta^2\text{H}$ vs. $\delta^{18}\text{O}$ plot compared to GMWL and LMWL to assess recharge origin. (b) $\delta^{18}\text{O}$ vs. elevation plot compared to the Local Altitudinal Line (LAL) to estimate recharge altitudes.

the GRPZ map, particularly in the southern and southeastern mountainous areas. This agreement between isotopic elevation signatures and modeled recharge zones enhances confidence in the GRPZ map as a decision-support tool for targeting recharge enhancement and protection strategies.

To further validate our GRPZ map, we refer to the isotopic evidence to validate GRPZ through isotope mass balance approach to estimate the contribution of snowmelt and rainfall to groundwater recharge in the Haouz, the estimation was based on the following mixing equation (Eq. 9):

$$\delta^{18}\text{O}_{GW} = (1 - X) \cdot \delta^{18}\text{O}_{SN} + X\delta^{18}\text{O}_R \quad (9)$$

Where:

$\delta^{18}\text{O}_{GW}$ is the measured oxygen-18 value in groundwater,

$\delta^{18}\text{O}_{SN}$ is the isotopic composition of snowmelt,

$\delta^{18}\text{O}_R$ is the isotopic composition of rainfall,

X is the fraction of recharge originating from rainfall (thus $1 - X$ represents the snow contribution)

Using mean $\delta^{18}\text{O}$ values derived from Haouz [4], they estimated that approximately 57 % of the groundwater recharge in the Haouz plain originates from snowmelt, while 43 % is from direct rainfall. This confirms the dominant role of high-elevation snow-fed recharge from the High Atlas (2000–3500 m.a.s.l.) in sustaining groundwater resources, which is consistent with the spatial distribution of high recharge potential zones identified in our GRPZ map.

Discussion

GRPZ map vs field hydrological knowledge

This study developed a comprehensive approach to delineate Groundwater Recharge Potential Zones (GRPZ) in the semi-arid and anthropized basin using an Analytical Hierarchy Process (AHP) that integrate main parameters influencing groundwater processes. The key findings of the study are as follows: (1) Land Use and Land Cover (LULC) emerged as one of the most influential factors driving groundwater recharge in the basin, reflecting the strong impact of human activities such as irrigation and urbanization. (2) The spatial distribution of recharge potential shows clear differentiation, with high recharge zones primarily located in the piedmonts and irrigated plains, while low recharge zones are concentrated in urbanized or impermeable areas. (3) A total of 30.5 % of the basin was classified as having high to very high recharge potential, suggesting significant opportunities for managed aquifer recharge (MAR) interventions in these regions. (4) Finally, the GRPZ map was validated using hydrogeological reasoning and field-based isotopic data ($\delta^{18}\text{O}$ and $\delta^2\text{H}$), confirming the correspondence between modeled recharge zones and observed recharge signals from mountain sources.

Our findings are aligned with previous research in the Tensift basin and similar (semi)arid regions. The role of the High-Atlas mountains as the main source of groundwater recharge within our basin is well-documented. They receive sensibly higher amount of precipitation, as rainfall and snow [13], than the lowland plains. The high precipitation combined to the presence of extended outcrops of Jurassic and Cretaceous limestone constitute primary factors that make the High-Atlas mountains a high potential zone of GwR. These findings are consistent with the results of previous research works that emphasized the significant impact of mountains on the recharge of adjacent lowland aquifers, such as piedmont and plains, through both regional and localized flow paths originating from mountain blocks [3]. This so-called mountain block recharge, driven by altitude-related precipitation gradients and geological features, was revealed using ^{18}O and ^2H , chloride and tritium tracers along with end-member mixing analysis. Furthermore, the substantial number of current and historical springs within the mountains (Fig. 10) underscores the large occurrence of groundwater in this area. However, it suggests that groundwater would flow in a multitude of separated aquifers (blocs) given the rocky and fractured nature of the geological terrain.

Areas in the piedmont and along streams have been identified as zones of high potential for GwR. Several studies have demonstrated that recharge occurs in the piedmont, specifically in the mountain front, where water losses occur through streams [8,14]. Furthermore, returns from traditional irrigation supplied by mountain streamflow have been shown to generate significant recharge in the piedmont [2].

Plains were ranked as moderate potential zones of GwR. Stable isotopic data (^{18}O , ^2H) indicated that the recharge of the alluvial aquifer of the Haouz plain exhibits isotopic signatures of the high-altitude precipitation water originating in the High-Atlas range [4]. This supports that direct rainfall infiltration in the plain has a low contribution to GwR due to low rainfall and high evaporative demand. As shown by the piezometric map (Fig. 1), recharge could come from the piedmont, allowed by the continuity of the alluvial deposits and their good permeability, which ranges from $2 \cdot 10^{-6}$ m/s to $3 \cdot 10^{-2}$ m/s [7]. Modern irrigation techniques have been demonstrated to generate deep percolation, a process that could lead to GwR. Indeed, water balance calculations in drip irrigated fields in the plain showed that >30 % of supplied water went as deep percolation mainly due to over irrigation [23]. The presence of nitrate contents that exceed the natural background are also in favor of deep percolation of water from the surface, a phenomenon that is observed at different plains within the study area [30].

Low recharge potential zones dominantly characterize the Paleozoic massif of Jebilet in the northern part of the basin. The Jebilet massif is the most arid area of the basin, and it is largely composed of crystalline metamorphic rocks, which are known to be poor groundwater reservoirs. The existing wells in the area are generally utilized for drinking water in small villages and frequently exhibit either very low productivity or high salinity.

Insights and issues from mapping GRPZ over large anthropized basins

Delineating GRPZ over large basins has become more accessible due to the development of GIS tools and remote sensing global products on climate, topography, and LULC. However, the accuracy of RS products for hydrology frequently necessitates prior validation by ground truth data; otherwise, significant biases may be generated.

The Analytical Hierarchy Process (AHP) is a methodological framework that has gained significant recognition for its efficacy and ease of use [20]. Nonetheless, a principal constraint of the process is its reliance on expert judgment to select the appropriate key factors and to assign them a weighting [16]. The resulting biases may be improved according to the injected knowledge on GWR processes for selecting and prioritizing the recharge factors.

Despite this limitation, AHP continues to be widely adopted in groundwater studies due to its methodological strengths, which offer several practical advantages in complex environmental settings. The key strengths of the (AHP) method in delineating groundwater recharge potential zones include its ability to systematically evaluate multiple criteria. AHP facilitates the assignment of weights to these criteria based on their relative importance, allowing for a comprehensive overlay analysis in a geospatial context. This method enhances decision-making by producing dense data that supports sustainable groundwater resource management, particularly in regions with limited water resources.

LULC has been inserted in delineating GRPZ generally to take into account the effects of vegetation or urbanization [20,37]. Over anthropized basins under semi-arid and arid conditions, LULC should be systematically considered as an essential key factor in delineating GRPZs. LULC data could additionally provide information on the surface water network, streams and other water bodies (natural lakes, water reservoirs), which represent important potential sites of recharge in (semi)arid regions [32]. In agricultural regions, LULC are pivotal in delineating zones for potential irrigation-induced recharge, [2], and for managed aquifer recharge through off-season irrigation, as outlined in recent studies [24].

While the integration of LULC could improve the delineation of GRPZs, the impacts of groundwater depletion, which is currently affecting numerous anthropized basins, could present a significant challenge to identifying those zones. Indeed, the increasing thickness of the unsaturated zone due to water table decline, generates more space for water interception that could impede or restrict direct groundwater recharge through percolation [5]. Identified favorable potential zones may no longer be as favorable, because the groundwater may become too deep to be rapidly replenished.

By identifying high recharge zones appropriate for protection or managed aquifer recharge (MAR) in a (semi)arid and anthropogenic basin, this study provides useful information for sustainable groundwater management. The findings immediately promote SDG 13 (Climate Action) by directing adaptive land-use planning and water management strategies under changing climatic circumstances and SDG 6 (Clean Water and Sanitation) by indicating where groundwater resources can be sustainably replenished. In this context, the alignment of our results with broader sustainability strategies reinforces the importance of integrating environmentally sound interventions. Moreover, increased groundwater availability supports agricultural productivity and rural livelihoods, which are essential for achieving SDG 1 (No Poverty) and SDG 2 (Zero Hunger) in water-stressed communities. Nature-based methods advocated in current climate resilience literature are in line with implementing ecosystem-based adaptation (EbA) measures like riparian buffer maintenance or vegetation restoration in recharge regions [17]. This makes our land-use-sensitive, process-based approach to integrated water and land management in vulnerable areas even more pertinent.

Conclusion

The present study aimed to delineate groundwater recharge potential zones within a large authorized mountainous basin, majorly under arid to semi-arid climate. Remote sensing and GIS techniques were applied through the analytic hierarchy process (AHP). This approach assigned weights to key thematic layers including rainfall, land use and land cover, lithology, lineament density, slope and drainage density. The study highlights the critical importance of using land cover and use in such contexts as a pivotal key recharge factor. The latter incorporates several components that can have significant influence on groundwater recharge. These components principally comprise surface water networks, which could serve as focal points for recharge along streams, lakes, and dam reservoirs. Additionally, irrigated crop lands could generate irrigation returns, while urban areas may impede water infiltration.

The resulting map revealed that Moderate recharge zones dominate, 82.5 % (17,832.7 km²) of the study area, indicating a balanced recharge potential over the plains majorly formed of alluvial deposits. High recharge zones follow, 7.6 % (1636.1 km²) of the study area, representing favorable hydrological conditions over mountains, piedmont and streams that receive the highest amounts of water. Low recharge zones represent 9.8 % (2126.7 km²), likely due to low precipitation or less permeable surfaces over the Jebilet massif and urban areas. Very low recharge zones cover only 0.1 % (17.4 km²), while very high recharge zones are minimal, occupying 0.001 % (0.3 km²).

Further field investigations are needed to advance knowledge on groundwater recharge in the basin. In the High-Atlas mountains qualified as the water tower of the basin, studies should be conducted on the type and extent of aquifers given the geological diversity of the terrains, and on the types of recharge (focused or diffused), and on the recharge fluxes to lowland aquifers through mountain blocks. In the plains, which are heavily utilized for irrigation, the impacts of groundwater depletion on recharge processes should be elucidated. Due to the development of thick unsaturated zones, identified favorable potential zones may no longer be as favorable because the groundwater is too deep to be easily replenished.

Our combined AHP-GIS method showed five groundwater recharge potential zones in the Tensift Basin. About 30.5 % of the area was classified as high to very high recharge zones, mostly in the southern High Atlas and piedmont zones. These spatial patterns are consistent with the expected recharge dynamics in mountainous terrains. Validation using stable isotope data ($\delta^{18}\text{O}$ and $\delta^2\text{H}$)

confirmed that recharge primarily occurs from high-altitude precipitation, with inferred recharge elevations between 1800 and 2800 m.a.s.l., and snowmelt contributing up to 57 % of total recharge. These results align with the modeled GRPZ map, thereby enhancing the reliability of the delineated recharge zones and demonstrating the effectiveness of integrating isotopic validation in GIS-based multicriteria approaches.

Future studies could look into how modern modelling methods, such machine learning algorithms and artificial neural networks, could be used to more dynamically measure groundwater recharge rates. In particular, combining these models with remote sensing and in-situ monitoring could help us understand better how recharge processes change over time, how people affect them, and how climate change affects them. This would help us manage water resources in arid and semi-arid areas in a way that is good for the environment.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to enhance language clarity and structure. All scientific content, interpretations, and conclusions were developed by the authors, who take full responsibility for the final manuscript.

Declaration of competing interest

We confirm that this manuscript has not been published previously and is not under consideration elsewhere. The authors have no conflicts of interest to disclose and have all approved this submission.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.sciaf.2025.e03025](https://doi.org/10.1016/j.sciaf.2025.e03025).

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