Groundwater potential of Middle Atlas plateaus, Morocco, using fuzzy logic approach, GIS and remote sensing

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ABSTRACT
Groundwater is a most important resource in arid and semi-arid regions and is required for drinking, irrigation and industrialization. Assessing the potential zone of groundwater recharge is extremely crucial for the protection of water quality and the management of groundwater systems. To identify the groundwater potential zone in the study area, thematic layers of lithology, slope, karst degrees, land cover, lineament and drainage density were generated using topographic maps, thematic maps, field data and satellite image, and were prepared, classified, weighted and integrated in a geographic information system (GIS) environment by the means of fuzzy logic. The fuzzy membership values have been assigned to different thematic layers according to their classification on respect for their contribution and their occurrence in groundwater. Based on the generated groundwater potential map, it was found that about 8% of the investigation area was categorized as very high potential for groundwater recharge, 31% as high, 28% as moderate, 17% as low and 16% as very low potential for groundwater recharge. Finally, the results were verified using well-yield data. The highest recharge potential area is located towards the downstream regions related to more fractured and karstified limestone.

KEYWORDS
Fuzzy logic; GIS; remote sensing; groundwater potential; Middle Atlas plateaus (Morocco)

1. Introduction
Water resources in Morocco are unevenly distributed over its regions and heavily dependent on climatic variations. Pollution from households, industry and agriculture poses an ever-greater threat. Increased demand for drinking water for agriculture, industry and tourism has led to the overuse of water resources, with major implications for the country’s socio-economic development. In fact, groundwater is a most important resource in arid and semi-arid environment and is required for drinking, irrigation and industrialization. Currently, remote sensing and geographic information system (GIS) provide important data and tools for groundwater exploration (Krishnamurthy et al. 1996; Teevw 1999; Jaiswal et al. 2003; Singh & Prakash 2003; Sener et al. 2005; Chowdhury et al. 2009; Ganapuram et al. 2009). Remotre sensing play a major role for generating information in spatial and temporal domain (Engman & Gurney 1991; Saraf & Choudhury 1998; Epstein 2002), which is very crucial for successful analysis, prediction and validation (Saraf 1999). The remote sensing technique using aerial photographs and satellite imagery has proved significant in the field of hydrogeological investigation (Singh & Singh 1980; Edet et al. 1998). Identification of groundwater occurrence location using remote sensing data is based on geological structures, geomorphology and hydrology.
characteristics (Kouamé 1999; Jourda et al. 2006). GIS tools can be useful to facilitate the evaluation process and serve to implement a multicriteria analysis (MCA) (Malczewski 1999; Mahdavi 2004; Weng 2005; Ghayoumian 2007; Cano-Casas & Escobar-Martinez 2011; Eastman 2012; Kumar & Shaikh 2013; Esquivel 2015).

A MCA is a method used to evaluate several criteria defined for specific objective, whose results enable making decisions (Saaty, 1980). This method with help of GIS-based geospatial analysis was performed to identify those areas suitable for pumping wells by considering different criteria, such as topography, hydrography, lithology, lineaments and land cover… etc. Some of the major MCA techniques available as follows: fuzzy set analysis, analytical hierarchy process (AHP), ELECTRE, PROMETHEE, TOPSIS, multi-attribute utility theory (MAUT)… etc (Figueira et al. 2005). The AHP method was used for quantitative assessment of groundwater potential in Middle Atlas plateaus. Based on the generated potential map, it was found that about 40% of the investigated area was categorized as high potential for groundwater recharge, 29% as moderate and 31% as low potential for groundwater recharge (Aouragh et al. 2015).

In recent years, the applications of artificial intelligence techniques have been used to convert human experience into a form understandable by computers (Ayse & Ahmet 2006). One useful model for combining information concerning hydrogeological characteristics is fuzzy logic (Chang & Chen 2001; Gemitzi et al. 2006; Rezaei et al. 2013; Kord & Asghari-Moghaddam 2014), and can be easily implemented within a GIS environment (Pradhan 2011). A fuzzy set is a collection of degrees of membership (Zadeh 1987). Membership of a fuzzy set, however, is expressed on a continuous scale from 1 (full membership) to 0 (full non-membership). The membership function methods are based on fuzzy logic of segment features to classify image objects.

The objective of this study is to delineate the groundwater potential zone using remote sensing, GIS and fuzzy set theory and finally the results were verified using well-yield data.

2. Study area

The study area is a part of Sebou basin, and located between the latitudes of 33°30′ and 34° N and the longitudes of 4°30′ and 5° E (figure 1). The surface elevation of the area ranges between about 1000 m and about 2100 m. The Climate is Mediterranean with an average annual precipitation ranges from 650 mm at El Hajeb City to 1600 mm at Ifrane city. The mean annual temperature ranges from about 3 to 30 °C. In term of geology, the outcropping rocks are of metamorphic, sedimentary and volcanic origin and cover a lapse of time ranging from Paleozoic to Quaternary (Michard 1976; Martin 1981; Piqué 1994). The structural control is clearly visible in the landscape with mainly long faults (ANMA: Accident North Middle Atlas; ASMA: Accident South Middle Atlas). The basement complex is characterized by an alternation of hard (marbles, sandstones and quartzites) and soft rocks (shales and phyllites), intensively folded in typical Variscan NE-SW directions and ranging in age from Ordovician to Lower Permian. Upon this basement complex, Triassic sandstones and red clays followed by doleritic basalts, outcropping along the entire western border of the plateaus (Piqué & Laville 1993). Jurassic carbonate rocks dominate and outcrop the major portion of Middle Atlas plateaus, composed of dolostones, calcareous dolostones and limestones (Colo 1964; Martin 1981). Upper Cretaceous red marls and clays with conglomerate intercalations followed by pure and marly limestones start a new sedimentary cycle. During the Tertiary, a thick sequence of sandstones, gypsum and claystones of Palaeocene and fossiferous limestones of Eocene age complete the sequence (Rahhali 1970). The upper part is composed of lacustrine limestones, sands conglomerates and basaltic rocks extend over more than 400 km² on the plateau of Azrou–Ifrane (El Azzab & El Wartiti 1998), after volcanic cones such as: Outgui, (1430 m) at east of El Hajeb ; El Koudiat (1785 m) west of Ifrane ; and Hebri (2100 m) south-east of Azrou. Geomorphological units identified in the plateaus include springs, karst landforms (polje, dolines, caves, sinkholes, stone forests and cryptokarstic dolines), carbonate depositional landforms (travertines and waterfalls), fluvial landforms (meanders, canyons, palaeo-valleys, etc.), structural landforms (triangular facets,
hogbacks, cuestas, residual outcrops, etc.) and volcanic landforms (volcanoes, caldeira, pyroclastic cones, lava tube, etc.) (Martin 1981; Waele & Melis 2009).

In hydrogeological terms, it is a karstic aquifer of dolomitic and calcareous-dolomitic of lower and middle Lias reaching up to 300 m thickness (Amraoui 2005). The specific flow of groundwater from Liasic land is very high: 8.3 to 9.3 l/s/km², while this rate does not exceed 5 l/s/km² from post-domerien land and 3 l/s/km² in basalts (Bentayeb & Leclerc 1977). This groundwater plays a crucial role for drinking water supply of big cities (Meknes, Fez) and irrigation of surrounding areas (Bahzad 1985; Essahlaoui et al. 2001).

3. Materiel and methodology

3.1. Materiel

In this study, multispectral images from Landsat 7 ETM + (April 2001 and May 2000), and Landsat 8 image (August 2014) and a digital elevation model (ASTER-GDEM), as well as geological and topographic maps covering the study area at a scale of 1:50,000, were acquired, scanned and geo-referenced in GIS. All these images and maps have been orthorectified, mosaicked in geographic coordinates of Lambert Conic Conform (Merchich Morocco). The spatial resolutions for these bands were 30 m for the visible to infrared and 15 m for the panchromatic. Radiometric correction for the satellite images was applied using Top of Atmosphere reflectance and Dark Object Subtractions for atmospheric correction.

3.2. Methodology

Development of thematic layers involves digital image processing of remote sensing data, digitization of existing maps and field data for extraction of pertinent information. To identify the groundwater potential zone in the study area, thematic layers of lithology, slope, karst degrees, land cover
(normalized difference vegetation index [NDVI]), lineament and drainage density were generated using topographic maps, thematic maps, field data and satellite image, and were prepared, classified, weighted and integrated in a GIS environment by the means of Fuzzy logic (figure 2).

3.2.1. Fuzzy logic implementation
Zadeh (1965) first used fuzzy set theory in the development of decision support models. It was later applied in MCA applications (Leberling 1981; Buckley 1984). Fuzzy set theory is based on a gradual transition from one class to another. Items can have partial membership in multiple sets. This can be particularly powerful in handling uncertainty inherent in MCA problems. Fuzzy approaches may apply concepts from the other MCA methods (Hajkowicz & Collins 2007).

A fuzzy set is a collection of degrees of membership. Membership of a fuzzy set, however, is expressed on a continuous scale from 1 (full membership) to 0 (full non-membership). Using fuzzy functions can be separated maps of a few classes. Then each class is given a membership degree based on their influencing, in the range (0, 1) (Bernardinis 1993). A variety of operations can be employed to combine the membership values together (fuzzy AND, fuzzy OR, fuzzy algebraic product, fuzzy algebraic sum, and fuzzy gamma).

3.2.2. Fuzzy membership function
The membership function of a fuzzy set is a generalization of the indicator function in classical sets. In classical sets, an element belongs to a set or not. If (A) is a classic set, then the formula $\mu_A(x)$ is true or false. In fuzzy logic, it represents the degree of truth as an extension of valuation (Zadeh

Figure 2. Flow chart depicting methodology adopted.
A membership function for a fuzzy set $A$ on the universe of discourse $U$ is defined as $\mu_A(x)$: $U \rightarrow [0,1]$, where each element of $U$ is mapped to a value between 0 and 1. This value, called membership value or degree of membership, quantifies the grade of membership of the element in $U$ to the fuzzy set $A$ (figure 3).

The selection of a suitable membership function for a fuzzy set is one of the most important activities in fuzzy logic. It is the responsibility of the user to select a function that is a best representation for the fuzzy concept to be modelled. In this study, the fuzzy linear transformation functions were applied to the optimal interpolation between the specified minimum and maximum values. In fuzzification of deterministic criteria, Linear transformations are commonly used (Fisher 2000).

3.2.3. Weighting fuzzy membership thematic classes

First, the fuzzy membership values have been assigned to different thematic maps according to their classification on respect for their contribution and their occurrence in groundwater. The fuzzy membership values should reflect the relative importance of each map, as well as the relative importance of each category of a single map (Aouragh et al. 2015). The information and values based on the degree of membership have been appropriately modified to the following parameters in the opinion of experts and field observations (figure 4):

1. The map of slope was classified based on soil-terrain model (SOTER). The slopes between 0% and 60% will be considered in this area. The flat lands were assigned a value of 1 and the upper land 60% were assigned to 0, the other degrees were reclassified between 0 and 1 (table 1).

2. The drainage density was ranked by a negative linear equation from 0 to 3.5 km/km$^2$ according to the probability scale from 1 to 0. The densities greater than 3.5 km/km$^2$ receive value of 0.

3. The density map of lineaments was reclassified by positive linear equation from 0 to 5.5 km/km$^2$ according to the probability scale from 0 to 1. A density greater than 5.5 km/km$^2$ receives a value of 0, and values less than 5.5 km/km$^2$ are gradually values from 0 to 1.

4. The mapping of land cover shows the importance of vegetation in this area (about 30%) and bare soil (about 70%), thus the factor of vegetation index (NDVI) was considered in the calculation of groundwater potential. NDVI map was reclassified based on histogram of Caloz (1992). The interval $(-0.457$ to $0.010]$ indicates the presence of water as lakes, and is negatively affected by the linear equation (black line). A (1) degree of membership has been assigned to this interval. The interval $(-0.0109$ to $0.257]$ is the bare ground, $[0.258$–$0.415]$ of less dense vegetation and the interval $[0.416$–$0.799]$ of more dense vegetation (forest) will be reclassified according to positive linear equation (blue line) from 0 to 1.
The weights of the lithological formations map were determined in Table 2. The lakes having a very high weight received a membership value of 1, those marls have a value of 0, and by calculating the correspondence has other values for each formation. Similarly, based on the weights of karst degrees map, high karst pixels were assigned to 1 and non-karst areas impervious have a value of 0 (Table 3).

### Table 1. Regional slope classification based on soil-terrain model (SOTER).

| Slope (%) | Classification       | Groundwater storage potentiality |
|-----------|----------------------|----------------------------------|
| 0—2       | Flat                 | Very high                        |
| 2—8       | Undulating           | High                             |
| 8—15      | Rolling              | Moderate                         |
| 15—30     | Moderately steep     | Low                              |
| 30—60     | Steep                | Very low                         |

3.2.4. **Aggregation fuzzy membership thematic classes**

All the maps were integrated by overlay techniques using GIS to delineate groundwater potential zones. During weighted overlay analysis, the ranking was given for each individual parameter of

### Table 2. Lithology memberships.

| Lithology                  | Memberships |
|----------------------------|-------------|
| Dayats (lakes)             | 1           |
| Limestone and dolomites    | 0.65        |
| Alluviums                  | 0.43        |
| Quaternary basalts         | 0.25        |
| Calcareous marl            | 0.15        |
| Shale, clay and basalts    | 0.06        |
| Marls and sandy marls      | 0           |
each thematic map, and weights were assigned according to the multi-influencing factor of that particular feature on the hydro-geological environment of the study area (Shaban et al. 2006) (figure 5). This schematic sketch shows that the detailed effects of each influencing factor may contribute to delineate the groundwater potential zone; these factors arrive at a relative value of 1 or \(\frac{1}{2}\) based on major or minor effect between different layers. The cumulative weightage of both major and minor effects is considered for calculating the relative rate. This rate is further used to calculate the score of each influencing factor. The factor of 1 major effect was given 1 pts, while the minor effect was given \(\frac{1}{2}\) pt as expressed as follows:

- Lithology (Lith): 4 major = 4(1) = 4 pts.
- Lineaments density (LD): 3 major = 3(1) = 3 pts.
- Karst degrees (KD): 2 major + 1 minor = 2(1) + 1(0.5) = 2.5 pts.
- Drainage density (DD): 2 major + 1 minor = 2(1) + 1(0.5) = 2.5 pts.
- Land cover (LC): 1 major + 3 minor = 1(1) + 3(0.5) = 2.5 pts.
- Slope (S): 1 major + 1 minor = 1(1) + 1(0.5) = 1.5 pts.

In order to evaluate the weight of each parameter, a matrix of pair-wise comparisons of the criteria for the AHP process was determined. Examining the consistency of the comparisons based on consistency ratio (CR) was considered. For the comparisons to be consistent, and thus acceptable, the CR must be less than 0.1. Based on the number of major and minor effect, we are considering that lithology is ranked 1, lineament is ranked 2, karsts domains, drainage and land cover are ranked 3, 4 and 5 successively, and slope is ranked 6 (table 4).

| Karst degrees | Memberships |
|---------------|-------------|
| High          | 1           |
| Moderate      | 0.52        |
| Non karst/permeable | 0.19     |
| Non karst/little permeable | 0.07 |
| Non karst/waterproof | 0         |

Figure 5. The interactive influence of factors concerning the recharge property (Shaban et al. 2006).
The factors influencing the groundwater recharge potential of the Middle Atlas plateaus, in descending order, are lithology; lineaments, karsts domains, drainage, land cover and slope. Lithology and lineaments are the major factors influencing the basin groundwater recharge potential. Weighted linear combination (WLC) method was used to estimate the groundwater potential index (GWP). WLC is usually specified in terms of normalized weightings for each parameter as well as normalized rates for all options relative to each of the criteria. The final map is then calculated using the following formula (Eastman et al. 1993):

\[ A = \sum_{i=1}^{n} W_i X_i \]  

where \( A \) = aptitude; \( W_i \) = weight for each map partition; and \( X_i \) = individual map

Then,

\[ \text{GWP}_{\text{indice}} = 25\% \text{ Lith} + 18\% \text{ LD} + 16\% \text{ KD} + 16\% \text{ DD} + 16\% \text{ LC} + 9\% \text{ S} \]  

4. Groundwater potential model (GWP) and validation

The final thematic map of the GWP model (figure 7) was qualitatively displayed in one of the categories, such as (1) very high, (2) high, (3) moderate, (4) low and (5) very low based on a natural breaks classification (‘Natural breaks (Jenks)’) (figure 6).

In this study, a MCA-fuzzy set-based methodology that supports the relative importance of various thematic layers and their corresponding classes affecting groundwater has been used to evaluate groundwater potential zone. Table 4 represents the weight of each thematic layer using AHP. The groundwater potential evaluated by the WLC of these weights is shown in figure 7. Results indicated that 20% of the area was classified to have very high groundwater potential and 33% of the area was classified as high groundwater potential, with over 16% being moderate and 14%, area is low. Sixteen

| Lith | LD | KD | DD | LC | S | Weights | % |
|------|----|----|----|----|---|---------|---|
| 1/1  | 4/3| 4/2.5| 4/2.5| 4/2.5| 4/1.5| 0.249 | 25 |
| 3/4  | 1  | 3/2.5| 3/2.5| 3/2.5| 3/1.5| 0.187 | 18 |
| 2.5/4| 2.5/3| 1  | 2.5/2.5| 2.5/2.5| 2.5/1.5| 0.156 | 16 |
| 2.5/4| 2.5/3| 2.5/2.5| 1  | 2.5/2.5| 2.5/1.5| 0.156 | 16 |
| 2.5/4| 2.5/3| 2.5/2.5| 2.5/2.5| 1  | 2.5/1.5| 0.156 | 16 |
| 1.5/4| 1.5/3| 1.5/2.5| 1.5/2.5| 1.5/2.5| 1  | 0.094 | 9  |

Note: Consistency ratio (CR) = 0.0001.
per cent of the area is of very low groundwater potential (figures 7 and 8). The obtained map shows that the promising zones for groundwater storage are almost located in areas where limestone rocks in fractures is concentrated.

Validation of groundwater potential zone with yield data at various locations is shown in figure 7. From 64 bore-wells sampled in the study area (after Sebou Hydraulic Basin Agency), 39% of the bore-wells are on ‘high to very high’ groundwater potential zone, 28% are on
‘moderate’ and 33% of the bore-wells are on ‘low to very low’ groundwater potential zone (figure 9).

The yield of bore-wells upper than 15 l/s which represents 33% of all bore-wells shows a non-random distribution of drillings. Indeed, 55% of such wells are located in ‘high-very high’, 25% in ‘moderate’ and 20% in ‘low-very low’ groundwater potential areas. The yield of bore-wells between 10 l/s and 15 l/s, which represent 16% of all bore-wells, are divided, respectively, into 30%, 40% and 30% in ‘high-very high’, ‘moderate’ and ‘low-very low’ groundwater potential areas. The yield of bore-wells under than 10 l/s which represents 33% of all bore-wells, which represents 34%, are redistributed into 32% ‘high-very high’, 27% ‘moderate’ and 41% in ‘low-very low’ groundwater potential areas (figure 10). Although some wells exist in all groundwater potential zones, the best yielding wells lie in the very high and high groundwater prospect zone.

Study of yielding-water capacity of bore-wells reveals that there is ample scope for development of groundwater by tapping the fractured zones in the area of carbonate rocks covered with alluvium and locally with quaternary basalts. Furthermore, this result has yet support the validation of the groundwater potential model ‘GWP’ and therefore the reliability of the method used. The smooth (not random and haphazard) distribution of bore-wells in the most promising portions of groundwater showed fairly significant correlation or agreement with the discharge data (figure 7).

The model generated will help as a guideline for designing a suitable groundwater exploration plan in the future. The spatial distributions of the various groundwater potential zones obtained from the model generally show regional patterns of lineaments, drainage, landform and lithology.

Spatially, the very high and high categories are distributed along areas near to lineaments and less drainage density and where secondary structure and having interconnected pore spaces affect the lithology. This highlights importance of lineaments, geology and hydrogeo-morphological parameters in the project area. Areas with moderate groundwater prospects are attributed to contributions from combinations of the land cover, lithology, slope, drainage density and karsts domains. The low to very

Figure 9. Relationship between bore-wells and groundwater potential (GWP).

Figure 10. Relationship between bore-wells yield and groundwater potential (GWP).
low categories of groundwater potential zones are spatially distributed mainly where the lithology is basaltic and far from lineaments. The results reveal that groundwater characteristics depend on various geomorphic, geologic and hydrologic factors. Multicriterion evaluation has been performed by assigning weights to all the chosen parameters and the suitable model derived out of these techniques, including remote sensing, and GIS platform has proved to be an easier as well as a challenging method in identifying groundwater resources.

5. Conclusion

In this study, MCA -based fuzzy logic approach, remote sensing and GIS techniques have been successfully used and demonstrated for cartography and identification of groundwater potential zones. The optimal use of water resources for drinking water supply, agriculture and industrialization is a complex problem that involves subjective assessments with multiple criteria. Multicriteria analysis prevents imposition of limits and provides opportunities and analysis for decision makers to a final decision. GIS provides a single platform for combining these data types for visualization, mapping, analysis and decision-making. This paper aims to provide well location based on multicriteria analysis, satellite imagery and DEM. The study reveals that integration of six thematic maps such as drainage density, slope, geology, geomorphology, lineament density and land cover gives first-hand information to local authorities and planners about the areas suitable for groundwater exploration in the Middle Atlas plateaus (Morocco), since it is a simple and efficient tool for topics related to water resources.

The results show that 20% of the area was classified to have very high groundwater potential and 33% of the area was classified as high groundwater potential, with over 16% being moderate and 14% of area is low and 16% of the area is of very low groundwater potential. The obtained map shows that the promising zones for groundwater storage are almost located in areas where limestone rocks in fractures are concentrated. The yield of bore-wells upper than 15 l/s which represents 33% of all bore-wells, showed significant correlation or agreement with the discharge data. Indeed, 55% of such wells are located in 'high-very high', 25% in 'moderate' and 20% in 'low-very low' groundwater potential areas. Study of yielding-water capacity of bore-wells reveals that there is ample scope for the development of groundwater by tapping the fractured zones in the area of carbonate rocks covered with alluvium and locally with quaternary basalts. Spatially, the very high and high categories are distributed mainly where the lithology is dolomitic limestone and along areas near to lineaments (Tizi N’Tretten fault). It is also determined in karstic areas between Imouzzer and Ifrane marked by sinkholes, poljes and leading to springs with very high flow rates along contact of carbonate plateaus and Sais basin, between Tizgueute valley and toward the northwest at the base of the foothills of Sefrou-Bhalil (Ribaa-Bittit springs complex). Hence, the fuzzy logic and GIS technique can be suggested for assessment groundwater potential, specifically in no-data regions.

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