

## COMPUTER MODELLING OF GROUNDWATER OVEREXPLOITATION: CASE STUDY FROM THE PLAIN OF SIDI BEL ABBÈS (NORTHWESTERN ALGERIA)

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### ABSTRACT

In the plain of Sidi Bel Abbès, the Plio-Quaternary aquifer is the most important groundwater reservoir. Its computer modelling shows that it resembles a toboggan, formed by a succession of connected underground pools. The simulation conducted between 1971 and 2014 reproduced well the average water-table drop of about 11m across the entire aquifer, emphasizing its clear overexploitation, resulting mainly from withdrawals increase parallel to considerable precipitation diminution, especially between 1982 and 2006. The prediction phase simulated between 2015 and 2030 translated significant aquifer drawdowns, especially for scenarios 2 and 3, particularly East and South of the plain. The computer modelling of the aquifer illustrated its continual destocking and reflected its dangerous overexploitation, which if maintained at this rate, could have devastating consequences (complete drying of boreholes, subsidence, water and soil salinization, etc) on the plain of Sidi Bel Abbès.

**Keywords:** Plain of Sidi Bel Abbès, Plio-Quaternary aquifer, Computer modelling, Destocking, Overexploitation.

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## 1. INTRODUCTION

Groundwater represents the largest reserve of accessible freshwater and secures around one-third of the withdrawals worldwide [1,2], which has put this resource in serious jeopardy. Unlike surface water, aquifers are buried underground, which makes controlling their exploitation a very hard task to achieve [3]. Uncontrolled and unregulated use of groundwater has caused its overexploitation and contamination worldwide [4-7] and in many areas, its depletion at an unprecedented rate [8,9].

In the U.S., groundwater provided in 2010, respectively 37% and 98% of the total public and self-supplied freshwater [10], whilst in the EU, the total public water supply based on groundwater is estimated around 70%. In China and India, rural households using groundwater for irrigation purposes were estimated in 2005 around 30% and 50% respectively [11]. The rate of groundwater abstraction in India increased over the last 50 years by tenfold, making the country the largest consumer of groundwater in 2010 [12]. In South Africa, recent studies showed that overexploitation of groundwater led to a continuous drop of groundwater levels [5]. In the arid Middle East and Northern Africa, mining of “fossil” aquifers (nonrenewable, slowly or negligibly recharged in comparison to withdrawals) has attained alarming stages in countries like Jordan and Egypt (drawdowns up to 60 m and a cone of depression extending to Sudan are observed in the Nubian aquifer) [13,14]. In the Maghreb region, the fast development of groundwater based agriculture became unsustainable in many regions, due to aquifer overexploitation, water/soil salinization and feeble recharge rates [15]. The multiplication of pumping wells especially for irrigation (frequently carried out informally by farmers [16]) has put the Maghreb region, in the front seats with respect to intensive use of groundwater for agriculture [4]. In northern Algeria for instance, the average rate of groundwater exploitation is around 80%; the aquifers of the Bas-Cheliff, the Mascara Plain and the Mostaganem Plateau are quite edifying examples [17, 18]. This overexploitation has also led to saline intrusion [17] and soil salination in many regions around the country. The Stalination in the Bas-Cheliff region for example (derived from the irrigation with salty groundwater) aggravated the secondary soil salinization, which rose by 35% between 1950 and 2000 [19], with recent works showing that the continuing sodification of soils in this area is causing their gradual deterioration [20]. Another example of aquifer overexploitation is the

Western Sahara Aquifer System (WSAS), shared by Algeria, Tunisia and Libya, which is drained at a rate ( $2.2 \text{ Bm}^3/\text{year}$ ) much higher than its estimated volumes of recharge ( $1 \text{ Bm}^3/\text{year}$ ) [15]. The destocking of said aquifer has occasioned a serious drop of its piezometric level, which has decreased by over 100 meters in certain areas (example of the Ghadames area) [21] and led to the disappearance of artesianism in others [22].

The Mitidja aquifer suffering from seawater intrusion and piezometric level decline in the order of 20–50 m per decade and the groundwater salinity in the Annaba coast are also example of documented cases of aquifer overexploitation in Algeria [23,24]. This situation is unfortunately expected to worsen in the years to come due to the expected drop of rainfall in the Mediterranean zone [25].

From the above, it appears clearly that the study of climate change and the monitoring of human activity in arid and semi-arid zones (like Algeria) are prerequisites to permit an adequate management of water resources and account for all the uncertainties characterizing these zones [26,27]. With respect to groundwater, understanding hydrogeologic processes is necessary in order to ensure a continual monitoring of the quality and quantity of groundwater and permit its efficient and sustainable management. Still, understanding those processes can sometimes be a tough task to achieve. To alleviate this problem, more and more studies are relying on computer modeling, which has become a valuable tool, when designing efficient strategies and management policies for groundwater assessment and preservation. Notwithstanding that, aquifers are complex and heterogeneous systems, with multiple temporal and spatial varying parameters (withdrawals, recharge, level of storage, water quality, etc.) [28], which makes their modeling a challenge [29,30].

A model is a simplified conceptual representation of a natural system. The simplification is based on a number of assumptions reflecting the nature of the system. The establishment of a model for a given hydrogeologic system requires knowledge of its extension, thickness, and the hydraulic properties of its different formations, such as the hydrological units controlling the flow, the horizontal and vertical distribution of the hydraulic loads, the losses towards the surface or in depth, the distribution of the recharge, pumping wells, etc. Modeling studies usually focus on the quantitative study of water resources and/or the qualitative aspect, which associates with the flow simulation the transfer of substances (pollutants) and is therefore

more difficult to model, because it combines hydrodynamic and physicochemical parameters. In this paper, we present the calibrated computer groundwater flow model of the Plio-Quaternary aquifer (PQA) of Sidi Bel Abbès (SBA), generated using MODFLOW for the period 1971-2014, with an emphasis on the quantitative aspect. This paper presents the first 3D simulation attempt of the Plio-Quaternary system over a period of 44 years, with the main objectives of the study being 1) produce a model sufficiently capable of reproducing the Plio-Quaternary system behavior 2) prove that the Plio-Quaternary aquifer undergoes an alarming rate of overexploitation and 3) briefly propose solutions to remedy or at least alleviate the situation.

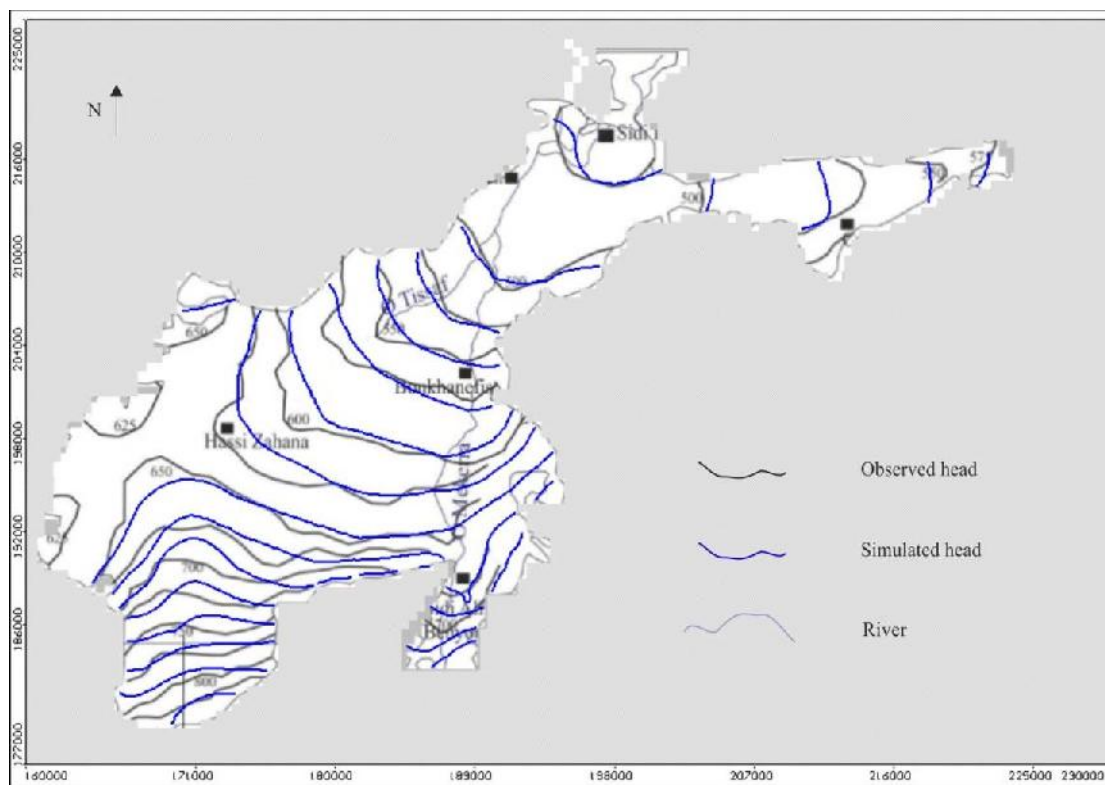
## 2. RESULTS AND DISCUSSION

### 2.1. Steady state

The data introduced in the model was adjusted in order to reproduce the behaviour of the PQA system in January 1971. The examination of figure 1, shows that the simulated piezometric map traces well that of January 1971. Indeed, the general appearance of the curves is drawn according to the same flow directions (especially for the major axes of flow) and respecting the same values of the hydraulic gradient. In addition, the piezometric trends simulated along the wadis Mekerra and Tissaf are fairly similar to those observed, which denotes the good reproduction of the relationship between the rivers and the PQA.

The results in table 1 show that precipitations are the major source of entries in the PQA system with more than 70 Mm<sup>3</sup>/yr. Lateral recharge from adjacent aquifers is also considerable and it equals around 23 Mm<sup>3</sup>/yr. The infiltration by the river beds is quite low in comparison to foresaid entries and could be rounded to 4 Mm<sup>3</sup>/year.

The drainage of the PQA is mainly done by wadis, with volumes almost equal to 65 Mm<sup>3</sup>/yr. Withdrawals, especially for irrigation, are the second destocking source of the PQA, with extracted volumes of almost 30 Mm<sup>3</sup>/year. As for the derivation canal towards the Sarno dam, volumes reaching the barrage equal around 4 Mm<sup>3</sup>/year and are consistent with the flow rates measured on this derivation between 1970 and 2005, equal on average to 125 l/s.



**Fig.1.** PQA piezometric maps (January 1971).

**Table 1.** PQA balance results in steady state.

Volume in m <sup>3</sup> /yr	Recharge by precipitation	Lateral recharge	Pumping wells	Rivers	Drains	Total
In	71033400	22368688		4760722		98162810
Out			29859830	64202627	4100255	98162712

**2.2. Transient state**

The calibration of the model in transient state from 1971 to 2014 (figure 2) was effectuated based on the piezometric chronicles of 13 piezometers from 1998 to 2014 (January 1998 - January 2007, July 2009 - August 2011 and September 2013 - December 2014), located in the North (upstream from SBA), East (around Caïd Belarbi), Centre (Centre of the plain of SBA) and South (South of Hassi Zahana and Sidi Ali benyoub) of the plain of SBA.

The model reflects well the overall evolution of the aquifer head drop (in accordance with the average 11 m water table drop observed across the entire PQA between 1971 and 2014).

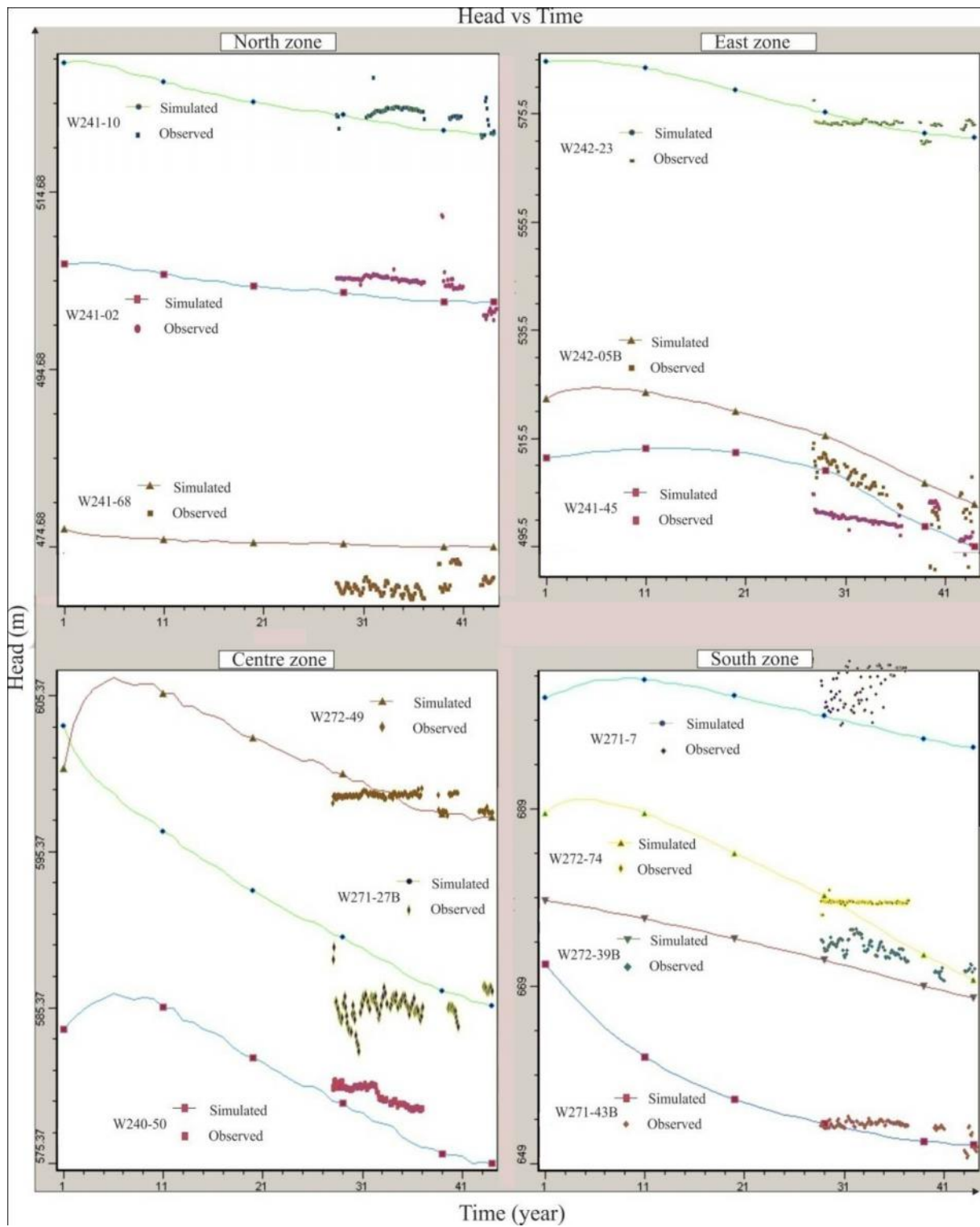
In the North, the difference between the observed and calculated head is on average inferior to 2 m for the piezometer W 241-10 and 1 m for W241-02. For W241-68, the gap between the simulated and calculated head is more important (3 to 5 m), due to the presence of a large number of illegal wells (impossible to model) in this area.

In the East zone, the piezometers W242-23, W242 - 05b and W241-45 reproduces well the piezometric trends East of the plain of SBA, where a drop of 15 metres between 1971-2014 is noticed.

In the Centre zone, the piezometry simulated (especially After 1988) for W272-49, W240-50 and 271 - 27B is almost similar to that observed, with a water table drop of about 2 m between 1971 and 2014.

In the South zone, the average difference between observed and calculated heads is inferior to 2.5 m for W272 - 39B and 1.5 m for W271 - 43B. The change recorded from 2001 to 2007, respectively for W272 - 74 and W271-7 is attributed to the influence of the Mekerra on the piezometric level for the first piezometer (the water levels in the rivers in reality are not constant, but due to the lack of data, they were considered as so for the duration of the simulation) and to the temporal variability of the recharge of the PQA (near the borders of modelled domains, flows are greatly influenced by the boundary conditions) by the limestones of Remailia /dolomites of Tlemcen for the second piezometer.

The biggest head drop (17 m on average) between 1971 and 2014 is noticed East of the plain, around Caïd Belarbi, due to the feeble extension of the PQA aquifer formations (small section and thickness) and the abundance of pumping wells (legal and illegal) in this area. The North zone on the other hand, witnesses the lowest head drop (4 m on average) due to the convergence of most of the aquifer's water in that direction (main outlet of the aquifer).



**Fig.2.** Head evolution from 1971 to 2014

The recharge of the PQA follows the inter-annual variation of precipitations in the plain of SBA (figure 3). The lowest values are observed between 1981 (26 Mm<sup>3</sup>/yr) and 1989 (28 Mm<sup>3</sup>/yr) while the highest are attributed to the early 1970s. The volumes infiltrating the PQA



from the adjacent aquifers are almost always superior to 10Mm<sup>3</sup>/yr and exceed 15 Mm<sup>3</sup>/year for the humid years (precipitations > 400 mm/yr). The largest volumes come from the Pliocene sandstones of Tenira to the East and the Jurassic-Cretaceous limestones of Rmailia /dolomitic rocks of Tlemcen, South of the study area. The volumes infiltrated by rivers beds start to increase by 1975 augmenting from 15 Mm<sup>3</sup>/yr to more than 24 Mm<sup>3</sup>/yr between 2005 and 2014. This is due to the head drop along the rivers Mekerra and Tissaf in parallel to the considerable increase in withdrawals and decrease of rainfall between the beginning and the end of the simulation.

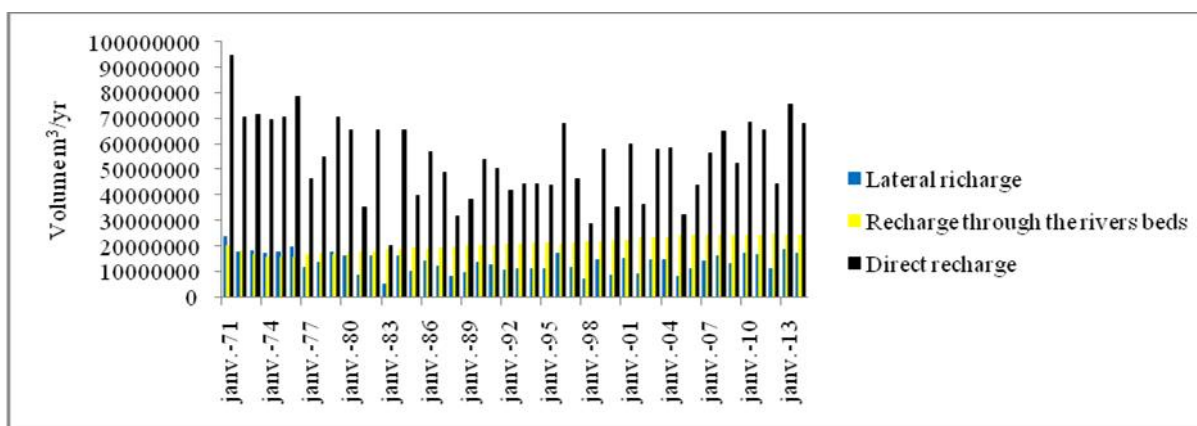


Fig.3. PQA total recharge evolution from 1971 to 2014.

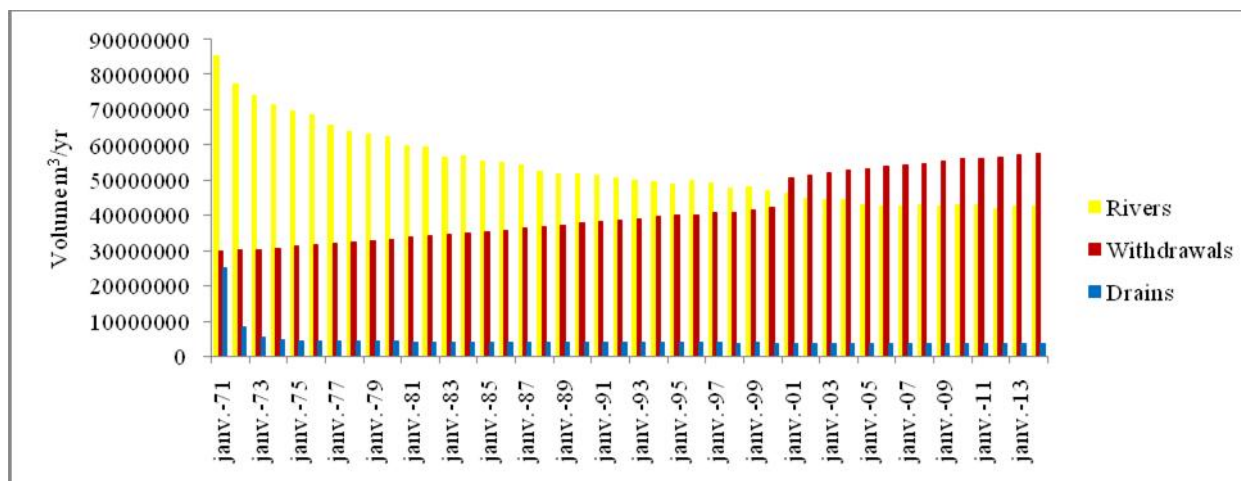
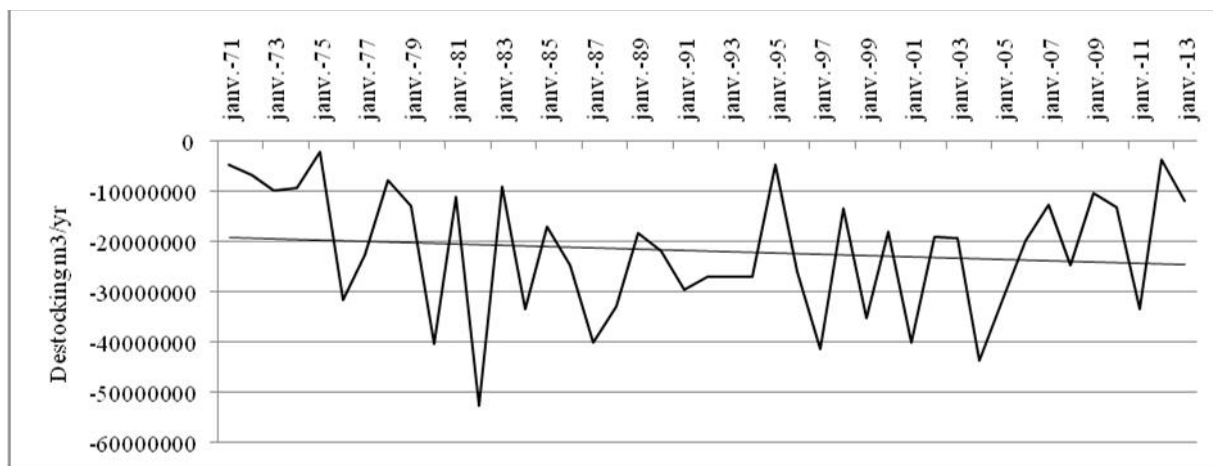


Fig.4. PQA total losses evolution from 1971 to 2014

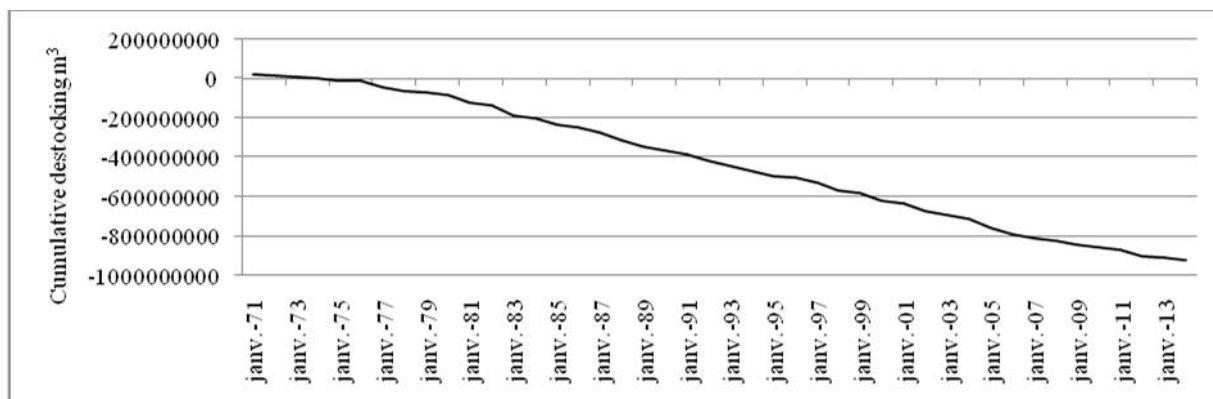
The volumes drained by wadis are quite important at the beginning of the simulation, especially between 1971 and 1980 (figure 4). Going from 1989 however, the volumes drained by the rivers are almost identical to those estimated by Sourisseau (1972, [31]) (48.5 Mm<sup>3</sup>/year).



The withdrawals represent the second major output at the beginning of the simulation and become the first source of destocking of the PQA towards the end of it. With the exception of the years 1971, 72 and 73 (start of the simulation), the simulated volumes (around 4 Mm<sup>3</sup>/yr) transferred (derivation canal) towards the Sarno dam correspond to the flow rates (equal on average to 125 l/s) measured on the Mekerra River between 1970 and 2006.



**Fig.5.** PQA Interannual destocking variation from 1971 to 2014.



**Fig.6.** PQA cumulative destocking from 1971 to 2014

The term overexploitation is employed, when the amount of water withdrawn from any given hydrogeologic system exceeds its recharge, to the point that it causes persistent undesired effects (continuous water level drawdown and quality deterioration), over such a long period of time (as opposed to a period of drought), that it becomes virtually impossible for the system to recover fully, even in wet years [32-37].

Based on the above, it appears clearly that the PQA system has been overexploited for a long period of time. Indeed, figures 5 and 6 illustrate that the draining of the PQA is done

throughout the entire simulation. The years 81, 83, 88, 98, 02 and 05 coincide with the largest annual decline of the reserve, with volumes equal or superior to  $-40 \text{ Mm}^3/\text{yr}$ . The lowest reserve drop (of about  $-10 \text{ Mm}^3/\text{yr}$  or less) however, corresponds the years 72-76, 79, 84, 96, 2010 and 2013. The infernal overexploitation rate of the PQA system is simply shocking when analyzing its cumulative destocking (entries - outputs), which reaches nearly -1 billion  $\text{m}^3$  ( $920 \text{ Mm}^3/\text{yr}$ ) at the end of the simulation.

### 2.3. Predictions

The approach adopted to simulate the future behaviour of the PQA system assumes 3 scenarios of exploitation over a period of 15 years from 2015 to 2030. This period, while long enough to allow the study of the reactivity of the aquifer, is also short enough to admit certain predictions about the evolution of withdrawals and recharge in the plain of SBA.

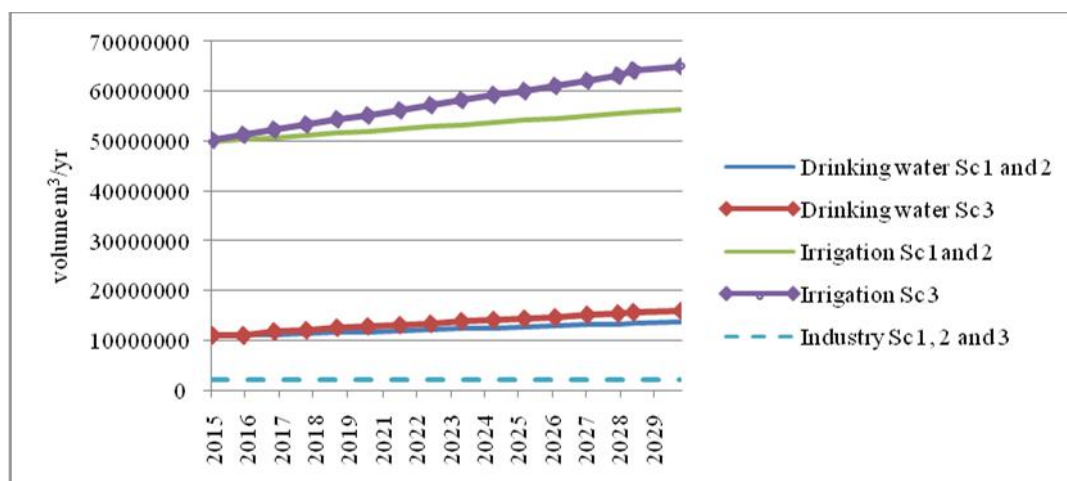
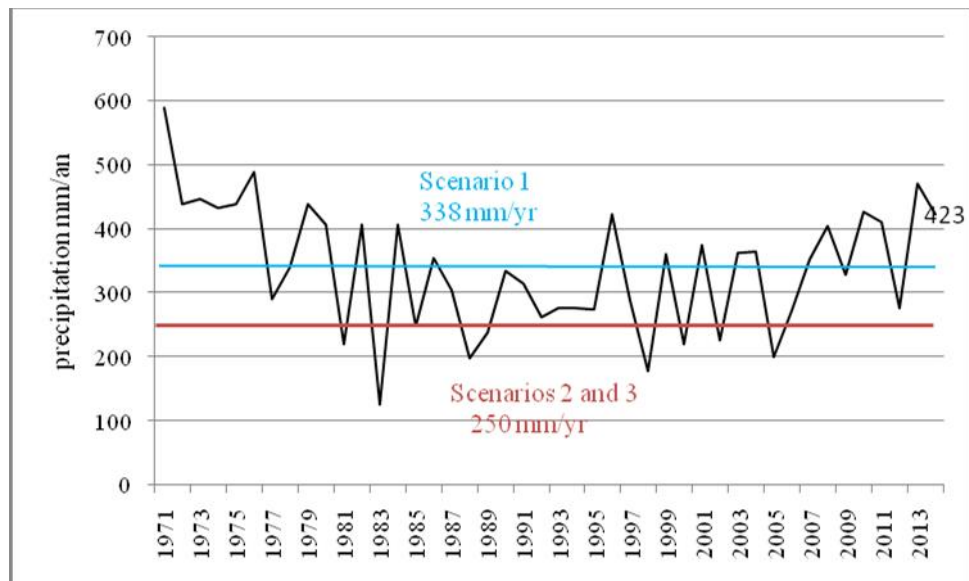


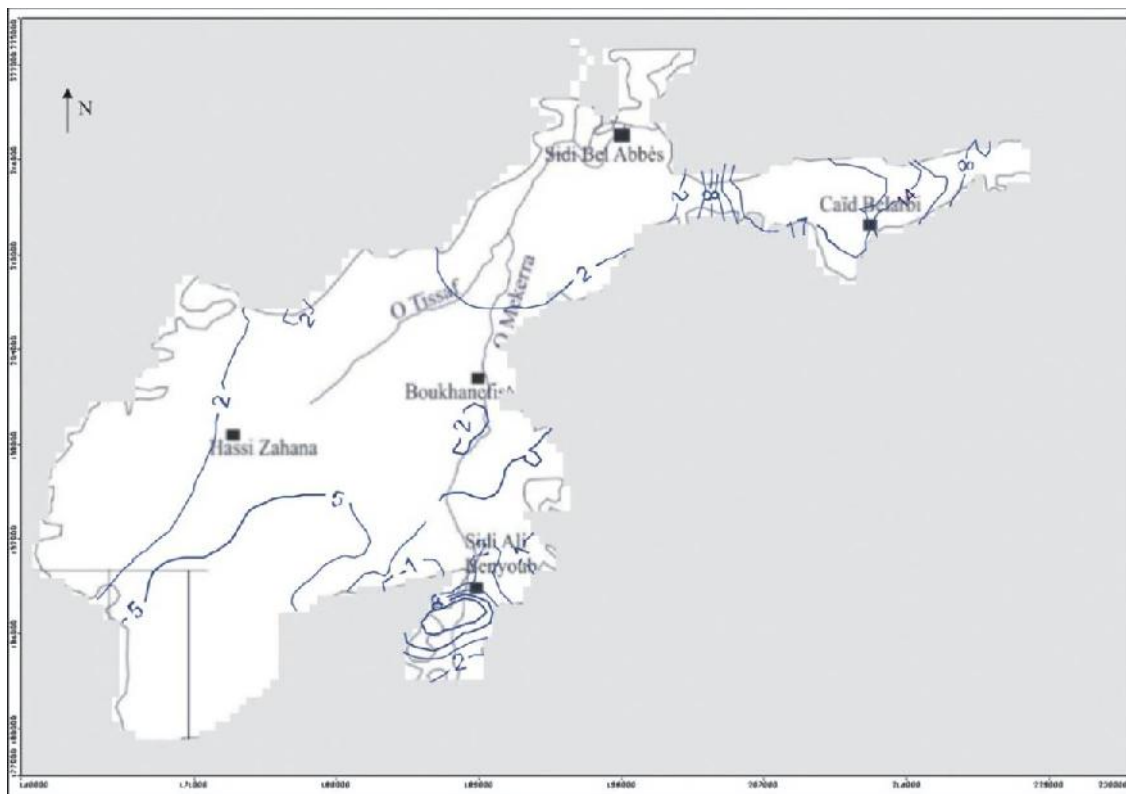
Fig.7. Withdrawals evolution for scenarios 1, 2 and 3

#### 2.3.1 Scenario 1

In this scenario, it is assumed that the drinking and irrigation water withdrawals continue to increase between 2015 and 2030 while those pertaining to the industry remain constant (figure 7). The withdrawals for drinking water are estimated on the basis of the population evolution of the city of SBA, which increases at a rate of 1.57% annually since 2008. As for irrigation water, the annual increase of the withdrawals was estimated at 0.8%/year, corresponding to the annual increase of the irrigated surface in the plain of SBA. Scenario 1 also assumes a rainfall of 338 mm/year, equivalent to the average rainfall recorded between 1971 and 2014 in the plain (figure 8).



**Fig.8.** Precipitations for scenarios 1, 2 and 3



**Fig.9.** PQA drawdown between 2014 and 2030 according to scenario 1.

The most important water-table drawdown between 2014 and 2030 (figure 9) is observed East of the plain (3 to 17 m) and to the South of Sidi Ali Benyoub (2 to 11 m). As for the rest of the aquifer, it appears that the drawdown is around 2 m.

The PQA destocking between 2015 and 2030 remains somewhat constant (23.5 to 25.5 Mm<sup>3</sup>/year), with a general downward tendency, favoured particularly by an appreciable recharge. However, the comparison of the aquifer balance between 2014 and 2030 shows that the evolution of the PQA system according to scenario 1 will occasion a multiplication by 2 of the destocked volumes.

### **2.3.2. Scenario 2 (intermediate state)**

In this scenario, the evolution of the total withdrawals is similar to that of scenario 1. However, the rainfall equal to 250 mm/year is chosen to characterize a dry period. This rainfall rate is fairly representative of the deficit periods in the plain of SBA.

The Piezometry of the PQA in 2030 according to scenario 2 in comparison with scenario 1, illustrates a general drop of the water-table. The biggest drawdown (4.5 m) is located East and South of the study area. The aquifer drawdown remains however limited (1.5 m) in the centre and North of the plain.

The recharge difference between scenarios 1 and 2, is translated not only by an augmentation of the aquifer destocking (more than 13 Mm<sup>3</sup>/yr at the beginning of the scenarios), but also by a longer period of renewed stability of the water-table, which does not occur for Scenario 2 until 2026.

### **2.3.3. Scenario 3**

Scenario 3 simulates a significant increase of the withdrawals, respectively 3 and 2% for drinking and irrigation water parallel to a dry period rainfall rate (250 mm/yr).

The head drop (figure 10) for scenario 3 is more important but seems to follow the same trends observed for the two previous scenarios, i.e., a maximum drawdown of the water-table East (piezometer W241-45) and South (piezometer W272-74) of the plain of SBA and a relative low head drop across the rest of the study area.

The drawdowns between scenarios 1/3 equal almost 2 times those registered between scenarios 1/2 in the vicinity of the recharge zones. This difference is due mainly to the decrease of the direct recharge of the PQA by precipitations (338 to 250 mm/year), but also by the adjacent aquifers.

the drawdown (figure 11) of about 25 m East of the plain (around Caïd Belarbi) between 2014 and 2030 according to scenario 3, will theoretically (exact thickness of the aquifer unknown

in this sector) either occasion a very important decline of the water levels in wells, or their complete drying.

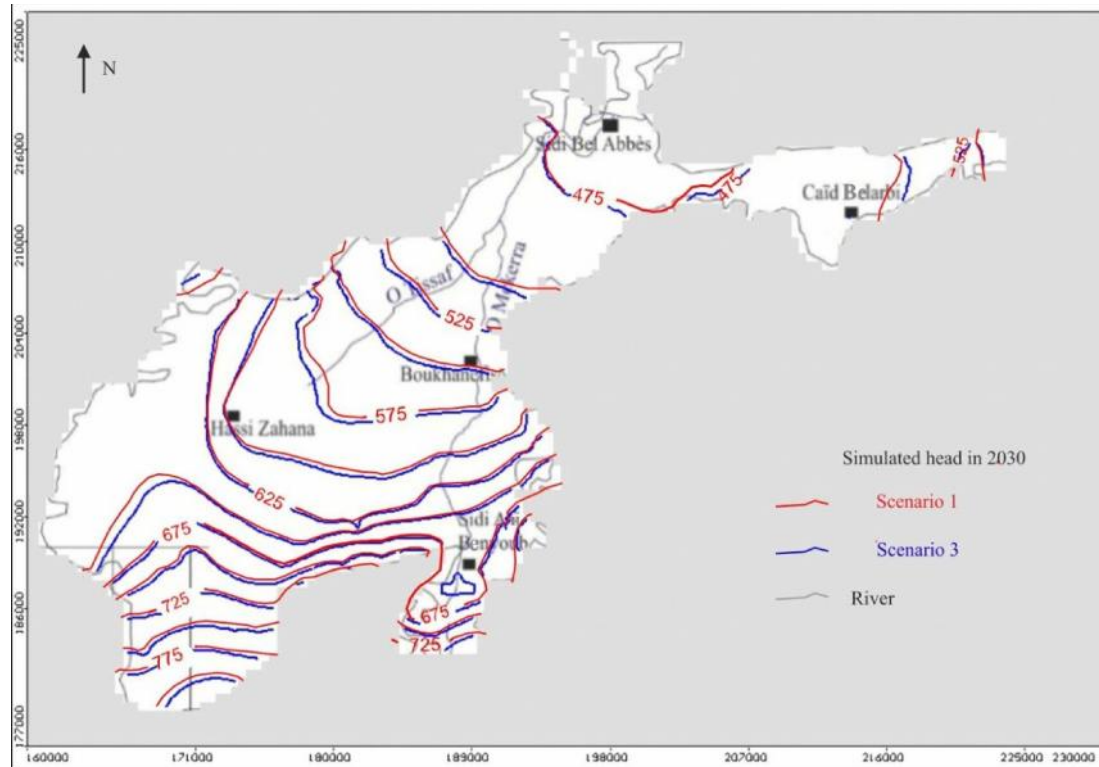


Fig.10. PQA piezometric maps in 2030 according to scenarios 1 and 3.

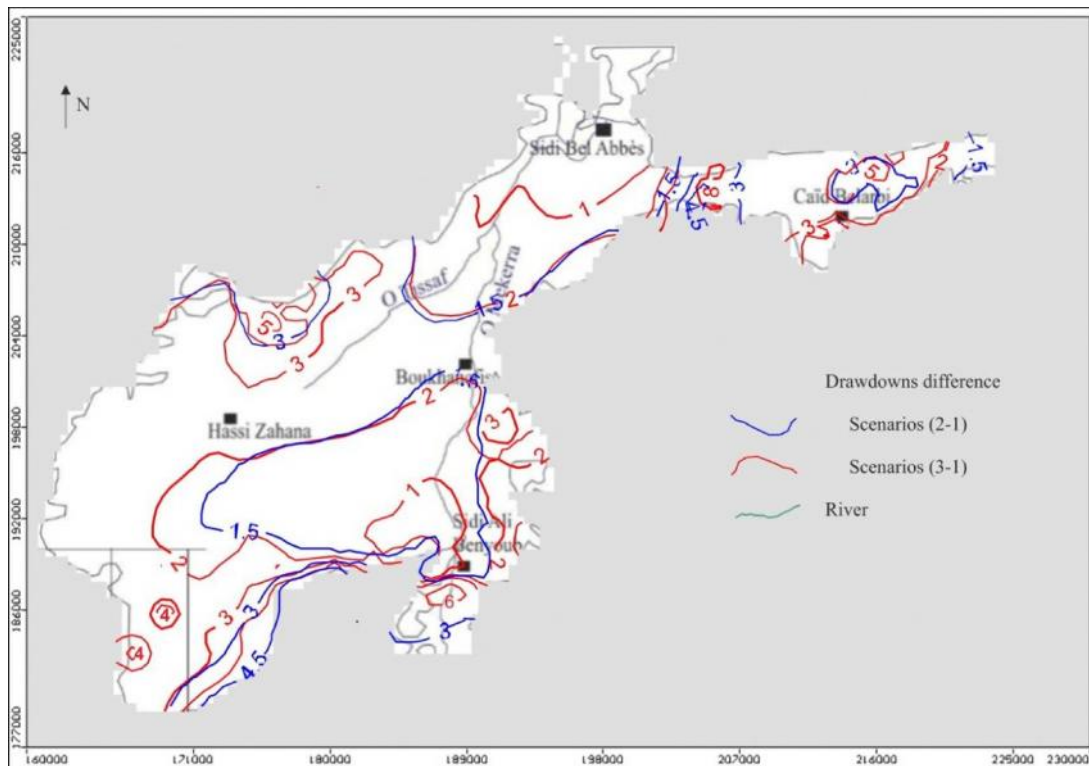


Fig.11. PQA drawdown differences in 2030 according to the different scenasrios.

The PQA destocking in scenario 3 (figure 12) varies between 37 and 39 Mm<sup>3</sup>/yr from 2015 to 2028. A slight decline of the destocked volumes of about 1 Mm<sup>3</sup>/yr is observed afterwards up to 2030. The comparison of the destocking in the 3 scenarios indicates that the PQA is more affected by climate change rather than the volumes of withdrawals. Indeed, the difference in the cumulative aquifer destocking (figure 13) in 2030 between scenarios 2 and 3 (withdrawals increased / constant recharge) is only equal to 47 Mm<sup>3</sup>/yr, while it exceeds 163 Mm<sup>3</sup>/year between scenarios 1 and 3 (withdrawals increased / recharge decreased).

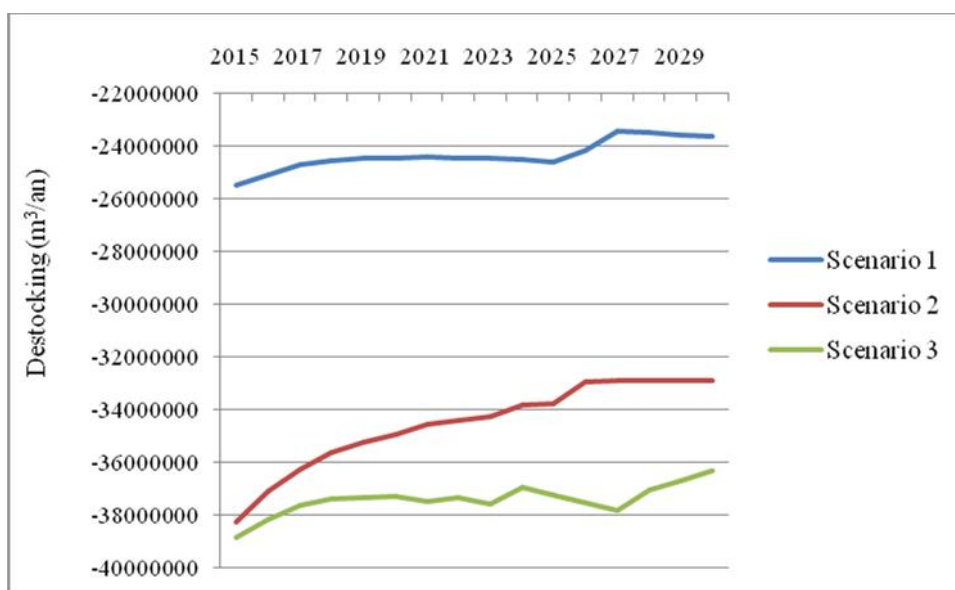


Fig.12. PQA annual destocking from 2015 to 2030 according to scenarios 1, 2 and 3.

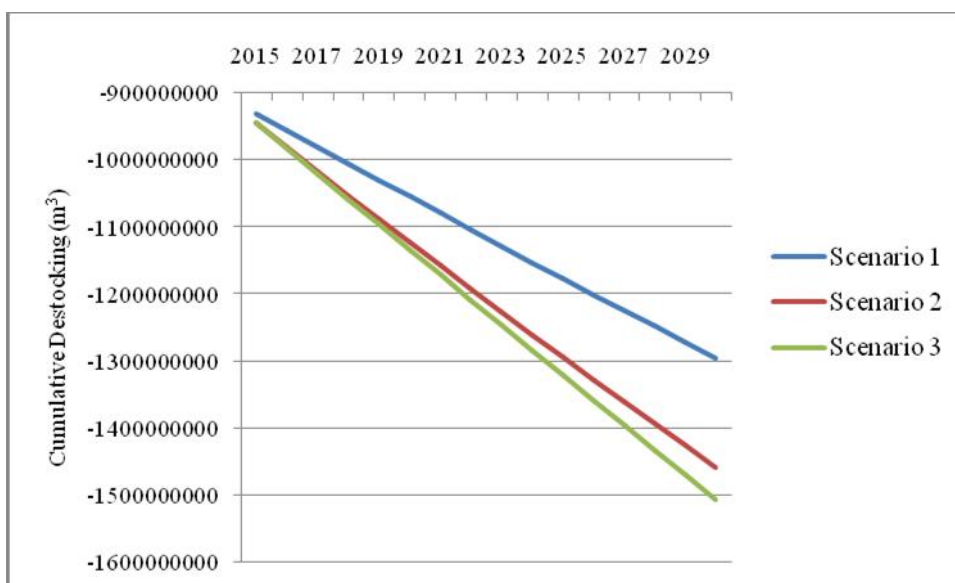


Fig.13. PQA cumulative destocking from 2015 to 2030 according to scenarios 1, 2 and 3



**Table 2.** Balance sheets inputs - outputs for scenarios 1, 2, and 3

(m <sup>3</sup> /yr)	2014	2030		
		Scenario 1	Scenario 2	Scenario 3
Entries	92203586	82263754	69993300	65570326
Outputs	104047480	105904048	102890331	104431844
Inputs - outputs	-11843894	-23640294	-32897031	-36326021
Difference 2030 - 2014		-11796400	-21053137	-24482127
Annual destocking rate (2015_2030)		-24272079	-34307102	-37414833

Table 2 shows that the inputs / outputs deficit in 2030 will be two times that of 2014 for scenario 1 and will almost triple for scenario 2 and quadruple for scenario 3.

**Table 3.** Annual means for the entire simulation (1971-2014)

Destocking	Recharge	Head	Withdrawals
-22 Mm <sup>3</sup> /yr	50.7 mm/yr	0.25 m/yr	42 Mm <sup>3</sup> /yr

Based on the data on table 3, it will take almost 31 Mm<sup>3</sup>/yr (roughly 27mm/yr over the entire plain of Bel Abbès 1150 km<sup>2</sup>) of excess recharge (input-output) to register a 0.1 m rise of the piezometric level. Even with this “unrealistic” demarche, it will still take more than 100 years for the PQA system to recover from the 11m drawdown registered between 1971 and 2014.

The only realistic approach that could be adopted would be to maintain the global withdrawals under 20 Mm<sup>3</sup>/yr, assuming a precipitation rate around 340 mm/yr (withdrawals could be increased or decreased proportionally to the recharge), which will stop the watertable drop as a first step. The second step would be to artificially recharge the PQA system. Artificial recharge is an efficient and environmentally friendly solution for aquifer recovery that has been successfully used in similar cases to the plain of SBA [38,39]. Importing surface water from outside river catchments, recharge basins, field wells and Managed Aquifer Recharge (MAR) through percolation tanks are among other techniques used to increase groundwater availability and eventually improve water quality [40]. In Algeria, recharge basins (constructed in 2004) have been used previously in the central area of Mitidja (Chebli Region) with satisfactory results.

Because the length of the present article does not permit it, the proposed solutions to the overexploitation of the PQA system will be treated in details in another paper (currently in preparation), where the most adaptable techniques, with respect to the context of the SBA plain will be highlighted.

### 3. EXPERIMENTAL

#### 3.1. Description of the study area

The city of Sidi Bel Abbès (SBA) (Figure 14) potential in terms of surface waters is derisory and the majority of its potable water supplies comes from the neighbouring cities Tlemcen and Mascara (around 28 Mm<sup>3</sup>/yr). The city of SBA rises on both sides of the Mekerra River; 430 km WSW of the capital Algiers. It shelters one of the most fertile plain of the country, which occupies a surface of about 1150 km<sup>2</sup> at an altitude varying from 500 to 700 m. The plain has a semi-arid climate.



**Fig.14.** General localization of the city of SBA, Algeria

The plain of SBA is a large basin that rests on top of a Mio-Pliocene substratum formed by gray green clays and marls. The plain is surrounded by terrains with great disparity (figure 15); in the North, the Tessala Mountains are essentially made of Cretaceous formations, roofed by a thick Tertiary cover (Sourisseau, 1973 [41]); in the South, the Tlemcen-Saïda mountains are represented by materials of the Middle/Superior Jurassic and the Inferior/Middle Cretaceous; on the Western Border, the Helvetian Marl hills separate the basins of the Isser and Mekerra rivers; to the East, the plain is limited by the Miocene Marl series of Bou Henifia (city of

Mascara). The plain of SBA hosts one major groundwater reservoir surrounded by four secondary aquifers (Sourisseau, 1973 [42]; MH, 1974 [43]) namely (figure 16):

the Plio-Quaternary alluviums (PQA) : this aquifer is unconfined, formed of heterogeneous alluviums and conglomerates along the Rivers Tissaf and Mekerra and rests on top of a blue Marls substratum (sometimes sandy) of the marine Pliocene. Its recharge is done by precipitations, adjacent aquifers or infiltration by the Rivers beds. The principle outlet of the PQA is located in the « Rocher » district; North of the city of SBA, where the Mekerra River drains most of the aquifer's waters,

the Limestones of Zigyne: A small aquifer East of the plain near Caïd Belarbi formed essentially of Limestones from the Aptian,

the Dolomite rocks and Limestones of Sidi Ali Benyoub: due to the abundance of faults in the Jurassic Cretaceous formations (the Limestones of Remaïla and the Dolomitic Limestones of Tlemcen), they are considered a one sole aquifer horizon. The latter is mostly present in the South of the plain and communicates with the PQA either by lateral infiltration or through springs, the Pliocene Sandstones of Ténira: this unit is comprised of Conglomerates from the continental Pliocene at the base, surmounted by sandy Sandstones, sometimes silty or clayey. the main importance of this formation resides in the fact that it contributes greatly to the recharge of the PQA, the Eocenes limestones of Sidi Ali Boussidi: limited at the bottom by Marls of the middle/superior Cretaceous and the middle marine Miocene. This aquifer has good hydrodynamic proprieties and relies on its watershed for its recharge.

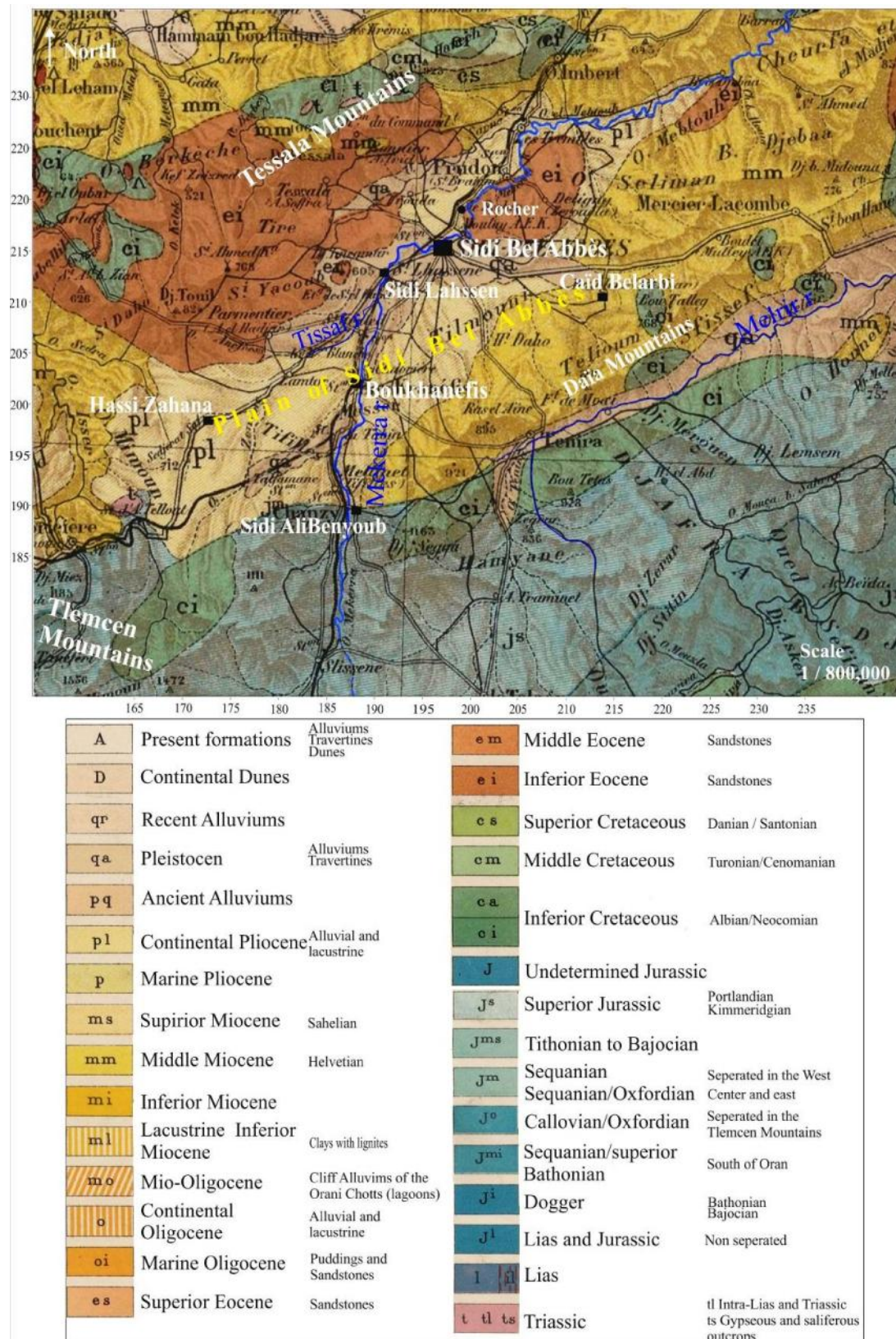
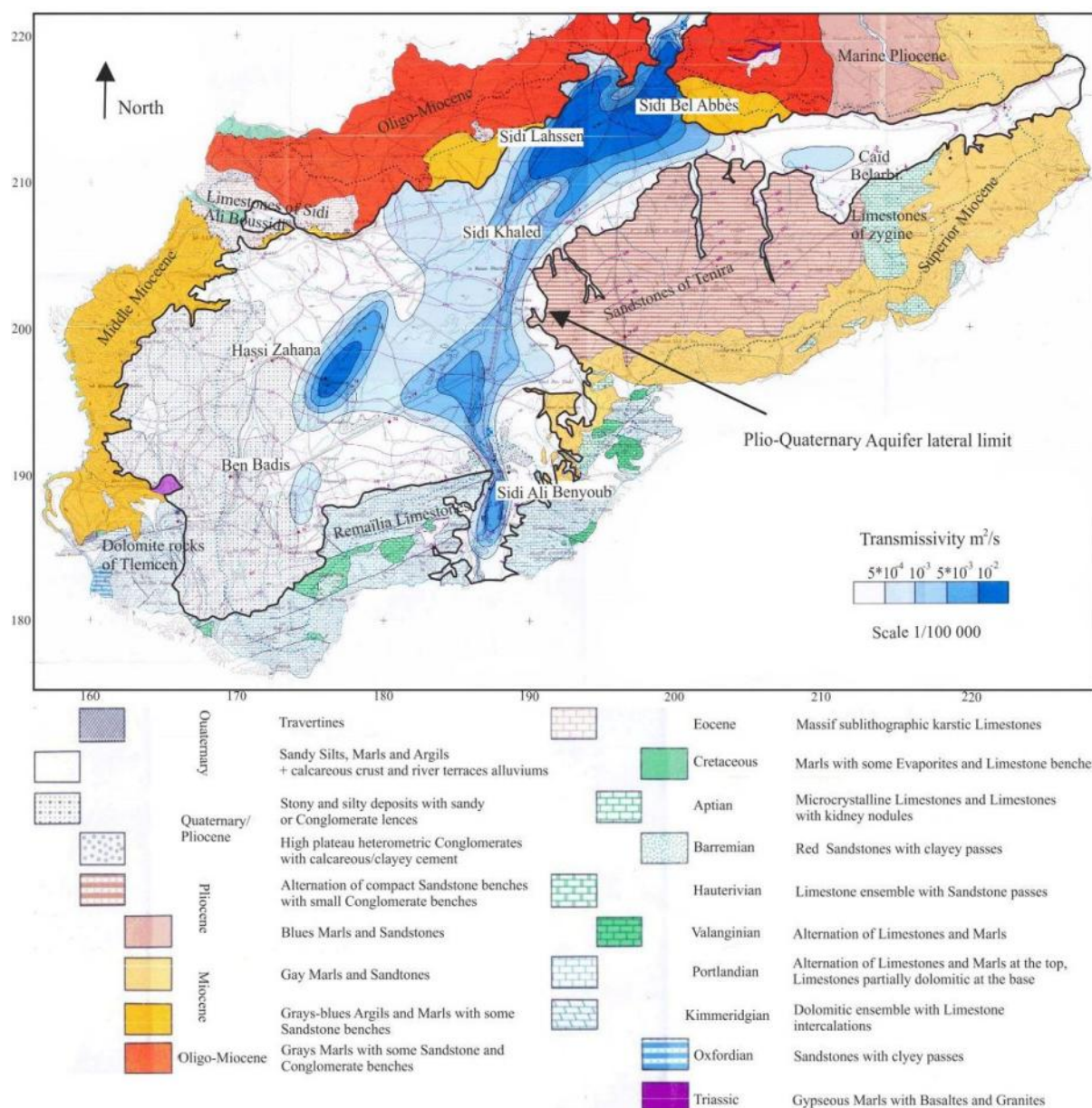


Fig.15. Geologic map of the plain of SBA, Extract of the geologic map of Algeria, third edition, Ministry of public works



### 3.2. Description of the model

The computer modelling of the underground waters in the plain of SBA concerned mainly the PQA (the other 4 aquifers mentioned previously are integrated in the model as recharge areas), due to its hydrogeologic importance in comparison to the other aquifers present in the study area, which does not only reside on the fact that it is the largest underground reservoir in the plain of SBA but also due to its communication with the other four aquifers surrounding it, which contribute greatly to its recharge (Lerolle, 1976 [44]).



**Fig.16.** Hydrogeologic map of the plain of SBA (K. Achi, A. Salem and F. Caquel & F.Zwahlen, 1974, based on the work of B. Sourisseau, P. Bonnet, S. Ramon with the collaboration of P. Combs and J. Leroux)

The computer modelling of the PQA system was performed using Visual Modflow (VMF) 4.2, which is an interface of the MODFLOW code, developed by the USGS (McDonald & Harbaugh, United States Geological Survey) in 1988 (WHI, 2006 [45]).

### **3.2.1. Simulation period**

The simulation is conducted on two stages. First, in steady state, in order to reproduce the initial conditions of the system; with the point of reference (calibration) being the piezometric map of January 1971 (Sourisseau, 1971 [46]). Secondly, in transient state, where the behaviour of the aquifer is simulated over a period of 44 years, from 1971 to 2014; with the control points being the piezometric data relative to the years 1971, 1998-2007, 2009-2011 and 2013-2014.

### **3.2.2. Model extension**

The plain of SBA was discretized in 13440 quadrilateral meshes of 500 m side each. The PQA boundaries were drawn with polygons, inside of which, all meshes are marked active and those outside, inactive.

The lateral extension of the model represents an area of about 800 km<sup>2</sup>;

the northern boundary is represented by the Tessala formations: clayey Marls of the middle/upper Cretaceous and the gray Marls of the Oligo-Miocene.

the southern boundary is assimilated to the Tlencem-Saida mountains formations,

the western boundary is materialized by the Marls hills of the Middle Miocene, separating the wadis Isser and Mekerra watersheds and finally the eastern boundary is represented by the impermeable Marl series of BouHenifia.

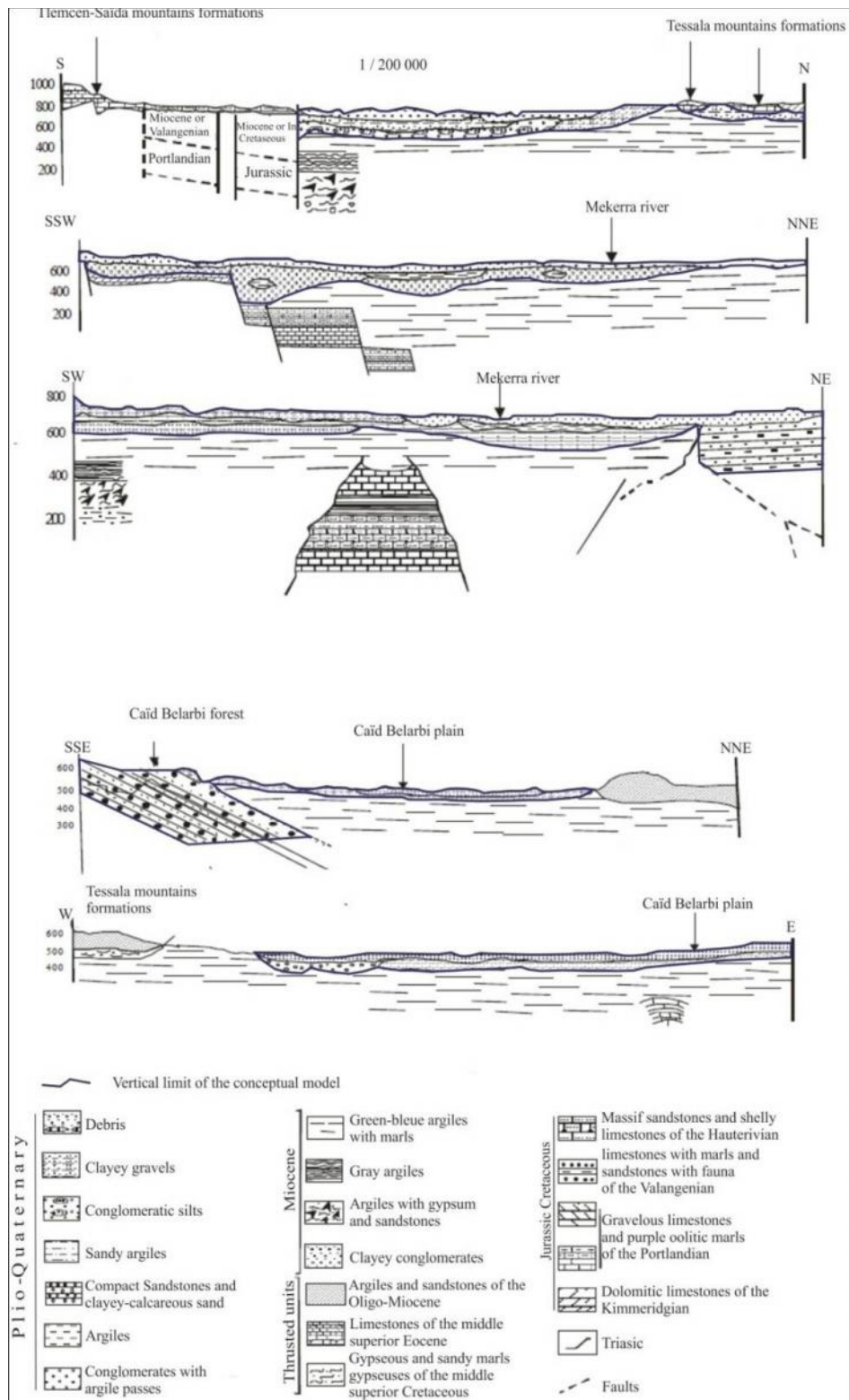
The vertical limit of the model is drawn based on the geological cuts by Sourisseau (1973, [42]) and the ANRH (MH, 1974; [43]) (figure 17 and 18). The lower limit is represented by the impermeable Clays and bluish-grey Marls of the marine Miocene while the upper limit is admitted to correspond to the top of the plio-quadernary alluviums.

### **3.2.3. Thickness of the aquifer**

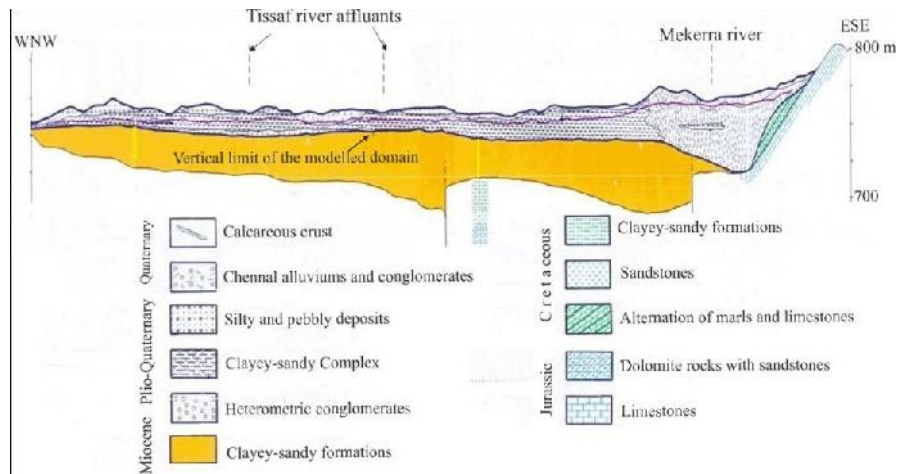
The thickness of the PQA varies considerably. It can reach more than 150 m to the South and does not exceed 40 m to the limits and North of the plain of Sidi Bel Abbès. In the centre, (between Hassi Zahan, Boukhanefis and Sidi Khaled), it appears that the aquifer thickness oscillates between 70 and 80 m.



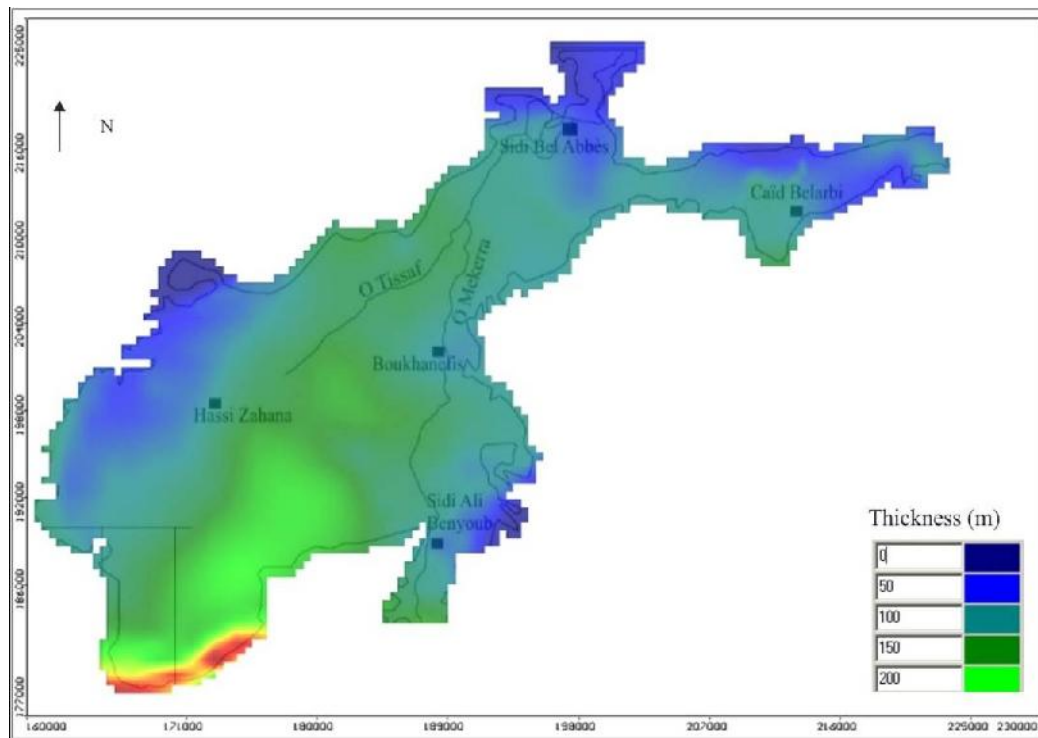
The altitudes of both the upper and bottom limit of the PQA were introduced under VMF, which permitted the estimation of the aquifer thickness across the whole grid (figure 19).



**Fig.17.** Vertical limits of the conceptual model based on the geological cuts drawn by Sourisseau (1973)



**Fig.18.** Vertical limit of the conceptual model based on the geological cut edified by the ANRH (MH, 1974)



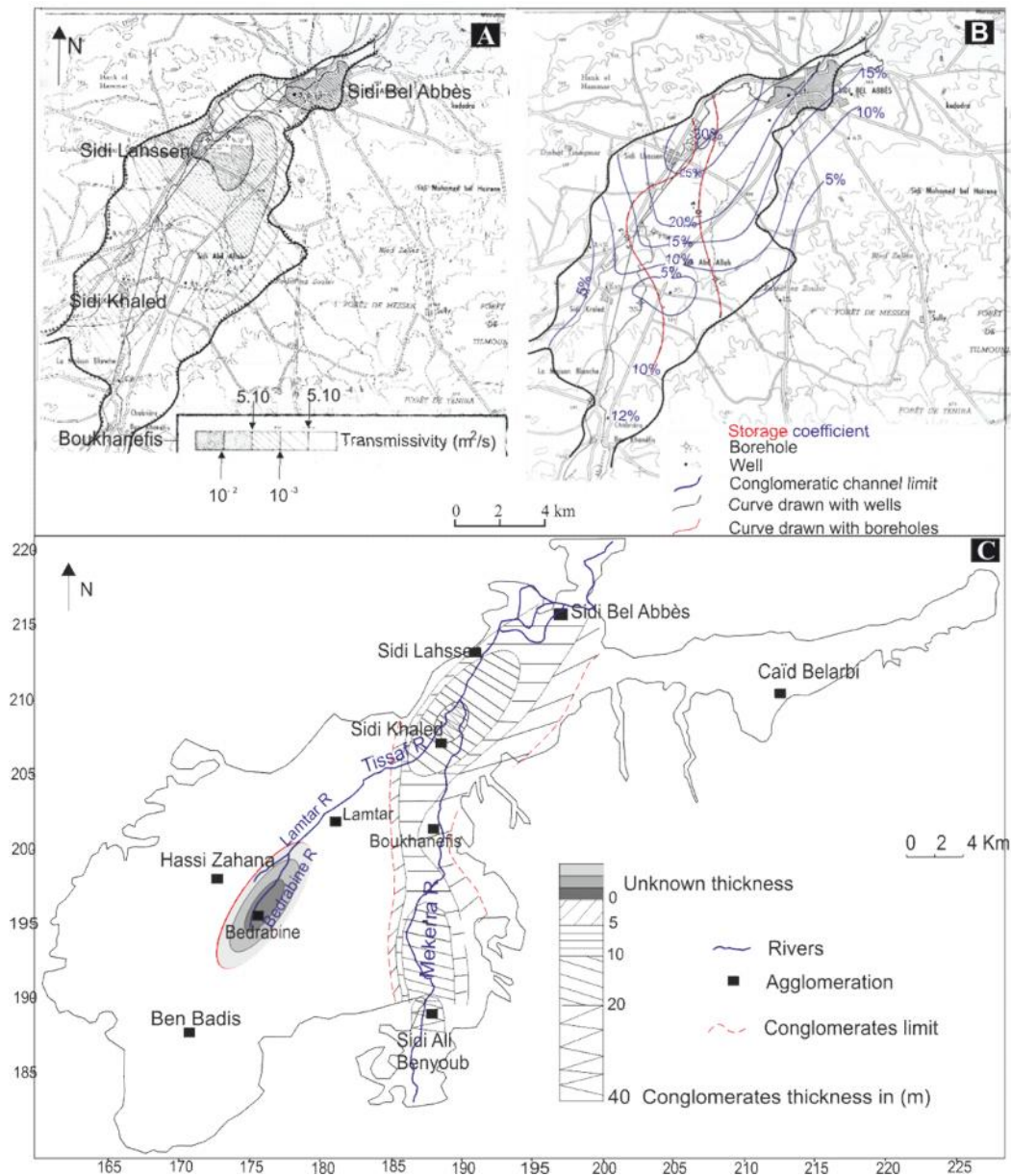
**Fig.19.** Discretization of the PQA thickness

### 3.2.4. Transmissivity and coefficient of storage

The spatial distribution of the transmissivity reaches  $10^{-2} \text{ m}^2/\text{s}$  in the Conglomerates and decreases in the plio-quaternary alluvium, where it varies between  $10^{-5} \text{ m}^2/\text{s}$  and  $10^{-4} \text{ m}^2/\text{s}$ .

Figure 20 shows clearly that the most transmissives areas are located along the Wadi Mekerra, especially, at Tabia, Sidi Ali Benyoub and between Sidi Lahssen and Sidi Bel Abbas, where

the conglomerate channel is the thickest. Around Bedrabine (upstream of Wadi Tissaf), the high transmissivities are relatives to stony and loamy deposits quite permeable conveyed by the Wadis Bedrabine and Lamtar.



**Fig.20.** Conglomerates thickness (C) and hydrodynamic proprieties (A and B)

The areas with the highest storage potential ( $S = 25-30\%$ ) are the valleys of Bedrabine, Tabia and Sidi Ali Benyoub (figure 20). Other areas such as the valleys of Tattfmane and Wadi Annefress also present good storage capabilities ( $S=10\%$ ).

### 3.2.5. Losses and recharge

The recharge of the PQA is ensured indirectly by the adjacent aquifers (lateral infiltration) and directly by precipitations. The recharge of the PQA by rains was estimated in 1973 by Lerolle (1976, [44]) at 88 mm/year for a precipitation rate of 550 mm/year. This estimate seems exaggerated in comparison with the rainfall rates observed in the plain of Bel abbes in the early 1970s, equal on average to 450 mm/year. Based on the works of Sourisseau (1971, [46]), the average recharge by the precipitation was equal to about 63 mm/year for an average rainfall of 448 mm/year. Generally, percentages between 1 and 20% are considered for semi-arid regions. In the plain of SidiBelAbbès, precipitations are generally higher than 300 mm/yr. The relative humidity of the study area encouraged us to choose an initial recharge percentage of 20% for the PQA, which was adjusted to 15% during the calibration of the model. The rainfall recharge is introduced in model as an imposed debit (mm/year) over the entire surface of the aquifer.

The lateral recharge by adjacent aquifers was introduced in the model as imposed positive debits, which were calculated based on the lateral extension of each watershed of the adjacent aquifers, assuming a uniform recharge for all aquifers considered. The volumes estimated were then introduced in the model, by drawing polygons along each aquifer and by assigning the corresponding debit at the centre of each cell (figure 21).

The losses represented by the derivation canal towards the Sarno barrage were represented in the model by a drain, whose conductance was adjusted during the calibration of the model.

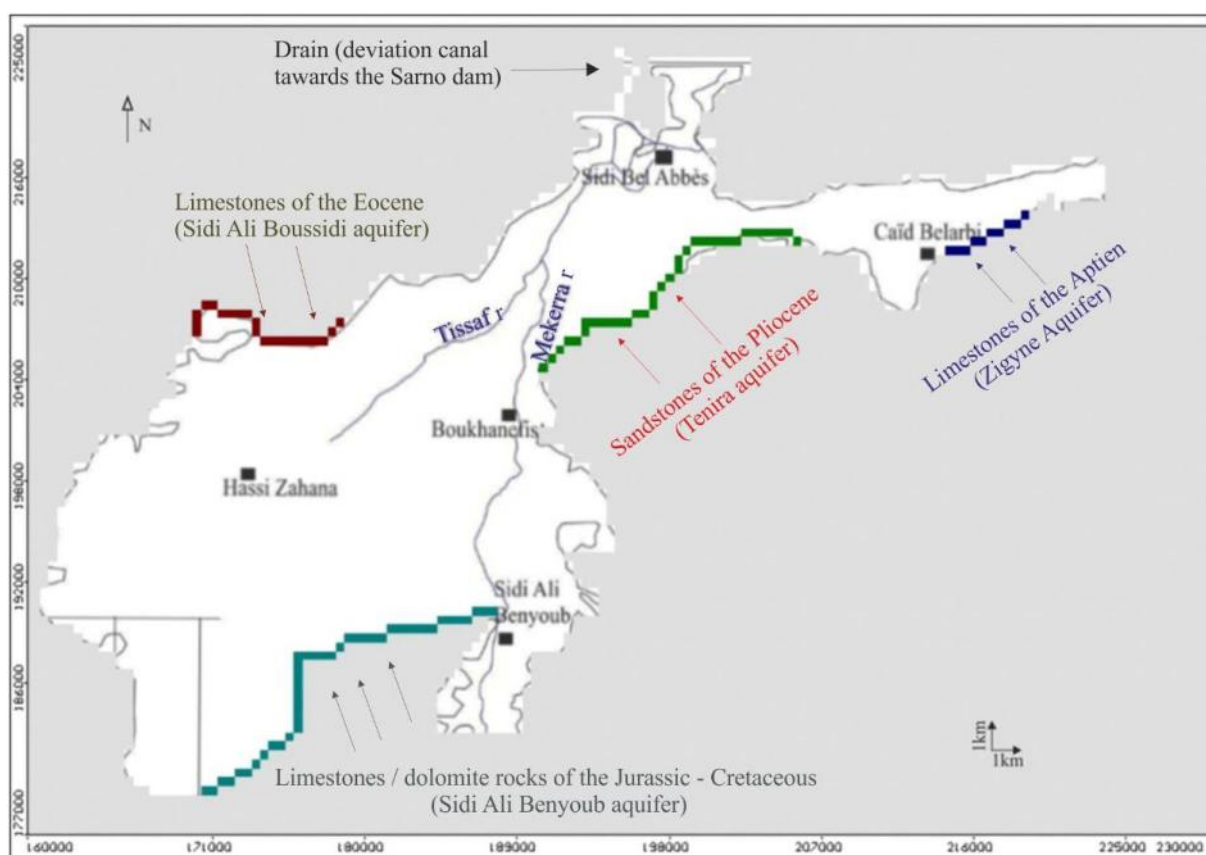
The losses represented by the derivation canal towards the Sarno barrage were represented in the model by a drain, whose conductance was adjusted during the calibration of the model (figure 21).

### 3.2.6. Interaction aquifer/Rivers

There are two major rivers in the study area, the Mekerra and the Tissaf Wadis. The first is the most important and traverses the entire plain of SBA South northwards up until the system outlet (Rocher district), where it drains most of the PQA waters. The river Tissaf is the major affluent of the Mekerra.

Due to the lack of recent data pertaining to the wadis, the approach adopted was to extrapolate the data relating to the studies carried out in the 1970s (flow rates and levels of water in the

wadis), up until 2014 and assume that the PQA/rivers relation remains unchanged throughout the entire simulation. This approach will allow us to have an approximate idea of the water volumes exchanged, either by drainage or infiltration between the aquifer and the rivers, even if the prevailing conditions throughout the simulation period are not 100% reflective of the realities in the field. The characterization of the interaction aquifer/Rivers was done by the study of the topography along the two wadis, the analysis of the available piezometric maps of 1971, the data relating to the differential gaugings conducted in the 1970s (Mostefa, 1972 [47]; Sourisseau, 1972; [31]) and the rivers flow chronicles between the gauging stations of Sidi Ali Benyoub (upstream of the Mekerra) and SBA (downstream of the Mekerra) from 1970 to 2006.



**Fig.21.** Discretization of the lateral recharge and losses

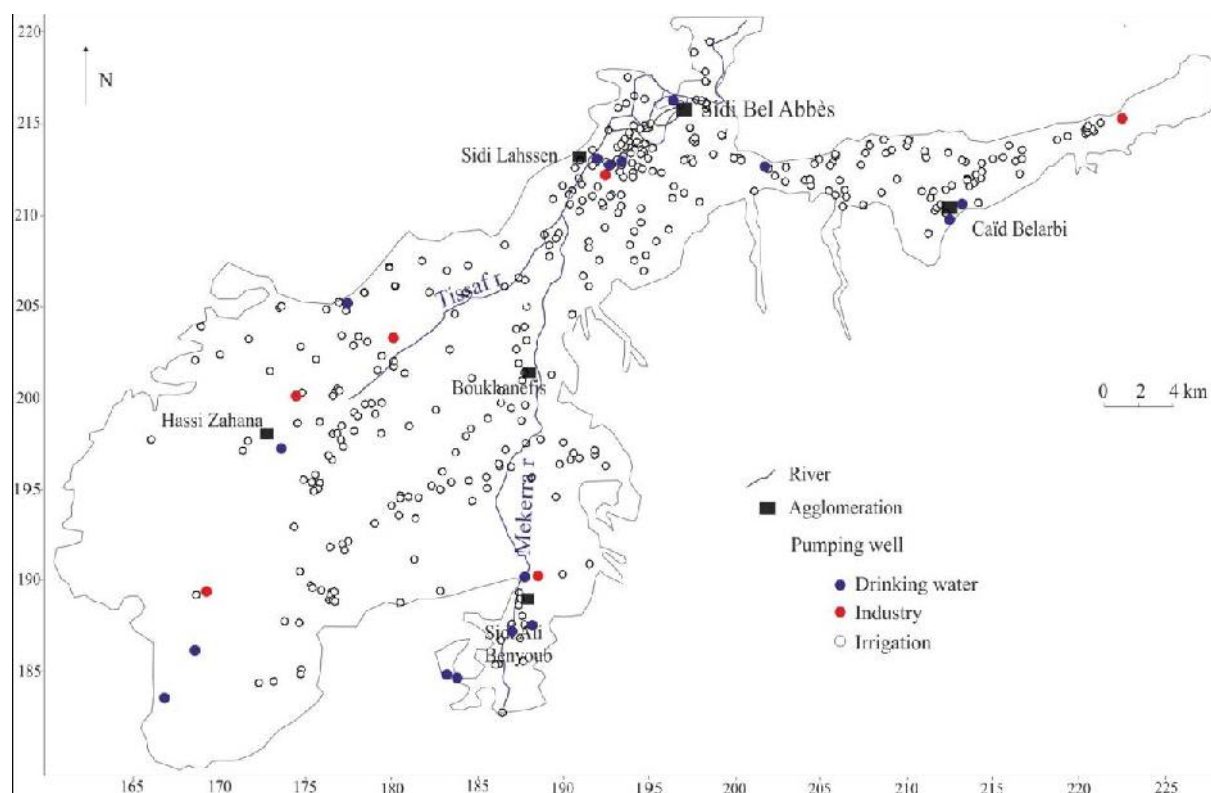
The hydrographic network was relatively simplified; for the Mekerra: the major arm was modelled as being the Wadi, the derivation canal towards the Sarno dam as a drain, while the floodway was not introduced in the model (field visits showed that canal is almost always dry, except during flood episodes); for the Tissaf, only the main affluent was introduced in the



model. The respective water levels and conductance (resistance to flow between the surface water body and the groundwater) for each Wadi were then introduced in the model under the Boundary condition “river” available in VMF.

### 3.2.7. Pumping wells

Due to the lack of data for the entire duration of the simulation, the volumes extracted from the PQA for all drinking, agricultural and industrial purposes are assumed to follow a linear evolution from 1971 to 2014 (except when data is available).



**Fig.22.** Pumping wells exploiting the PQA

Based on the works of Sourisseau (1971, [48]), Bennabi *et al* (2016, [49]) and the data provided by the services of the “Algérienne Des Eaux” (ADE, 2011; [50]), the “Direction de l’Hydraulique de la Wilaya de SBA” (DHW, 2013; [51]), the “Wilaya de SBA” going from 1999 to 2014 [52], the “Agence des bassins hydrographiques” (ABH, 2010; [53]), in addition to the indexes of population growth of SBA provided by the “office Nationale de Statistique” (DPSB, 2013; [54]), the estimated volumes extracted from the PQA for drinking purposes are summarised in Table 1.

Volumes mobilized for the industrial sector were estimated in 2013 to 1.3 Mm<sup>3</sup> (DHW).



According to the scarce data provided by the services of the ADE, those volumes did not exceed 300,000 m<sup>3</sup> in 2010. Based on the work of Kalaliz (2013, [55]), the volumes mobilized for the industry from 2002-2013 did not exceed 1.5 Mm<sup>3</sup>/year on average. Given the lack of data (location, collected volumes for each industrial activity, etc.) the volumes extracted from the PQA for industrial purposes were estimated based on the occupancy and type of activity of each industrial area (table 2).

The extracted volumes for irrigation approximated based on the BIRH inventory of 1972 (Mostefa, 1972; [47]) data, the studies of Sourisseau (1973; [42]) and Lerolle (1976, [44]) and the data provided by the “Direction des Services Agricoles de SBA” (DSA, 2012 [56] DSA, 1999-2014 [57]), the “Direction des Statistiques Agricoles et des Systèmes d’Information” (DSASI, 2001-2012 [58]) and the SOGREAH (1969, 1970, and 2006 [59, 60]) are presented on table 3.

In total, 300 pumping wells were introduced in the model; 16 for drinking water, 300 for irrigation and 5 for the industry.

**Table 4:** Global volumes extracted from the PQA

Years	Mobilized volume m <sup>3</sup> /yr								
	1971	1999	2001	2002	2004	2005	2006	2007	2014
irrigation	24000000	34240000	43700000	-	-	46000000	-	-	49000000
Drinking	6870000	9450000	-	-	9920000	-	10120000	-	10800000
Industry	217000	320000		580000	-	-	-	1200000	2020000

#### 4. CONCLUSION

The computer modelling of the PQA system of the plain of SBA shows that one is dealing with an unconfined aquifer, resembling a toboggan formed by a succession of connected underground pools, spilling their waters from one to another until the “Rocher” outlet, North of the plain. The PQA is formed by permeable alluviums of the Plio-Quaternary, laid on top of a substratum made of marine marly -sandy argiles of the Mio-Pliocene.

The modelled system reached an area of approximately 800 km<sup>2</sup> and is limited in the North by the marls of the Miocene and the Oligo-Miocene, to the South by the Jurassic and Cretaceous formations of the Tlencem-Saida mountains, to the West by the helvetic marls hills separating the watersheds of the rivers Isser and Mekerra and to the East by the Beni Chougran reliefs of

Bou Hanifia. As for the upper and lower vertical limits, they are respectively, assimilated to the top of the Plio-Quaternary alluviums and the Mio-Pliocene substratum.

Initial transmissivities introduced in the model varied between  $10^{-2}$  m<sup>2</sup>/s (conglomerate channel) and  $10^{-5}$  to  $10^{-4}$  m<sup>2</sup>/s (Plio-Quaternary alluviums) and were later readjusted during the calibration of the model according to a range of permeability between  $8 * 10^{-7}$  and  $8 * 10^{-3}$  m/s. The storage coefficient values adopted for the model varied from 20 to 30% for the conglomerate channels along the wadis, while the rest of the plain was characterized by a storage potential ranging between 5 and 15%.

The recharge by rain of the PQA system was estimated to 15%, while the lateral recharge was mostly attributed to the waters infiltrating the PQA from the sandstones of Tenira to the East and the limestones of Remaïlia / dolomitic rocks of Tlemcen to the South. The draining of the PQA is mostly done by the wadis and the withdrawals and to a lesser degree by the Sarno derivation canal.

The computer simulation reflected well the average head drop of about 11m between 1971 and 2014 across the entire study area. It also emphasized the clear overexploitation of the PQA, mainly the consequence of the continual increase of the withdrawals, especially for irrigation (via both legal and illegal wells), parallel to a low recharge, especially between the years 1981 and 2006.

The conditions imagined between 2015 and 2030 based on the realities on the ground during the prediction phase for scenario 1 translate a slight decline of the head in 2030, especially in the centre and North of the plain. For scenarios 2 and 3, the drawdowns are more significant, particularly in the eastern and southern sectors; particularly, near the recharge areas (most affected by climate change), where the hydraulic gradients are most important and where the section and thickness of the aquifer are small.

The results obtained by the PQA model reflect a significant head drop between 1971 and 2014 and assume an even more important decline of the piezometric level in 2030. These results depict a dangerous overexploitation of the resource, which if continued at this rate, could even occasion the complete drying of the PQA in some parts of the plain of SBA. The results also illustrate that the possible natural recovery of the PQA is practically impossible (due to the expected drop of precipitation and increase of withdrawals in the future) and that maintaining

the extractions under 20 Mm<sup>3</sup>/yr and artificially recharging the PQA system could stop the overexploitation and perhaps even restore the initial state of aquifer.

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