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Estimation of the recharge potential of aquifers in the Sahel-Doukkala region (Morocco)

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During these periods of greater changes, as climatic as demographic, the region of Sahel Doukkala is to confront with questions of pollutions and degradations of the groundwater. The preservation of the balance so requires, a rigorous management to guarantee the durability of water resources in Sahel Doukkala, as well as everywhere else. Therefore, we were interested in the behavior piezométric present tablecloths in said region, in the various fluctuations and the hydrodynamic parameters using geographic information system (SIG) and the climatological data.

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Introduction

Cumulative combination of different demographic, technological and economic variations; explain in certain way the modification of the natural environment which has changed the landscape of the earth including that of the natural resource especially water [22-18-29].

In several semi-arid regions in the world, surface water provides a considerable source of water supply. We observe rivers as permanent as temporary, which flow at a high flow rate during the rainfall while some of those rivers do present a low water flow [9]. In those cases, water reserves are needed to support human needs in the agricultural, industrial and domestic domains.

In Morocco, the excessive exploitation of aquifers increases its vulnerability [3-11-19-21-24-40]. In addition to problems related to marine invasions in some littoral mark; it is being reduced in quantity.

There is no considerable recent studies in the dynamic of the aquifer in this zone despite the importance of the region. Indeed, we can notice studies by Younsi (2001) [39] on the rain index on free costal aquifers in the region of Chaouia; located in the North (Beyond the right hand side of the Oued Oum Er R'Bia region), Fadili (2015) in the evaluation of the mineralization of the costal aquifer in the Oualidia region [10].

Therefore, to answer questions relative to fluctuations, initiated by the Oum Er R'Bia watershed agency (ABHOER), the study presents a methodology for estimating the punctual recharge of the aquifer. Investigations are restricted to the surface area between the ground and the top of the aquifer;

making it possible to reproduce short-term and long-term punctual recharge. This will be a crucial point on decisions, in particular to compensate for the regions with ls water and in the choice of artificial recharge site.

Materials and methods

Study area

With an area of 7700 km^2, the region of the Sahel-Doukkala is located downstream of the watershed of Oued Oum Er R'Bia. This region has a littoral of about 150 km between the latitudes 32°15' and 33°15'. Bordered in the north and the east by the Oued Oum Er R'Bia, in the south by the base of Mouissate hills and in the southeast by the Rehamma massif. The region has two parts: the Doukkala in the East with altitudes from 300 meters around the Rehamma to 120 meters beside the Sahel where we can find an Appalachian relief type due to the series of parallel dune in the littoral [20].

Geological and hydrogeological context

On geological basis, the Sahel-Doukkala is defined by a tabular regime of secondary and tertiary deposits based on primary terrains highly folded by the hercynian orogenesis, which is an essential characteristic of the geological unity of Meseta [4-15].

The primary base made of shale and quartzite flushes at the northeast and the east of Doukkala, especially in the Oued Oum Er R'Bia valley. It is nevertheless hidden elsewhere by secondary deposits expect in the El Jadida Cambrian mark. It is unknown despite surveys revealing presence of shale between 1500m and 4000m of average depth.

In addition, the Permo-Trias is known in the valley of the Oum Er R'Bia in the form of deposits of clays and red pelites, with basaltic flows. At M'Tal, these formations are associated with red carboniferous conglomerates. It seems that the Triassic is very widespread in the basement with a very large and an important development of saliferous facies.

In the South, we find the Jurassic. It flushes at the south of Doukkala showing hills and Mouissate, at times a dispersed outcrop or covered of Plioquaterian layer in the region of Safi (figure1).

With a total power estimated at 200 meters, we notice the importance of the gypsum facies development by drilling.

According to the Cretaceous, studies by Chtaini (1987) [6] revealed that it corresponds to a generalized marine transgression in the region following the Jurassic without apparent gaps in Safi, nevertheless presenting the same thickness variations and facies.

On the other hand, from lithology studies of the stratigraphy, survey work [1-12-13-16] has enabled us to notice that the region of Sahel Doukkala has potential reservoirs.

In order to characterize the aquifers mark by mark, we have presented the region in function of the stratigraphic system according to the superficial superposition and major flow (South East, North-Ouest).

The region is dominated by Plioquaterians formations. The sets are merged into a unique permeable set, but it is usually the underlying marine facies, more cemented and less clayey containing the groundwater.

Two types of characteristics of aquifers circulations are distinguished in the detrital limestones:

- Permeability of gaps, casting in sandy horizons (3.10^{-5} m/s and an average superpipe storage coefficient of 8.10^{3})
- Permeability of predominant fractures in the cement rich horizons (6.10^{-4} m/s and an average superpipe storage coefficient of 5.10^{-2}).

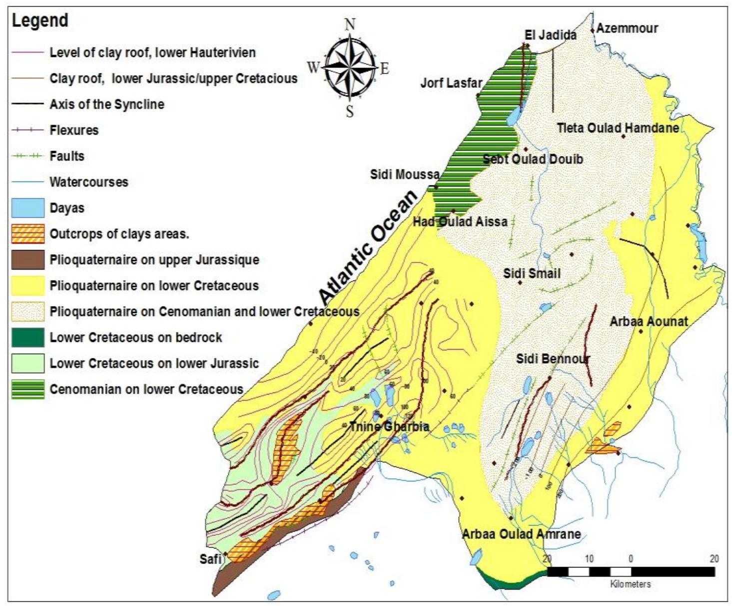

Fig. 1: Geological overview of the Sahel Doukkala

We should notify that it is the injection trials and not the pumping which helped to prove the coexistence of these two type of permeability.

Analytical method

Research and selection of measures points

The first stage of the realization of the piezometric study started with the research of the measurement points.

About 100 measurement points were selected in order to obtain the most possible uniform geographic coverage. In addition, this was based on valid reasons from previous measurement. With an area of about 7700 km^2, an average density less than 100 km^2 per point.

Obtained from the Oum Er R'bia watershed agency, we recorded several types of structures; including wells and boreholes with varying depths.

With regard to wells; They are the most numerous and deep 20 meters on average in the most permeable quaternary silt zones while they reach 80 meters in karstic environments.

Realisation of piezometric campaign

Realized by the help of a piezometric probe, the measures were taken during 7 days in order to obtain states relatively synchronous to the dawn of high water periods (7th December 2015).
For each of the measuring points, the followings activities were realized:

- Verification or modification if necessary of the localization of the openings
- Postponement of measures and observations on the terrain sheets.
- Measure of the static water level according to the chosen landmark
- Evaluation of the altitude soil based on the data.

The piezometric coast of the groundwater according the general levelling of the Kingdom of Morocco (its altitude) was calculated by the difference between the altitude of the landmark and the depth of water referred to that landmark.

$$Hp = Z - Hz \quad (1)$$

With
Hp: Piezometric coast (meter)
Z: Altitude of the landmark (meter)
Hz: Depth of groundwater (meter)

Experimental procedure

To process the data obtained, we proceed by spatial interpolation. It is indeed a mathematical operation allowing us to assign a value to an unknown space from a sowing of known points. Used in many studies, [25-7], we applied the geostatistical tool analysis; including kriging [26] for the production of piezometric curves and the inverse distance weighting cause of « bulls eyes » around data locations.

Results and discussion

Understanding the subsurface water dynamic means determining the different fluctuation of water. It is in this optic that we drew a 2015 piezometric map; representing tops of groundwater during the December 2015 period.

Overview of the December 2015 piezometry

The piezometric map enables the instant vision of the state of the groundwater at a precise moment; in this case the December 2015 period.

It enabled us also to materialize:

- The hydroisohypes curves (lines of same altitude as the piezometric surface) whose equidistance and quality will depend on the density of measured points and the adopted scale for the work.
- Oriented orthogonal lines following slopes and corresponding to piezometric courant; which underline the direction of flow of the measured groundwater.
- The geometry of the hydroisohypes curves; resulting in combinations of some simple elementary forms for interpretation means.

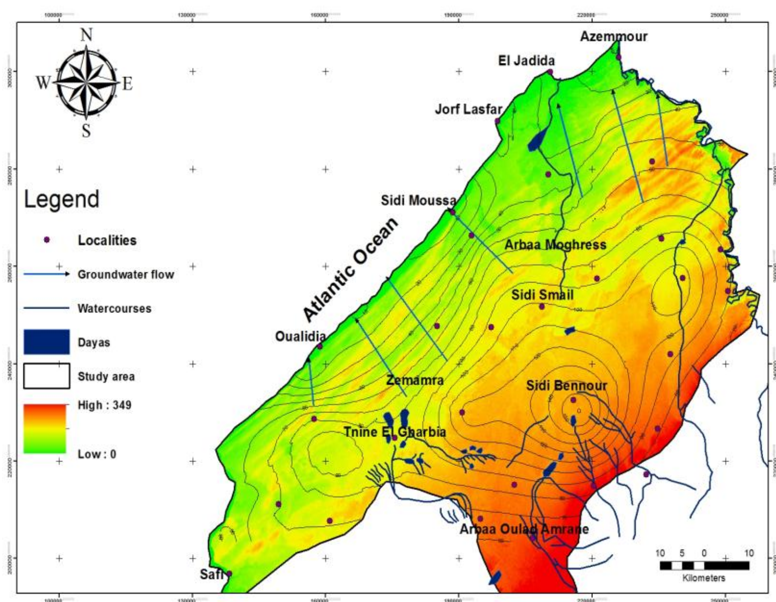

Fig. 2. Piezometric map, against a background of the digital elevation model (December, 2015)

According on location, we distinguish linear continuities with rectilinear and parallel equipotential line translating a relatively uniform flow (Sahel); curves and concavities indicating privileged drainage axes (Doukkala) and closed curves representing piezometric domes.
We can also notice in figure 1 that both the subsurface and surface flow is directed from the Southeast towards the North-West. It is indeed a flow highly influenced by the altitude gradient as the piezometric lines tighten in the Sahel; characterized by an Appalachian relief.
Indeed, costal inputs facilitate accumulation water in the inter-dune space that explains infiltration and the variation of the hydraulic gradient.

Table 1. Summary table of hydraulic gradients across the region

Plioquaternaire on Cretaceous			
Location	East limit (Rehamna)	South east limit (Mouissate)	Center (Zemamra)
Direction	North and North East	West and Southwest	North West
Hydraulic gradient (ΔH %)	$0{,}12 < \Delta H \leq 0{,}16$	$0{,}13 < \Delta H < 0{,}2$	$0{,}2 < \Delta H < 1$
Plioquaternary on Cenomanian and Lower Cretaceous			
Location	East limit (Rehamna)	South East limit. (Mouissate)	Center (Zemamra)
Direction	North and North East	West and Southwest	North West
Hydraulic gradient (ΔH %)	$0{,}07 < \Delta H \leq 0{,}2$	$0{,}13 < \Delta H < 0{,}16$	$0{,}07 < \Delta H < 1{,}7$
Plioquaternary on Cenomanian and Lower Cretaceous			
Location	-	Center (Had Hrara)	North zone
Direction	North and North East	West and Southwest	North West
Hydraulic gradient (ΔH %)	Not applicable	$0{,}11 < \Delta H < 0{,}3$	$0{,}14 < \Delta H < 0{,}43$
Cenomanian on Lower Cretaceous			
Location	Southern zone (Sidi Moussa)	Center (Had Hrara)	South zone (Sidi Moussa)
Direction	North and North East	West and Southwest	North West
Hydraulic gradient (ΔH %)	$0{,}09 < \Delta H < 1{,}3$	Not applicable	$0{,}14 < \Delta H < 0{,}4$

Values of the obtained gradients by the aquifers systems are lower than 2%. Following the Henri Darcy's equation of flowrate (1856) [8], adaptable to the horizontal flow of the groundwater:

$$Q = K.A.i \quad (2),$$

where $i=\Delta h/L$ (3),

Q: the volumetric flow rate (m^3/s)
K: the hydraulic conductivity or "permeability coefficient" of the porous medium (m/s), which depends both on the properties of the porous medium and on the viscosity of the fluid.
A: the area of the section studied (m^2)
The hydraulic gradient ($i = \Delta H / L$), where ΔH is the difference of the piezometric heights upstream and downstream of the sample, L is the length of the sample.
We can therefore deduct that the hydraulic gradient i (equation 3) translate a good flow of the groundwater. Indeed, we found temporary rivers, which recharge the groundwater during dry periods, helped by the geomorphology (plateau, more or less irregular) as well as the nature of present rocks and silt layer.

Everything seems to indicate that there is a continuity in the groundwater flowlines in the Sahel Doukkala region despite the spatial repartition of vadose zone. From the East Doukkala boundary (formations of Plioquaternian on lower cretaceous) fluxes are oriented towards the North-East (Lower Cretaceous on the Upper Jurassic) passing by the formation of the Plioquaterian on the Cenomanian and the lower cretaceous
The figure above represents the spatial distribution of the unsaturated zones in the region. From west to east, it is noted that the coastal areas as well as the near lively thalwegs (Sidi Benour in the South of Tnine El Gharbia and on both sides of the Oued Oum Er R'bia. Those regions show a stability in type of flow and orientation in the groundwater.
In addition, we have groundwater at depth more than 25 meters, reaching 70 meters. We found them essentially in the center as well as in the south. Prospections as enable us to notice a presence of karstic network (*in the south nearby Safi*), with alternation between active and empty wells whereas the silt forming almost the entire layer of the Doukkala.

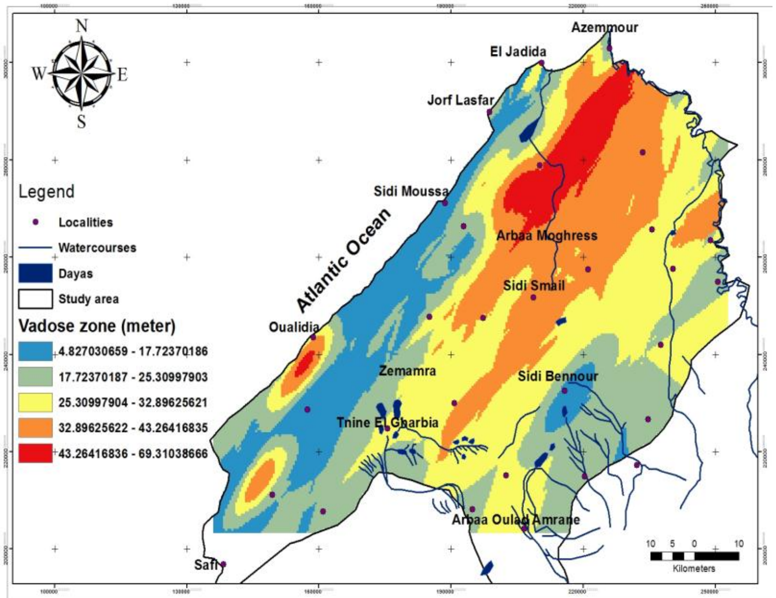

Fig. 3. Representative map of unsaturated Area (December 2015)

Analysis and comparison of historic data

Results have allowed us to determine the direction of flow as well as the hydraulic gradient at certain points. We started from discrete data to establish via geostatic; the rest of data on the entire studied area. This despite its area.

It appears that during the hydraulic season, we have a succession of seasons influencing the groundwater; which allows us to observe the variation of water pressure on each piezometer. In addition to that, anthropic changes caused by pumping as well as the water return due to infiltration. With rainfall history and piezometric measurement, we have been able to study the different fluctuations of the groundwater to properly understand its function.

Precipitations

This is to showcase the rainfall activity of the Sahel-Doukkala region and that of the Oued Oum Er R’Bia basin that it belongs. Indeed , rainfall plays a major role in the aquifer recharge [2]; by the way, Sophocleous (1991) suggested a simple modeling approach to obtain recharge from precipitation records, vadose zone water balance analysis and water-table fluctuations in wells [38].

From the figure 4, the monthly average billows values were obtained from measurement from more 30 stations between the 1989 and 2011 for the entire oued oum Er R’bia basin and the 39 years old historical measurements in the Sahel-Doukkala.

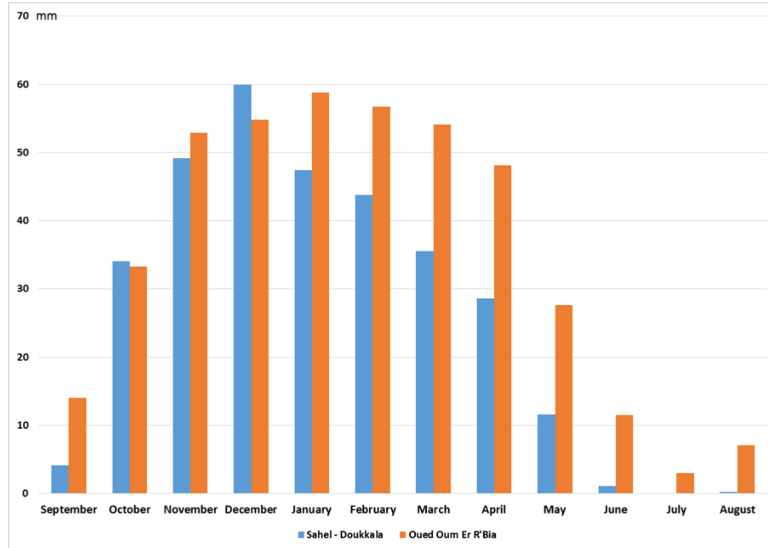

Fig. 4. Overview of average rainfall in the Sahel Doukkala region and the hydraulic basin of Wadi Oum Er R'Bia

The figure shows indeed a variation; which results from the fact that there is a reduction of rainfall activities towards the Atlantic Ocean, and the downstream position of the region gives it a hotter climate than regiosn located around the Atlas.

We can distinguish two pics, first that of December in the Sahel-Doukkala and January in the Oued Oum Er R’Bia basin. Those pics correspondence to periods of high water level. We have therefore separated the year into two (September – February and March–August) to understand the hydrodynamic characteristic of the region. February corresponds to the time of response of the groundwater (2 months).

Table 2. History of rainfall in the Sahel - Doukkala from 1990 to 2002

Periods	Nb. Station	Average (mm)	Min (mm)	Max (mm)
1990/1991	10	281,55	114,6	480,7
1991/1992	24	110,77	30,4	269
1992/1993	24	130,35	33	246,6
1993/1994	24	327	133,6	506,5
1994/1995	23	121,39	71,5	165
1995/1996	23	553,735	30	911,3
1996/1997	23	482,58	187,2	687,2
1997/1998	23	256,504	53,9	414,5
1998/1999	23	164,169	97	291
1999/2000	23	202,3956	132,5	327,6
2000/2001	23	138,087	74,9	255,3
2001/2002	9	237,22	150,5	327,8

It therefore follows that the region of the Sahel-Doukkala had an important rainfall fluctuation during about a decade (1990 – 2002). With low values recorded in 1991 – 1992, about an average of 110.77 mm against 553.735 mm recorded in 1995 – 1996.

Comparative study of unsaturated zone

The undersaturated zone, particularly its subsurface constitutes the crucial buffer for the transport of various pollutants.

The vulnerability of the groundwater and the risk of its pollution depend on the structural constitution and the importance of that particular zone.

The effectiveness of prevention against possible pollution by the use of a model depends on the latter. It is a step, which in turn relies on a thorough knowledge of the system.

Indeed, the saturated zone presents two major aspects with respect to transfer.

- The storage of water and dissolved substances.
- In addition, the deep drainage of the mobile fraction of water or toxic substances conditioning the recharge of the aquifers.

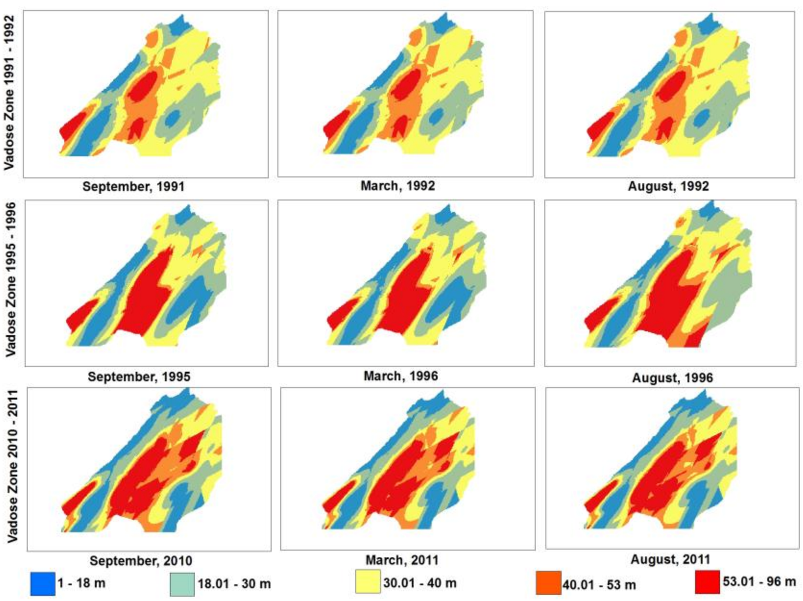

Fig. 5. Maps of unsaturated area over three specific years

The difference between the hydrological years is on the rainfall level. Meanwhile, non-saturated zones are similar. We notice that during the 3 years, the groundwater is at identical depth in September, March and August. The large difference is on years. Thus, as time goes by the vadose zones become larger.

In order to understand the different fluctuations of the groundwater, we analyzed the data by year.

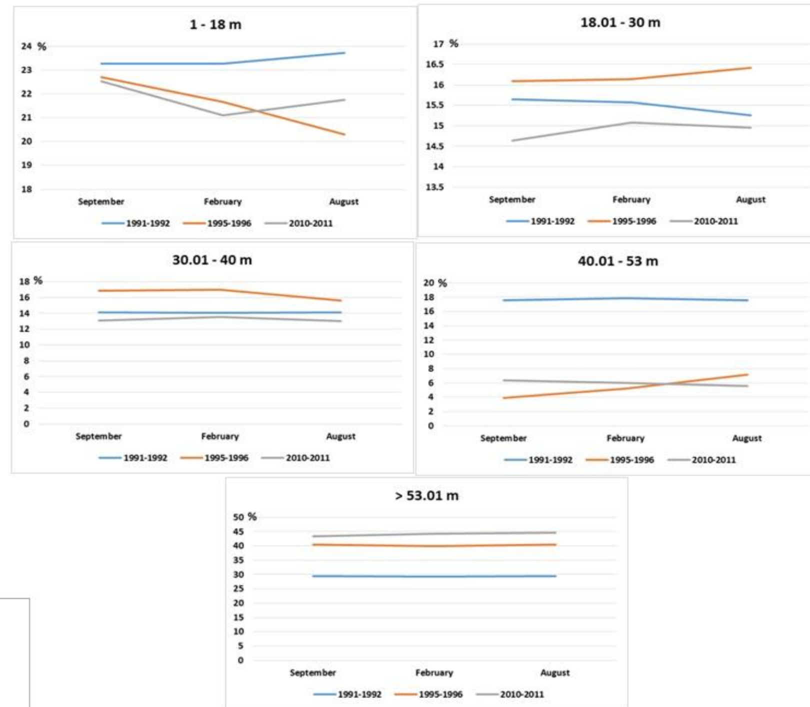

Fig. 6. Spatial distribution of unsaturated zone as a function of depth

Indeed, from the above (figure 6), above 53.01 m there is a 50% increase in area whereas the others changes in both ways (increase and reduction) in function of the recorded rainfall. It is the case of the 18.01 – 30 m and 30.1 – 40 m intervals, which increase respectively from 5.13% and 21.48% between 1991 and 1996 before reducing from 7.92% and 20.6% in 2011.

All the variations can be explained by:

- Demographic thrust, with an average growth rate of 2.02% from 1960 until now, including 3.46% for the ban population against 0.98% of the rural population according to the country's plan committee.
- Agricultural activities on more than 35 000 ha, justifying the presence of several wells and boreholes
- Industry along the littoral source of exploitation of the groundwater
- The semi-arid climate doesn't strongly facilitate the water balance

Historic of water table measures

A precise estimation of an artificial recharge is very important for the good management of the groundwater system. There are various approaches for the estimation of an artificial recharge; among them, the one based on the groundwater level data [36-37-34-23-33].

Changes on various groundwater level can be considered as recharge or flow; recharge when the level increases while flow when there is a lateral change (upward – downward).

Considering evaporation or not, two equations were established:

$$R = \Delta S^{gw} + Q^{hf} + ET^{gw} + Q^{gwoff} + Q^{gwon} \qquad (4)$$

Where R is the recharge coefficient, ΔS^{gw} the change is the subsurface storage, Q^{hf} the base flow, ET^{gw} the evapotranspiration from the groundwater and Q^{gwoff}, Q^{gwon} the net subsurface flow from the area of study including pumping. All terms are expressed as rates.

$$R = S_y\left(\frac{dh}{dt}\right) = S_y\left(\frac{\Delta h}{\Delta t}\right) \quad (5)$$

Where S_y is the specific yield coefficient, *h* the water-table height and *t* the time.

Water-level rise begins during the steepest part of the previous peak's recession. For an estimate of the net recharge, Δh is the difference of height between the second and first time of the water-level measurement. The difference between the total and net recharge is equal to the sum of the evapotranspiration from the groundwater, the base flow and the net subsurface flow from the site.

This method has been applied in various studies [32-14-17].

Based on years previously chosen, we obtain the cartography of the fluctuation amplitude on periods of rising waters and low water.

From figure 7, a, c and e; correspond to the variations recorded during the rising water period (September to February), b, d and f are data recorded from March to August. Measures from 1991 to 1992 correspond to a and b while that of 1995 to 1996 correspond to c and d whereas d and f are from 2010 to 2011.

Given these results, it is clear to notice that the region is uniform, despite some differences. Weak well /drilling fluctuations are more marked in the center of the region (Zemamra. Sidi Smail, Tleta Oulad Bouaris).

However, the differences reside in years, because of variables rainfall seepage influence in the region. Thus, we note that the periods of low water have low fluctuations while at high water they are higher.

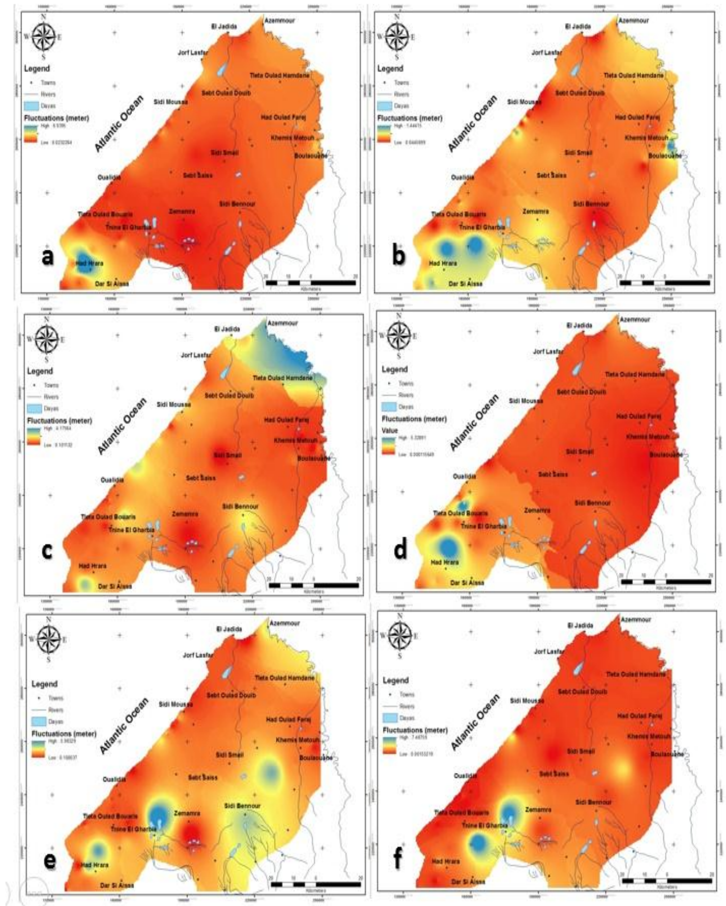

Fig. 7. Representation of the global water table fluctuations in the region during three distinct years

Water table regime

It is clear that so far there has been a question of differentiating the zones according to the fluctuations recorded. This spatial analysis has revealed among other things; the zones according to the depths of the piezometry. From this spatial distribution, we were interested in certain wells or boreholes to get an idea of the maximum drawdown in order to deduce the storage variation of all the aquifers (figure 8).

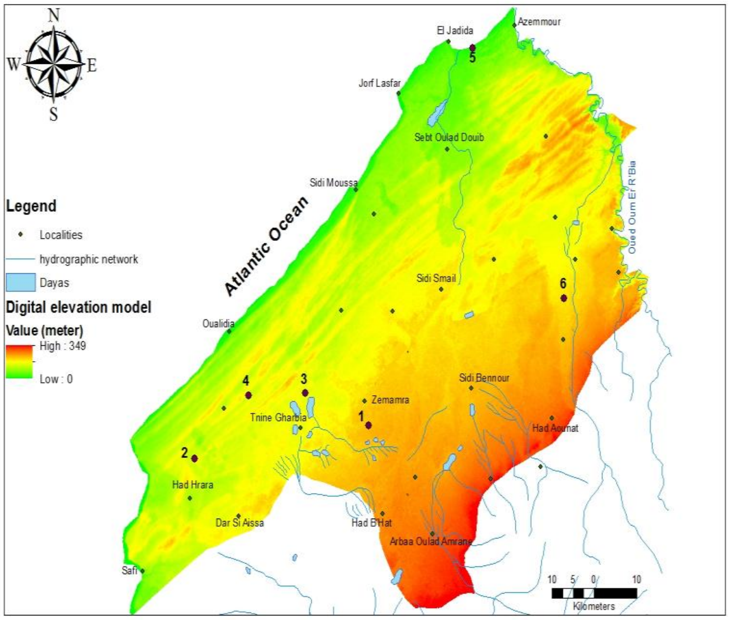

Fig. 8. Distribution of scored points

We obtain the graphs this above (Fig.9), just like the works realized by Moon and al (2004) [31]. There is a clear difference between the selected wells / boreholes. Indeed, upstream wells have a much lower storage variation than those downstream. This difference is even more striking because of the distribution of the unsaturated zones indicated in figure 5.

We found in the central region; which has superior depths in terms of unsaturated zone with amplitudes of the order of 5 meters against 16 meters downstream, despite the shallow depth of the saturated zones.

To confirm the previous results, we produced two geological profiles based on the geophysical data and maps produced by Choubert (1955, 1956) [4-5], representing the Doukkala and the Sahel.

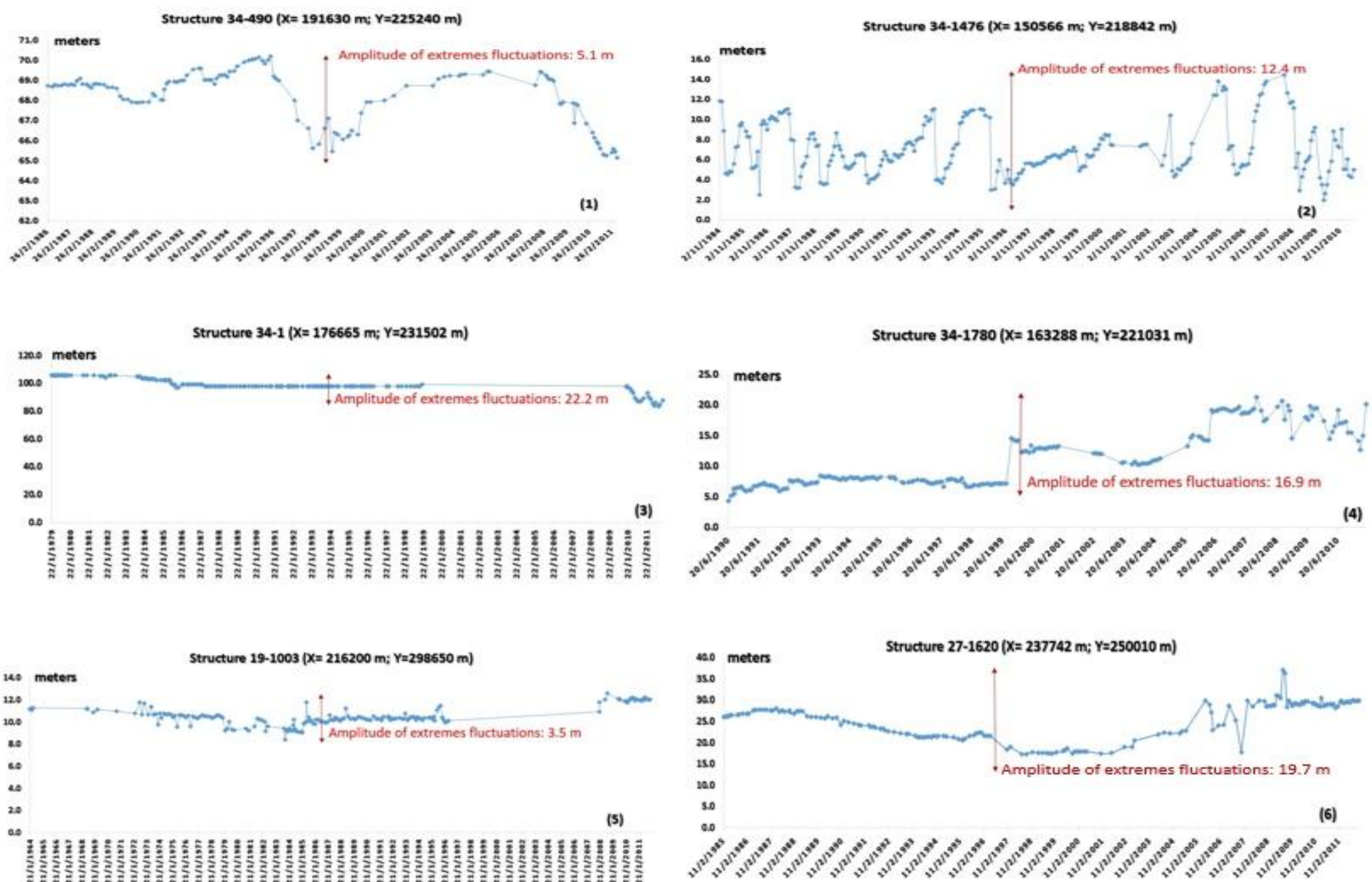

Fig. 9. Representative graphs of water table's evolutions.

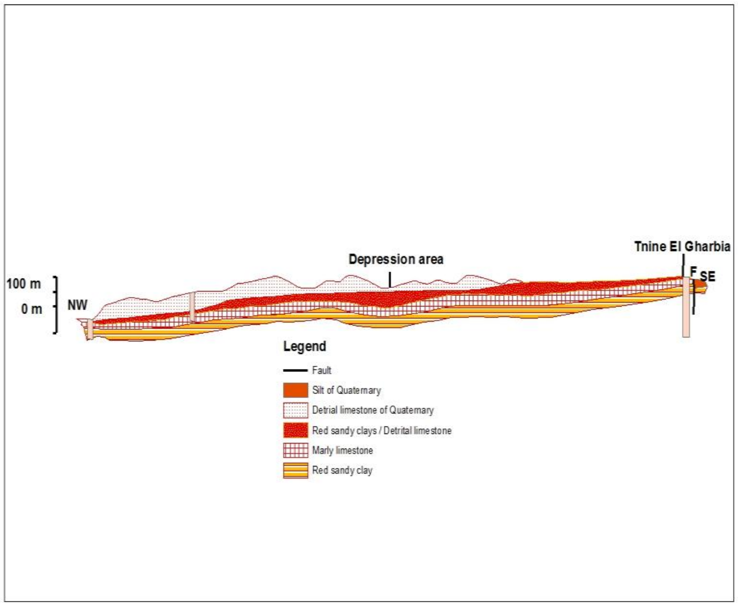

Fig. 10. Extract of a geologic profile in Sahel

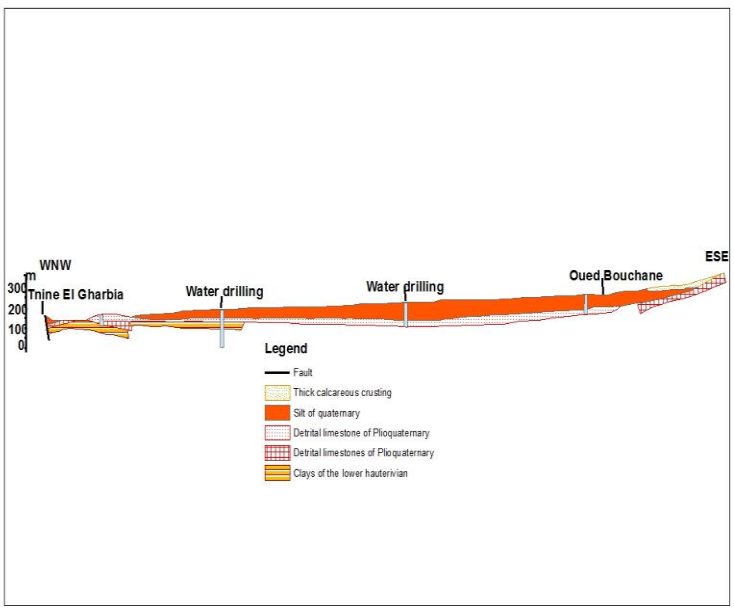

Fig. 11. Extract of a geologic cup in Doukkala

We can thus perceive the notable difference between both zones because in fact the aquifers located upstream and following the direction of the current are captive, even semi-captive, sometimes karstic and covered by important layers of clays. It also lets appear a syncline which allows to maintain the variation of storage.

Always according to the direction of the currents, geomorphology; The Doukkala aquifers covered by clays, have detritic calcareous formations dating from the plioquaternary, provided with water. Groundwater, which recharges farther upstream, tends to accumulate at the synclinal axis, hence the small variation in drawdown over several years.

Further downstream, these formerly masked limestone formations surface in the Sahel. This naturally gives anticlinal axes, with the presence of an important dune cord. The phenomenon is completely different at this level, the variations of storage are more than variable and reach the 20 meters; Despite the shallow depths of saturated areas.

Indeed, it has been demonstrated in previous works [9] that the Sahel has several lakes because of the hillsides. Here, it can be added that these lakes depend strongly on the permeability of the soil but also on the use of groundwater.

Depending on the direction of the currents, the anticline axes, and the grandwater parting, it can be deduced that there are numerous points of recharge in the Sahel region at the eastern limit of the Sahel but also at certain points more interior.

Conclusion

Water resources management is an important pillar for the development of the regions. Our lives depend on it, hence the attention it attracts. In this work, we updated the database in order to optimize the resources of the watershed.

Considered the main source of water supply, the Sahel Doukkala region; semi-arid can hardly meet a growing demand for population growth, improved living conditions and economic development. As in many studies, displacement as well as quantity and quality of water are major concerns [35-30].

Our study in this case allowed us to draw up a recent piezometric map; Based on which we have been led to estimate the different hydraulic gradients and the distributions of the zones, according to their saturations.

The drawdown of the aquifer, based on the history of the measurements, confirms the presence of captive and semi-captive aquifers upstream and aquifers rather superficial downstream.

Investigations are restricted to the top of the aquifer on average between 24 and 40 meters of depth. It emerges from it that unsaturated areas more than 50 meters deep are located more centrally and represent about 50% of the region bounded by those with shallow aquifers

In this way, we understand that the Sahel, which is highly vulnerable from a quantitative point of view, and confronted with marine intrusion by its littoral (western) border, should be the subject of more detailed surveys.

Acknowledgment

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