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CHAPTER 12

An assessment of the groundwater resources in the western margin of the Taoudenni basin, Mauritania

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ABSTRACT: An extensive study was made of the hydrogeology of the region around Zouerate in the north-western part of Mauritania. This area consists of two main zones: the Archaean basement in the west and the margin of the Taoudenni sedimentary basin in the east. The geometry of the aquifers in the Taoudenni basin was deduced by a combination of different techniques including: refinement of the geological map using remote sensing, interpretation of aerial magnetometric data and construction of a hydrostratigraphic log. A survey of 624 groundwater points, including GPS levelling, was conducted. It became apparent that a few sebkhas are the main regional discharge zones. To estimate the fluxes, a 2D regional model was constructed and calibrated. It allowed a comparison of different recharge scenarios and may be used to run long-term simulations. A great deal of uncertainty remains in the model results, especially concerning the recharge area distribution.

1 INTRODUCTION

To develop the Mauritanian mining sector, the World Bank funded the PRSIM2 project whose aim, among others, was the evaluation and mapping of the groundwater resources around Zouerate, in the north-western part of Mauritania (Figure 1). To sustain the mining exploitation in this part of the Sahara a reliable water supply is required.

1.1 *Climate and hydrology*

The climate in this region is of Saharan type. It is characterized by high daily temperatures and less than 70 mm/year of rainfall. The rainfall is highly variable both in space and time (Figure 2). Furthermore, since 1970, the annual rainfall has decreased by 35% (Figure 2) as in most parts of North Africa.

The city of Atar is situated in the south of the area and Zouerate in the north. In the west, there is a plain called Amsaga in the south and Tiris in the north; in the east there is a series of plateaux constrained by north-south oriented cliffs. The whole structure is locally covered by the Hammami, the Maqteir and the Oum Arouaba sand dunes.

There are no perennial rivers in the area. Except near the highest topographical points, but the hydrographic network is otherwise not developed. It drains water for only a few days per

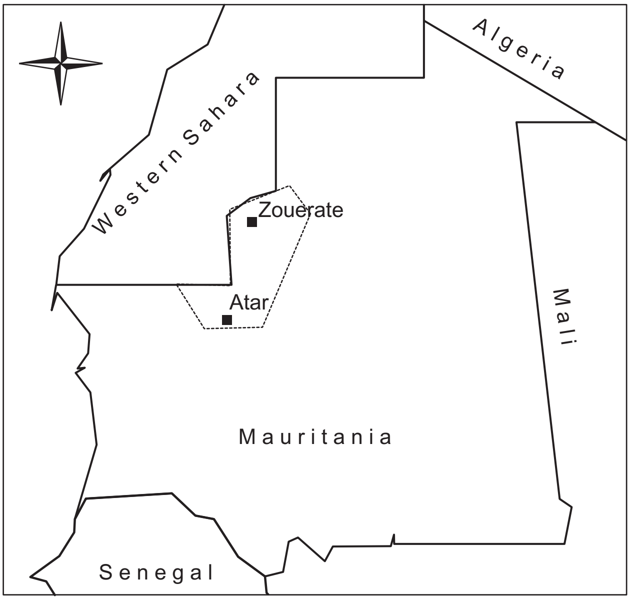

Figure 1. General map of the study area location.

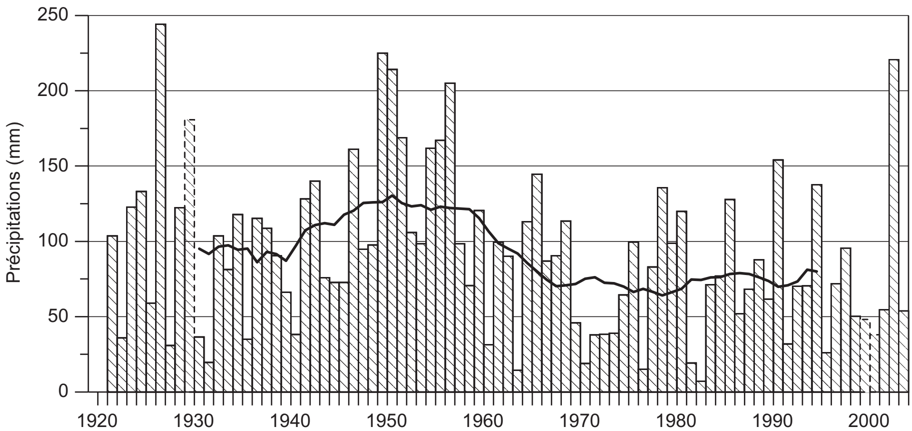

Figure 2. Annual rainfall and moving average over 20 years in Atar city.

year and can remain dry during long periods. When rainfall does occur, the surface runoff both on the plains and in the wadis converges towards a large number of closed endorheic depressions. Among them are the sebkhas and the garaas. The sebkhas, or saline lakes, are characterized by an abundance of soluble salt, especially chloride and sulphates that are precipitated at the surface. The piezometric levels below the sebkhas are shallow and there is intense groundwater evaporation (up to 4 m per year). The garaas are humid zones depending on the runoff in the ephemeral wadis. They are less brackish than the sebkhas.

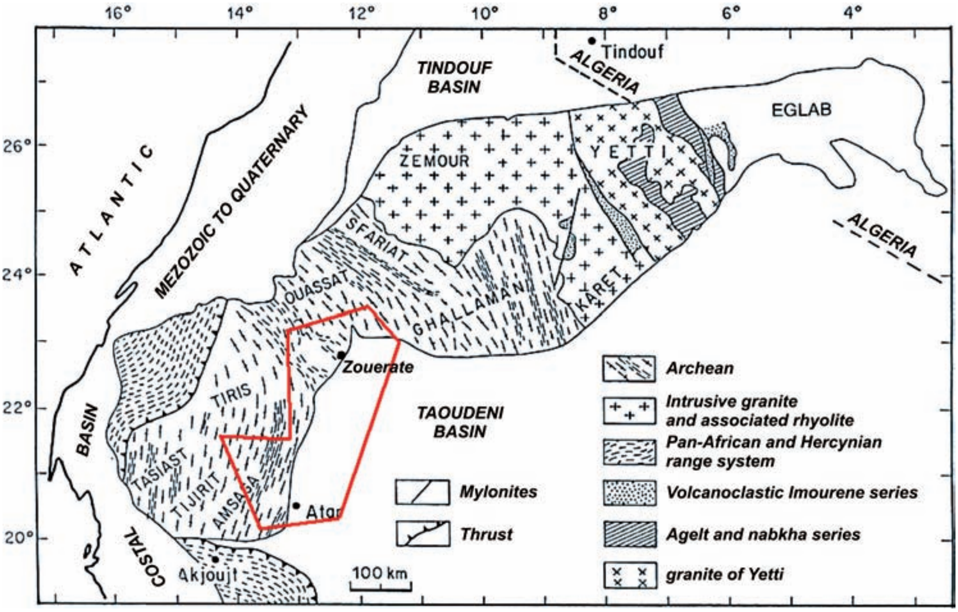

Figure 3. Extent of the studied area drawn on a geological sketch modified from Lahondere et al. (2003).

1.2 *Geological setting*

The study area (80 000 km^2) comprises two distinct zones: the north-western part of the Taoudenni sedimentary basin in the east, and the Precambrian basement in the west (Figure 3).

The basement includes mainly fractured metamorphic formations, intrusive granite and a few allocthonous units forming small or major inselbergs like the Kédia d'Idjil, the M'Haoudat, or the Guelb el Rhein. These units belong to the Idjil group, which is considered to be an old deformed sedimentary system, metamorphosed and displaced within the basement. This group is mainly comprises ferruginous quartzite, quartzite and mica schist. Other lithologies are present including amphibolites, metagabbros, dolomite. The depth of the basement eastward under the Taoudenni basin is not precisely known.

To the east, the sedimentary cover corresponds to the north-western extremity of the Taoudenni sedimentary basin, which is composed of a complex series of fissured limestone, sandstone, conglomerates and shale. The lithology and the stratigraphy of the basin have been described in detail (Delpy et al., 1963; Trompette, 1973; Lahondere et al., 2003; Pitfield et al., 2004). The oldest deposits are regrouped under the denomination of the Hodh Supergroup (Infra-Cambrian Series). They are covered by deposits of the Adrar Supergroup (Cambro-Ordovician Series) from which they are separated by the so-called lower tillite (glacial deposits). These supergroups have been subdivided into groups, each one comprising several sub-ensembles. The groups rest uncomformably on top of each other and some groups are not present everywhere. The whole sedimentary basin is not folded, but is affected by minor shear deformations (Villemur, 1967).

1.3 *Groundwater systems in the oldest sedimentary formations*

In the south of the area, the outcrop limits of the oldest basin formations (Char Group and Atar Group formations) are sites where small parallel valleys have formed, all of them draining into the Seguelil wadi toward the Archaean plain of Amsaga in the south. In these valleys, often partially filled by Quaternary deposits, are the oases of the sector of Atar, irrigated by numerous wells. Moussu and Trompette (1966a, b) describe the hydrogeological setting of this area based on the oasis wells in the Quaternary deposits. Up to the 1970s, these wells exploited the alluvial aquifer. With the decline in rainfall, this aquifer now dries up after the recharge episodes. The oasis wells have very often been deepened to reach the sedimentary formations under the Quaternary alluvium. The main outlet of the system is, at present, still beneath the oases, where more than 6.5 Mm^3/year are extracted, but more and more is pumped from the old sedimentary formations. In this sector, in addition to the 2500 wells, located in the 22 oases, the aquifers have been explored around Atar by drillings. An analysis of these data shows the discontinuous nature of the aquifers. 25% of the boreholes have a yield of less than 1 m^3/h and 20% have a yield greater than 15 m^3/h. Only the most productive wells have been hydraulically tested and the transmissivities range between 1×10^{-4} and 5×10^{-3} m^2/s. The boreholes intended for the water supply of Atar city produce some 0.6 Mm^3/year in addition to the water drawn from the oasis wells.

In the north of the area, the relief is dominated by the plateaux of the oldest formations of the Hodh Super-group. The slope of these plateaux, drained by the valley of Assabet el Hassiane, is gentle. The main relief is that of the Kédia d'Idjil and the M'Haoudat, on the border of the basin, partially covered by sedimentary formations. Plote (1966) drew a hydrogeological map based mainly on observations in the Kédia d'Idjil, where iron ore is mined. The first boreholes were drilled in the Taoudenni basin to supply water to the mining industry in the early 1970s. The withdrawal for this activity represents some 27.8 Mm^3 since its inception. Pumping at present is 0.9 Mm^3/year for the mines and a total of 2.4 Mm^3/year for the Zouerate city water supply and other uses. As for the Atar sector, the main characteristic of the aquifers is a strong variability of productivity indicating a discontinuous aquifer. 33% of the wells have a yield of less than 1 m^3/h and 10% have a yield greater than 30 m^3/h. The range of transmissivities for the highly productive wells is between 1×10^{-4} and 4×10^{-3} m^2/s. The piezometric variations of the Zouerate sectors have been well known since the start of the exploitation of groundwater in this zone. However, the evolution of the numerous piezometers does not show the same trend around the well fields. Even if the general trend is toward is of decline, it does not occur everywhere at the same rate. The piezometric records often present strong or weak changes that deviate very strongly from a clear overall trend (Figure 4) and there are phases when the water levels rise and there are fast and erratic variations. The fast rises are sometimes limited to one or two boreholes and only sometimes visible in all the boreholes.

The aquifer system of the oldest Taoudenni basin formations (Hodh Supergroup) consists of a series of three main lithologies:

1. Sandstone horizons are present over the whole stratigraphic log. Their thickness is highly variable from small interbedded lenses to large monotonous horizons. Their primary porosity is often very low, but they have a significant secondary porosity due to fissures and fractures.
2. Carbonate horizons are localized mainly at the base of the stratigraphic log. They have features that indicate a karstic development.

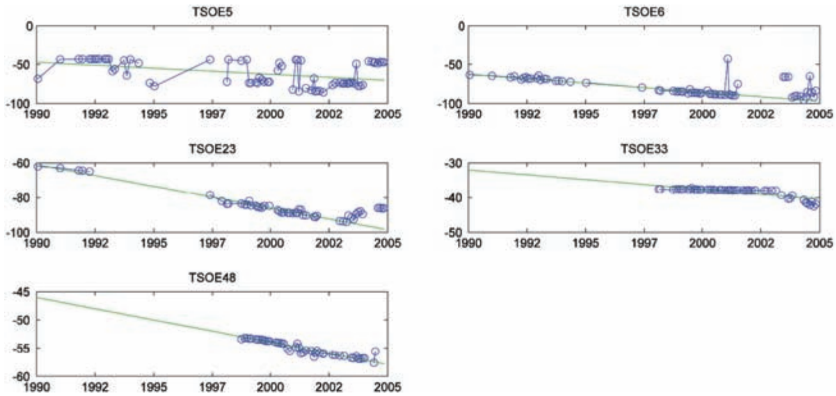

Figure 4. Drawdown measured in boreholes of the mining company and average trend.

3. Mudstone horizons, usually considered of low permeability. The hydraulic communication between these aquifer horizons occurs through the dense fracture network that cross-cuts the whole series. The transmissivities are not correlated with the thickness of the aquifer or with the lithology. It appears that the main controlling factors are the orientation of the fractures with respect to the current state of stress and the relative position of the boreholes with respect to the topography (Fénart et al., 2006). The most productive fractures are oriented N120E in the south and between N140E and N010E in the north. In the sectors where the relief is marked, the boreholes located at the foot of the cuestas are less productive than the wells located at top.

The hydrogeological potential of the oldest Taoudenni basin formations was identified in the late 1960s but not quantified. Although the existence of one or several aquifer systems was clear to all the hydrogeologists working in the area, their spatial extent, the regional flow directions and more generally their behaviour were unknown. The recharge processes were unknown as well; furthermore, the vertical continuity between these horizons has never been ascertained. The work presented in this paper aims at clarifying these points and providing a basis for future water management in the region.

2 METHODOLOGY

Using ArcView® and ArcGis® (ESRI products), a spatial database was built to store all the collected data, process them and generate map output. This GIS database contains different types of cartographic data such as the digital elevation model, the location of groundwater observations and withdrawal points, and the geological map (polygons) that constrains the extent of the groundwater model.

2.1 *Measuring groundwater levels*

Over the study area, 624 groundwater points were identified and levelled using high precision differential GPS. The geographical distribution of this network is irregular; the water points are mainly located around the two cities, Atar in the south and Zouerate in the

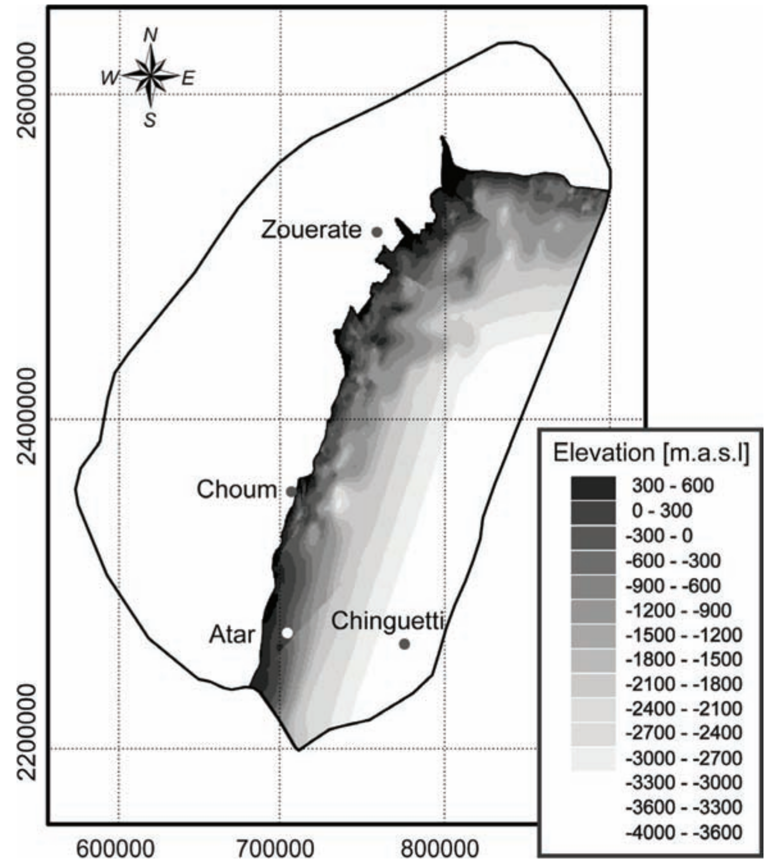

Figure 5. Result of kriging on the zone of interpolation representing the depth of the basement under the basin of Taoudenni.

north. A 20-day piezometric field study allowed us to measure more than 532 water levels including 421 static ones.

2.2 *Bedrock mapping and aquifer geometry*

An interpreted map of the depth of the basement under the Taoudenni basin was created (Figure 5) by combining an interpretation of the main tectonic events, inverted geophysical data and extrapolation of the observed thicknesses of the outcropping sedimentary layers and their dip angles. All these data were combined by kriging. This analysis shows that it is highly probable that the overall thickness of the sedimentary system can reach more than 4000 m in the eastern part of the area.

2.3 *Groundwater modelling*

The numerical groundwater modelling was carried out with Feflow® (Diersch, 2005). This regional model is conceived in 2D because of the lack of hydraulic conductivity data

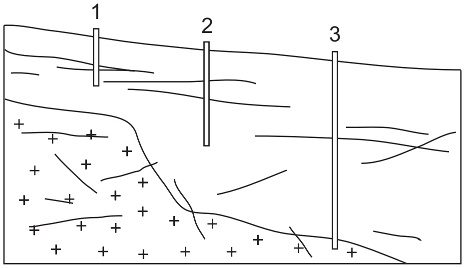

Figure 6. Conceptual model of the transmissivity used in the groundwater model. The transmissivity of the first and second wells will probably be higher than that of the third well because of the number of fractures penetrated.

as a function of depth and because of the wide lateral extent of the aquifer as compared to its thickness (the ratio is less than 1%).

During this study, a series of pumping test data were re-interpreted. Surprisingly, all but one data set showed typical 2D radial flow behaviour (constant log derivative). There was no evidence of double porosity behaviour or finite fracture behaviour. This shows that even if the medium is fractured, the fractures must be continuous enough in space to produce radially convergent 2D flow around the wells. As a result, it is reasonable to assume that an equivalent continuous medium can represent the large-scale regional flow. A study was made of the sensitivity of the groundwater model to the presence of preferential flow directions. It was done by including five major faults oriented N120°E in the south and N140°E in the north, and by testing different regional anisotropy factors while keeping the same principal anisotropy directions.

The measured transmissivities do not correlate with the thickness of the aquifer. An acceptable conceptual model for the Taoudenni basin is to assign to each geological formation a transmissivity value that is independent of its thickness because borehole measurements of transmissivity depend on the number of fractures crossed by the borehole (Figure 6). However, the degree of open fractures may be different from one formation to another.

The sebkhas constitute the principal natural groundwater outlets in the area. The location of potentially active sebkhas was determined by satellite radar images, the ENVISAT pictures present a characteristic signal of the moisture presence on the earth surface. An estimate of the order of magnitude of the evaporation rates beneath the sebkhas was made with the formulas by Coudrain-Ribstein et al. (1998), based on an evaluation of the water table depth (0.4 to 4 m). The output fluxes were imposed as source terms on the surface shape of the sebkhas, allowing the use of PEST and automatic calibration of these fluxes.

Evaluation of the recharge is always difficult in arid zones. Published values are extremely variable, from less then 1 mm/year in New Mexico to 110 mm/year in the Neguev desert (Scanlon et al., 1997). Recharge may be significant as demonstrated by Ould Baba Sy and Besbes (2006) for the North Western Sahara Aquifer System. Recharge was calibrated in the model, by zone, as a constant source term. Three variants for the spatial distribution of recharge were tested (Figure 7). The choice of these possible preferential recharge areas is based on an analysis of existing data:

1. The Kédia d'Idjil, where groundwater is locally fresher than elsewhere in the area and the piezometry reacts to the most intensive rain events.

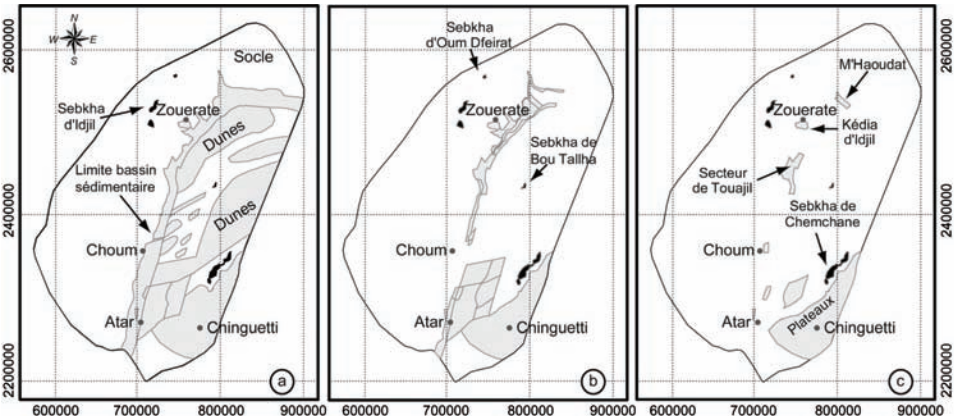

Figure 7. Delimitation of the potential recharge zones (grey) considered in the three recharge scenarios.

2. The M'Haoudat in the north of the Kédia, which presents comparable geological and hydrogeological settings.
3. The dune massifs (Hammami, Maqteir, Oum Arouaba) where precipitation can penetrate quickly.
4. The most permeable formation outcrops: Azougui, Aguéni, and Foum Chor, with a high density of open fractures at the surface.
5. The concentration zones of the hydrological network and of runoff accumulation.

There are three scenarios: all of these zones are assumed to be potentially active, infiltration through the dunes is considered negligible, and only local recharge is considered.

Based on the model for transmissivity distribution and the three scenarios of recharge distribution presented above, three steady-state flow models were successively and satisfactorily calibrated. The calculated steady-state heads were used as initial conditions for the transient simulations, covering the period from 1957 to 2004. In addition, different time-dependent or constant-recharge scenarios, as well as different values of the storage coefficient, were tested.

3 REGIONAL FLOW SYSTEMS

The piezometric map constructed from the groundwater levels measured in all the Hodh Supergroup formations shows a remarkable coherence. It shows at least two major flow systems, separated by a piezometric crest: the *Atar system* in the south of the Oum Arouaba dunes massif, and the *Bou Talha system* to the north of these dunes. In the south-eastern part of the area, there is an upper aquifer system located within the Adrar Supergroup, and overlaying the Hodh another which is isolated by a thick aquitard.

3.1 *The Atar system*

Overall, water flows from the north (Oum Arouaba dunes) to the south (Amsaga plain). The groundwater is drained by the oases in the small Adrar valleys. The share of this

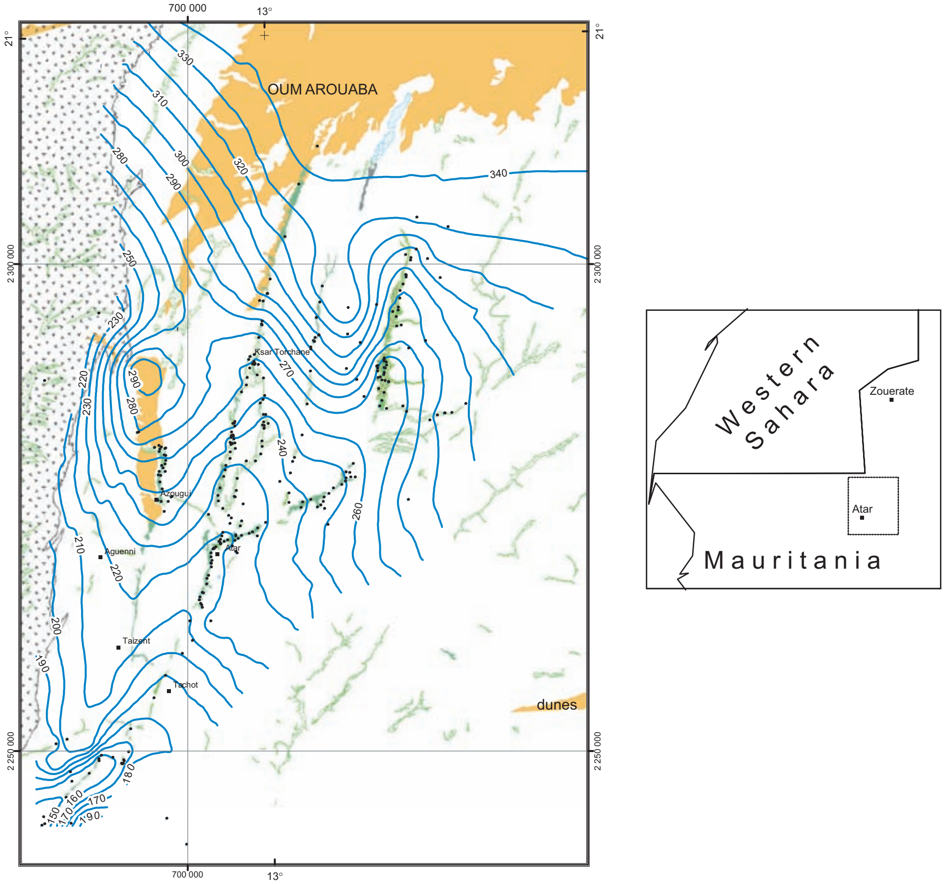

Figure 8. Piezometric map of the Atar system, May 2005.

regional flow that reaches the southern outlet is probably very small, on the order of 0.2 Mm^3/year.

If part of the recharge of the system can occur during the floods beneath the alluvial deposits, which fill the wadies, and may also occur during rainy episodes between valleys beneath the sandstone and limestone outcrops, whose surface is heavily fractured, the piezometric map suggests that the system is recharged from the piezometric crest in the North, under the Oum Arouaba dunes massif. On the whole, the recharge by rainfall may be on the order of 5.4 Mm^3/year. The piezometric variations reported by the operators of the oasis wells show that the system refills during very rainy seasons. Depletion is then observed until the following heavy rains, one to four years later (Figure 2). During seasons with heavy rainfall, the recharge is intensive and the piezometric levels in the oasis wells are often less than 1 to 2 m below the ground surface. As the withdrawal is limited by the depth of the wells, the system is in a state of unstable equilibrium between maximum recharge during very rainy seasons and maximum drainage after several years without recharge, when the piezometric levels reach the limit of the well depth. In addition to rainfall recharge, the system is also recharged from the overlying system of the Adrar Supergroup, probably by around 2.1 Mm^3/year.

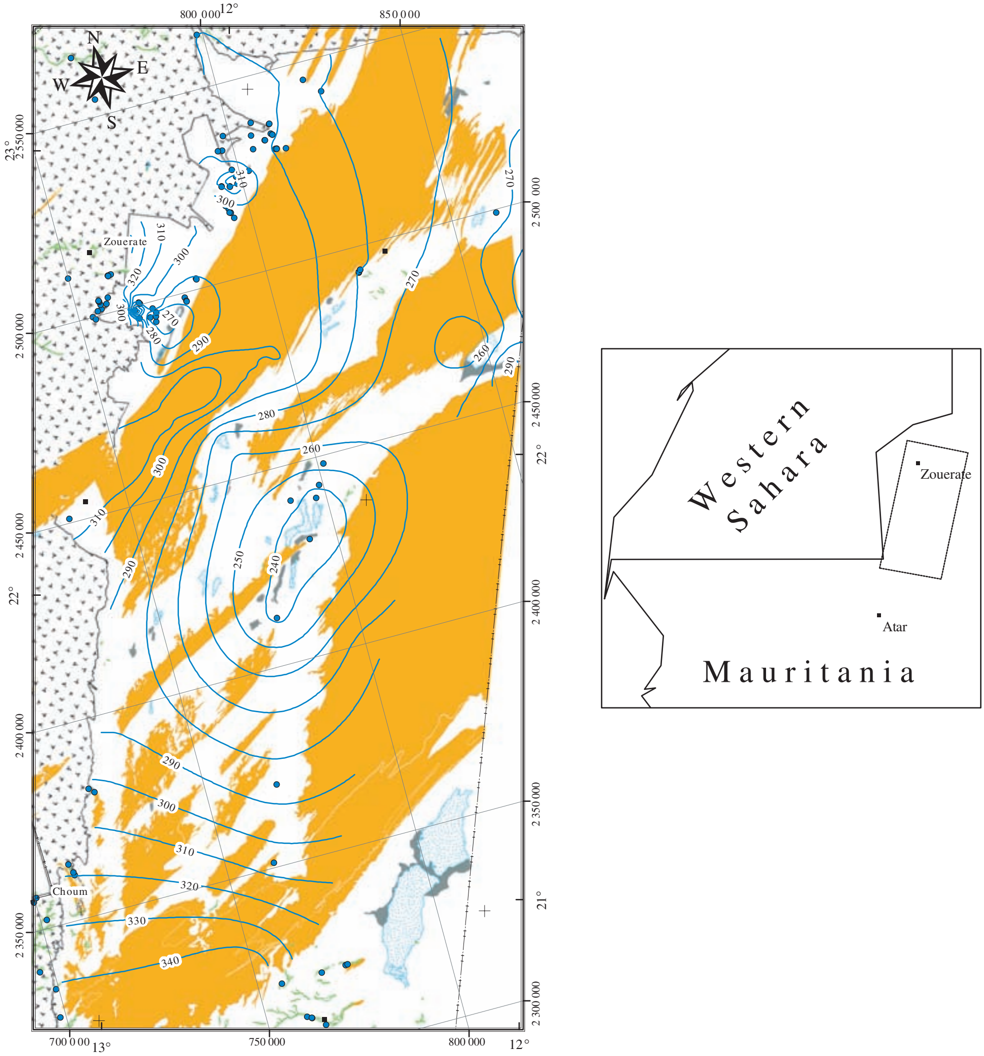

Figure 9. Piezometric map of the Bou Talha system, May 2005.

3.2 *The Bou Talha system*

The Bou Talha aquifer system is, like the Atar system to the south, part of the aquifer formations in the Hodh Supergroup. It extends over a vast domain from the piezometric crest beneath the Oum Arouaba dunes massif in the south up to the northern border of the sedimentary basin (Figure 9). In the west, it is also limited by the border of the sedimentary basin. In the east it extends beyond the mapped zone, certainly under the Maqteir dunes massif (the available piezometric information is too scarce to define the extent of the system eastward). Two zones can be distinguished in this system, to the south and in the north of the Bou Talha sebkha.

The piezometry in the south is known only at a few groundwater points (10). It seems that it follows the topographic slope to converge towards the Bou Thala sebkha. It should be noticed here that the piezometric crest beneath the Oum Arouaba dunes massif also corresponds to a topographic high. The flow comes from the dunes massifs: Oum Arouaba in the south, Maqteir in the east and Hammami in the west and north-west, and converges towards the Bou Thala sebkha which seems to constitute the main outlet. Between Bou Talha and Tourine, a watershed is outlined between the water from the southern sector drained by the Bou Thala sebkha and the water from the north drained by the Meddahia sebkha.

In the northern sector of the Bou Talha system there are numerous boreholes supplying water to the mines around Zouerate. Large drawdown cones have formed beneath the well fields, which tap the groundwater on the border of the basin. The piezometry in the rest of the zone is less well known with only 29 measurement points. The sector east of the Hammami dunes massif is drained eastward by the Meddahia sebkha which, together with the boreholes for the mining company, represents one of the major outlets of the northern sector of the Bou Talha system. This sebkha also drains flow from the western extremity of the Hammami, which is not diverted towards the Bou Thala sebkha. Furthermore, it seems to drain groundwater stored beneath the Maqteir dunes massif, in the south-east.

Like the Atar system, the discontinuous aquifer layers in the oldest sedimentary formations are recharged by rainfall, probably some 6.8 Mm^3/year. Uncertainties persist, however, concerning the exact recharge sites, i.e. beneath the dunes massif (Oum Arouaba in the south, Maqteir in the east and Hammami in the centre) and/or beneath the most permeable rocky outcrops or beneath the surface water accumulation sites, notably in the alluvial valleys of wadis. The system is also recharged by the basement formations (of the order of 1.4 Mm^3/year), in particular from the Kédia d'Idjil and the M'Haoudat. The current data sets are not sufficient to clarify whether or not recharge occurs beneath the dunes and it would be necessary to know the hydraulic gradients in the basin in the east and the south-east of the zone, under very remote, hardly accessible, dune massifs. The interpretation here is important because it modifies the regional balance by an amount of the order of 15 Mm^3/year, which corresponds, for example, to five times the current withdrawal required by the mining activity. The existence or the absence of such a recharge in the dunes is thus a major question, which remains to be answered in order to understand the hydrogeology of the region.

The system is drained naturally at the low points where there are springs (0.1 Mm^3/year) and oases at the border of the basin (Choum wadi and Char) and the Bou Talha sebkhas and nearby Aouchich, Meddaiha and Erguiya where evaporation is high (11.3 Mm^3/year). It is also drained by the numerous production boreholes (2.4 Mm^3/year), in particular those supplying the mines. Between the Hammami dunes massif and the Bou Talha sebkhas, it is very likely that the system is drained by evaporation beneath the Timnjati sebkha. This draining does not modify the flow direction, as it only affects the flow from the north-west. The quantitative balance proposed by the mathematical models shows a depletion of the reserves on the order of 2.4 Mm^3/year. It thus seems that the withdrawal through boreholes, although localized, diverts only an insignificant part of the groundwater flow away from the sebkhas.

4 CONCLUSION

The data analysed in this work made it possible to describe the main behaviour of two vast aquifer systems in the region. In the Atar system in the south, a long term equilibrium is established, constrained by the limitations on the withdrawals, in particular due to the shallow depth of the wells. In the Bou Talha system in the north, the high withdrawal rates for the mining activities are concentrated to the border of the Taoudenni basin and do not in practice divert any significant component of the large flow away from the sebkhas. In this system, unlike that of the Atar, the withdrawals have led to a continuous decline of the piezometric levels.

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