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ÍNDICE

ABDELLAH KHOUZ, JORGE TRINDADE, PEDRO PINTO SANTOS, FATIMA EL BCHARI, SÉRGIO C. OLIVEIRA, RICARDO A. C. GARCIA, ASMA BOUGAYOU, MUSTAPHA IKIRRI, MOURAD JADOUD, SAID RACHIDI, AND BLAID BOUGADIR
Contributo de modelos estatísticos na avaliação da suscetibilidade a cheias na província de Essaouira, Marrocos
Contribution of statistical models in flood susceptibility assessment in Essaouira Province-Morocco

ASMA BOUGAYOU ; ABDELLAH KHOUZ ; FATIMA EL BACHARI; JORGE TRINDADE; MUSTAPHA IKIRRI; SIHAM AFRAOU; FARID FAIK; BLAID BOUGADIR
Avaliação do potencial de águas subterrâneas na área de Ait Abdellah com recurso à deteção remota e SIG
Assessment of groundwater potential in the Ait Abdellah area by using remote sensing and GIS

JOÃO CARRILHO, ABDELLAH KHOUZ, JORGE TRINDADE
Águas subterrâneas na governação do nexo Água-Energia-Alimentação em áreas periurbanas exteriores
Groundwater in the Water-Energy-Food nexus governance in outer peri-urban settlements

GUSTAVO DGEDGE, CELSO CHIVALE, JAIME MAGAIA, JORGE TRINDADE
Avaliação das áreas suscetíveis a cheias na sub-bacia do rio Revúboè, Moçambique
Assessing Flood Susceptibility Areas in the Revúboè river sub-basin, Mozambique

ANDREIA ALVES DA SILVA; LUÍS PEDRO ALMEIDA; ANTÓNIO H.F. KLEIN
Abordagem multiescalar baseada em dados de satélite para a análise de tendências da linha de costa em Portugal Continental
Satellite-driven multi-scale approach for shoreline trend analysis in Mainland Portugal.

ANDREIA ALVES DA SILVA, JORGE TRINDADE; JORGE ROCHA
Avaliação do perigo e da exposição à subida do nível do mar em Portugal Continental
Hazard and Exposure Assessment to Sea Level Rise in Mainland Portugal.

MOHAMED LOUAZANI, ABDERRAFIE EL MAKNISSI
Sistemas de gestão da água nos oásis saariano e o desafio da sustentabilidade face às alterações climáticas: estudo de caso dos oásis de Oued-Noun, sul de Marrocos
The Water Management Systems in Saharan Oases and the Sustainability Challenge in the Face of Climate Change: A Case Study of the Oued-Noun Oases, Southern Morocco.

RICARDO ACÁCIO XAVIER; PEDRO PINTO SANTOS; JOSÉ MANUEL MENDES
Risco de cheias em Moçambique: estratégias comunitárias para a redução da vulnerabilidade a partir de dois estudos de caso
Flood risk in Mozambique: communitarian strategies for vulnerability reduction from two case studies.

SUSANA PEREIRA; JORGE TRINDADE; ANDREIA ALVES DA SILVA; PEDRO PINTO SANTOS; EUSÉBIO REIS; JOSÉ LUÍS ZÊZERE
Perfis de risco de perigos costeiros em Portugal Continental à escala da freguesia
Risk profiles of coastal hazards in mainland Portugal at the civil parish level.

RECENSÕES

PAULO OSÓRIO
História do Pensamento Linguístico-Gramatical em Portugal e no Brasil de Batista, Ronaldo de Oliveira; Fernandes, Gonçalo; Bastos, Neusa Barbosa & Assunção, Carlos (eds) (2025).

JEFFREY CHILDS
Inventions of a Present: The Novel in its Crisis of Globalization, by Fredric Jameson

TESTEMUNHO(S)

HERMANO CARMO
Prémio Armando Rocha Trindade

Avaliação do potencial de águas subterrâneas na área de Ait Abdellah com recurso à deteção remota e SIG

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Asma Bougayou
Abdellah Khouz
Fatima El Bchari
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Siham Afraou
Farid Faik
Blaid Bougadir

Resumo

Este estudo avalia o potencial de águas subterrâneas na região de Ait Abdellah (Anti-Atlas Ocidental, Marrocos) através da integração de técnicas de Sensoriamento Remoto e SIG com o método Analytic Hierarchy Process (AHP). Dez fatores, incluindo densidades de lineamentos e drenagem, declive e permeabilidade, foram ponderados para gerar um mapa de potencial aquífero validado pela curva ROC (AUC = 80%). Os resultados identificam zonas de alto potencial associadas a características estruturais e litológicas, oferecendo um instrumento de apoio à decisão para a gestão sustentável de recursos hídricos em regiões áridas.

Palavras-chave: potencial aquífero; sensoriamento remoto; SIG; AHP; Anti-Atlas.

Abstract

This study assesses groundwater potential in the Ait Abdellah region (Western Anti-Atlas, Morocco) using Remote Sensing and GIS integrated with the Analytic Hierarchy Process (AHP). Ten factors, including lineament and drainage densities, slope, and permeability, were weighted to produce a groundwater potential map validated by the ROC curve (AUC = 80%). Results identify zones of high potential correlated with structural and lithological features, providing a valuable decision-support tool for sustainable water resource management in arid regions. The methodology offers an efficient, replicable framework for hydrogeological assessment in similar hard rock terrains.

Keywords: groundwater potential; remote sensing; GIS; AHP; Anti-Atlas.

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Introduction

In Morocco, water scarcity represents a major challenge, particularly in semi-arid regions like the Anti-Atlas, where the effects of climate change exacerbate the pressure on already limited water resources [1-3]. The Ait Abdellah region, located in the western Anti-Atlas, exemplifies these issues. Understanding a discontinuous aquifer within a fractured Precambrian basement covered by Paleozoic formations [4,5], along with complex tectonic constraints, is essential to analyze the distribution and dynamics of groundwater. In this context, the study aims to explore the use of remote sensing techniques (Sentinel-1 and Landsat 8 OLI images) combined with the Analytic Hierarchy Process (AHP) to map groundwater potential in this region [3, 6-11]. By using factors related to fracturing, such as lineament density and proximity, as well as hydrogeological and topographic variables, this study aims to enhance the understanding of local hydro-structural processes and map groundwater potential areas. The accuracy of the results was validated using the ROC curve [3, 7-11]. This multidisciplinary approach offers practical solutions for sustainable and effective water resource management, particularly by identifying zones suitable for future exploratory drilling.

Study Area

The study area, located in the southeast of the Kerdous massif in the western Anti-Atlas, covers 467 km² between latitudes 29°60'00"N and 29°40'00"N and longitudes 8°60'00"W and 8°40'30"W (Figure 1). Characterized by an arid climate, this region receives an average annual rainfall of 150 mm, with summer temperatures reaching approximately 30°C [8,12].

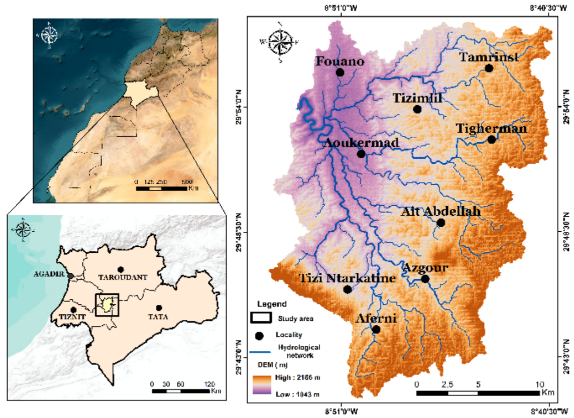

Figure 1. Geographical location of the study area.

The geology of the Ait Abdellah area is characterized by the presence of Upper Precambrian II conglomerates, discordant on the quartzites of Lower Precambrian II, as well as a basal series composed of siltstones intercalated with limestones, sandstones, and volcanic formations [13]. Specific formations, such as the silicified dolomites of Tamjout, with a thickness of 17 m, and the dolomitic sandstones, are also observed [13, 14]. Furthermore, the dominant layers belong to the Tata-Taroudant group. This series, with a thickness of 50 m, consists of an alternation of limestones, marls, and black dolomites [15-17]. Structurally, the Ait Abdellah area, located to the east of the Kerdous massif, exhibits a sub meridional Hercynian structure affecting the Precambrian basement and the Cambrian cover of the Issafen syncline to the east and the Fouano syncline to the west [5]. This region has recorded several major tectonic events, including the Eburnean, Pan-African, and Hercynian orogenies. The dominant structures are oriented N-S, particularly visible in the Ait Abdellah and Alma buttonholes, while the Fouano syncline shows NE-SW and NNW-SSE directions, with secondary orientations of E-W and NW-SE [4, 17]. From a hydrogeological point of view, the region has a discontinuous aquifer, resulting from the interaction between geological formations and the presence of faults, which increases the capacity of these formations to store and transmit water.

Methodology

The methodology (Figure 2) for modeling GWP is based on data collection (Souss Massa Hydraulic Basin Agency, water service, satellite images), and remote sensing analysis (OLI and Sentinel-1 images). Ten conditioning factors are selected (Intersection of the hydrographic network and lineaments, drainage density, lineament density, node density, drainage distance, lineament distance, distance to nodes, permeability, slope) and an inventory of 117 boreholes, wells, and drills. The application of the AHP method is based on a pairwise comparison matrix (Table 1), and the validation of results through field data and the ROC curve [3, 8, 11].

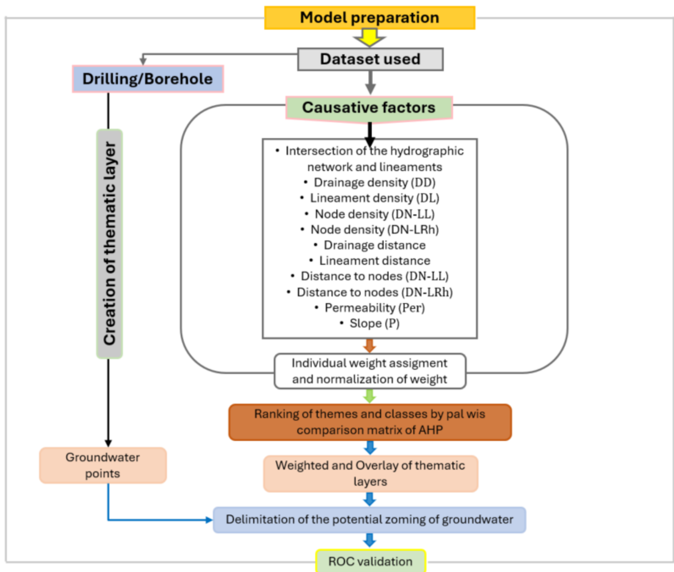

Figure 2. Schematic diagram of the methodology used.

The consistency of the matrix of selected factors for the groundwater study was verified using the consistency ratio (*CR*), as described in Equation 1 [18,19]. This ratio measures the degree of consistency by comparing the consistency index (*CI*) of the matrix with that of a random reference matrix, called the random index (*RI*).

$$CR = \frac{(CI)}{(RI)}$$

The consistency ratio (*CR*) evaluates consistency using the consistency index (*CI*), derived from Equation 2. The random index (*RI*) is calculated based on the average consistency index obtained from a sample of 500 randomly generated pairwise comparison matrices. The value of *RI* depends on the number of factors used.

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

The significant absolute eigenvalue of the pairwise comparison matrix, , is determined from Equation 3 [18]. The corresponding eigenvector, W, is associated with , while (i = 1, 2, ..., n) represents the weighted value of each factor, easily obtained from the matrix specified in equation (3) [19]. In this context, (n) denotes the number of factors conditioning groundwater [20, 21].

$$\lambda_{max} = \frac{1}{n}\sum_{w_i}^{n}\left(\frac{(AW)_i}{W_i}\right)$$

Fac										
Dr-D	1									
Dist=R	1/2	1								
D-L	1/3	1/2	1							
Dis-L	1/2	1/2	1/2	1						
L-N-den	1/3	1/2	1/2	1/2	1					
Dis-N	1/2	1/3	1/2	1/3	1/2	1				
D-N L/ Rn	1/3	1/2	1/3	1/2	1/3	1/2	1			
Dis-N Rn	1/2	1/4	1/2	1/3	1/2	1/3	1/3	1		
S	1/4	1/3	1/2	1/3	1/3	1/2	1/4	1/3	1	
Per	1/3	1/3	1/5	1/4	1/3	1/2	1/3	1/2	1/2	1

Table 1. Pairwise comparison matrix of the various factors influencing potential groundwater zones.

The consistency of all judgments is verified by ensuring that the AHP method suggests a consistency ratio (*CR*) of 0.1 or less. However, if the consistency ratio exceeds 0.1, it is necessary to revise, reevaluate, recalculate, and correct the judgments in the matrix by identifying the source of inconsistency and making adjustments until a *CR* of less than 0.1 is achieved [22]. In this study, the consistency index (*CI*) is calculated for an eigenvector of 10.87, with *n* equal to 10 and a *RI* of 1.49. The consistency ratio is calculated as *CR* = 0.065, which is below 0.1. Since the *CR* value is lower than the threshold (0.1), the consistency of the matrix is confirmed.

Once the thematic layers corresponding to the different evaluation factors have been developed, along with their normalized weights and respective individual classes, all these elements are then integrated into a GIS environment. This integration is carried out using the weighted overlay technique, which combines the different layers at the pixel level, according to Equation 4.

Where, **GWPA** = (Drainage density × 2,01) + (Lineament density × 1,31) + (Lineament node density × 0,98) + (Density of lineament hydrographic nodes × 0.96) + (Distance from rivers × 1.62) + (Distance from lineaments × 1.25) + (Distance from lineament nodes × 0,78) (Distance from lineament nodes to hydrographic network × 0.57) + (Slope (*S*) × 0,40) + (Relative permeability (*Per*) × 0,34) **(Equation 4).**

The ROC curve was used to assess the capability of the AHP method in mapping potential groundwater [3, 8, 23].

Results

The groundwater potential map, generated by the AHP method (Figure 3), was classified into five categories, ranging from very low to very high potential (Table 2). It shows that the very high potential class represents 19.52% of the studied area, with a predominance of zones with moderate potential. The very high potential zones are mainly located to the north of Tizi Mlil, west of Awkermad, and downstream, characterized by a high density of faults and nodes, as well as the permeability of geological formations near drainage networks. Favourable geological formations include limestones, dolomitic limestones, volcanic formations, conglomerates, and alluvial plains. The main localities, such as the lower basin, Awkermad, and Tizi Mlil, are located in areas with high to very high potential, thus recommending site selection near these zones to avoid water shortages. In contrast, areas with low potential are situated in mountainous terrain or in lithological formations with low permeability, such as rhyolites and ignimbrites. Avoiding these areas would reduce the costs of exploration and exploitation of groundwater resources. These results are consistent with those of [10] in the Tata basin, [3] for the Ifni basin, and [9] in the Kerdous region, which show similar trends.

GWPA	
Very low	22.35
Low	20.46
Moderate	19.17
High	18. 50
Very high	19.52

Table 2. Percentage surface of the GWPA class corresponding to each model.

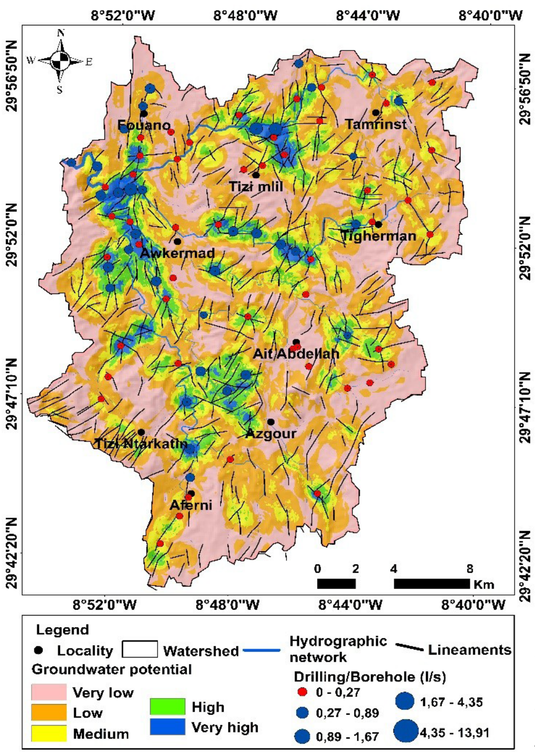

Figure 3. Groundwater potential in the watershed using the AHP method.

The validation of the potential results was carried out using the area under the ROC curve (AUC), as indicated by [3, 24, 25]. The ROC curve shows that the AHP method achieves a validation rate of 80%. These results are consistent with the studies of [7], [7] and [3]. Indeed, the ROC curve highlights the high predictive capability of the AHP method.

Conclusion

The mapping of groundwater potential areas in the Ait Abdellah was carried out by applying the Analytic Hierarchy Process (AHP) model, along with remote sensing techniques and Geographic Information System (GIS) technologies. Various geological, hydrogeological, and topographical factors were integrated to generate multiple thematic maps, which were then weighted and overlaid in a GIS environment. Weights were assigned based on the impact of each factor on water availability. The Groundwater Potential area (GWPA) map was developed from this combination of factors and classified into four classes: very high, high, moderate, and low. The validation of the results was performed by comparing the GWPA map with 117 existing wells, and the AUC was calculated at 80%, indicating the predictive accuracy of the AHP method. The results can serve as a valuable tool for water resource management by professionals in the field. To improve the accuracy of the AHP method, the use of high-resolution geospatial data is essential. This approach can be extended to similar mountainous areas.

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