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Saloua Agli[1], Algouti Ahmed[2], Algouti Abdellah[3], Farah Abdelouahed[4],
Said Moujane[5], Kabili Salma[6], Errami Maryam[7]

Delineation of Groundwater Storage and Recharge Potential Zones Using Multi-Influencing Factors (MIF) Method: Application in Synclinal Coastal Basin of Essaouira (Western High Atlas of Morocco)

Abstract: Unpredictable rainfall caused by climate change and pollution directly impacts groundwater demand, making the exploitation of groundwater reserves necessary. To achieve this, a study in the synclinal basin of Essaouira (Western High Atlas) used GIS, remote sensing, and the Multi-Influencing Factors (MIF) method, to identify areas ideal for the installation of productive wells. An overlay analysis created a groundwater potential zone (GWPZ) map, showing 30% of the basin with high potential, 51% with moderate potential, and 19% with low to very low potential. The groundwater potential zone map was validated using geophysical surveys, piezometric data, and well water levels, showing a 69.3% prediction accuracy with the ROC curve.

Keywords: groundwater potential zone, Essaouira, remote sensing, GIS, multi-influencing factors (MIF), ROC

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[1] Cadi Ayyad University, Faculty of Sciences Semlalia, Marrakesh, Morocco, email: saloua.agli@gmail.com (corresponding author), https://orcid.org/0009-0008-3672-0081 (corresponding author)

[2] Cadi Ayyad University, Faculty of Sciences Semlalia, Marrakesh, Morocco, email: algouti@uca.ac.ma, https://orcid.org/0000-0002-2344-0821

[3] Cadi Ayyad University, Faculty of Sciences Semlalia, Marrakesh, Morocco, email: abalgouti@uca.ac.ma, https://orcid.org/0000-0001-7501-5221

[4] Cadi Ayyad University, Faculty of Sciences Semlalia, Marrakesh, Morocco, email: farah6farah@gmail.com, https://orcid.org/0000-0001-6302-4622

[5] Cadi Ayyad University, Faculty of Sciences Semlalia, Marrakesh, Morocco, email: said.moujane02@gmail.com, https://orcid.org/0009-0001-9109-9610

[6] Cadi Ayyad University, Faculty of Sciences Semlalia, Marrakesh, Morocco, email: salmakabili@gmail.com, https://orcid.org/0009-0004-0979-2304

[7] Cadi Ayyad University, Faculty of Sciences Semlalia, Marrakesh, Morocco, email: maryamerrami@gmail.com, https://orcid.org/0000-0002-0452-6996

1. Introduction

Groundwater is the most important source of freshwater throughout the globe [1]. As a result of the increase in population and the development of the industrial and agricultural sectors, the demand for groundwater is increasing [2]. The accessibility of potable water is one of the major objectives of development projects in rural and semi-rural areas throughout the world. However, 1.69% of total freshwater is available as groundwater (compared to a total global freshwater availability of 2.50%) [3]. It is necessary to protect this limited quantity of resources (in particular, groundwater), which is a vital and essential source for humans (especially during protracted dry periods). In the Essaouira synclinal basin, groundwater is the principal water resource for the daily consumption of the population. According to previous studies on the topic of the Essaouira synclinal basin that were completed in 2001 and 2007, we have realized that the hydrogeological prospections have identified several aquifer systems such as the Pliocene-Quaternary aquifer (with a sandstone matrix) and the fractured Turonian calcaro-dolomitic. Their alimentation comes from rainwater infiltrations; these present hydrodynamic characteristics that vary significantly according to their lithological and structural properties (which differ from one aquifer to another) [4, 5].

The results of the piezometric campaigns that were realized in the Essaouira basin during the years of 1990, 1995, and 2004 demonstrated that the variations of the piezometric levels of the aquifer are influenced by rainfall conditions. Indeed, climatic variations (especially the rainfall regime) can affect the water tables. The authors stated increases after rainy seasons and decreases after drier seasons. In this study, the effect of the drought of 1995 [5] resulted in a remarkable reduction in the groundwater level over the entire year. However, these piezometric level variations are also influenced by overexploitation and climate change, which have had permanent effects to the present day. Thus, the cartography of groundwater potential zones is obligatory in order to preserve groundwater and precipitation for semi-arid regions and the Essaouira synclinal basin. Indeed, identifying groundwater has long been based on the tracing of the levels of aquifers, having better hydraulic characteristics, and the use of geomorphology for identifying favorable geological structures [6]. This process can lead to a significant number of wells that are unfortunately non-productive; even among those that are positive, more than 45% have flow rates that are below 1 m^3/h [4]

In contrast, groundwater surveillance and management has been prepared in recent studies using high-performance tools such as geographic information systems, remote sensing, geophysics, and geostatistics [7–16]. These tools have proven that aquifers that are marked by fractures of a kilometer extension and the strong interconnections of the networks of fractures can constitute veritable groundwater reservoirs and often present great productivity; this favors the implantation of wells with high flow rates. The integration of GIS tools and remote sensing has become a necessity for achieving the better mapping of sites that are favorable for establishing productive wells. Indeed, evaluating the existence of groundwater based on the interactions of different hydrogeological, geological, and atmospheric factors (such as topography, groundwater level, lithology, precipitation, fracturing, vegetation cover, drainage system, and land use) is beneficial. Calculating of probable correlation among the dependent and independent variables is done based on different approaches, such as the multi-influencing factors (MIF) technique [3, 14, 16], the analytic hierarchy process (AHP) [7, 11, 12, 17], multi-criteria decision making (MCDM) [1], and machine learning [13].

In the present study, appropriate groundwater sites were identified by using the MIF technique. This involves attributing a score to each parameter according to its degree of influence on the other parameters and considering the minor and major interactions among those parameters that determine groundwater potentiality. This indicates the degree of the influence of this parameter on the delineation of potential recharge areas in the Essaouira synclinal basin. Thereafter, all of the layers were integrated and meshed in the GIS platform using the weighted overlay method. In the recent past, the techniques that were largely used to validate the level of accuracy of the MIF method were generally based on the depths of the water that were measured in existing wells in the study area. The validation data is treated with statistical software such as SPSS or R-studio in order to obtain a receiver operating characteristic (ROC) curve. Several authors have used the ROC curve for the validation of the geospatial approach coupled with the FIM technique with a good level of accuracy and applicability [3, 16]. On the other hand, other methods exist for validating this type of modeling, such as Kappa, positive and negative predictive values, and the square root of means [18].

Climate change and the expanding population as well as economic growth in the region have led to an intensifying need for drinking water, which makes available water scarce and leads to overexploitation of them. One of the priorities for officials is to delve into the fissured aquifers that can be found in this region where they can be discovered all over through their searches for subterranean reservoirs. To ensure a reliable supply of drinking water and address this issue, our study aims to delineate potential recharge zones in the Essaouira coastal syncline. This will enable us to identify suitable sites for installing productive wells in areas with high recharge potentials, considering regions with high agricultural and demographic activities in the Essaouira syncline.

2. Study Area

Located in Morocco's Western High Atlas, the Essaouira basin is part of the El Jadida-Agadir coastal basin [19]. Our study area is located in a vast syncline opening onto the Atlantic Ocean (Fig. 1). It is a semi-arid region with very irregular rainfall (generally not exceeding 300 mm annually), high humidity, and an average monthly temperature of around 43°C (with significant daily variations). The hydro-rainfall regime of the synclinal basin is monogenic, with a period of surplus from November through February and a period of deficit from June through September. Analyses of monthly variations in flow and rainfall show that the monthly and annual flows are strongly conditioned by rainfall. Indeed, the proximity of the ocean plays a very important role in these climatic variations [20, 21]. The main aquifers in the study area are recharged by the three main rivers: the Ksob River (in the north), the Tidzi River (in the middle), and the Igouzoulan River (in the south). More than 50% of the water volumes of these rivers flow between November and January.

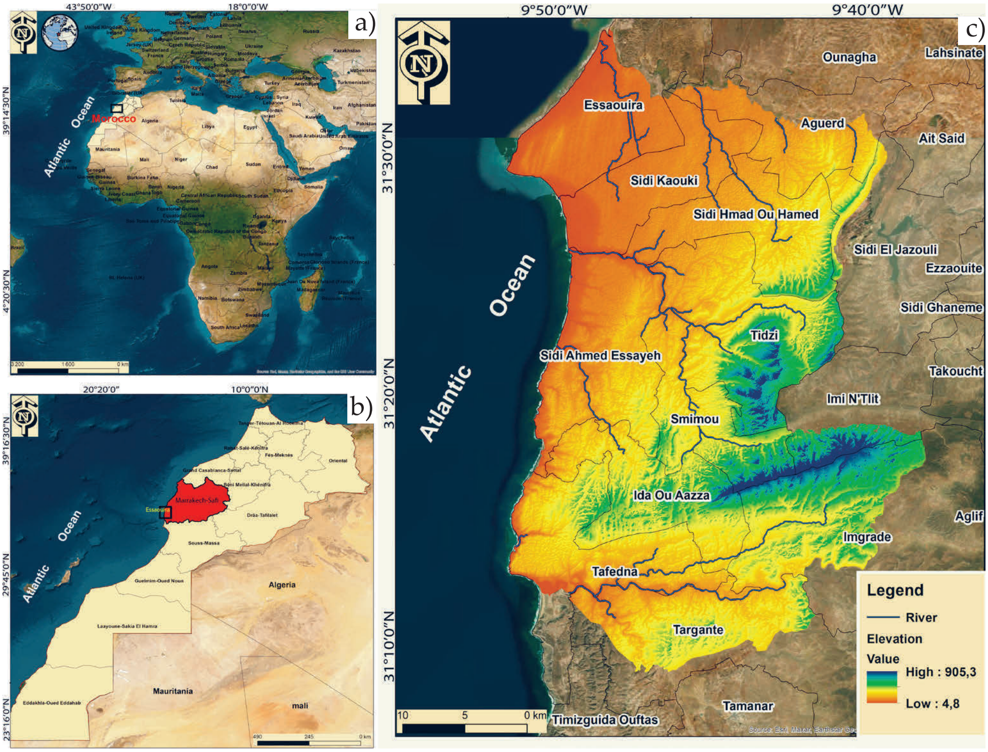

Fig. 1. Location of study area at African view (a);
location of study area at Moroccan and regional view (b);
elevation model of synclinal basin of Essaouira (c)

In the Essaouira synclinal basin, groundwater is the main source of water for the daily drinking water needs of around 116,000 inhabitants (as well as for agricultural purposes). The growing demand for water supplies is linked to population increases in the rural and semi-rural communes of the study area. This increased demand is split between 64.4% for agricultural use and 35.6% for domestic use and recharged drinking water.

3. Geological Setting

The basin is affected by several folds and accidents that are represented by a succession of anticlines and synclines. For the geological context, the Paleozoic effluents of the Essaouira basin were once strongly affected by the Hercynian orogeny. The Triassic and early Lias were marked by extensive normal faults that controlled the deposits and led to the formation of tilted blocks and thick red detrital series (as well as salts and dolomites). Anhydrites and marine carbonates were the most dominant outcrop types during the Jurassic and Cretaceous periods [21]; the Cretaceous formations are mostly concentrated in the hinterland, while Tertiary (phosphate formations) and Quaternary (superficial deposits) formations can occasionally be found in the synclinal basins. Pliocene and Quaternary dune formations cover a strip of the coastline that is about 20 km long and are parallel to the ocean [22]. The hydrogeological context of the Essaouira basin is marked by a complex and diverse aquifer system (Fig. 2); its alimentation comes essentially from rainwater infiltration.

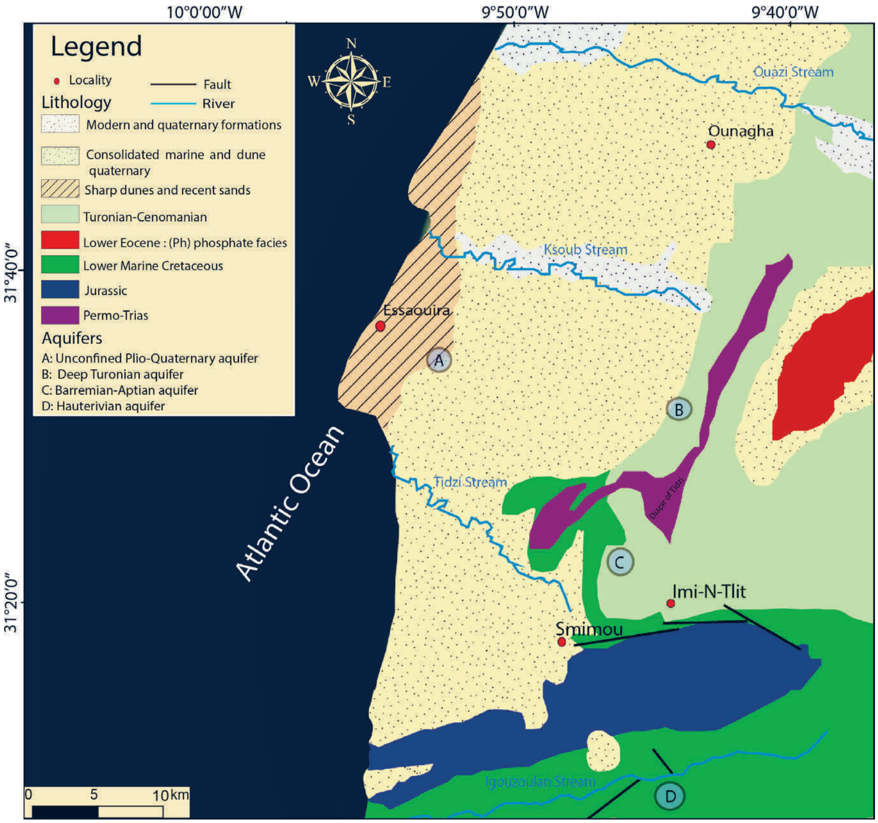

Fig. 2. Simplified geological map of Essaouira synclinal basin

Source: [22], modified

This aquifer has variable hydrodynamic characteristics depending on their diverse lithological and structural properties; indeed, the combination of lithological diversity with the effects of tectonics and those of diapirism have caused the division of this basin into several aquifer systems. The most important of these are located in the synclinal basin of Essaouira (such as the Pliocene-Quaternary aquifer, with a sandstone matrix) and the fractured calcaro-dolomitic aquifer of Turonian [22].

4. Materials and Methodology

4.1. Data and Generation of Thematic Maps

Identifications of potential recharge areas in the Essaouira synclinal basin were carried out based on the multi-influencing factors method while considering several factors that influenced the recharge process, such as lithology, slope, fractures, land use, drainage, and soil moisture; all these factors were mapped using remote sensing data. Classifying the generated thematic maps was done according to the infiltration capacities of the different units; then, evaluations of the interactions between the different classes were performed. The first step that was adopted in this methodology focused on describing the control factors (Table 1), while the second part was devoted to classifying and acquiring all of these factors, followed by assigning weights and integrating them [23]. Mapping the thematic layers necessitated the processing of a various remote-sensing data and digital images (Fig. 3) as well as extracting information from the digital versions of the existing maps and the field data (Table 1). The lithology of the study area was mapped from the digitization of a geological map at a scale of 1:100,000 in the GIS software. The slope map was obtained from a digital elevation model (DEM) of the study area at a resolution of 30 m using the spatial analyst tool in the ArcGIS software. The land-use map was generated from Landsat 8 OLI (Operational Land Imagery) imagery at a resolution of 30 m (dated July 23, 2023 LC08_L2SP_201038_20230723_20230729_02_T1) using supervised classification with the algorithm of maximum likelihood. The drainage-density map was referred to when using the drainage map, which was showcased by interpolating the cumulative length of the drains that were extracted from the DEM (30 m) in the ArcGIS software. The methodology that was adopted for identifying the wetlands in the Essaouira synclinal basin included two steps (Fig. 4); this led to the determination of two types of moisture. From the Landsat 8 OLI imagery, we generated the surface soil moisture (SSM) map using the normalized difference water index (NDWI) that was obtained from the combination of the original radiometric data (namely, the visible and near-infrared bands). The NDWI also included estimating the percentages of water in the plants [24]. The deep soil moisture (DSM) map was generated using the top-hat transformation index. To map the lineament criteria, we started with the treatment of the noisy appearance of the image by reducing any shimmers; this reduction was done using the "Lee" filter on the ENVI program. The next step was to identify the existing discontinuities in the basin, which was done by applying directional filters after a principal component analysis (PCA). In this study, 0°, 45°, and 90° directional filters were applied in order to facilitate the manual extraction of the different structural lineaments. The manual extraction was done by digitizing the lineaments that were obtained after the filtering was carried out using the ArcGIS software [25].

Table 1. Descriptions of recharge control factors

Thematic layers	Materials used	Justification of indicators	Source
Geology	Geological map at scale of 1:100,000	Lithological characteristics provide important information on soil-infiltration capacity; they determine rock's compactness and degree of alteration as well as presence of diaclases and joints	[26]
Lineament	Landsat 8 OLI	Lineament density indicates highly fractured zones that represent permeable zones; fracture density mapping was therefore very useful for identifying potential recharge zones	[26]
Slope	SRTM DEM (with 30 m resolution)	Higher slopes accelerate runoff, reducing water infiltration; conversely, low-slope conditions are ideal for accumulation and infiltration	[26]
Drainage density	SRTM DEM (with 30 m resolution)	Drainage system influences nature and structure of soil, slope angle runoff, infiltration, soil moisture, and vegetation type	[23]
Land use	Landsat 8 OLI	Most important hydrogeological factors are vegetation and impermeable areas – impervious areas (buildings, roads, etc.) considerably retard recharge process; contrarily, vegetation cover improves recharge, limits runoff, and favors infiltration of water	[23]
Soil moisture	Landsat 8 OLI	Soil moisture is very important parameter for determining soil's water balance since it corresponds to quantity of water stocked in superficial part of soil (about 5 m) or at deeper level (soil root zone)	[24]

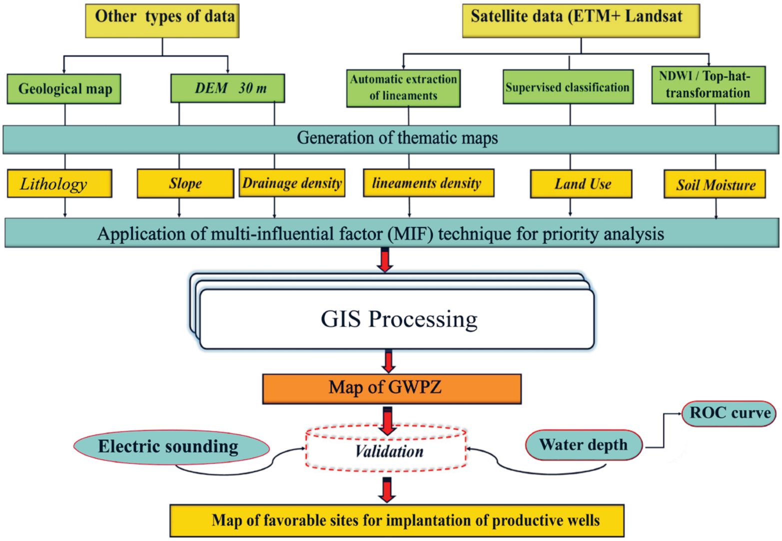

Fig. 3. Organizational methodology that was adopted in study area

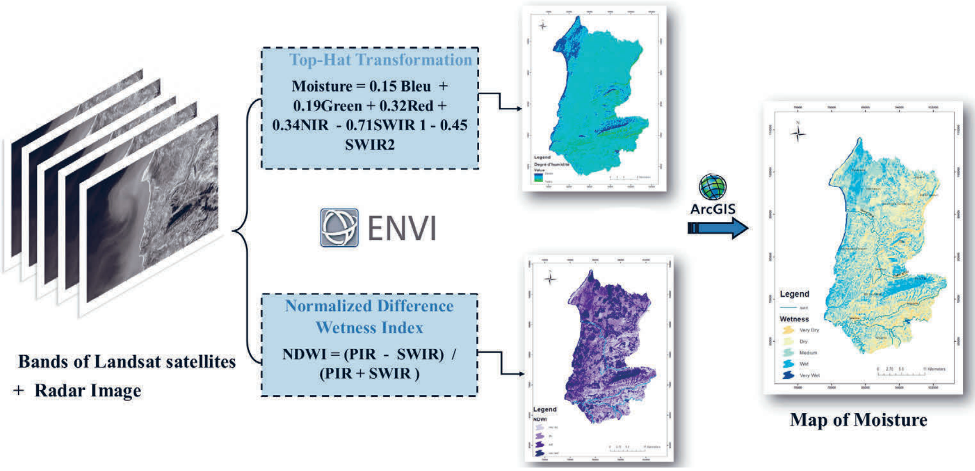

Fig. 4. Combination of maps that were generated by NDWI and top-hat transformation for creating final soil-moisture map of study area

4.2. Multi-influencing factors (MIF) Technique for Analysis of Priorities

The multi-influencing factors (MIF) technique that was adopted in this study is based on a “criteria Hierarchy” method that was inspired by a technique that was adopted in previous studies that were realized in the Mandal River basin in India as well as in the western part of Bengal, India [16, 23, 27]. The method of weighting that is adopted in the MIF technique was based on a literature review that considered the interrelationships and interdependencies among different influencing parameters. Using this method, weights are assigned to each factor depending on its importance regarding their influence on reservoir formation as well as the infiltration capacities of the different units. The interrelationships of those factors that influence groundwater potential are illustrated in the schema of interactions in Figure 5. From this schema, two types of effects can be identified based on the degree of the influence of each factor as related to the others: major effects, and minor effects. Each major variable receives a score of 1 wt., and each minor variable receives a score of 0.5 wt. (Table 2). Then, the weight of influencing factor is calculated using the following equation:

$$S = \frac{A+B}{\sum\left(A+B\right)} \cdot 100 \tag{1}$$

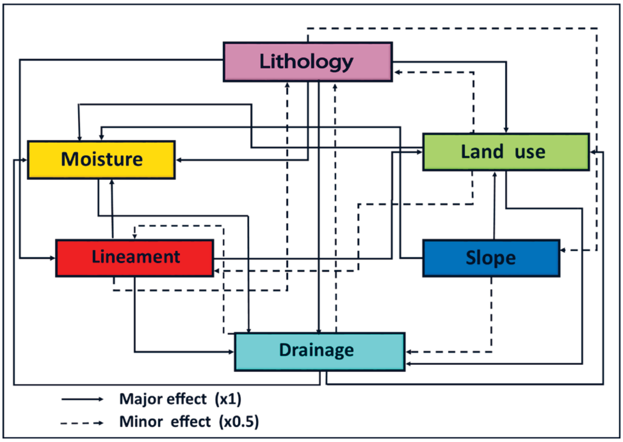

Fig. 5. Schema of interactions among factors that influence recharge

Table 2. Major and minor effects of influencing factors as well as proposed relative rates and score

Influencing factor	Major effect	Minor effect	Relative rate (A+B)	Scores of influencing factors
Lithology	1 + 1 + 1 + 1	0.5	4.5	26
Lineament [km/km²]	1 + 1 + 1	0.5	3.5	20
Land use	1 + 1	0.5 + 0.5	3	17
Slope [degree]	1 + 1	0.5	2.5	14
Drainage [km/km²]	1 + 1	0.5 + 0.5	3	17
Moisture [%]	1	0	1	6
Total	–	–	Σ17.5	Σ100

Subsequently, the weights of the individual factors were divided by the number of subclasses and distributed among the sub-classes [27]. For the first highest-influencing subclass (Si_1), the same weight as the concerned parameter (Pi) is assigned; for this, the following formula was adopted:

$$Si_1 = Pi \tag{2}$$

Next, factor (Pi) is divided by the total number of sub-classes (nT); the obtained value (Ai) is then subtracted from the most influential sub-class (Si_1), and the resulting value is attributed to the next sub-class (Si_2). This procedure is followed for each subsequent subclass. The following formula was adopted to realize this procedure:

$$Si_2 = Si_1 - \frac{Pi}{nT} \text{ when } Ai = \frac{Pi}{nT} \tag{3}$$

Similarly, Si_3 is the result of the subtraction of Ai from Si_2. For the following subclasses, the same weight-assignment procedure will be repeated (Table 2).

4.3. GIS Processing

The GIS software was used to create the groundwater-potential map through the integration of six thematic maps (Table 3) using the following formula:

$$\mathrm{GWPZ} = \mathrm{GLW} \cdot \mathrm{GLS} + \mathrm{LMW} \cdot \mathrm{LMS} + \mathrm{LUW} \cdot \mathrm{LUS} + \mathrm{SW} \cdot \mathrm{SS} + \mathrm{DDW} \cdot \mathrm{DDS} + \mathrm{MW} \cdot \mathrm{MS} \tag{4}$$

GWPZ signifies the groundwater potential zones. The notations are defined as follows:

GLW – the weight of the geology; GLS – the score of the theme;
LMW – the weight of the lineament; LMS – the score of the theme;
LUW – the weight of the land use; LUS – the score of the theme;
SW – the weight of the slope; SS – the score of the theme;
DDW – the weight of the drainage density; DDS – the score of the theme;
MW – the weight of the moisture density; MS – the score of the theme.

Table 3. Thematic layers with subclasses, their ranks, and their weightages

Factors	Parameters	Description	Theme weighted	Score
Lithology	Dune sandstones, conglomerate, shell limestone	Excellent	26	26
	Dolomite, dolomitic, limestone, gypsum, and anhydrite	Good		20
	Marly-limestone and dolomitic limestone	Good		14
	Alternation of calcareous marls and clays	Low		8
	Silty argillite and doleritic basalt	Low		2

Table 3. cont.

Lineament [km/km^2]	[0.2–0.6]	Low	20	20
	[0.6–1.0]	Very low		15
	[1.0–1.6]	High		10
	[1.6–3.2]	Very high		5
Land use	Water and rivers	Excellent	17	17
	Agricultural land	Good		13
	Dense forest	Good		9
	Clear forest	Moderate		5
	Barren land and urban	Low		1
Slope [degree]	[0–5]	Excellent	14	14
	[5–10]	Good		11
	[10–20]	Low		8
	[20–40]	Low		5
	[40–58]	Low		2
Drainage [km/km^2]	[0–65]	Excellent	17	17
	[65–130]	Very good		13
	[130–195]	Good		9
	[195–260]	Moderate		5
	[260–325]	Low		2
Moisture [%]	[7; 100]	Excellent	6	6
	[−18; 7]	Good		5
	[−31.2; −18]	Low		4
	[−46.05; −31.2]	Low		3

4.4. Validation of Findings of Groundwater Potential Zone

The validation procedure of the thematic potentiality map is based on the exploitation of the data; this is not integrated as criteria in the spatial modeling of the groundwater potentiality, but these parameters condition the potentiality of the presence of water. Indeed, these parameters represent an indicator of exploitability for this study that correspond to the depth of the water that was used to draw the ROC curve. The piezometric levels and geophysical data were also used to ensure the good validation of the approach that was used in this study.

5. Results

5.1. Influencing Factors for Groundwater Potentiality

Soil Moisture

Through the combination of the maps that were generated by the NDWI and the top-hat transformation (Fig. 4), we obtained the final soil-moisture map of the study area (Fig. 6); according to the degree of the soil moisture, we obtained four classes: "very dry," "dry," "medium," and "wet." The hydrogeological descriptions of these classes are recorded in Table 3.

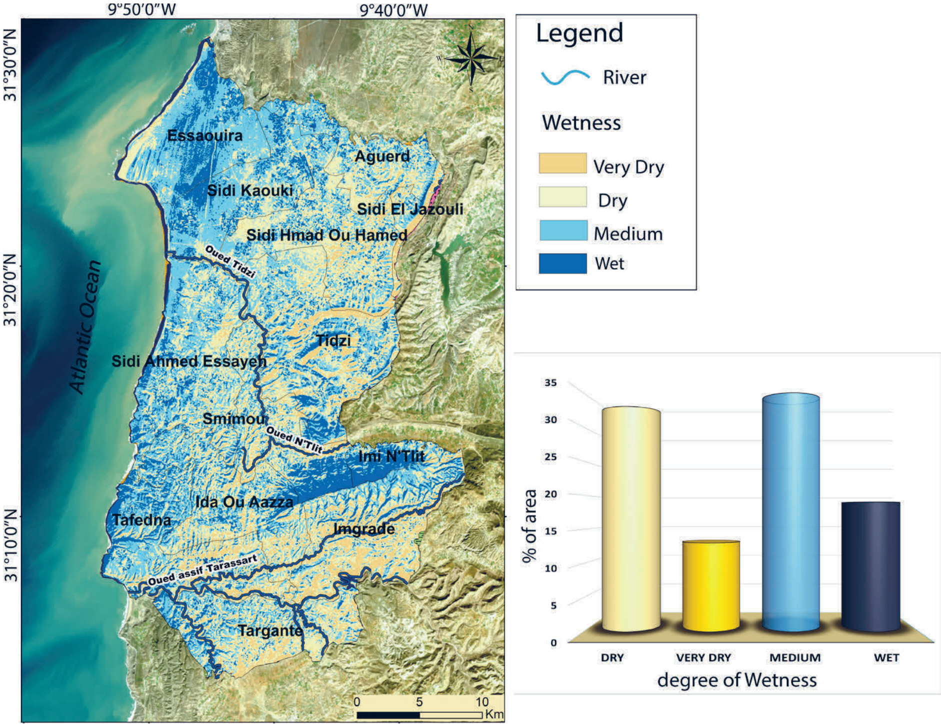

Fig. 6. Map of moisture soil of study area and degree of wetness of each class

Lithology

The groundwater flow depends on the nature of the rocks (specifically, their degrees of porosity and permeability), which differ from one rock to another [28]. The most important parameter in groundwater recharge is the formation of exposed rock [3]. The lithology of the study area consists largely of loose Pliocene-Quaternary formations (57%); these formations have a very good permeability for groundwater recharge, and they are very conducive to excellent groundwater potential. They were assigned the highest MIF weighting score among the other sub-factors (Table 3). The rest of the terrain in the study area is generally marked by impermeable carbonate formations that are affected by intense fracturing; these provide good groundwater flow. From this geological map (Fig. 7), we can generally identify five main homogeneous geological units (Table 4). The hydrodynamic characteristics and the hydrogeological interpretations of these geological units are recorded in the table.

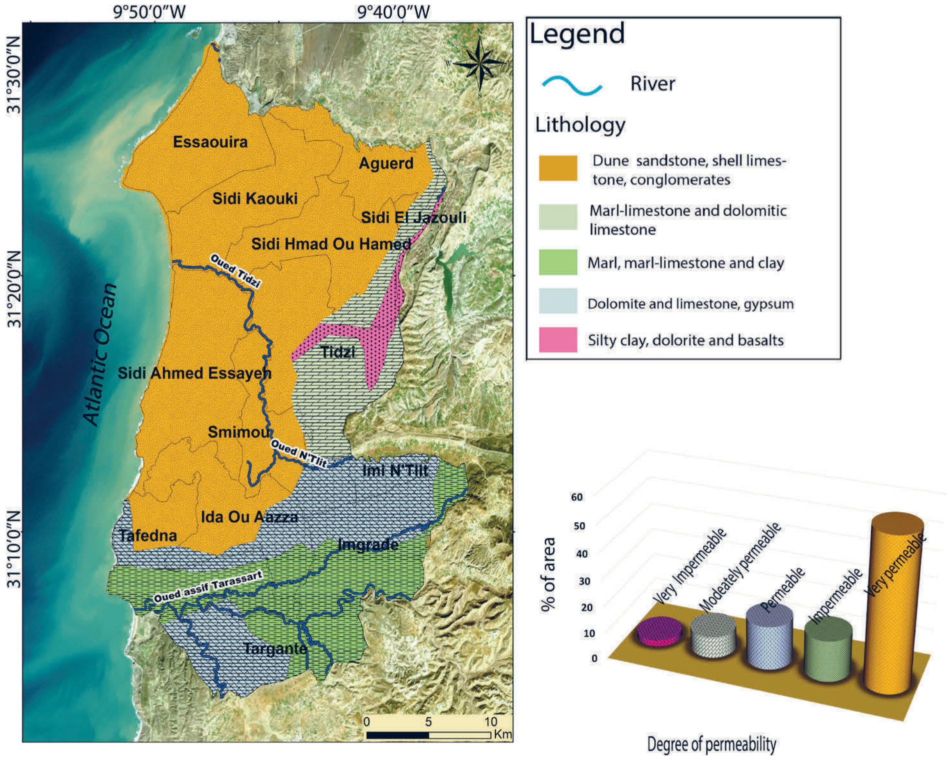

Fig. 7. Lithology map of study area and area in percentages of degrees of permeability of geological formations

Table 4. Hydrogeological classification of lithology

Unit	Description	Hydrogeological properties
Sandstone dunes, conglomerate (unconfined aquifer of Pliocene-Quaternary)	Detrital sediments are very permeable, which improves recharge of aquifers by rainwater and, thus, promotes implantation of wells	Excellent
Dolomite, limestone-dolomitic, gypsum, and anhydrite (Jurassic aquifer)	These formations ensure infiltration of water through intense fractured levels, including fault of Cap Tafelney (NNE-SSW) that resulted from Jurassic distension	Good

Table 4. cont.

Unit	Description	Hydrogeological properties
Marly-limestone, calcaro-dolomitic (confined aquifer of the Turonian)	Infiltration of water is through fractures; indeed, dolomitic limestone of this aquifer is affected by fracturing N110, which promotes the recharge of aquifer	Good
Dolomitic limestone, marly clay, siliceous limestone (Lower Cretaceous aquifer)	These formations are impermeable and less fractured, which allows for limited water infiltration into aquifer	Low
Silty clays, doleritic basalts (Triassic aquifer)	These saliferous Triassic formations are quite impermeable by nature, which prevents infiltration of water	Low

Slope

Surface water intrusions are directly influenced by the inclinations and degrees of the slopes. The present study area was classified into five slope classes: [0–5°], [5–10°], [10–20°], [20–40°], >40° (which are, respectively, "very low," "low," "medium," "high," and "very high." An extreme degree of slope can be observed in the eastern and southeastern parts of the basin; this factor is inversely proportional to the recharge. A high hydrogeological property was given to the lowest slope class, followed by the moderate classes (Fig. 8).

Land Use (LU)

The land-use map (Fig. 9) informs us about the landscape units that characterize our study area; through this, we can know the state of the environment that can be crossed by rainwater that contributes to the recharge of the aquifer. Various LU features were identified according to their influence on the recharge. The LU map includes water, forests, agricultural land, barren land, and urban areas (Table 5).

Table 5. Hydrogeological classifications of land-use types

Unit	Description	Hydrogeological properties
Water	This is represented in study area by permanent river and streams that contribute to supply of aquifer during rainy seasons [23]	Excellent
Cultivated areas	Promote infiltration of rainwater; due to limited evapotranspiration, these cultivated areas further improve recharge of aquifer [23]	Good
Forests	These units are characterized by great dispersion of vegetal cover, which favors infiltration [23] and, consequently, confinement of groundwater in vegetal zone	Moderate/Good
Barren land and urban	These components retard recharge of aquifer since they represent impermeable surfaces that prevent infiltration and promote stormwater runoff [23]	Low

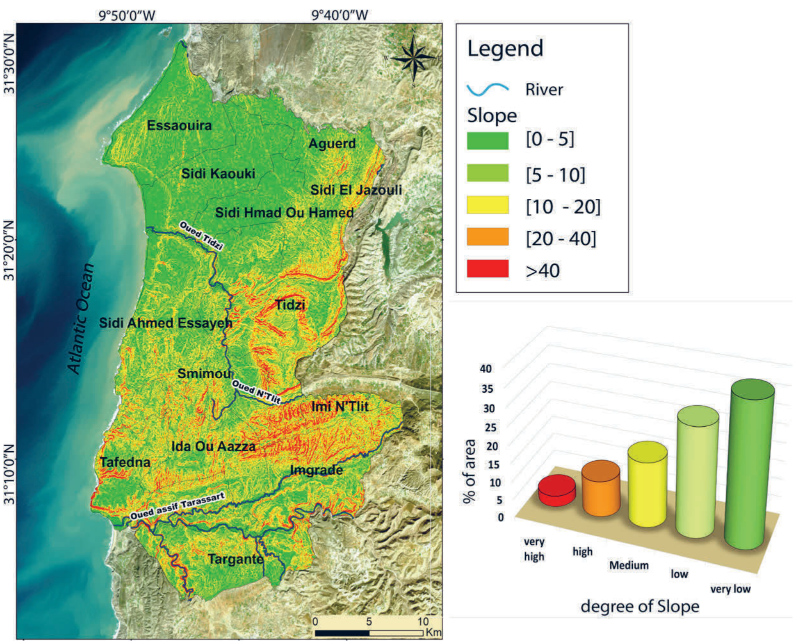

Fig. 8. Slope map and percentages of classes in study area

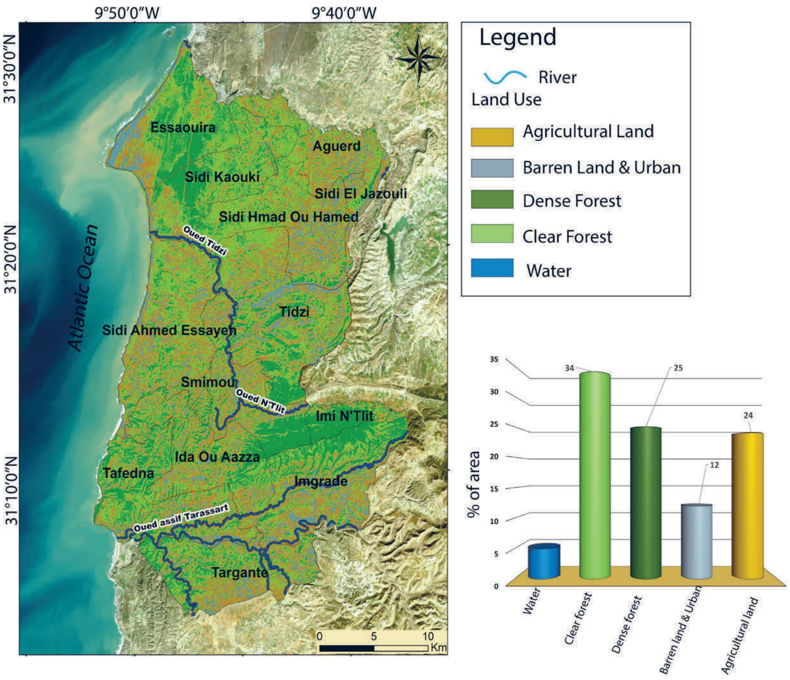

Fig. 9. Land-use map and area percentages in study area

Lineaments

According to previous studies [29–32], lineaments are a significant factor when identifying groundwater-recharge zones; these influence the flow and storage of this groundwater, as they represent the fractures, faults, joints, cleavages, and other discontinuous areas through which water can infiltrate. Thus, a higher lineament density (represented as red in the map in Figure 10) indicates a higher infiltration rate and, consequently, a permeable area that reveals a good potential recharge area for groundwater, the existence of a potential reservoir, and zones with very low lineament densities. Those zones that are represented as green in the map constitute areas that are unfavorable for the presence of a reservoir.

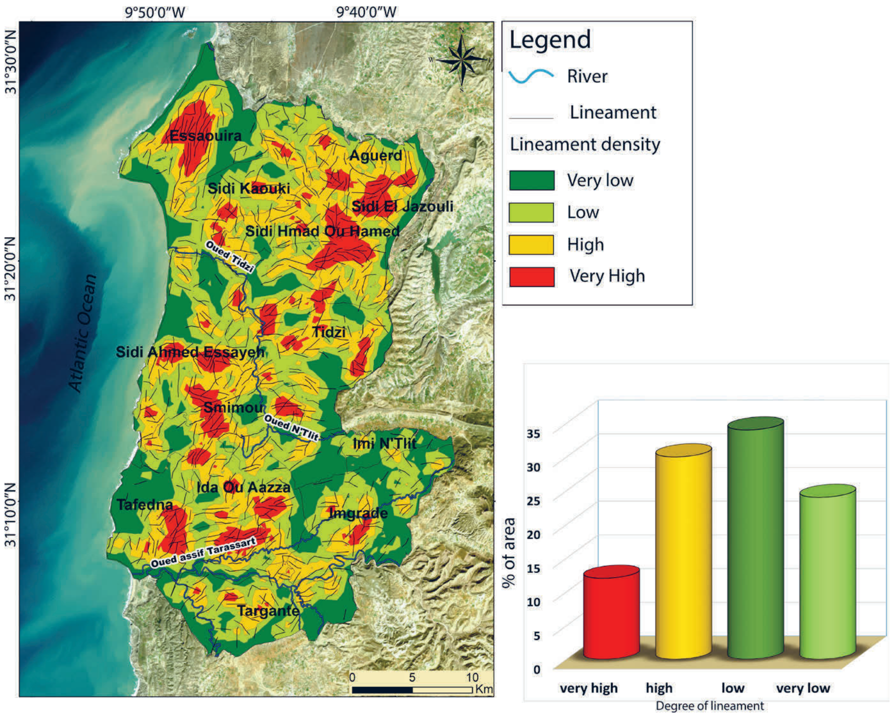

Fig. 10. Lineament density map and percentages of degrees of lineaments in synclinal basin

Drainage Density

The study of a drainage network is paramount to any research study in hydrogeology; drainage density represents the dynamic expression of geology, slope, geomorphology, and precipitation [33]. The densest areas are represented as orange and green in the drainage density map in Figure 11. This drainage density is inversely proportional to the permeability; areas with high densities correspond to impermeable regions that are characterized by pronounced relief; this promotes runoff.

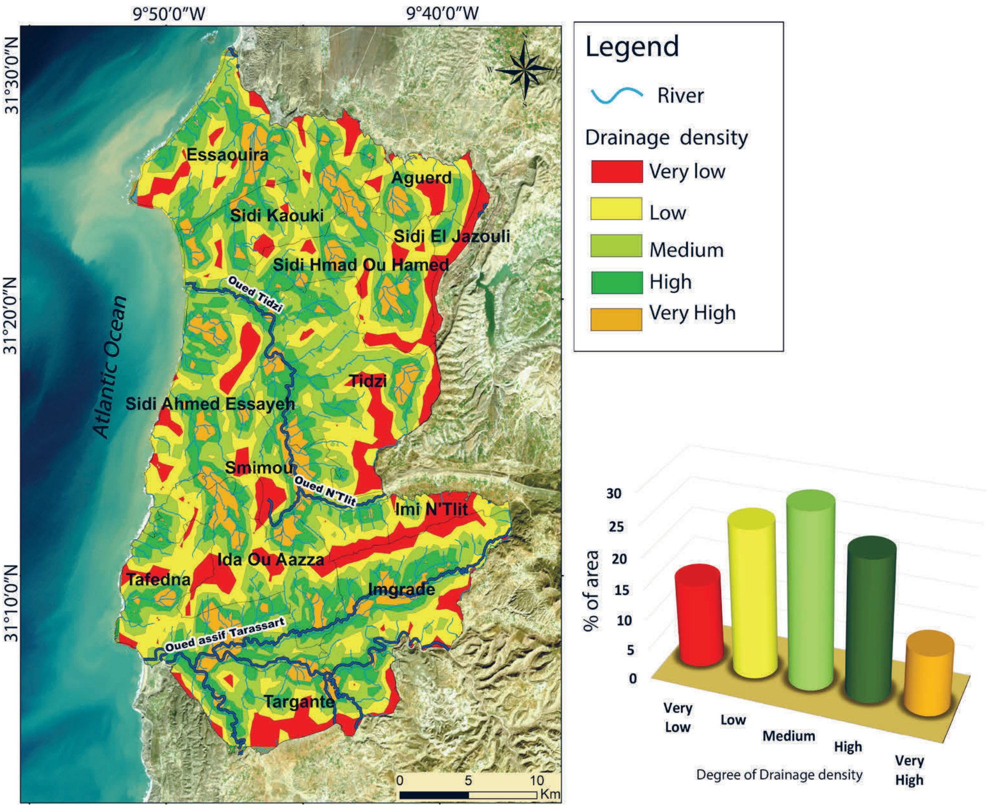

Fig. 11. Map of drainage density of study area and areas in percentages of degrees of drainage density

Delineation of Groundwater Potential Zone

The groundwater-potential-zone map in Figure 12a was created using the weighted index overlay analysis by appending the weight value of each factor. Applying the GIS programs, all the layers were integrated in order to find the groundwater-potential zones; these areas were grouped into four classes: “high,” “moderate,” “low,” and “very low,” with percentages of 30, 51, 18, and 1%, respectively (Fig. 12c). The “high” recharge zones are shown in blue on the map; they are primarily located in highly permeable formations, such as the fossilized Pliocene-Quaternary dunes in the north and center parts of the study area. These areas are also marked by dense vegetation cover (Fig. 12b) and gentle slopes with high densities of lineaments, providing favorable conditions for the accumulation of rainwater in aquifers.

Concerning the zones of moderate potentiality, they represent the quasi-totality of the basin, with a significant concentration in the center and southern parts of the basin. These essentially appear in the detrital formations of the Quaternary as well as in the fissured carbonate formations of the Cretaceous; these moderate potential areas are marked by relatively low slopes and moderately low fracture densities; the infiltration in these areas is susceptible to be moderate.

The unfavorable and very unfavorable recharge zones correspond to the low and very low potential zones and are located largely in the eastern part of the study area (with some disseminated zones appearing in the south). These areas are characterized by low fracture densities and very high slopes that prevent the infiltration of rainwater; these traits considerably retard the groundwater recharge.

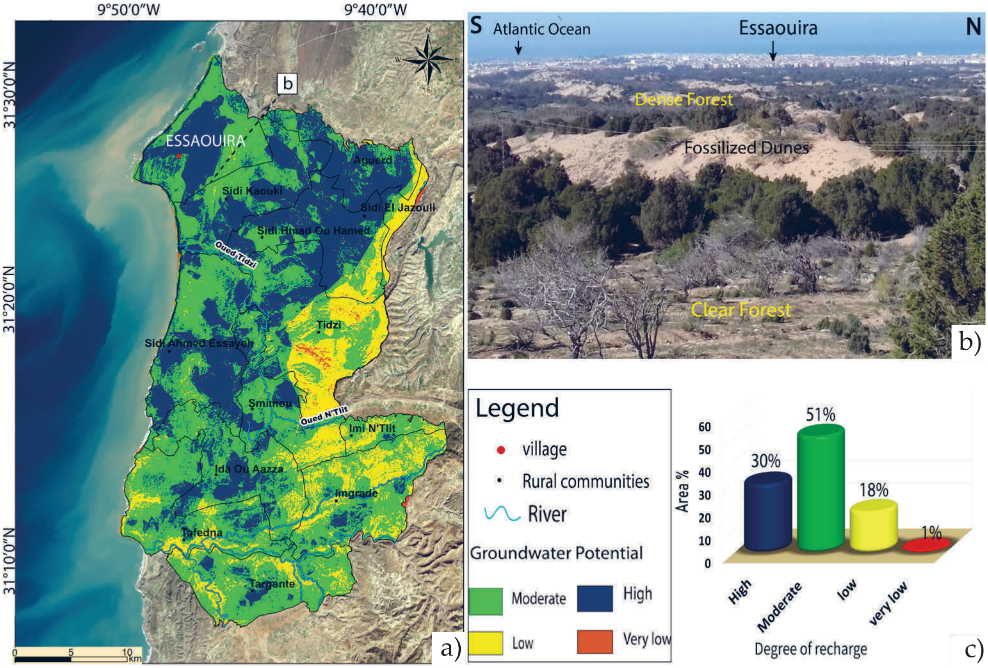

Fig. 12. Map of groundwater-potential zones of Essaouira syncline (a); panoramic view of city of Essaouira (b); areas in percentages of degrees of recharge (c)

5.2. Validation of Results

Validation by Water-depth Level and ROC Curve

The validation of the groundwater potential map (Fig. 13a) was an important task in this study; this was based on an analysis of the receiver operating characteristic (ROC) curve (Fig. 13c) from water levels measured in meters below ground level (mbgl) at 98 existing wells in the study area (Fig. 13b). The water depths varied from 2.3 to 71.3 mbgl. There were four distinct classes for all water levels: very low (<20 mbgl), low (20–40 mbgl), high (40–60 mbgl), and very high (>60 mbgl). A low water depth relative to the soil level indicates extreme groundwater potentiality, while a high-water depth level signifies low groundwater potentiality. An attempt was made to incorporate the water levels with the groundwater potentiality; then, an agreement was calculated by combining the water level values and the groundwater potentiality data according to the agreement results. The ROC curve was plotted using the SPSS software, and the area under the ROC curve (AUC) was found to be 0.693; this indicated the good predictive ability of the MIF method.

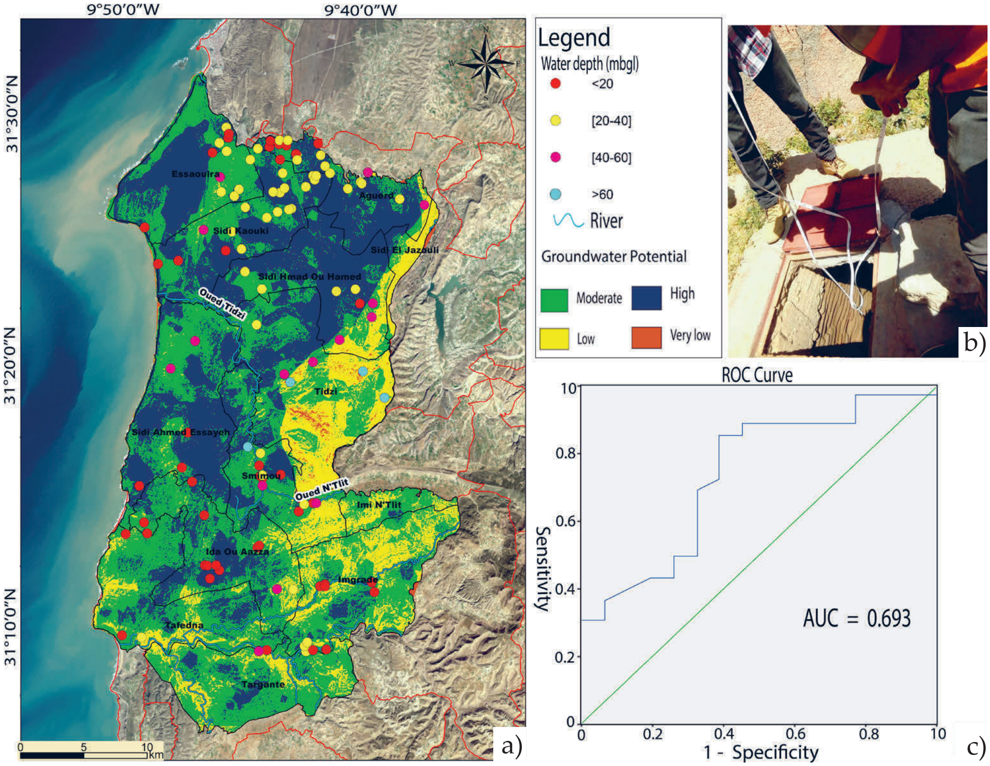

Fig. 13. Validation map with water depths of existing wells in Essaouira synclinal basin (a); measuring water depth at well in Essaouira synclinal basin (b); ROC curve of validation of MIF method (c)

Validation by Piezometric Level

To validate this study, we superimposed the piezometric map from Bahir et al. [4] (which was conducted in three aquifers of the Essaouira synclinal basin) with the map of the potential recharge zones (Fig. 14). To the north of the study area, we can see the Pliocene-Quaternary aquifer (Fig. 14 – A), which has a higher piezometric level in its eastern part (200 m) than in its western part (40 m). The aquifer is recharged from upstream, with a flow direction from the southeast to the northwest.

The Barremian-Aptian aquifer (Fig. 14 – B) presents isopiezometric contours at altitudes that range from 360 m upstream (the eastern section) to 200 m downstream (the western section), with a flow direction from SE to NW; this is imposed by the uplift of the lower Cretaceous substratum in the eastern part. The piezometric data for the Hauterivian aquifer (Fig. 14 – C) was used to draw isopiezometric contours with altitudes that varied between 120 and 280 m, with an overall flow direction from NE to SW.

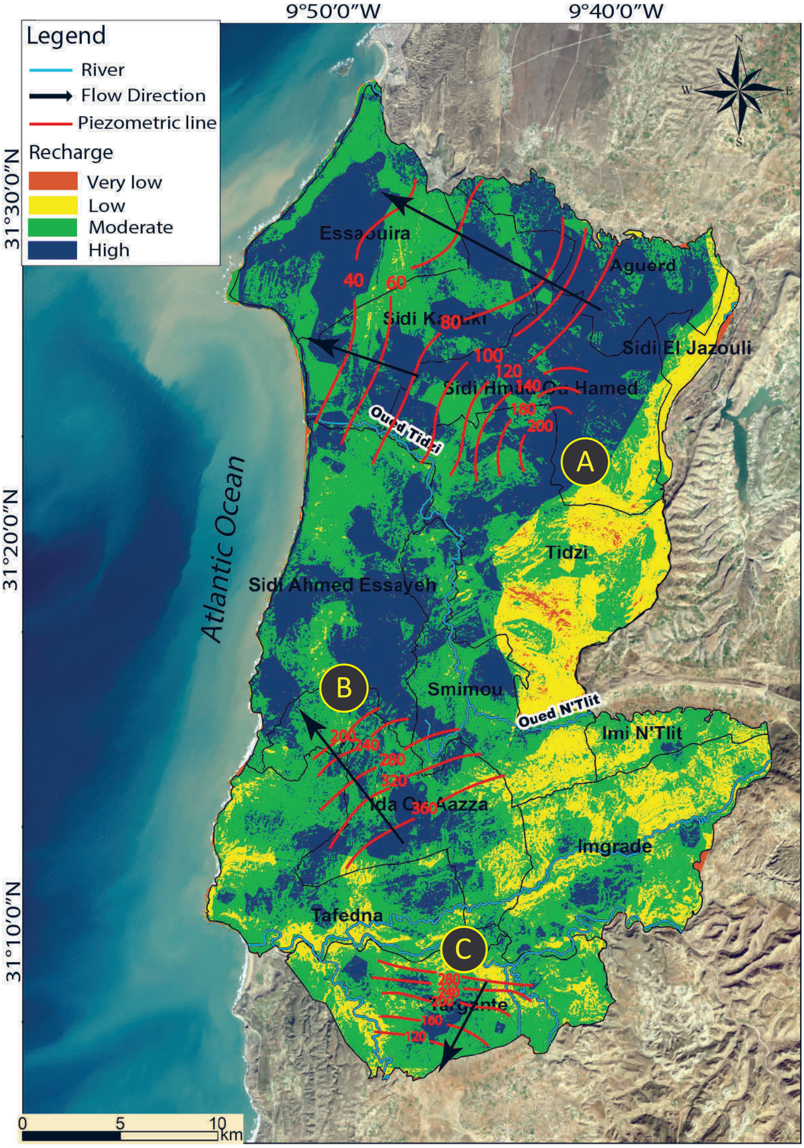

Fig. 14. Piezometric map of synclinal basin superimposed on map of groundwater potential zones: A – Pliocene-Quaternary aquifer; B – Barremian-Aptian aquifer; C –Hauterivian aquifer

From the directions of the groundwater flows in the three examined aquifers, we can deduce that the water-fed areas correspond to the potential recharge zones that were identified by the MIF model coupled with GIS and remote sensing. This represents a kind of validation for the model that was used in this approach.

Validation by Electrical Soundings

On June 16, 2023 (Fig. 15c), under the supervision of the GEOANALYSIS Morocco engineering office, electrical soundings from the piezometric campaigns were carried out in the northern part of the study area using GER DETECTED and 16-channel water-imaging-detector equipment. This contributed to the tracing of the thickness map of the Turonian aquifer in this area (Fig. 15b). This map identifies the existence of underground basins that are precisely located in those areas with high groundwater potentials (Fig. 15a). Indeed, these areas represent the most favorable locations for implanting deep wells since they represent an ideal place for the accumulation of rainwater.

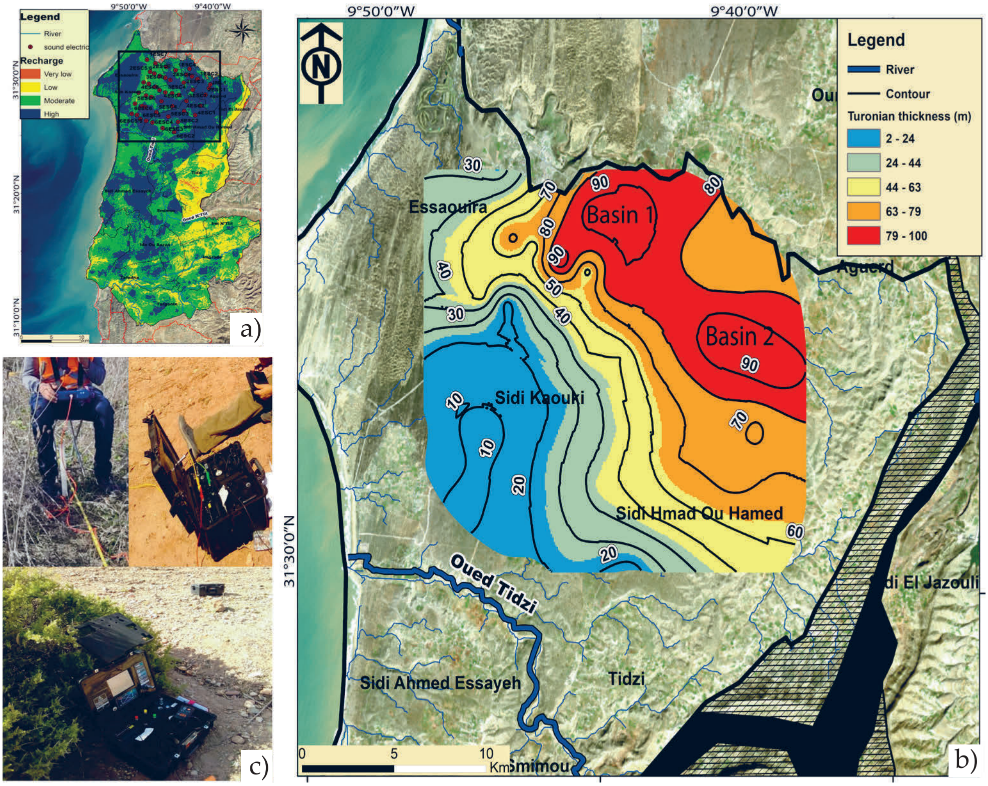

Fig. 15. Locations of electrical soundings in northern part of syncline (a); locations of underground basins in thickness map of Turonian aquifer (b); geophysical campaigns carried out in study area (c)

These basins, which have been identified by geophysics in the Turonian aquifer, reflect the validity of the map of the potential recharge area that was established by the multi-influence factor method coupled with the remote sensing and GIS software.

6. Discussion

In the present work, the combination of remote sensing, GIS, and the MIF technique has allowed us to obtain important qualitative information on the spatial distribution of potential recharge areas. The methodology that was used is based on the interconnections and interactions among many factors that affect groundwater flow compared to the AHP and MCDM methods, which are generally based on literature reviews and previous studies (which include a percentage of incertitude). Indeed, the MIF method has been largely used in the modeling studies of potential recharge zones for the implantation of productive wells.

The potential areas with "high" recharges are the most-searched areas because they are susceptible to holding considerable groundwater reserves. The study revealed that the areas with very high groundwater potentials are generally located in the north of the study area as well as in the center (largely at the impermeable formations of the detrital Pliocene-Quaternary sandstone dunes, conglomerates). These areas are characterized by a high density of fracturing and flat-to-gentle slope conditions and are mainly parts of cultivated lands and forest areas; this promotes the infiltration of rainwater. These areas combine the conditions for the accumulation of groundwater and, consequently, provide the formations of important reserves.

The potential zones that were identified in the recharge map were used to identify and map the most-favorable sites for implanting productive wells. This is based on the results of previous studies that have suggested that the most productive wells should be located at the intersections of faults and at kilometric faults considering the areas of high potentiality [34, 35]. After superimposing the lineament map and the potential areas of the Essaouira synclinal basin, more than 50 susceptible zones for implanting future productive wells at the unconfined aquifer level were mapped (Fig. 16).

Validating the potential zone map was a primordial step for this study; this was done before the mapping of the zones that were favorable for implanting productive wells. This validation procedure was based on two parameters of exploitability that corresponded to the water and piezometric levels; these were not integrated as criteria in the spatial modeling of the groundwater potential. However, they conditioned the presence or absence of drilling. Indeed, 98 wells were used to validate the obtained results using the ROC curve, which indicated that the MIF method had a good prediction level of 0.693.

Without overlooking the role of the geophysical data that was obtained from the results of the conducted electrical soundings in the northern part of the study area, it is necessary to have a global idea of the depths of the existing aquifers. In order to gain better accuracy when validating the recharge map that was obtained from the MIF and remote-sensing methods, the integration of the electrical prospecting data allowed us to identify those basins that offered good accumulations of groundwater at the areas of high potentiality that were identified via MIF.

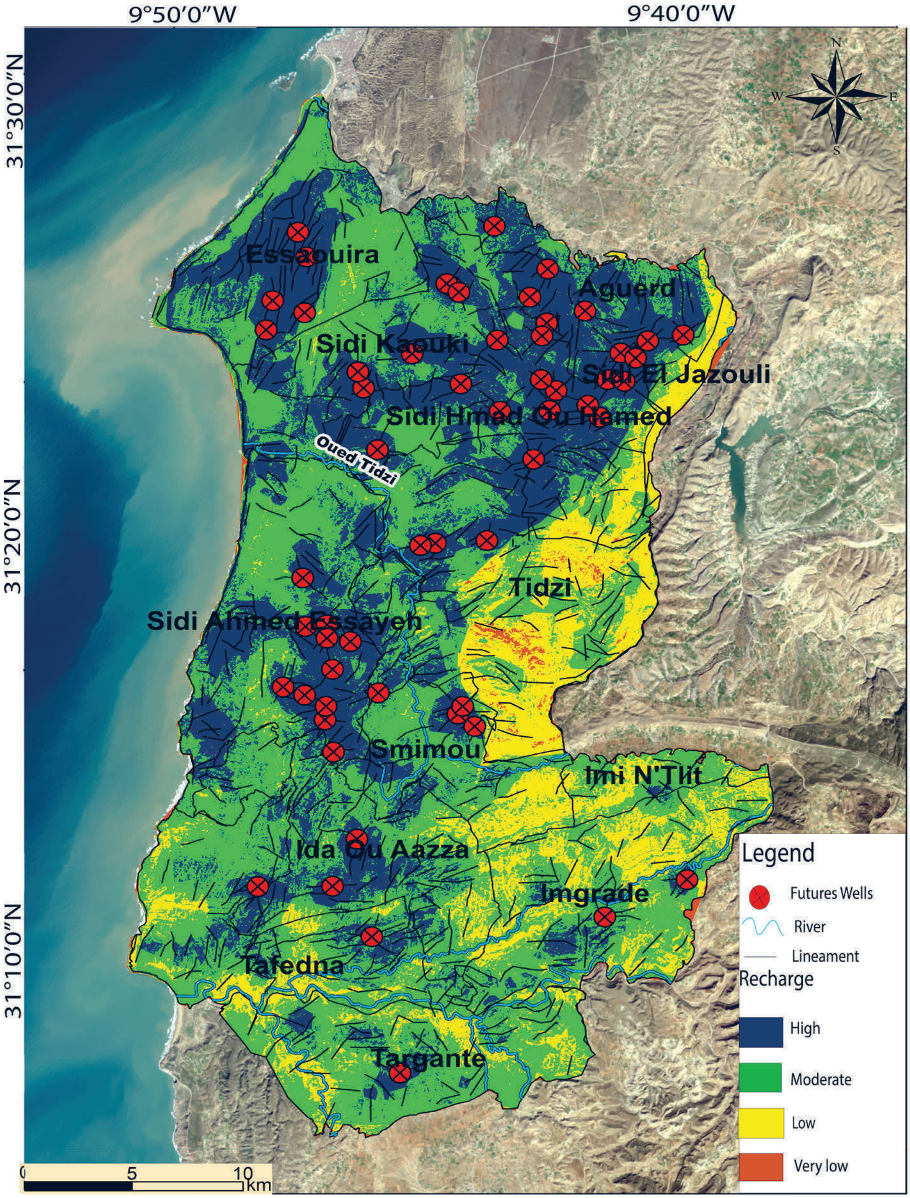

Fig. 16. Sites favorable for implanting productive wells in study area

The conventional methods that were used in previous studies [4, 5] for identifying potential areas of recharge in the Essaouira synclinal basin were based on isotopic studies, which allowed the authors to estimate the recharge areas of the aquifers. According to the results of the oxygen-18 isotopic analyses that were conducted in these studies, each aquifer presented an average oxygen-18 concentration of (−4‰ δ^{18}O vs. SMOW for the Pliocene-Quaternary waters; those aquifers of the Turonian waters averaged around −5‰ δ^{18}O vs. SMOW). This represented the local recharge of these aquifers; increasingly, the values grew more negative as the altitudes of the recharges increased [36]. In comparison with the above-mentioned conventional methods for groundwater research, the new techniques that were used in this study (based on GIS processing coupled with remote sensing) offered significant advantages. Indeed, the used method made it possible to reduce prospecting work in favorable areas and to more precisely identify the sources of information and complementary data for the hydrogeological investigation. In addition, this approach made it possible to reduce exploration-drilling time – particularly over large areas. For these reasons, the method that was used in this work could be considered to be the initial basis for other prospective studies such as isotopy and geophysics [37].

Despite the effectiveness of the MIF model in delineating potential recharge zones, it has two limitations. The first is that it does not explicitly integrate the precipitation factor, which plays a crucial role in the aquifer-recharge process and allows for accurate identification from a quantitative perspective. However, the advantage of the qualitative approach that we used is that it is not affected by short-term climatic variations and changes; this allows for a more stable evaluation that is less vulnerable to annual precipitation fluctuations. The second limitation is that the weights that are assigned to the different parameters can vary depending on the researchers' level of knowledge. Therefore, a miscalculation could lead to the inaccurate identification of potential recharge zones. Nevertheless, this approach remains very useful for guiding future research and water-resource-management measures, and its results have been supported by geophysical and piezometric data in order to increase their reliability.

7. Conclusion

This study confirmed the importance of combining geospatial methods (GIS and remote sensing) with the MIF technique for delineating potential groundwater zones. The obtained map of the potential recharge zones shows that the spatial distribution of potential groundwater zones in the basin is not homogeneous; these are mainly located in the northern and central areas of the basin (and appear in a fragmented manner in the southern part). High-potential zones cover 30% of the Essaouira synclinal basin. These zones have enabled us to identify the most-favorable sites for more than 50 future production wells. In order to respond to the growing demand for authorizations to drill wells in the rural and semi-rural areas of the study zone due to demographic increases, the identification of favorable drilling zones that was carried out in our study will allow for effective water-resource management. This will ensure a stable supply despite climatic variations and promote the agricultural and economic development of the region.

The exploitation of geophysical data is a crucial step that confirmed the reliability of the results and the effectiveness of the model that was used in this approach. For this reason, we aim to complete geophysical surveys in the rest of the synclinal basin in order to obtain a more-precise understanding of aquifer thicknesses and ensure a more-comprehensive validation that covers the entire study area.

List of abbreviations

ABHT – Agency of Hydraulic Basin of Tensift
AUC – area under ROC curve
DEM – digital elevation model
DSM – deep soil moisture
GIS – geographic information system
GWPZ – groundwater potential zones
MCDM – multi-criteria decision making
MIF – multi-influencing factors
MSW – municipal solid waste
NDWI – normalized difference water index
OLI – Operational Land Imager
PCA – principal component analysis
ROC – receiver operating characteristic
SSM – surface soil moisture

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CRediT Author Contribution

A. S.: investigation, methodology, writing – original draft.
A. A.: validation – review & editing, supervision.
A. A. L.: validation – review & editing, supervision.
F. A.: investigation, methodology, writing – original draft.
M. S.: investigation, methodology, writing – original draft.
K. S.: investigation, methodology – original draft.
E. M.: investigation, methodology – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data supporting this study were provided by two organizations: GEOANALYSIS Morocco and the Agence du Bassin Hydraulique du Tensift (ABHT). GEOANALYSIS conducted geophysical surveys at multiple locations to validate the study and provided the corresponding data, which are publicly accessible. ABHT provided water level measurements from several wells in the study area.

Use of Generative AI and AI-assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

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