Characterisation of fissured aquifers in the semi-arid region of the mid-Atlas plateau (Oulmès, Morocco)

Ph. Orban[1], I. Ruthy[1], D. Elbatloussi[2], S. Dadi[2], A. Dassargues[1,3]

[1] *Hydrogeology & Environmental Geology, Dept of Georesources, Geotechnologies and Building Materials, B-52/3, University of Liège, 4000 Liège, Belgium*
[2] *Hydrogeology, Dpt of Earth Sciences, School of Mines, Rabat, Morocco*
[3] *also at Hydrogeology & Engineering Geology Group, Department of Geology-Geography, Katholieke Universiteit Leuven, Redingenstraat 16, B-3000 Leuven, Belgium*

corresponding author: Ph. Orban, p.orban@ulg.ac.be

The Oulmès plateau (mid-Atlas in Morocco) is known for its groundwater resources in this semi-arid region. In the studied zone (approximately 80 km^2), the mineral water of 'Sidi Ali' is exploited as well as the naturally semi-sparkling 'mineral water of Oulmès' which are main mineral waters marketed in Morocco. Their sources are located at less than four kilometers from each other. In the same time, the drinking water supply to the local rural populations is not sufficient. In addition the plateau is also the place where many fruit-bearing cultures have been undertaken for a few years. Irrigation and the use of pesticide and herbicide compounds as well as fertilizers could constitute threats for the groundwater quantity and quality and unpleasant consequences are expected for all dependent groundwater end-users. Thus, in this semi-arid zone, an acute problem of sustainable development arises in terms of groundwater quantity and quality.
An extended study has involved data collection, measurement campaigns (piezometric levels, sampling & analysis of groundwater), shallow geophysical prospecting, pumping tests, building of a data base, estimation of the recharge spatial distribution and hydrogeological mapping. On the basis of this study, a better understanding is possible about the state and the particular hydrodynamic behaviour of groundwater in the fissured hard-rocks of this plateau.
Results are expressed in maps providing explicit and useful information allowing future decisions in terms of groundwater exploitation.

Keywords : Groundwater, Characterisation, Recharge, Mapping, Oulmès, Morocco

Introduction

Water supply in arid or semi-arid regions is highly dependent on groundwater availability.
The Oulmès plateau (Fig. 1) located in the mid-Atlas in Morocco, 150 km from Rabat, at a mean altitude of approximately 1000 m a.s.l., and especially the eastern part of this plateau (approximately 80 km²), is known for bottled water production: the mineral water of Sidi Ali and the naturally semi-sparkling "Mineral water of Oulmès". Groundwater is also exploited for irrigation of fruit-bearing cultures. In the same time, difficulties are occurring for the drinking water supply of the local rural population. In addition, the development of the fruit cultures and the use of pesticides, herbicides and fertilizers could constitute threats for the groundwater quality. Another threat for the groundwater quality could be also the wastewaters from the city of Oulmès that are re-infiltrated without any treatment.
In order to insure a sustainable management of the groundwater resource, a good understanding about the state and the hydrodynamic behaviour of groundwater is needed.
Although the geology of the plateau is complex, the general description of the geological system is well known. A granitic intrusion is located in the middle of the studied zone and is

surrounded by Primary fissured hard-rocks (Termier, 1936). Alluvial and alteration layers of variable thickness are overlying these bedrock formations.
Two main rivers ("Oued Boulahmayal" and "Oued Afçal") form the boundaries of the plateau (Fig. 3) and are draining groundwater. The mean annual temperature and precipitation values are respectively 16°C and 701 mm (for the period 1972-1984). The rainy season stretches from October to April and 92% of the precipitation are registered during this period.

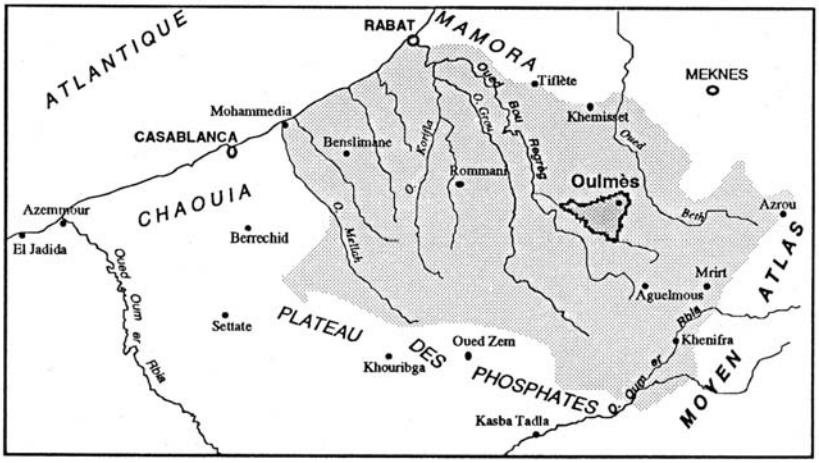

Fig.1: Location of the Oulmès Plateau

Methodology

Characterisation of the hydrodynamic behaviour of a fractured aquifer is a multidisciplinary complex task. Different processes such as the recharge, the spatial structure and values of the hydrodynamic properties have to be identified and quantified. A four year study was initiated by the Hydrogeology Group of the University of Liège (Belgium) in collaboration with the Hydrogeology Laboratory of the "Ecole Nationale de l'Industrie Minérale" of Rabat (Morocco). Agricultural engineers, geologists, geophysicists and geological engineers were involved in the project. They all have contributed to the project within the same general methodology: collection of existing data, completion or acquisition of new data by field measurements, management of data using database and GIS, production of maps and data interpretation.
Data considered for estimation of the recharge are precipitation, temperature, type of soils and their hydraulic properties, land-use and slopes. The climatic data were collected. A field campaign was carried out to sample the soils and their hydraulic properties were measured by the Agricultural Hydraulic Laboratory of the Faculty of Agronomy in Gembloux (Belgium). Maps and remote sensing were used to determine land-use and to derive the slope values. Different methods were used to estimate the rate of recharge to the aquifer. For this study, the studied domain is divided in zones and an estimation of the recharge was computed with a modified version of the EPIC code (Williams & al, 1984, Sohier & al, 2002) for each zone. Unfortunately, due to the lack of flow-rate measurements in the two main rivers, the calibration and validation of the model could not be performed.
Data were collected about the geological structure of the different layers forming the fissured aquifer. Then, maps of lineaments were drawn to identify the main direction of fractures. Measurement campaigns of shallow geophysical prospecting, including refraction seismic and electrical tomography were performed to characterise the lithological units, to determine the thickness of the alteration layer and to confirm the position of some fractures. Classical

techniques of signal processing and inversion techniques were used to interpret the results of these campaigns.
Two detailed hydrogeological measurement campaigns were performed to complete the available piezometric and hydrogeochemical data obtained previously (Dadi, 1998). All the accessible wells and piezometers were visited in the studied zone. Available information about exploited groundwater flow rates were collected. Different piezometric surveys (in summer and winter) were performed to define the position of the water table in dry and humid conditions. Groundwater samples were also taken in many wells and piezometers for physico-chemical analysis. Results of these analyses were plotted in Piper and Stiff diagrams allowing to characterise the hydrochemical facies of the groundwater. A particular attention is paid to geochemical indicators of anthropic contamination such as nitrates. Transient pumping tests were also performed to quantify the hydrodynamic properties of the different main geological formations. As most of the wells are large-diameter wells, the needed assumptions for application of the logarithmic approximation of the Theis equation are not verified (Mace, 1999). Other formula such as proposed by Papadopoulos & al. (1967) or by Bouwer & al. (1976) were applied.

Results
For the first time, a global description of the hydrodynamic behaviour of the fissured aquifers of the Oulmès plateau is provided. The main formations are characterised in terms of geophysical, hydrodynamic and geochemical properties. The geological formations are grouped together to form hydrogeological units depending on their hydrogeological characteristics (aquifer, aquitard or aquiclude, UNESCO, 1992). Values of the hydraulic conductivity measured in the pumping wells in the aquifer units are on the scale of $1x\ 10^{-5}$ m/s. Hydrogeochemical facies are determined with Piper diagrams and can be correlated with lithologies. Spatial variations in the geochemical composition are represented by Stiff diagrams (Fig. 2). Here, the Stiff diagrams are limited to three horizontal axes showing, on the left, the cations (Na + K, Ca, Mg) and, on the right, the anions (Cl, HCO_3, SO_4). An explanation for variation in geochemical composition of the groundwater is proposed based mainly on variation of encountered lithologies and on the time of residence. For example, the diagrams representing the chemical analysis of groundwater taken in the granites are characteristic of low mineralization. Among other uses, the chemical analysis of the groundwater allow to detect zones of less good chemical quality. One can observe mainly contamination by sulfates in pyriteous siltstones and claystones or by nitrates due to wastewater or fertilizers.

Commentaire [ad1] : ??????? ?

Four piezometric maps for the Oulmès plateau were drawn for rainy and dry conditions. The piezometric map of December 2002 is shown in figure 3. Generally, the water table is found a few meters below the ground surface and its position can most often be correlated with the topography. Consequently, the main directions of groundwater flow can be assessed. In the central part of the plateau, the flow direction is from North to South-West while, in the northern part of the studied zone, the flow direction is to North (to the river Afçal). A division of the plateau in hydrogeological sub-basins is proposed but uncertainty remains in areas where few data are available or in flat region where the elevation of the wells is not accurately determined. Seasonal variations of the piezometric head are studied thanks to monthly measurements by local producers. Around the wells exploited by the fruit producers, the drawdown caused by the pumping for irrigation during the dry season can be more than twenty meters.

Commentaire [ad2] : !!!!!!

A map of the spatial distribution of the mean annual estimated recharge is drawn. Mean annual values of recharge are found in the interval 20 – 200 mm. A sensivity analysis has shown that these values are mostly influenced by geological conditions.

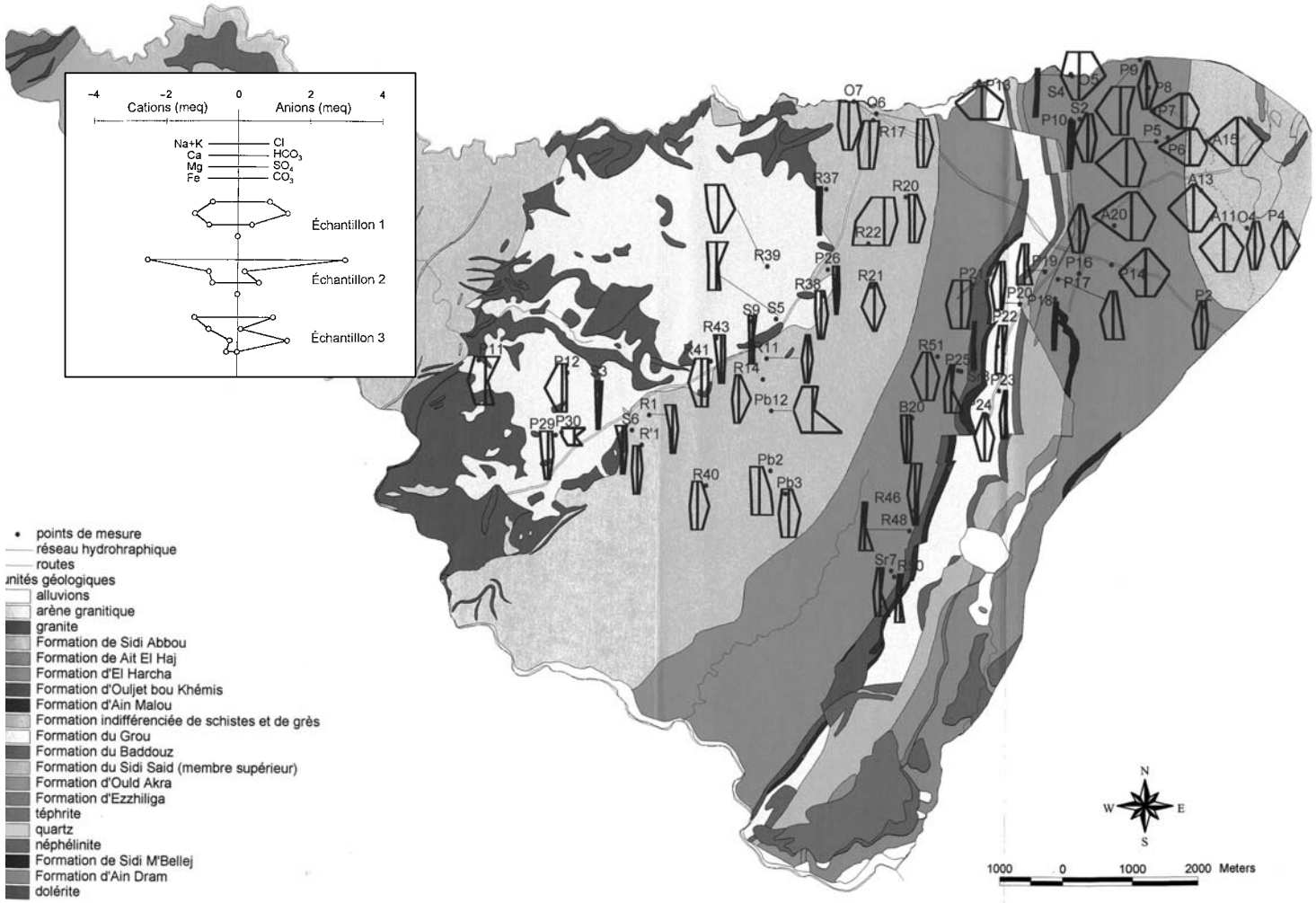

Fig. 2: Variation in the geochemical composition of groundwater expressed by Stiff diagrams

All the data and results are introduced in a georelational database (Ruthy et al, 2005). Coupling the geodatabase and a Geographic Information System (GIS) (Gogu et al, 2001), results can be mapped under the form of a hydrogeological map providing explicit and useful information. This map will allow to synthesize all available data in one document. It is a useful tool for taking future decisions in terms of groundwater exploitation and management in the area.

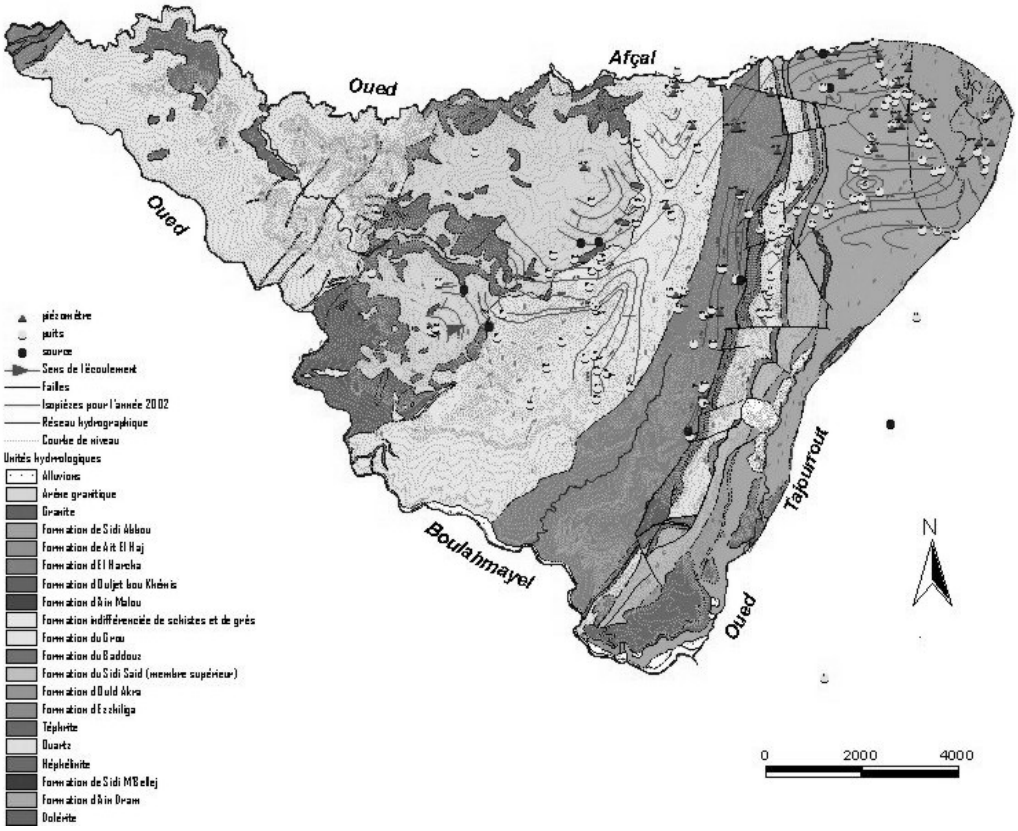

Fig.3: Schematic piezometric map (December 2002)

Conclusion

Commentaire [ad3] : Il faut donner un diagramme de Stiff typique en légende, avec les éléments repris…

For the first time, a detailed hydrogeological characterisation of the fissured hard-rock aquifers of the Oulmès plateau was carried out. An extended study has involved data collection, measurement campaigns (piezometric levels, sampling & analysis of groundwater), shallow geophysical prospecting, pumping tests and calculation of recharge spatial distribution. Coupling a geodatabase and GIS, results are expressed under the form of a comprehensive hydrogeological map. An explanation about the general hydrodynamic behaviour of the aquifer is proposed.

Future works could be focused on the hydrodispersive behaviour of the system. Tracer tests could be performed to identify and quantify the main processes of solute transport. Vulnerability maps and modelling tools could be used in complement of the hydrogeological maps to provide help for the management of the aquifer.

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