Environ Geol (2007) 52:477–487
DOI 10.1007/s00254-006-0481-0

ORIGINAL ARTICLE

Groundwater potentiality index: a strategically conceived tool for water research in fractured aquifers

Said Ettazarini

Received: 20 May 2006 / Accepted: 16 August 2006 / Published online: 7 September 2006
© Springer-Verlag 2006

Abstract Durable development requires full profit and knowledge of natural resources potentialities. Multi-criterion approaches that encompass geological, morphological, hydrological and Geographical Information System technologies are ones of exiting developments in environmental sciences. This work is a proposition of a numerical model based on a groundwater potentiality index (GPI) calculation, using data on rock fracturing, lithology, drainage, topography, rainfall and drilling water yield. It provides the ability to identify areas indicating favorable conditions for exploratory well positioning in semi-arid zones with non-permeable outcrops. It is therefore a helpful tool to assist water resources prospecting in deprived regions. The newly conceived approach has been applied in the southeastern boundary of the Bouregreg and coastal basins of Central Morocco, where Paleozoic fractured rocks outcrop. The suitability of the GPI method use was verified by comparing the GPI map values with water yield of thirteen pumping tests in a field checking area, which revealed promising results.

Keywords Water research · Pumping yield · Fractured aquifer · Groundwater potentiality index (GPI) · GIS · Morocco

Introduction

Needs in water continuously increase with the progressive evolution of human activities in industry, agriculture and urbanism. In poor regions of semi-arid and arid zones, the difficulties to access the water can hinder the sustainable development of populations. The task is more complex if fractured aquifers are the unique water resource in the region. In addition, water yields from wells in faulted and basement aquifers are typically low, compared to wells in alluvial, karstic or continuous aquifers. In the two first cases, wells that produce significant amounts of water usually occur in proximity to secondary permeability features such as fracture and fault zones. Consequently, the prediction of productive drillings location is the main task in programs of water resources management.

This study attempts to elaborate a groundwater potentiality index (GPI) map, based on the analysis of pumping test data and on the thematic maps assessed for different parameters controlling the occurrence of the water in fractured aquifers. It is a synthetic map in which zones are classified according to their capacity to provide acceptable yields in drilling wells. The calculation of the proposed index is based on field information collected on fracturing, lithology, drainage, topography and rainfall conditions that are compared with water yield measured during drilling process, using the rotary-air technique for the majority of drillings. For others, the percussion and the hammer-tool drilling techniques were used. Taking the southeastern boundary of Bouregreg and coastal basins of Central Morocco, dominated by Paleozoic outcrops, as an example, the use of multi-criterion model has led to

---

S. Ettazarini (✉)
Faculty of Sciences, Department of Earth Sciences,
Mohamed V-Agdal University,
Rabat, Morocco
e-mail: stazar@yahoo.com

encouraging results and proved the suitability of the GPI method use.

Site presentation

The investigated site constitutes a boundary zone between the Bouregreg and coastal basins that cover an area of 20,000 km^2 to the north and the Oum Er-Rabia basin that covers an area of about 35,000 km^2 surface to the south (Fig. 1). The large urban centers of the region are on the Atlantic coast such as Rabat, Casablanca and Jadida, while the majority of internal centers are rural and their development needs real assistance. The mean annual rainfall varies in the northern basins between 415 and 420 mm/year insuring an exploitable water resource of about 860 million m^3, while southern basin receives about 520 million m^3 and insures about 4,000 million m^3 of exploitable water resource. Lands of northern basins are drained by the Grou and Zamrine rivers, while southern terrains are drained by the Oum Er-Rabia river, indicating the watershed zone character of the region.

The investigated area is dominated by Paleozoic outcrops that are (1) Devonian calcareous schists of the Khatwat region to the west, (2) schists and sandstones with quartzite bars of the Ordovician and (3) schists containing *graptolites* of Silurian age, outcropping in the Bni Khirane region at the center, (4) pelitic sandstones and schists with calcareous levels of Carboniferous age to the east and (5) Permian continental conglomeratic sandstones and clays penetrated by sills and dykes of basalt and andesite in the Chougrane basin to the southeast. Granite outcrops are localized in the region of Zaer to the northwest. Paleozoic outcrops are locally overlain by Meso-Cenozoic cover that is developed in the Oum Er-Rabia basin (Bolelli et al. 1959; Vogel et al. 1976; Cailleux 1985). Paleozoic terrains are deformed during Hercynian and Atlasic tectonic phases, ending to the formation of NE–SW anticlines and synclines and to the development of a fault system whose intensity varies in the region. The fault families also affect the Meso-Cenozoic layers in the Oum Er-Rabia basin (Ettazarini 2002) indicating the reactivation of Hercynian faults during the Atlasic tectonic phases. Under these conditions, the fractured rocks are thus the unique reservoirs for groundwater resources in the Grou river basin (Rafik and Bouamoud 1989). Consequently, the prediction of drilling points location is an important task for regional sustainable development.

Parameters of groundwater potentiality index

The fracturing (F)

Approaches used to define zones of important groundwater potentiality are largely varied, but the

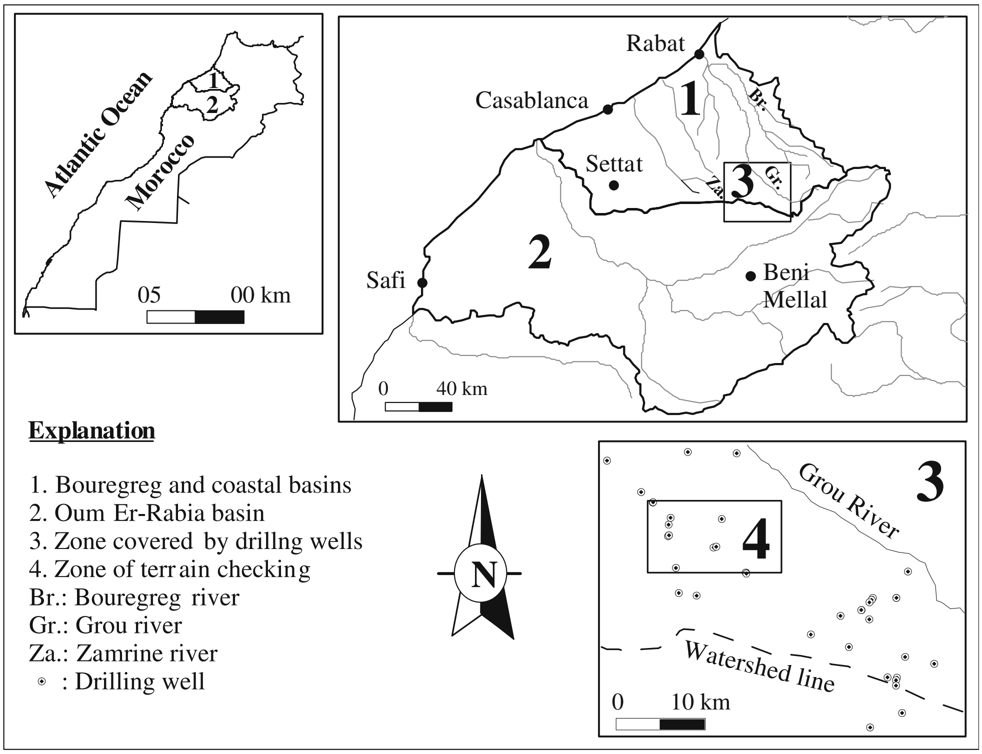


Fig. 1 Location maps of investigated terrains

majority of them have considered some parameters as essential for the migration of fluids in fractured rocks. The most recognized parameters are the geological features leading to fracturing state, the drainage, the topography and the rainfall (Murthy 2000; Sree Devi et al. 2001; Ligtenberg 2005). Faults are the main conduits of fluids in non-permeable rocks worldwide. Indeed, the fracture plan constitutes the useful void volume corresponding to the potential space able to be occupied by the water in such medium. The aperture, the spacing, the interconnection and the orientation of fracture plans play a significant role in the occurrence and movement of groundwater resources in fractured aquifers. Thus, zones with opened, frequent and interconnected fractures are potentially favorable for water occurrences. In addition, gently dipping fractures are more favorable than vertical ones for storage and infiltration of water. On this basis, states of rock fracturing, as well as other parameters, are conventionally classified following their capacity to promote the water existence (Table 1). Interconnected discontinuity plans of large extension are given a high notation (8–10) while spaced diaclases and non-fractured rocks are given low notation (1–3). Intermediate cases correspond to notation (4–7).

The lithology (L)

The lithology influences both the permeability of the aquifer rocks and the distribution of the fracture pattern. The lithologic units classification is inspired from their effective porosity in the literature (Table 2) that is the fractional volume of pore space that permits fluid flow in a rock sample. It is lower than the absolute porosity, which is the fractional volume of pore space in a porous medium, including the connected pores and dead ended ones. Thus, the conventional notation used for the groundwater calculation is given in Table 1, that distinguishes between favorable lithologies such as compact quartzite, non-fractured granite and compact schist that are given low notation (1–3) and fractured and porous sandstones and conglomerates that correspond to high notation (8–10). Notation (4–7) is reserved to intermediate cases.

The surface drainage network (D)

Main waterways as Grou and Zamrine rivers are linked to a series of affluents forming the drainage network. The order of a waterway is a classification that reflects the ramification of the system. The adopted classification (Schumm 1956; Strahler 1957) is based on the following points: a waterway without

Table 1 Summarized charter adopted for the ground water potentiality index calculation

Parameters	Description and notation		
Fracturing	8–10: interconnected major faults, kilometer long faults, shear zone	4–7: local faults, frequent fracture plans interconnected and neared plans	1: non fractured rock2–3: frequent diaclases, crack sand schistosity plans
Lithology	8–10: porous and fractured sandstone, fractured conglomerate, vacuolar basalts and dolerites	4: compact sandstone, compact micro-conglomerate, fractured schistose sandstone, pelite and sandstone alternation, alternation of fractured schist and sandstone, fractured siltstone 5: fractured sandy schist, fractured sandstone, fractured limestone 6: fractured micro-conglomerate, basalt 7: alternation of fractured sandstone and micro-conglomerate	1: compact schist, compact granite, compact quartzite 2–3: feebly fractured schist, weathered schist, schist and quartzite alternation, quartzite and sandstone alternation, siltstone
Drainage	8: waterway order (6) 9–10: permanent waterway of order up to 6	5: waterway order (3) 6: waterway order (4) 7: waterway order (5)	1–4: uphill area, isolated ravine, temporary waterways, waterway order <3
Topography (slope%)	8: slope 6–9 9: slope 3–6 10: slope <3	5: slope 24–30 6: slope 12–24 7: slope 9–12	1: slope >65 2: slope 54–65 3: slope 45–54 4: slope 30–45
Rainfall (mm/year)	8: 700< rainfall <800 9: 800< rainfall <900 10: rainfall >900	4–5: 300< rainfall <500 6–7: 500< rainfall <700	1: rainfall <100 2: 100< rainfall <200 3: 200< rainfall <300

Table 2 Effective porosity values for the main reservoirs

Lithology	Effective porosity (%)	Lithology	Effective porosity (%)
Gravel	20–30	Mud	0.1
Sandy gravel	15–20	Fractured basalt	8–10
Sand	5–20	Fractured sandstone	2.15
Alluvia	8–10	Fractured limestone	2–10
Chalk	2–5	Fractured granite	0.1–2
Silt	2	Schist	0.1–2

affluent has order one and the meeting of two waterways of order n gives a waterway of order *n* + 1. Consequently, the maximal order informs thus on the drainage importance in a basin. The quantity of water converging to a waterway increases with its order. Indeed, a downhill fractured and permeable zone that intercepts a waterway of high order should be alimented, while an uphill one should be drained. However, the impact of surface drainage should not be significant if non-permeable and non-fractured rocks are occurring. Thus the D-parameter is considered as a secondary parameter in the GPI conception. The charter in Table 1 gives high notation (8–10) to zones permanently crossed by waterways with order up to 6, while uphill zones and areas with waterways of low order (<3) conventionally noted (1–4).

The topography (T)

Slope is the principal factor of the superficial water flow since it determines the gravity effect on the water movement. If we consider the acceleration of the superficial water flow as a function of the sine of slope angle, it is theoretically reduced to 50% of *g* when the slope is near 30°, while it does not exceed 10% of *g* for slopes less than 10° (Fig. 2). On horizontal lands (slope <9%) the water flow is slow and the time is enough available to improve the infiltration of water to the underlying fractured aquifer (Table 1). Those conditions are given high notation (8–10), while high slopes (up to 30%) favoring superficial flow antagonistically to infiltration are given low notation (1–4).

The rainfall (R)

Rainfall and superficial water are the principal recharge source for a fractured aquifer. Moroccan region is characterized by semi-arid climate with contrasted seasons and a long summer period. Mean annual rainfall is varying in Morocco from values under 100 mm/year in arid zones to values up to 800 mm/year in mountains, indicating that odds of aquifer recharge are not identical. The classification and notation for this parameter are based on the mean annual rainfall at national scale (Table 1). High notation (8–10) is given to zones receiving up to 700 mm/year of rain, whereas zones with annual rainfall less than 300 mm/year are considered non-favorable and are given low notation (1–3).

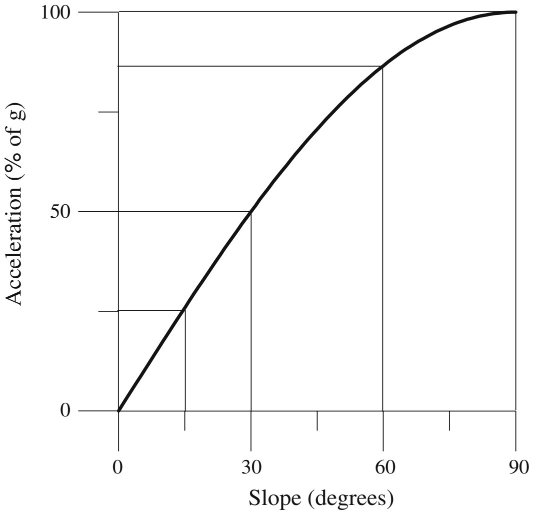


Fig. 2 Variation of theoretical acceleration of superficial water flow versus slope

Pumping test data play a significant role in the identification of groundwater potential zones (Subba Rao 2003). Water yield indeed constitutes good field information for the checking of direct and remote prospecting approaches.

Methodology

Forty drilling wells realized in anisotropic terrains by the "Direction Régionale de l'Hydraulique" (DRH) actually "Agence de Bassin Hydraulique d'Oum Er-Rabia" (ABHOR) that provide information on lithology, fracturing and water yields are used to elaborate the database. Topographic sheets at 1:50,000 scales were also used to determine slope and drainage conditions. The studied region was subdivided to classified zones according to rainfall rates using the isohyetal map of Morocco.

The classification of natural conditions by taking in consideration their ability to provide favorable conditions for water occurrence have allowed their transformation into numerical values using a logical notation. Conventionally, notes from 1 to 3 denote favorable conditions, 4–7 moderately favorable conditions and 8–10 highly favorable ones (Table 1).

The designation of weights for factors is elaborated by searching values of the coefficients α, β, γ, δ and ε, in the model proposed by Eq. 1, that give the highest possible correlation coefficient between the natural conditions matrix and the drilling yields matrix. A groundwater potential index GPI is proposed and computed on the basis of the five factors and the results of statistical analysis. The GPI is noted as follows:

$$\mathrm{GPI} = \alpha F + \beta L + \gamma D + \delta T + \varepsilon R \qquad (1)$$

where GPI is groundwater potentiality index, *F*, *L*, *D*, *T* and *R* are parameters, respectively, relative to fracturing, lithology, drainage, topography and rainfall and α, β, γ, δ and ε are relative factor weights.

To determine suitability of the GPI method, a GPI map is elaborated for an area of about 290 km^2 in the southern boundary of Bouregreg and coastal basins of Central Morocco, according to classified local natural conditions that are collected from the terrain. Geographical information system (GIS) technique is used for digitizing the terrain informations and transforming them into numerical values as well as derivation of slopes from digitized topographic surface. Water yields in thirteen drilling points are compared with the GPI calculated values.

Dataset description

The data used for this study are lithological sections and water yields from 40 selected pumping tests. The drilling files provide information on lithology and fracturing conditions, while slopes and waterway orders are determined from topographic sheets. The data set covers a 68 × 54 km area that shows heterogeneity of natural conditions. Indeed, the drilling points as shown in Table 3 indicate variable state of rock fracturing as well as contrasted lithology. Yields are varying between 0.1 and 20 l/s and about 50% of drillings have yields under 3 l/s.

The slopes are also varying between 1 and 18% and the waterway order is from 1 to 6 characterizing thus the watershed zone in the investigated area. The western part of studied site, covered by 50% of drilling points receives from 400 to 600 mm/year of rainfall, while the remainder is a watered zone that receives 600–750 mm/year. From the dataset in Table 3, it can be remarked that fractured sandy schists and microconglomerates are promising aquifers. The relative impacts of slope and surface drainage factors are not as evident as fracturing and lithology factors. They are considered as secondary factors for which the contribution to groundwater cannot be possible unless fracturing and lithology conditions are favorable. The rainfall impact is the less estimable since its variability is limited in the studied area and the dataset shows only two zone types. Thus a statistical treatment is aimed to determining the relationship between the water yield and the five parameters and estimating their proportional contributions to the existence of water in fractured aquifers.

GPI expression

The classification of the different conditions relative to parameters used for the explanation of drilling success is summarized in Table 1. According to this proposed charter, real conditions in the drilling dataset are classified and transformed into numerical values that constitute a (40×5) mathematical matrix traducing natural conditions and corresponding to *F*, *L*, *D*, *T* and *R* columns in Table 4. The determination of the GPI expression as a function of the five parameters resides in the determination of the coefficients α, β, γ, δ and ε in Eq. 1, in a manner to have the best correlation between the (40×1) GPI column vector corresponding to a combination of natural condition matrix columns according to Eq. 1 and the (40×1) yield column vector corresponding to the last column in Table 4.

$$\mathrm{GPI} = \alpha F + \beta L + \gamma D + \delta T + \varepsilon R \qquad (1)$$

Innumerable combining tests were undertaken, they consist in correlation analyzing when one of the coefficients varies while the others are kept constant. Every time one parameter is fixed, the GPI is calculated for the 40 observation points and the correlation coefficient between the resulting calculated GPI column and the yield column vector is researched using computer help. The step is remade as much as necessary for each coefficient until obtaining the adequate model with the yield column vector It was proven that on the basis of 40 equations corresponding to selected

Table 3 Natural conditions of drilling points relative to water yield, fracturing, drainage, topography and rainfall

No.	Lithology	Yield (l/s)	Fracturing	Order	Slope (%)	Mean annual rainfall (mm)
1	Weathered schist	0.3	None	1	2.5	600–750
2	Sandstone and micro-conglomerate	16.5	++++++++	1	2.5	400–600
3	Compact sandstone	0.3	None	1	2.5	400–600
4	Sandstone and micro-conglomerate	4.25	+++	1	3	400–600
5	Sandstone and micro-conglomerate	0.2	None	4	2.5	400–600
6	Sandstone and micro-conglomerate	0.2	None	3	2.5	400–600
7	Compact sandstone	0.8	None	3	2	400–600
8	Schist	0.1	None	1	5	400–600
9	Schist and quartzite	2.75	+++++	4	1	400–600
10	Sandstone	0.7	None	1	1	400–600
11	Fractured sandy schist	20	+++++++++	1	5	600–750
12	Sandstone	5.1	++++	3	2.5	600–750
13	Schist	0.27	None	2	3	600–750
14	Schist	3	++++	2	1.5	600–750
15	Schist	0.27	+	2	1.5	600–750
16	Sandstone and schist	5	++++++	1	5	600–750
17	Sandstone	9.7	++++++	3	2.5	600–750
18	Fractured sandstone and schist	5.55	++++++	2	6	600–750
19	Fractured schist	1.5	++++++	2	15	600–750
20	Schist and sandy limestone	1.95	++++	4	1	600–750
21	Schist	0.1	None	2	5	400–600
22	Schist	3	++++	2	18	400–600
23	Basalt and micro-conglomerate	7.4	+++++++	1	2.5	400–600
24	Sandstone and pelite	0.36	None	4	2	400–600
25	Sandstone and pelite	3	+++	2	2	400–600
26	Schist	0.5	++	1	5	400–600
27	Fractured schist	9.6	++++++++	1	5	600–750
28	Weathered schist	3.2	++++	2	5	400–600
29	Schist	1.75	+++	1	15	400–600
30	Schist	1.76	+++	1	2.5	600–750
31	Fractured schist	18	++++++++	6	5	400–600
32	Schist and sandstone	8.8	++++++++	1	1	600–750
33	Schist and sandstone	0.1	None	2	4.5	600–750
34	Schist	0.2	None	1	2	600–750
35	Schist and quartzite	4.5	++++++	1	15	600–750
36	Schist	0.1	None	3	2.5	400–600
37	Schist	0.1	None	3	2.16	400–600
38	Compact quartzite and sandstone	0.1	None	1	2.5	600–750
39	Quartzite and clay	10	+++++++	2	9.5	600–750
40	Schist and sandstone	10	++++++++	2	6	600–750

NB. For the fracturing state, the number of plus symbols is proportional to fracturing density

drillings, the expression of the GPI revealing the best correlation is as follows:

$$\mathrm{GPI}_{40} = 10.75F + 5.25L + 2.15D + 3.2T + 1.15R \qquad (2)$$

The comparison between the calculated GPI_{40} and the corresponding yields in drilling wells showed a positive correlation coefficient of 0.89 (Fig. 3). From the GPI_{40} expression in Eq. 2, it can be remarked that parameters do not equally contribute at the GPI. Thus, fracturing F and lithology L are the principal factors, whereas drainage D, topography T and rainfall R are revealed as secondary factors that cannot influence the existence of water unless the principal factors are favorable.

Mapping of GPI and field checking

The suitability of the GPI concept is verified in an area of 290 km^2 surface in the southeastern boundary of the Grou basin (Fig. 1). The information on natural conditions relative to parameters controlling the occurrence of water in the fractured aquifer, collected from the terrain in the field checking area, was digitized and transformed into numerical values by the help of the

Table 4 Notation given to natural conditions in drilling wells according to charter in Table 1 and their relative yields

	F	*L*	*D*	*T*	*R*	Yield (l/s)
1	1	1	2	10	8	0.3
2	8	7	2	10	6	16.5
3	1	4	2	10	6	0.3
4	3	7	2	9	6	4.25
5	1	4	6	10	6	0.2
6	1	4	5	10	6	0.2
7	1	4	5	10	6	0.8
8	1	1	2	9	6	0.1
9	5	2	6	10	6	2.75
10	1	4	2	10	6	0.7
11	9	5	2	9	8	20
12	4	5	5	10	8	5.1
13	1	1	4	9	8	0.27
14	4	2	4	10	8	3
15	1	1	4	10	8	0.27
16	6	4	2	9	8	5
17	6	5	5	10	8	9.7
18	6	4	4	9	8	5.55
19	6	2	4	6	8	1.5
20	4	4	6	10	8	1.95
21	1	1	4	9	6	0.1
22	4	2	4	6	6	3
23	7	6	2	10	6	7.4
24	1	4	6	10	6	0.36
25	3	4	4	10	6	3
26	2	1	2	9	6	0.5
27	8	2	2	9	8	9.6
28	4	2	4	9	6	3.2
29	3	1	2	6	6	1.75
30	3	1	2	10	8	1.76
31	9	2	8	9	6	18
32	7	4	2	10	8	8.8
33	1	3	4	9	8	0.1
34	1	1	2	10	8	0.2
35	6	2	2	6	8	4.5
36	1	1	5	10	6	0.1
37	1	1	5	10	6	0.1
38	1	3	2	10	8	0.1
39	7	2	4	7	8	10
40	8	4	4	8	8	10

GIS technique. In this step, only site information was used, while drilling data were ignored. Then, the GPI values, calculated from the combination of thematic maps of different parameters, are compared with the drilling yields.

The fracturing state

Fracture plans were plotted and the direction is noted for 735 faults. The statistical analysis allowed to highlight the main directional families (Fig. 4). Abundant faults are orientated NNE–SSW to NE–SW representing up to 50% of all detected structures. Faults of NW–SE and E–W directions are frequent, respectively, accounting for 10 and 6% of structures, while the remainder of directions is not abundant. Fracturing density is high in schists, sandy schists and sandstones compared to quartzites. Thematic map relative to the fracturing parameter is obtained by subdividing the study area into 0.25 × 0.25 km cells and a notation is attributed to each one following the density and the magnitude of rock fracturing as shown in Table 1. The resulting map shows a fuzzy network of somber color corresponding to fractured zones, while the clear zones are the less fractured (Fig. 5).

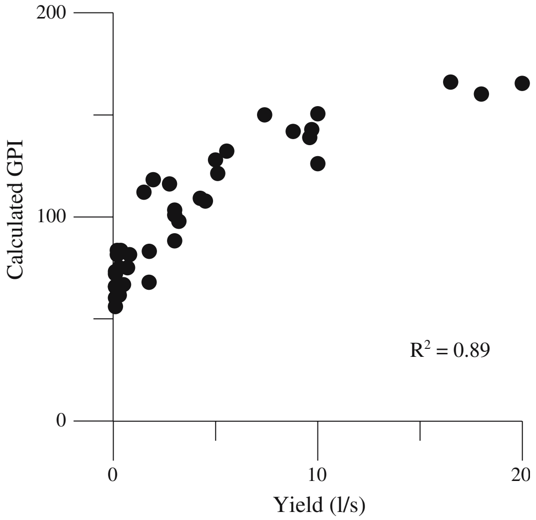


Fig. 3 Plot of calculated GPI_{40} versus water yields

The lithology impact

Outcrops in the field checking area (Fig. 4) are of Ordovician to Silurian ages. There are schists, sandstones and compact quartzites forming synclines and anticlines of NE–SW trend. Paleozoic terrains are locally and unconformably overlain by marls and limestones of Cenomanian. The map of the lithology impact (Fig. 5) is based on the geological map and the notation is attributed to digitized lithological units according to the charter in Table 1. The contrast in color thus indicates variable characteristics of different lithologies linked to their patchy porosity.

The drainage impact

The digitizing of topographic surface allowed the superposition of drainage network to the shaded relief of the field checking area. The Fig. 6 shows abundant streams of NE–SW trend as well as the watershed zone orientated NW–SE delimiting the northeastern part of the area, drained by the Grou river. The superficial waters of the southwest are collected by the Zamrine

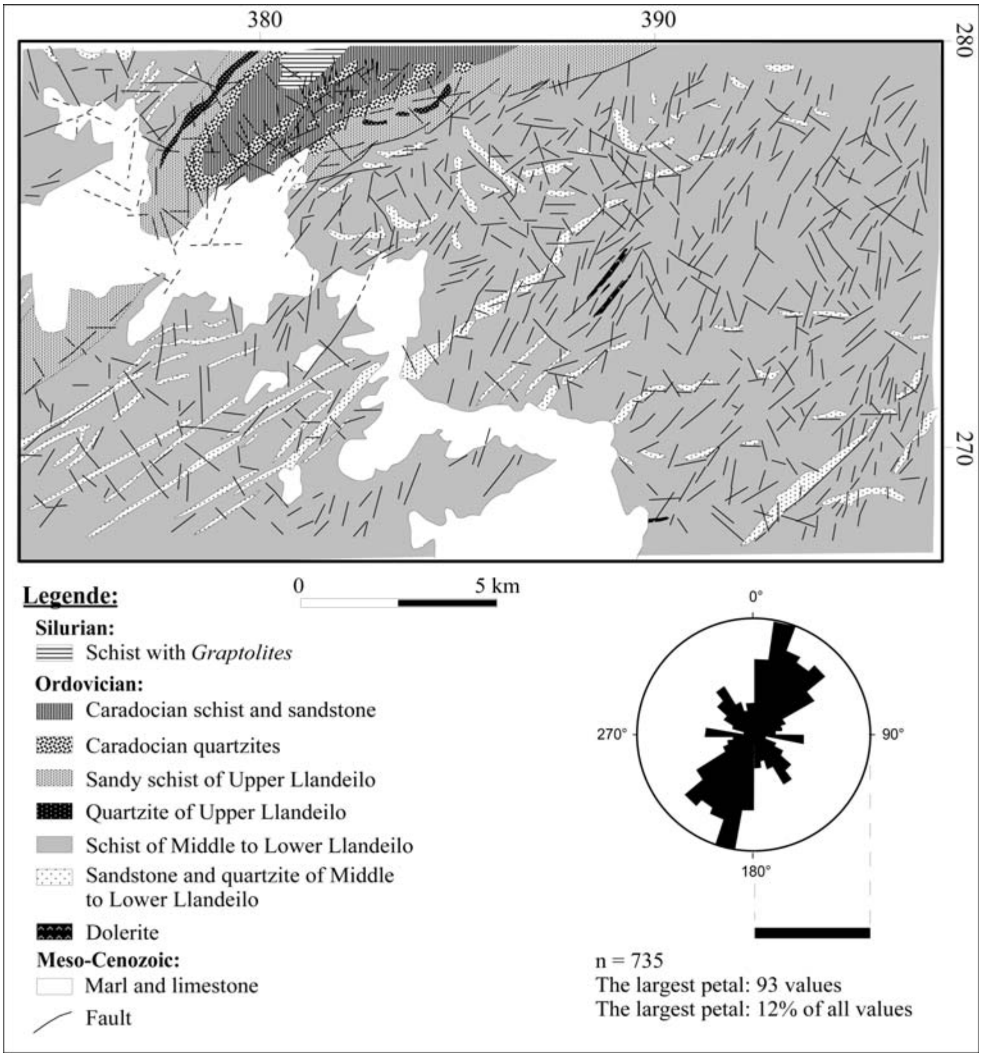


Fig. 4 Geological map of field checking area and directional distribution of fracturing network

river that leads to El Mellah river. Therefore, zones situated far of the watershed should have more odds to benefit from upstream waters and probably have a raised groundwater potential.

The area is subdivided into sub-basins drained by streams of the same order and the notation is attributed as shown in Table 1. The thematic map relative to the drainage impact (Fig. 5) shows that surfaces crossed by streams of order up to 3 are in the northeastern part of the area where underlying aquifer can benefit by water infiltration from superficial resources.

The topography impact

Elevation levels are between 610 and 960 m above sea level and low lands are northwest of the studied region. The 3D topographic model (Fig. 6) highlights surface features such as watershed zone in a NW–SE trend and a planar surface interrupted by projecting crests corresponding to sandstone and quartzite bars, while depressions are occupied by weathered schists. The slopes map obtained by derivation of elevation surface is characterized by dominant slopes between 0 and 9% for the majority of the area that have notation up to 8 (Fig. 5), indicating favorable conditions of water infiltration to underlying aquifer in a large part of the studied area.

The rainfall impact

The local distribution of rainfall is poorly known because of data constraints. Rainfall impact map is thus obtained from the isohyetal map of Morocco. The eastern part of field checking area is receiving a mean annual rainfall between 600 and 750 mm/year, while the western one is receiving between 400 and 600 mm/year. According to the charter in Table 1 and to rainfall rates in Morocco, varying from values under

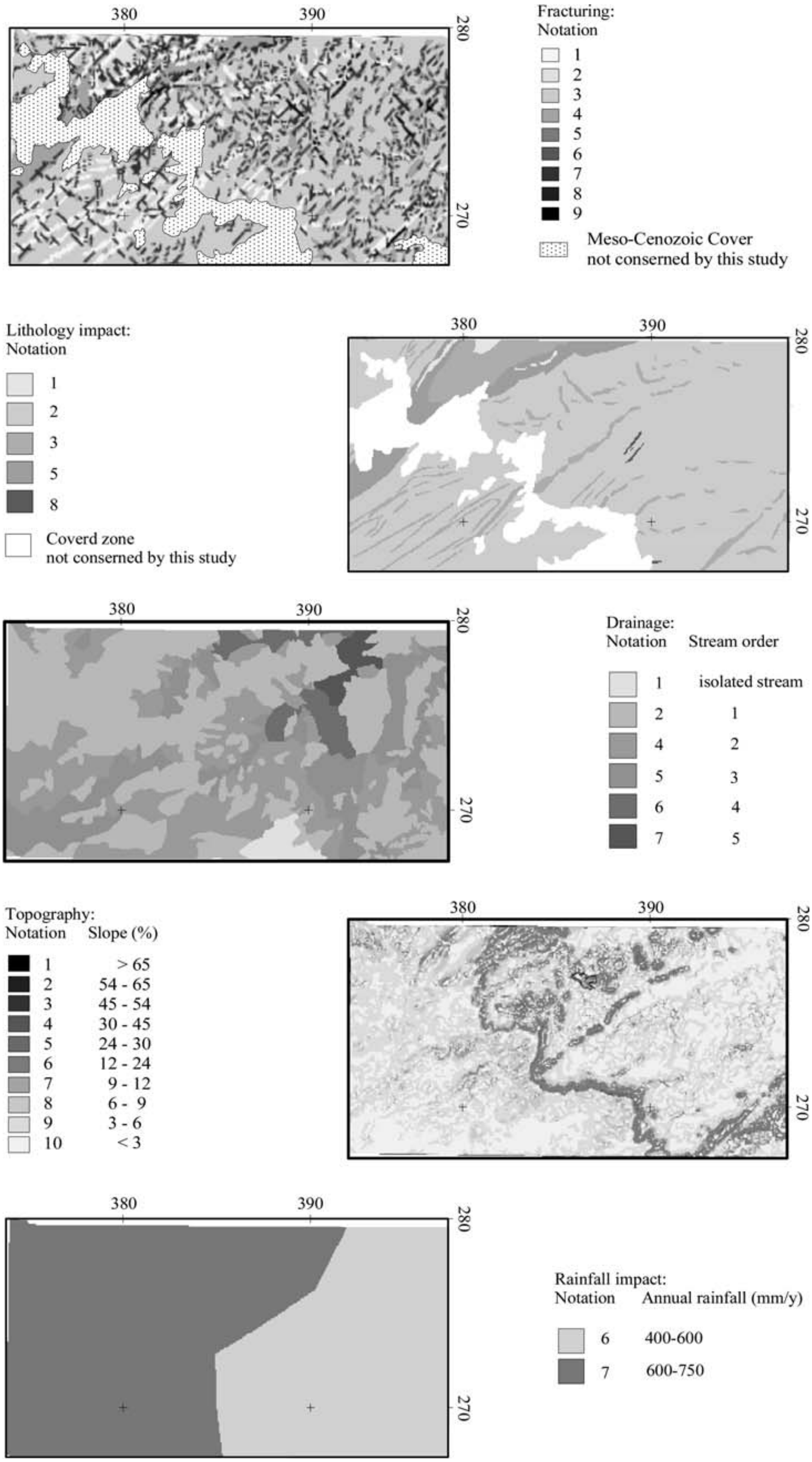


Fig. 5 Thematic maps of parameters used for the GPI calculation in the field checking area

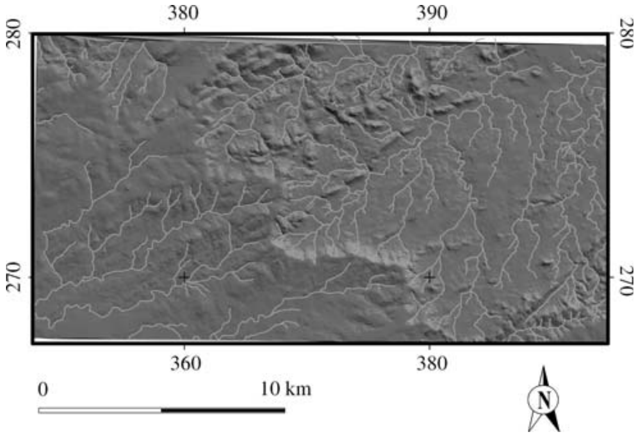


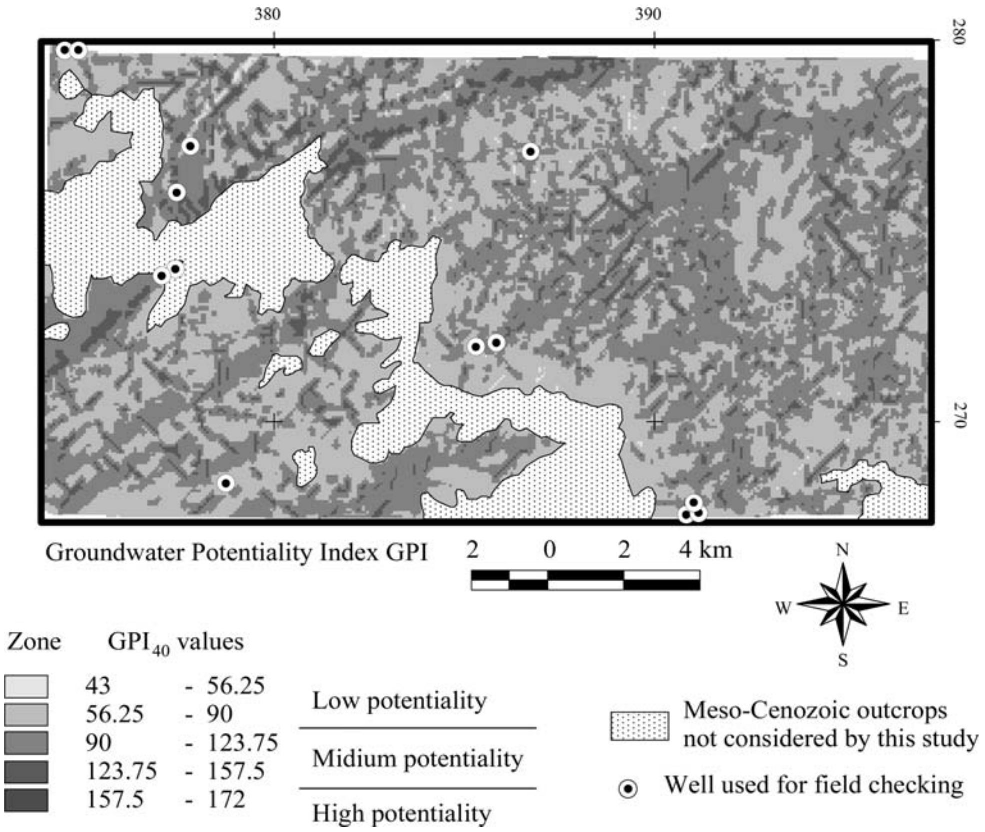
Fig. 6 Drainage network coupled with 3D surface model of field checking area

100 mm/year to values up to 800 mm/year, the notes given to the two local zones are six and seven (Fig. 5).

The map of groundwater potentiality index

The maps of different parameters were handled and integrated in a combined one by the use of ArcView software. The GPI_{40} model expressed in Eq. 2 is easily applied during the calculation process. The resulting map (Fig. 7) is a spatial distribution assessment of the GPI as previously described. According to the GPI_{40} expression, extreme values of the calculated index are between 22.5 and 225. Thus, three equal intervals can be distinguished that are: 22.5–90, 90–157.5 and 157.5–225 they, respectively, correspond to unfavorable zones, moderately favorable zones and very favorable zones. The level of groundwater potentiality is represented by the gray degree in the map where somber zones are the most favorable, allowing thus a rapid visual distinction between regions. The studied area showed values of GPI between 43 and 172 indicating the presence of the three levels of groundwater potentiality previously cited. Zones of high potentiality are the less extended and a large sameness between the fracturing and the GPI maps is noticed, due to the high coefficient attributed to this parameter in the model. The data of the GPI map are compared with the water yields in 13 drilling points in the region (Fig. 7). The GPI increases with the yield since this later exceeds 2 l/s (Fig. 8) and promising drillings are situated in favorable zones, encouraging thus the utilization of such method. The suitability of the GPI use, as a newly conceived method, should be in the future verified by testing it in several areas outside of the current checking zone. The advantage of the model resides in

Fig. 7 Map of groundwater potentiality index (GPI) in the field checking area



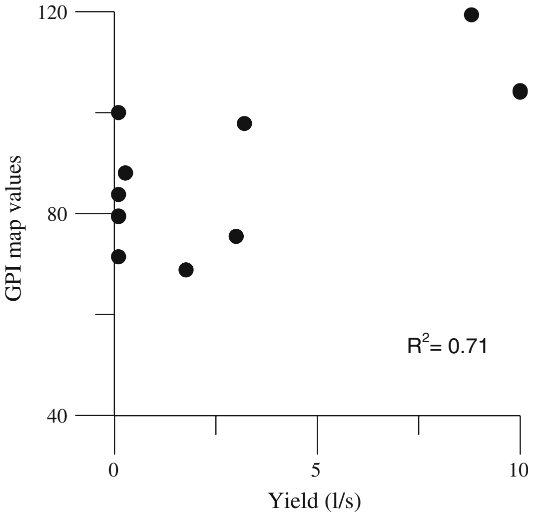


Fig. 8 Plot of the GPI$_{40}$ map values vs. water yields in the field checking area

the integration of the five parameters controlling the existence of water in fractured aquifer. However, the accuracy of information provided by the GPI map is mainly linked to the density and the reliability of the database.

Conclusion and discussion

In anisotropic and fractured aquifers and under semi-arid climate constraints, the prospecting and research of water constitute a burden for local collectivities that have no possibilities to lift this challenge. The use of strategic documents, such as the map of GPI, allows the ability to predict sites favorable for well positioning and to optimize expenses of new water resources research. The targeting of fracturing, lithology, drainage, topography and rainfall, as parameters controlling the water occurrence in fractured aquifers, is beneficial to locate successful drilling wells. The comparison between conventionally classified states relative to the five parameters and water yields for forty wells was helpful for the elaboration of a GPI$_{40}$ expression, based on field natural conditions. The GPI elaboration revealed principal parameters such as fracturing and lithology and secondary parameters that are surface drainage, topography and rainfall. The application of the resulting model in a semi-arid area of Central Morocco led to the establishment of a GPI map. The method is reveled valid for the studied area by comparison between the model values and the real yields of drillings in a field-checking site. However, the method suitability should also be verified in other zones. Due to data constraints, the method can thus be used as a first estimate of the groundwater potentiality that goes parallel with probability of drilling success, but local studies in favorable zones should provide precisions for drilling location. In addition, the assessment of the newly conceived GPI can profit by modern techniques so as to provide maps of natural conditions of high precision and enhance water migration pathways.

Acknowledgment Sincere thanks to the "Direction Régionale de l'Hydraulique" (DRH) actually "Agence de Bassin Hydraulique d'Oum Er-Rabia" (ABHOR) for providing the drilling data files indispensable for this work.

References

Bolelli E, Choubert G, Faure-Muret A, Salvan H, Suter G (1959) Geological map of the phosphates plateau and the tadla syncline zone 1:200 000. Notes et mém. Ser Géol Maroc, n° 137

Cailleux Y (1985) The Ante-Visean Ezzhiliga slices, their importance in the structural sketch of Central Morocco. C R Acad Sci Paris 7(301):497–502

Ettazarini S (2002) Weathering of sediments and its relationship with groundwater and meteoric water circulations in the Meso-Cenozoic series of the phosphates basin of Ouled Abdoun (Morocco). Doctorate thesis, Mohamed V-Agdal University, Rabat, p 286

Ligtenberg JH (2005) Detection of fluid migration pathways in seismic data: implication for fault seal analysis. Basin Res 17:141–153

Murthy KSR (2000) Ground water potential in a semi-arid region of Andhra Pradesh—a geographical information system approach. Int J Remote Sen 21(9):1867–1884

Rafik A, Bouamoud L (1989) Development of a water research methodology in the pedestal zone by automatic processing of drilling data. EMI/GEMIN report, p 123

Schumm SA (1956) Evolution of drainage systems and slopes in badlands at Perth Amboy NJ Bull Geol Soc Am 871:597–646

Sree Devi PD, Srinivasulu S, Kesava Raju K (2001) Hydrogeomorphological and groundwater prospects of the Paregu river basin by using remote sensing data. Environ Geol 40:1088–1094

Strahler AN (1957) Quantitative analysis of watershed geomorphology: EOS Trans AGU 38:913–920

Subba Rao N (2003) Groundwater prospecting and management in an agro-based rural environment of crystalline terrain of India. Environ Geol 43:419–431

Vogel TA, Williams ER, Preton JK, Walker BM (1976) Origin of the late Paleozoic massifs in Morocco. Geol Soc Am Bull 87:1753–1762