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Integrated 3D geological and hydrodynamic modeling for the water budget estimation: Sisseb El Alem Nadhour Saouaf case study

***Mohamed Hamdi*[1-2]*, Kalifa Goita*[1]*, and Mohamed Faouzi Zagrarni*[2]**

[1]Centre d'applications et de recherches en télédétection (CARTEL), Université de Sherbrooke, Sherbrooke (Québec), Canada

[2]U. R. Applied Hydrosciences UR 13 ES 81, Higher Institute of Water Sciences and Techniques, University of Gabes, Cité Erryadh, 6072 Gabes, Tunisia

ABSTRACT: The current situation of water resources and their uses in the Sisseb El Alem Nadhour Saouaf basin (Central Tunisia) is under strong pressure; human activities and climate change. To arrive at a realistic assessment of the underground water reserves in this basin, a diversified hydrogeological database was created (data from hydraulic and oil drilling, seismic sections, electrical surveys and gravimetric). A structural model is built and validated for the study area. Such a geomodel results from a geological interpretation, which makes it possible to identify the sedimentary series present and to specify their spatial and chronological relationships. This 3D geological model was integrated to Modflow model to assess the flow dynamic and to calculate the water budget. Many simulations were performed. The balance budget over 2020 will be in deficit -14.22 Mm^3 and the aquifer will remain in a critical situation: the exploitation will be of the order of 75.43 Mm^3. This depends enormously on the progress of the method of extraction of groundwater and over 2030: the global water budget is also deficit -14.5 Mm^3.

KEYWORDS: 3D geological modeling, Modflow, GIS tools, simulation, water budget.

1 INTRODUCTION

The current climate operates under the effect of numerous parameters (e.g. orbital parameters of the earth, variations in solar activity, the greenhouse effect, aerosols, albedo, etc.). The variability of climate is controlled by a set of controlling and response factors. However, spatio-temporal climate variability has the potential to directly affect the functioning of hydrogeological systems [3]. The functioning of aquifers is governed by the double influence of climate change and human activities. The current state of aquifers is the result of several cycles of "driving force - response" which date back several thousand years.

Recharge of aquifers can be defined as the slice of surface water that percolates through the unsaturated zone and reaches the saturated zone (the aquifer). It is largely influenced by the amount of effective precipitation. Therefore, the recharge variability is the result of climate variability [4]. In addition, since climate change directly influences recharge, therefore logically that water stock within aquifer systems is itself modified.

Today, in Central Tunisia, with the expected rise in temperature and increased droughts, the climatic changes suggest significant impacts on the availability, quantity and quality of groundwater. This situation leads to several fundamental questions such as: How much strategic groundwater do we have? Where are the most available groundwater resources for the future needs of the region? Are aquifers already being developed beyond their ability to regenerate naturally?

To answer these questions, Scientists have used new technologies to help understand the impact of climate change on the functioning of complex hydrogeological systems and the quantification and management of water resources. Indeed, these new technologies, in particular geoscientific modelling, provide useful means to simplify the reality, conceptualize hydrogeological systems and thus simulate their operation. In parallel with the development of hydrogeological models, research efforts are increasingly concentrated to link hydrological surface, climatic and underground models. A complete picture of the water balance for a well-defined system must integrate surface processes (runoff, interception, evapotranspiration, etc.) and climatological processes (evaporation, relative humidity, etc.) (Xin et al., 2019) as well as underground processes (underground flows in the saturated and unsatural area...) ([11], [8]). These phenomena interact with each other and present important interactions in the form of horizontal and vertical water flows (infiltration/exfiltration, resurgence to lakes and streams, etc.) ([16], [19], [20], [9]). In reality, surface water and groundwater are never isolated components but, on the contrary, they show several types of physiographic and biophysical interactions thanks to the nature of the land, the geological formations, fracturing and fault systems ([6], [11], [1], [7]).

In addition, following the above studies, multiple processes take place in the transition zones between soil and subsurface. Many methodological approaches have been developed over the last few years for estimating interaction flows and understanding these phenomena: such as direct measurements, field measurements, thermal tracing methods, or methods based on Darcy's Law, as well as mass balance approaches provided by algorithms and flow models based on the resolution of the diffusivity equation [18]. Nevertheless, these trade flows (known as flows, since they are water flows that vary according to time) are very little known and not very user-friendly because of the complexity of hydrogeological systems. This is why modelers often use separate models (surface, atmospheric or underground) or even semi-coupled models, one after the other. Moreover, despite all efforts, the calculation of interaction flows in the estimation of water balance components remains a very complicated operation.

Advances in applied mathematics increasingly provide useful and effective tools to facilitate the construction of coupled hydrological models, understanding and conceptualizing complex systems and quantifying the different transfers between atmosphere, snow, soil and vegetation ([14], [12], [13], [2]). These new visualization, processing and computation technologies have been widely applied in hydrological studies ([5], [15], [21], [20]). Hydrological modelling is increasingly being used as a tool to verify the coherence of available data, for a better understanding and more reliable analysis of a complex hydrological and climatic context. It uses different approaches, and its applications are widely discussed by several authors around the world.

The main objective of this research work is to use hydrogeological modeling to understand an aquifer system's response to climate change and anthropogenic stress.

2 MATERIALS AND METHODS

2.1 THE STUDY AREA

Among the regions most often cited as examples of fragility, the Kairouanais is particularly emblematic. Major syntheses and research ([10], [6]) have led to alarming findings: the mobilized water resources are of the order of 332 Mm^3 and the mobilized resources are 325 Mm^3. The resources exploited exceed 369 Mm^3. The examples of overexploitation of groundwater in the Kairouanais are already numerous, would be even more so and would force the availability of the resource to be reconsidered. This is particularly true of the Sisseb El Alem Nadhour Saouaf region studied in this work, where the hydrogeological system is evolving as rapidly as scientific knowledge. It is here that knowledge of the different processes and control of hydrogeological mechanisms is of great interest.

The study area is part of the Kairouan Governorate Hills Region. The area of the Sisseb El Alem Nadhour Saouaf basin is approximately 1100 km2. It extends on the southeast side of the Dorsal, upstream, and covers the valley bordered by the ridge line from «Djebel Serdj» north of Oueslatia to «Djebel Fikirin» west of En Nadhour, and the chain formed by the «Djebel Oueslat» and «Bou Dabbous» in the South (Fig. 1).

The various research works ([6], [17]) have highlighted a tectonic complexity of the study area: particularly in the northern (Saouaf) and western (Saouaf) coastal areas (Wadi Nebhana and Sbikha monoclinal) and on the East side (Jebel Fadheloun anticlinal, Drâa Souatir monoclinal and Ktifa buried anticlinal). This allow dividing the hydrogeological system of the SANS basin into four different units: The Sisseb hydrogeological unit; El Alem hydrogeological unit; the hydrogeological unit of Ktifa-El Guelta; Nadhour Saouaf's unit. Aquifers in the Sisseb El Alem Nadhour Saouaf basin are generally detritic in nature and occasionally carbonate (Hamza 1992). They are of lesser importance to the East and to the North because of their outcrops and their reductions. Reservoir levels are well developed in areas of high subsidence namely in the basin of El Alem which is bounded by deep faults. In fact, by their nature (detritic deposits) and their layout (subsidente zone), the Neogene series present the best qualities of true aquifer reservoirs. These show a lateral variation from north to south and from west to east. This variation is closely related to the movements of major tectonic accidents that constitute important fault corridors. The latter causing structural changes in the geometry of the basins during the Miocene and Pliocene in raised and low zones, which caused the accumulation of a large silico-clastic series.

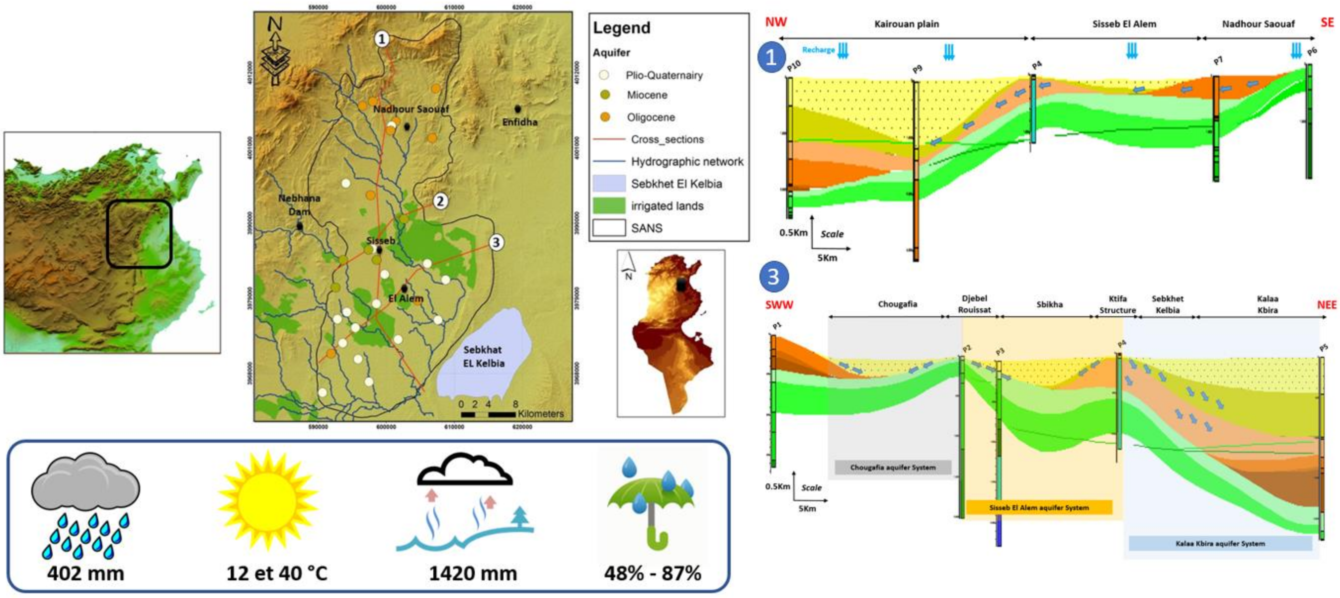

Fig. 1. Geographic localisation and climatological parameters of the study area

2.2 GEOLOGICAL MODELING AND AQUIFER GEOMETRY ASSESSMENT

A structural model is an assembly of geological surfaces that correspond to stratigraphic unit boundaries, faults, overlaps or more complex arrangements (fault networks, channels, chimney). Such a geomodel results from a geological interpretation, which makes it possible to identify the sedimentary series present and to specify their spatial and chronological relationships.

To arrive at the hydrostratigraphic model of the study area, several steps were taken: integration of seismic data; conversion of isochronal maps into isopaques maps under SMT; decoupling of isopaque maps and transformation into "log"; integration under Rock Works and interpolation of horizons. Thus, to build this model, the "solid modeling" package of the Rock Works software (version 15) was used. The resolution of the model is 1000 m × 1000 m × 5 m, the resulting grid consists of 113 nodes × 83 nodes × 55 nodes Z, so the model contains 60170 voxels.

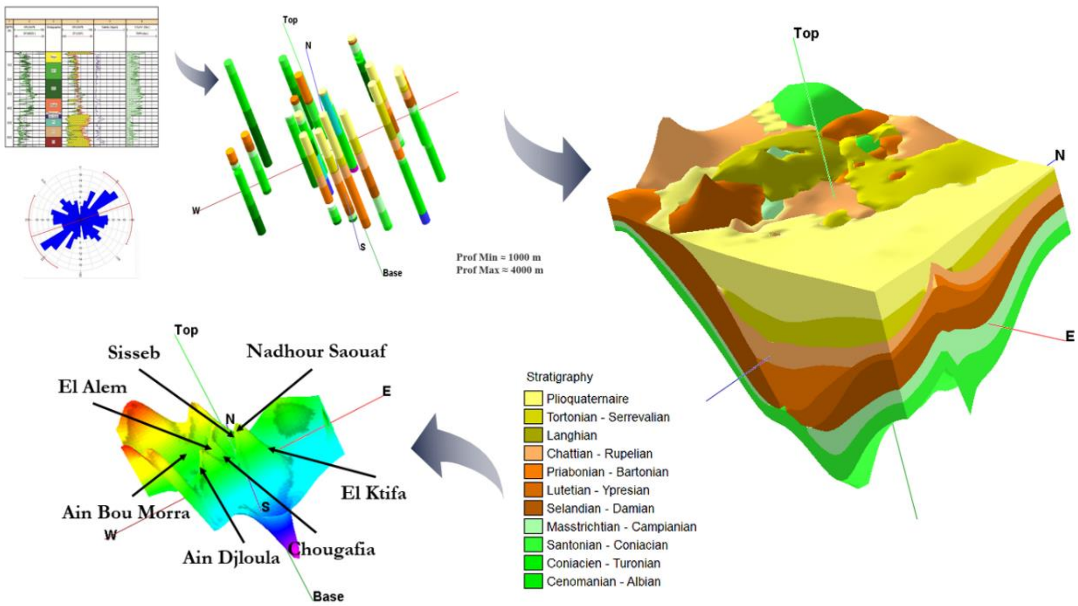

Fig. 2. Geological modeling of the Sisseb El Alem Nadhour Saouaf basin

2.3 HYDROGEOLOGICAL MODELING: MODFLOW MODEL CONCEPTION, CALIBRATION AND SIMULATION

The Modflow Hydrogeological Code is a multi-layered model in finite differences and is often used for modelling aquifer systems and complex groundwater flow problems. It was developed by the USGS and tested and used on a variety of practical cases. The name MODFLOW is directly related to how the calculation code is structured. Indeed, this code consists of a set of modules each solving a particular part of the underground flow problem. For each application, the appropriate modules are chosen to describe the flow problem studied in relation to the surrounding environment. This modular structure offers several advantages, including: the optimization of calculation times and the possibility of developing specific modules when needed. The elemental reference volume is the smallest subsystem isolable in the real environment system for the representation of a given phenomenon of interest to the whole system. The combination for the same elementary reference volume of all the recognized physical laws necessary to represent the flow phenomenon expressed in the form of the fundamental equation of motion. The equations that Modflow resolves are presented in

MODFLOW simulates both permanent and transient flows in an aquifer system with regular or irregular geometry and where aquifer layers may be free, captive or a combination of both. Flows related to external stresses to the system, such as flows to a well or to drains, flows induced by recharge or evapotranspiration, and exchanges across a river bed can be simulated. Hydraulic conductivities or transmissivities can be considered variable in the anisotropic space provided, of course, that the main directions of anisotropy are chosen as the directions of the meshes; likeage, the storage coefficient can be heterogeneous. On the limits, load-imposed or flow-imposed conditions, as well as flow-dependent load conditions outside the domain limit can be simulated by MODFLOW. It is currently the most widely used model for solving underground flow problems.

Table 1. Hydrodynamic equations governing the Modflow code

Definition	Equation	Acronyms
Equation of diffusivity	$\frac{\partial}{\partial x}\left(K_x \cdot \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \cdot \frac{\partial h}{\partial y}\right)=S_s \cdot \frac{\partial h}{\partial y}-\omega$	**K** is the permeability tensor of the medium **h** is the piezometric value **Ss** is the specific storage coefficient **ω** is a source term that translates a levy or contribution.
Finite Difference Equation	$\sum Q_e = S_s \frac{\Delta h_{i,j,k}}{\Delta t} \Delta V_{i,j,k}$	$V_{i,j,k}$ is the elementary volume
Darcy law	$q_{i,j-1/2,k} = K_{x,i,j-1/2,k} \Delta y \Delta z \frac{(h_{i,j-1,k}-h_{i,j,k})}{\Delta x}$	$q_{i,\,j-1/2,\,k}$ is the volume of water transferred from the mesh (i, j-1, k) to the mesh (i, j, k) through the facet (ΔyΔz).

The adopted methodology is described in the diagram below (Fig. 3).

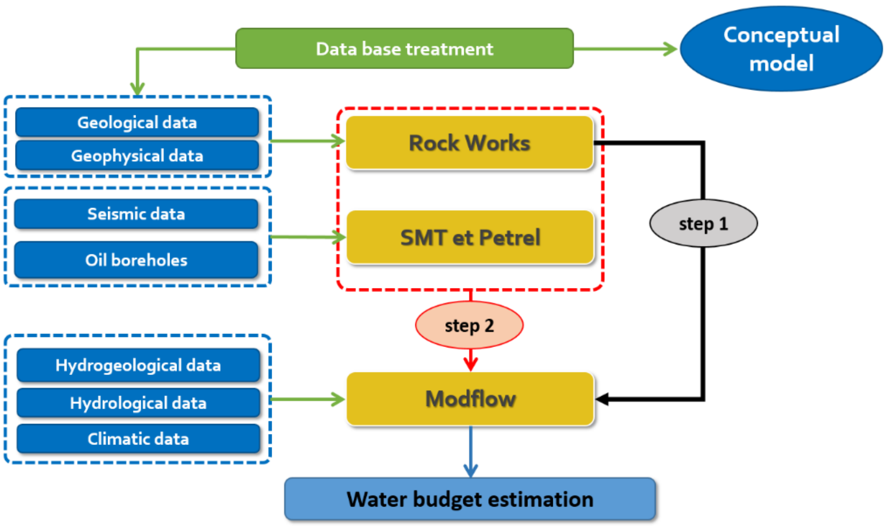

Fig. 3. Adopted methodology for the integration of the 3D geological model into the modflow model

3 Results And Discussions

3.1 Model Conception And Calibration In Steady State

The modelling domain is part of a matrix of 80 columns and 52 rows, or 8320 square and regular cells of 1000 meters of side. The model consists of two aquifer layers: (i) the first layer refers to the surface horizon. It represents the water table captured by the surface wells; (ii) the second layer covers all the deep horizons, that is to say the two permeable levels contained in the Mio-Pliocene filling and the Oligocene sandstones. In this first phase of the study, the model will be calibrated on a permanent basis. This involves simulating a quasi-stationary state of the system, not influenced by aquifer withdrawals. Permanent calibration ensures consistency between transmissivities and boundary conditions adopted by the model. In the second step, the model is calibrated in transient mode. To do this, the model is simulated over a historically known period during which the system has undergone severe sampling-related disturbances. Comparing the piezometric results calculated with the observed series makes it possible to judge the degree of representativeness of the developed model.

The choice of the reference state is mainly dictated by the availability of a piezometric map for the two deep water tables. The first piezometric map established for the Sisseb-El Alem system is that drawn by G. Castany in 1948 for the deep horizons of the Sisseb-El Alem basin. In 1996, Dr. Baba Sy drew piezometric maps for the two aquifers based on piezometric observations made between 1938 and 1964. The calibration process will then consist in reproducing the flow mechanism with an acceptable hydraulic gradient, with particular reference to the maps obtained from DGRE data for the year 1971.

The first calculations show a piezometry in the aquifer strongly influenced by the piezometry of the deep aquifer which becomes intensively exploited in the area of Sisseb-El Alem from 1978. We then further reduced the vertical link between the two layers over the entire domain except in the Nadhour region where the two aquifers and deep water are combined. After a dozen tests in which the transmissivity and the coefficient of drainance were modified, the calibration was stopped since the calculated piezometric maps show a similar pattern to that of the reference piezometry.

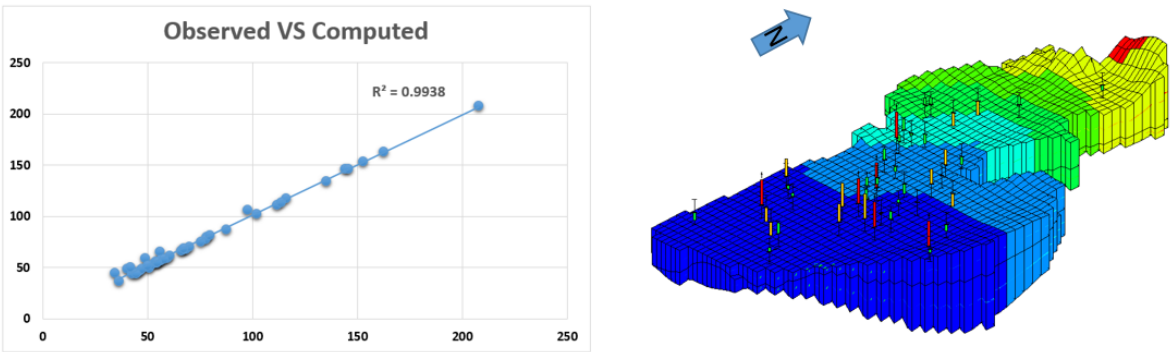

Fig. 4. Model calibration in the steady state

The overall balance calculated by the model indicates that the mobilizeable resources of the entire basin (Sisseb El Alem Nadhour-Saouaf) amount to 75.7 Mm^3/year. The Wadi of the North contribute 18% in the diet of the basin. Inputs from the Ksab, El Ogla, Essahel, Hdadda and Saadin wadis total 9.7 million m^3/year, or almost half of the total feed flow. The calculated balance sheet also shows that Wadi Nebhana's contribution is low (12%). Moreover, the modelled domain has been divided into two zones: the Nadhour-Saouaf sector, which is the subject of this study and that of Sisseb-El Alem, which is integrated into the hydraulic system, studied to study the exchanges between them. On a permanent basis, the entire supply flow in the Nadhour-Saouaf sector, which amounts to 286.7 l/s, passes in the absence of withdrawals to the Sisseb-El Alem sector (Fig. 5).

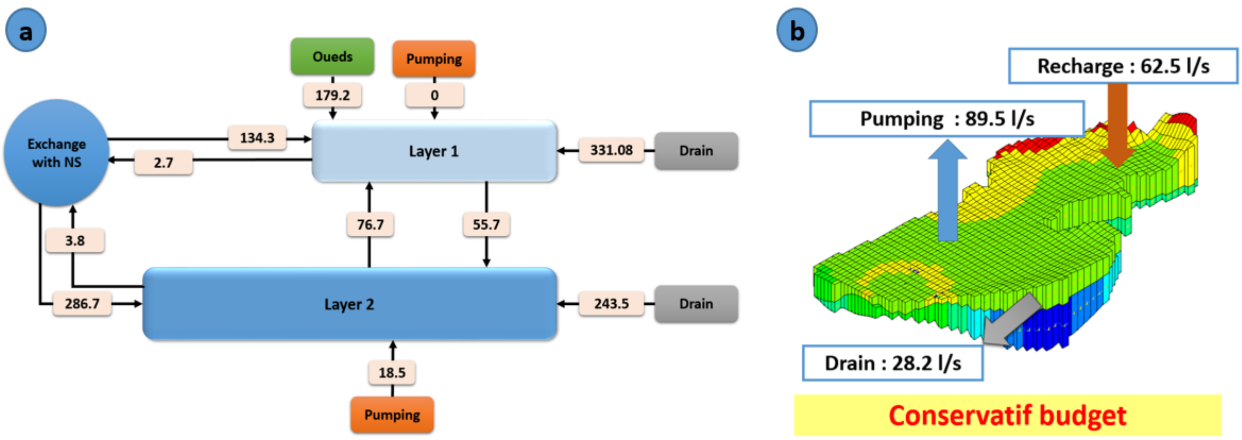

Fig. 5. (a) Water budget for the Sisseb El Alem region; (b) the global budget of the Sisseb El Alem Nadhour Saouaf basin in steady state

3.2 Model Calibration In Transient State

The transient model represents a continuity to the permanent calibration. The main objective of this step of the hydrodynamic modelling is the calibration of the storage coefficient and the homogenisation of the hydraulic system data in transient mode. The transient simulation was carried out by adopting the same hydraulic conductivity field obtained during the steady state calibration. The transitional simulation was performed over a period of 45 years: from 1971 to 2016. The time used is equal to one year.

Several transient calibration tests were carried out to reproduce in a relatively adequate manner the average behaviour of the slick. These tests involved modifying the following two main parameters: (i) the hydraulic conductivity field from the steady-state calibration of the model, introduced into the model, provides a solid basis for the hydrodynamic model. To do this, it was decided to wedge the model by first varying only the recharging of the system; (ii) the storage coefficient: Variations in this parameter were made while respecting the geology of the terrain.

Fig. 6 shows the evolution of calculated piezometry and that measured during the simulation period. Overall, the calculated piezometry has satisfactory results with that measured. The differences between the piezometric levels recorded at the control piezometers and those calculated by the model do not exceed 2m.

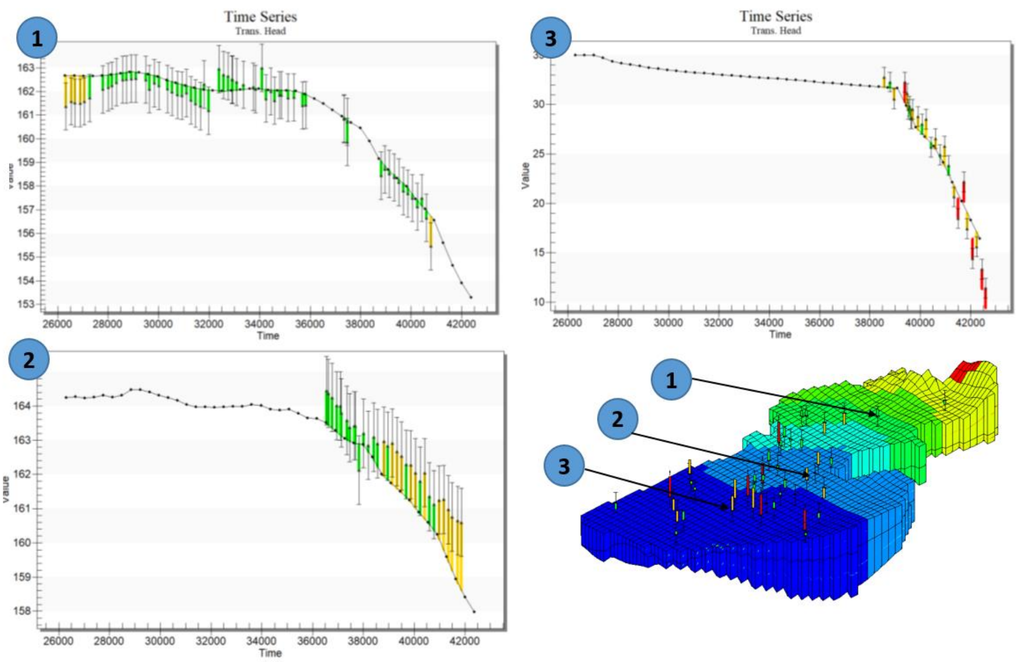

Fig. 6. Observed vs simulated heads in transient state (1971- 2016)

3.3 Water Budget Simulation 2020 And 2030 Under The Same Conditions

Simulations were tested out of curiosity to know the state of the Sisseb El Alem Nadhour Saouaf aquifer if we keep the same climatic pressures and the same exploitation rate we obtained the following results:

- In 2020: the balance sheet of the Sisseb El Alem Nadhour Saouaf basin will be in deficit -14.22 Mm^3 and the aquifer will remain in a critical situation: the exploitation will be of the order of 75.43 Mm^3. This depends enormously on the progress of the method of extraction of groundwater.
- In 2030: the global water budget is also deficit -14.5 Mm^3. We note that the farm will show a fall and this is due to the fall in the productivity of the drilling: the table will be dry.

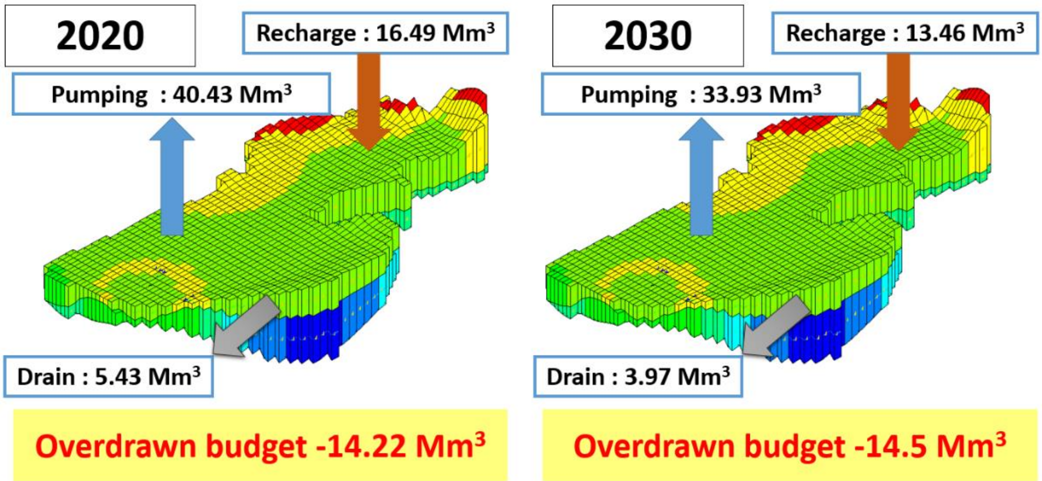

Fig. 7. Water budget simulation over 2020 and 2030

4 Synthesis And Conclusions

In Tunisia, in the SANS basin, northwest of the Kairouan governorate, water systems operate under natural, economic and human pressures. Information on the aquifer systems in this basin is still fragmentary and insufficient. In order to improve the knowledge of these aquifers, a fine geophysical characterization was developed. Indeed, a varied database has been built to achieve these objectives. All available water and oil drilling data were collected, controlled and corrected and processed. This hydrostratigraphic characterization confirmed the existence of several locally connected aquifer units with significant thicknesses in many locations as well as high porosities. The geophysical study allowed us to map the system of faults affecting the area. The combination of these results shows that the SANS basin is characterized by a succession of several sedimentary basins with contrasting resistivities, connected and with vertical and horizontal drainances. Some faults in the area represent hydraulic drains, connecting the different aquifer units (e.g. Nadhour Saouaf and Sisseb) and others materialize tight aquifer boundaries (e.g. El Ktifa and El Alem).

All these results were ultimately used to perform two types of modelling: deterministic (Modflow 2000) and remote sensing techniques that allowed us to establish a spatial prediction tool for groundwater availability. This study shows that: Hydrogeological modelling using the Modflow code is a very powerful tool for improving hydrodynamic parameters of aquifers. This modelling allowed us to clearly discern the variations in hydrodynamic parameters between the steady state (1971) and the disturbed regime represented by the SANS system today. In addition, this modelling work highlighted the importance of field investigations in improving the calibration of the model and the water balance.

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