NORTH WESTERN SAHARA AQUIFER SYSTEM

BASIN AWARNESS

MATHEMATICAL MODEL

(Synthesis)

October 2002

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INTRODUCTION

1970-2000, thirty years after the implementation of the study on water resources in Northwest Sahara (ERESS-Étude des Ressources en Eau du Sahara Septentrional) in Algeria and Tunisia, and further to the investigation of groundwaters in Libya during the 1970s, two indicators can be used to measure the progress made in Saharan hydrogeology:

- the number of inventoried water points in the main aquifers rose from 2000 to over 7000;
- abstractions per well have risen from 450 millions m^3/yr. to 2.2 billion m^3/yr.

As concerns knowledge of the aquifer system, the explosion of data and speculations accumulated during the last thirty years, which accompanied the socio-economic and hydraulic development of the Saharan regions, seems at least as intense and important as the knowledge acquired during the thirty years therebefore, a period whose profusion of knowledge was justified by the discovery of oil in the Sahara.

Hence, the requirements of the NWSAS project, with regard to researching, analysis and presentation of existing data, the complementary geological and hydro geological syntheses, and the designing and implementation of conceptual modelling of accurate, modern aquifer systems, give an idea of the size of the **challenge** of this new project.

The effort to analyse data and documents, the ability to make hydro geological syntheses, and the capacity to design the proposals needed for making a representative, up-to-date, time-valid model, all this must be as strong as the challenge.

The North-Western Saharan Aquifer System is composed of the watertables of the Continental Intercalary (CI) and the watertables of the Complex Terminal (CT). Each of these two watertables is subjected to constraints that limit the possibility of capitalising their potential. Besides the obvious economic constraints, the most decisive constraints at present stem from environmental risks connected to the exploitation and the vulnerability of Saharan aquifers because of their level of development.

The problem is allthemore complex because three countries share the same resource and the main desire for development but do not necessarily have the same vision for the future use of the Saharan aquifers. This is especially true when several users share a highly solicited aquifer; ignorance of effects makes users behave inconsiderately while **shared information can strengthen solidarity.** This applies to both individuals and States. **The model should be conceived as a powerful educational tool and an instrument for objective dialogue and mediation.**

The final report on the model covers the work done through the NWSAS project between January 2000 and June 2002 in order to produce a mathematical model of the North-Western Saharan Aquifer System.

This document has been preceded by a certain number of mid-way reports, including the report of the Model Evaluation Committee. The reports also include:

- *Élaboration du modèle conceptuel*, (production of a conceptual model) August 2000;
- *Rapport sur le choix du logiciel*, (report on the choice of software) June 2000;
- *Construction et ajustement du modèle de simulation*, (Construction and calibration of the simulation model), May 2001;

- *Deuxième phase d'ajustement du modèle. Révision de l'exutoire tunisien de la nappe du Continental Intercalaire*, (second model calibration phase. Revision of the Tunisian outlet of the watertables of the CI), October 2001;
- *Définition et réalisation des simulations exploratoires*, (definition and implementation of exploratory simulations), November 2001;
- *Avis du Comite Scientifique d'Evaluation sur le modèle du SASS*, (comments of the scientific evaluation committee on the NWSAS model), January 2002;
- *Reprise du Modèle dans le Bassin Oriental. Intégration des nouvelles données acquises en Libye*, (*reconsideration of the model in the Eastern Basin, Integration of new Libyan data*), May 2002;
- *Résultats des Simulations Prévisionnelles. Recherche de scénarios d'exploitation des aquifères*, (result of provisional simulations and preparation of scenarios for exploiting aquifers), May 2002.

This document is divided into three parts:

- Part One: Characterisation of the Aquifer System and Conceptual Model. This section includes the geological, hydrological and hydrodynamic characterisation of the basin.
- Part Two: Construction of the Mathematical Model. This section describes the steps in constructing and calibrating the model in the steady and unsteady state.
- Part Three: Implementation of Predictive Simulations. This section focuses on the definition and implementation of exploratory simulations, the construction of a miniature NWSAS model for reservoir investigation, and the definition and implementation of predictive simulations.

I - CHARACTERISATION OF THE AQUIFER SYSTEM AND CONCEPTUAL MODEL

A - Concepts and contours

1 - The implementation of the Conceptual Model entails:

- preparation of a hydro geological drawing of successive permeable and semi-permeable layers
- for each permeable layer selected, working out the spatial breakdown of:
  - piezometric level, at least for one given date,
  - transmissivity or permeability,
  - levels of top and of sub-layers,
  - inlet and drainage zones, with a preliminary estimate of flows,
  - potential exchange of flows with adjacent layers.

- for each permeable layer, identify, analyse, and give proper form to historical series on levels, abstractions, and salinity; further, work out the spatial distribution of storage coefficients. The first step in the analysis of the North-Western Sahara Aquifer System involves a three-part characterisation:
  - geological;
  - hydrological;
  - hydrodynamic.

2 – Observations on outcropping make it possible to define the CI as a continental ensemble located between the Hercynian folds, which chased the waters off the Saharan platforms, and the Upper Cretaceous marine invasion. This ensemble is mainly composed of continental Lower Cretaceous sandstone-clay formations combined with marine or laguna post-Palaeozoic and pre-Cenomanian sediment.

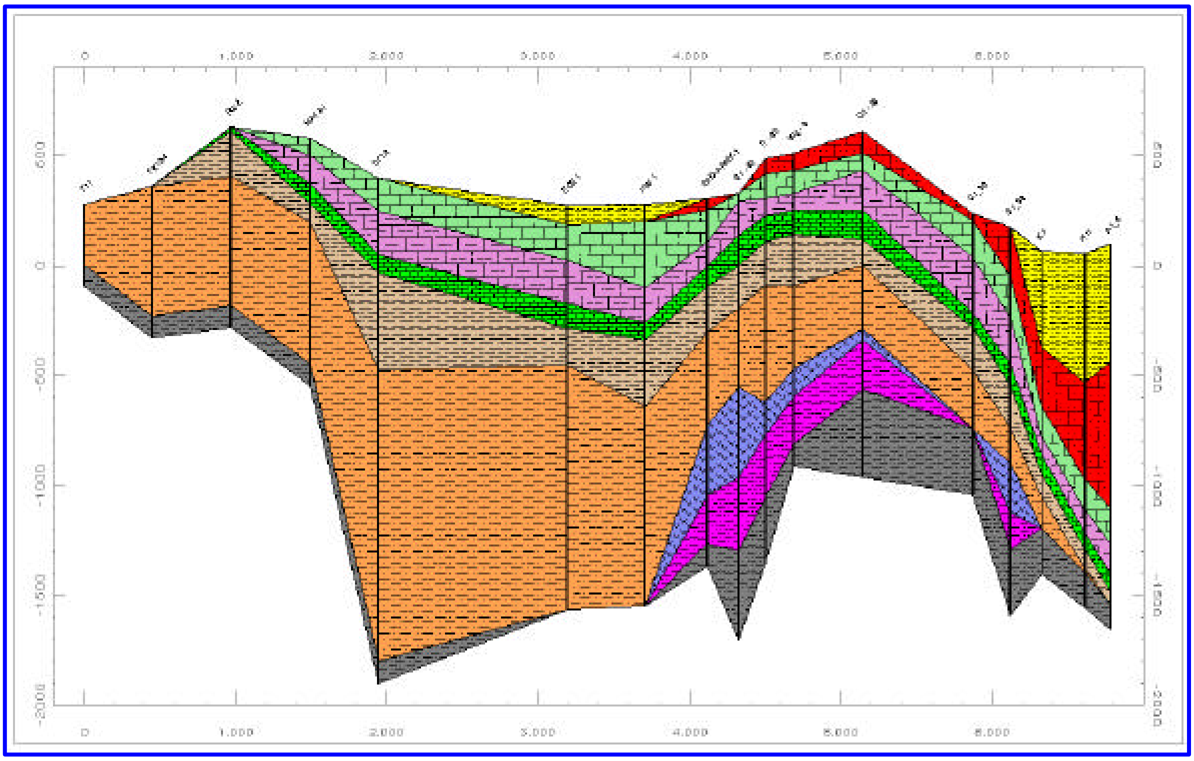
The Continental Intercalary, (which makes up the most vast aquiferous formation in the region), as thus defined, determines the contours of the study zone of the North-Western Sahara Aquifer System.

The limits are: the Saharan Atlas to the north-west, the Ougarta Palaeozoic outcroppings to the west, the Tassilis and Dj. Hassaouna to the south, the end of the brackish waters of Graben de Hun to the east, the outcroppings of the CI on Dj. Nefussa and Dahar to the north-east, and the hilly south Atlas to the north, extended to the Gulf of Gabès by the El Hamma fault.

B – Geological characterisation

3 – Traditionally, the **“Continental Terminal”** refers to the continental, sandy-clayey formations of the MioPliocene Epoch. But the watertables of the CT are connected to those of the Eocene, the Senonian and the Turonian, which means that at the trans-Saharan level, we can say that these different levels together form one level; they even form one watertable, that of the **“Complex Terminal”**. The interconnections between the Senonian, the Eocene and the MioPliocene are obvious throughout the basin, except in the chotts region where the pervious middle and upper Eocene are intercalated. The Turonian aquifer is more isolated because of pervious cover by the lagune Senonian. But along the edges of the basin, these levels coincide with those of the Senonian and the MioPliocene systems.

Fig. 1 - Southerly west-eastern cross-section of NWSAS, from Foggaras d'Adrar to Graben de Hun



4 – The Conceptual Model has been made from a series of simplifications that originally came from the recognised stratigraphic division of geological outcropping, and vertical cross-sections on borehole logs. The results of these investigations make it possible to understand the overall structure of the NWSAS in three basins:

- the Western Basin dominated by the Grand Erg Occidental and the foggaras sector;
- the Central Basin, which is the largest in size and depth, and has the deepest aquiferous zone, with resources in the three countries, demarcated to the west by the M'zab dorsal, and to the east by the of the Hamadah el Hamra plateau;
- the Eastern Basin, characterised by the collapse of the Graben de Hun and the accumulation of tertiary sedimentation.

5 – Thanks to the stratigraphic scale, which ensures temporal conformability and spatial correspondence, and thanks to all the lithostratigraphic cross-sections that have been made, it has been possible to combine the Algeria, Tunisia and Libya situations. Since the aim was to construct a coherent entity from the hydro geological angle, the first exercise had to be (respecting the terminology adopted by each of the countries) to attach the lithostratigraphic formations recognised at the universal stratigraphic level and then translate these formations using purely lithological terms in order to assess their degree of permeability, and then translate the lithological formations thus obtained in terms of aquifer formations or aquitards and aquicludes.

Fig. 2 - NWSAS Aquifers and Aquitards

Stratigraphic unity		Aquifers & Aquitards		
		ALGERIA	TUNISIA	LIBYA
Pioquaternary	Mio-Pliocene			
Miocene		2 nd sandstone aquifer	impermeable top	local aquifer
Aquitanian		semi pervious		Semi pervious
Oligocene		1 st sandstone aquifer	Djerid sandstone aquifer	Aquifer
Middle Eocene		semi pervious		Local aquifer
Lower Eocene		semi pervious	semi pervious	Bad aquifer
Paleocene		Limestone aquifer	Non exploited aquifer	
Upper Senonien	Maestrichtian		semi pervious	Upper Cretaceous-Paleocene MIZDA Aquifer
	Campanian		Nefzaoua upper seonian limestone	
	Santonian		semi pervious	
Lower senonien		Impermeable	Lower limestone/Nefzaoua	semi pervious
Turonian		TURONIAN aquifer	semi pervious	
Cenomanian		Impermeable	TURONIAN aquifer	NALUT Aquifer
Albian		CONTINENTAL INTERCALARY aquifer	Impermeable	Impermeable
Aptian			CONTINENTAL INTERCALARY aquifer	Jurassic – Low Cretaceous : KIKLAH Aquifer
Barremian				
		Salt water		
Neocomian		Jurassic aquifer	Semi pervious	
Malm	Kimmeridgian		JURASSIC aquifer	
	Callovo-Oxfordian			
Dogger	Bathonian			impermeable
Liasic		Impermeable top	Impermeable	
Keuper				
Mushelkalk				Triassic: AZIZIA Aquifer
Bundstandstein		Triassic salty aquifer	TRIASIC aquifer	

6 – Setting aside the saltwater aquifers of the Trias, Jurassic and Neocomian in Algeria, the aquifers of the Trias and the Jurassic in Tunisia (which are usually salty) and the aquifers in the sandstone Trias in Libya (includes freshwater, but rather well isolated from the rest of the aquiferous system), we have, on the basis of criteria that are purely lithostratigraphic, four superimposed aquiferous systems, of varying importance. The vertical organisation and regional connections can be clearly seen. From the bottom to the top, there are:

- The CI watertables in Algeria-Tunisia, which, in Libya, traverse the Kiklah-Aquifer formation that includes the Jurassic and Lower Cretaceous.
- The Turonian watertables in Algeria-Tunisia, which, in Libya, traverse the Nalut-Aquifer formation.
- The calcareous watertables in Algeria [carbonated Senonian + carbonated Eocene], which, in Tunisia, traverse the Nefzaoua (lower and upper) calcareous aquifers, whose equivalent in Libya is the Mizdah-Aquifer;
- The sandy watertables of the MioPliocene in Algeria, which, in Tunisia, traverse the sandy watertables of Djerid whose equivalent in Libya is the Aquitanian and the PlioQuaternary watertables.
-

7 – An additional degree of simplification would make it possible to draw up a multilayer Saharan diagram. Were we to use the classical method of grouping calcareous watertables from the Upper Cretaceous and the carbonated Eocene, and the sandy watertables of the MioPliocene (Mizdah and PlioQuaternary), the NWSAS multi-layer would appear as three

superimposed aquifer systems, separated by (or communicating via) semi-pervious formations, i.e.:

- The aquifer of the Continental Intercalary – Kiklah;
- The aquifer of the Turonian – Nalut;
- The aquifer of the Complex Terminal – Mizdah.

Fig. 3 -Diagram of the Saharan Multi-layer

HYDROGEOLOGIC SCHEME OF THE NORTH WESTERN SAHARA		
ALGERIA	TUNISIA	LIBYA
Impermeable top		
Sandstone aquifer	Djerid Sandstone aquifer	Lower Miocene sandstone and limestone
TERMINAL COMPLEXE AQUIFER – Upper Cretaceous		
Sandstone aquifer	Nefzaoua Sandstone aquifer	Upper Cretaceous Mizdah
Semi pervious		
Turonian aquifer – Nalut Aquifer		
Semi pervious		
CONTINENTAL INTERCALARY AQUIFER – KIKLAH AQUIFER		
Lower Cretaceous Jurassic Triassic	Lower Cretaceous upper Jurassic	Lower Cretaceous upper Jurassic
Impermeable or semi pervious Substratum		
Palaeozoic	Lower Jurassic Triassic	Carboniferous
		Cambro-Ordovician

C – Hydrological characterisation

8 – Interpolation of the rainfall map in isohyetal contours, (Dubief, 1953), gives a surface that represents an average water depth (average over 25 years, 1926-1950) for across the NWSAS region. This makes it possible to define the average water depth as equal to 51 mm. For a total area of 1,050,000 km^2, the "average" volume of rainfall in the NWSAS amounts to **52 billion m^3/yr**.

9 – The validity of the FERSI (1979) equation to estimate average annual runoff was checked in two catchment basins in the Saharan Atlas: Oueds Segguer and Namous. Applying the equation to all of the catchment basins in NWSAS gave the following estimates for average runoff:

- Saharan Atlas: **450 Mm^3/yr.**;
- Dahar **45 Mm^3/yr.**;
- Aurès-Gafsa **300 Mm^3/yr.**;
- Mzab-Mya **140 Mm^3/yr**.

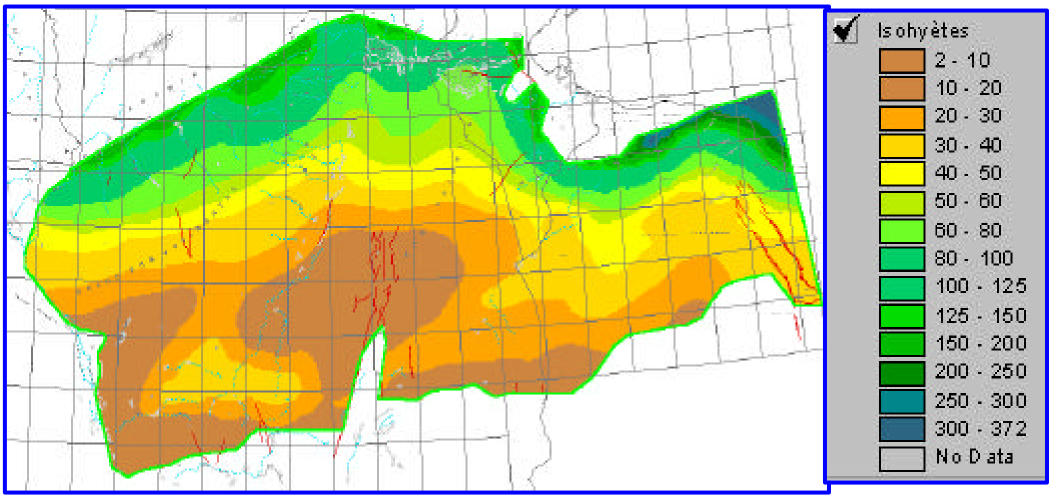
The average inter-annual runoff for NWSAS as a whole, thus, can be estimated at approximately **1 billion m^3/yr**.

10 – Thanks to the average rainfall data at all points, maps of geological outcropping, and a preliminary evaluation of runoff volumes, we can start estimating watertable recharge from two sources:

- infiltration by *oued* (wadi) floodwaters,
- direct infiltration of rainfall.

Little reference is available on the infiltration of floodwaters in the wadi beds in the arid zones. Documents on the infiltration of floodwaters from the Zeroud and Merguellil wadis in the Kairouan plain indicate that **30% of the total infiltration** come from runoff. Were an analogy to be drawn, we would see that total infiltration from floodwaters in the NWSAS might be around **300 Million m^3/yr**.

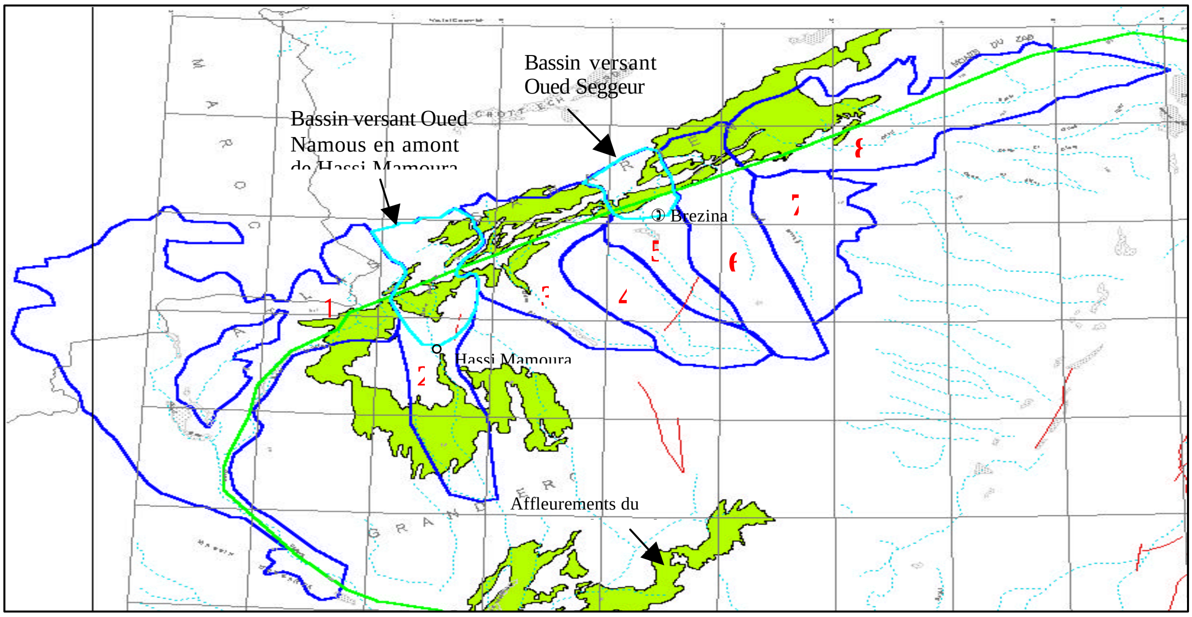
Fig. 4 - Map of isohyets in NWSAS in mm/yr



11 – In regions with unconfined watertables, the extension of "**useful**" outcropping, which contributes to recharging the watertables of the CI and the CT through direct infiltration, and the map of average rainfall provide the following information:

- useful pervious outcroppings cover close to **60%** of the total NWSAS area;
- in the outcroppings, in the inter-annual average precipitation makes up **30 billion m^3/yr.**;
- when the rainfall infiltration coefficient varies between **1% and 10%**, volumes that infiltrate the NWSAS region vary between **0.3 and 3 billion m^3/yr**;
- and for NWSAS recharge estimates as a whole, information published to date is around **1 billion m^3/yr.** [2/3rds for the CT, 1/3rds for the CI]. This, if infiltration from wadi floodwaters is included, will represent a direct infiltration coefficient for rainfall of about **2%**.

Fig. 5 - Southern catchment basins of the Sahara Atlas



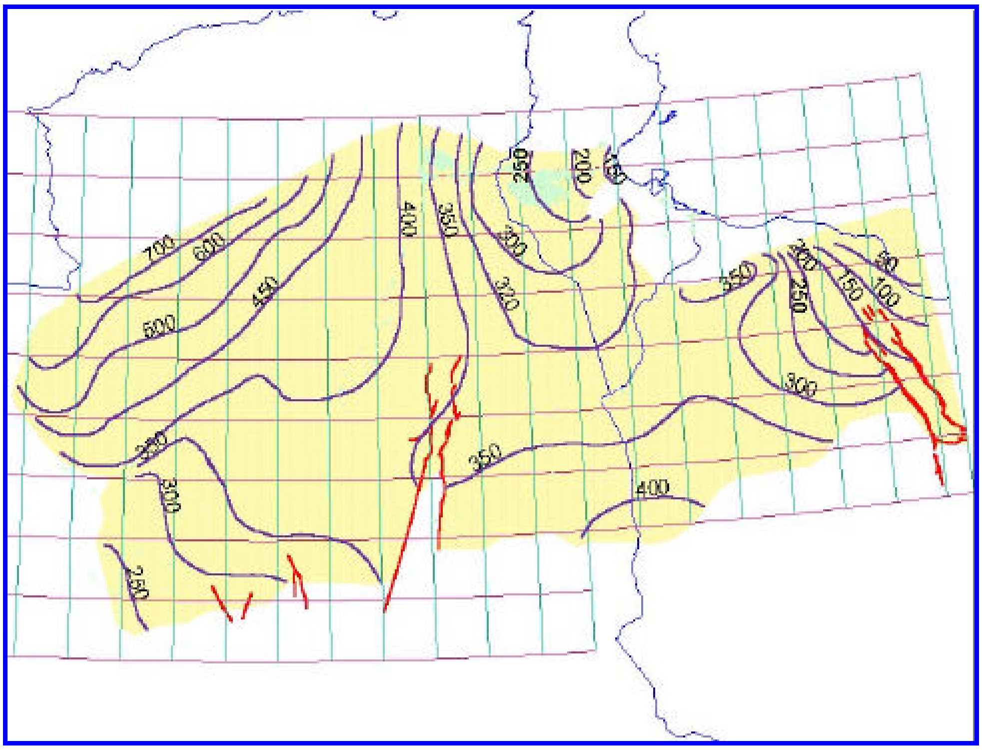
D - Hydrodynamic characterisation

12 – The first level in hydrodynamic modelling is cartographic representation of groundwater flow. Knowledge on the origins, directions and future of these flows is needed as a prerequisite.

This type of map did not exist for the NWSAS territory, although representations of parts of the territory were available, and each one added to the knowledge base.

The project had to produce a piezometric map that included earlier contributions in order to present a coherent groundwater flow diagram for the basin as a whole. This map defined respective outflow for the CI and CT in their "**natural**" state, in other words, with little or not effects from pumping.

Fig. 6 - Initial piezometry, a reference for the Continental Intercalary
NWSAS, 2002



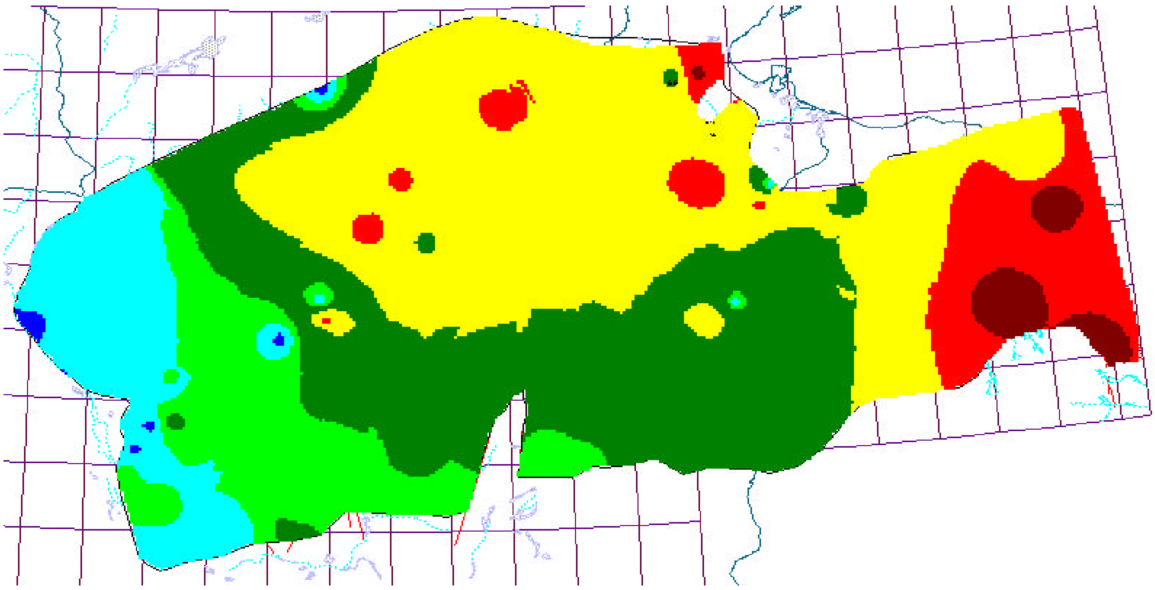
13 – The isotope data concerning the Carbon 14 activity of the CI watertable were compiled, together with corresponding ages. The oldest ages were **45,500 years**, (the wells near the Tunisian outlet and the ones located in the southern part of the Graben de Hun).

The youngest dated waters are **25 years old**. An initial analysis indicates that they are located in the identifiable recharge zones, i.e. Dahar, the Saharan Atlas, and the Grand Erg Occidental. For the sample as a whole, the average age is **18,000 years**.

The ages map includes geological deposits of the aquifer and its hydrodynamic behaviour. Actually, and although it is difficult to match the hydrodynamic age of waters with the radiometric age, the NWSAS is clearly organised into three geological and hydrodynamic basins:

- the Central Basin, where all water resources are ancient, with ages evolving from the periphery to the Gulf of Gabès, thus indicating convergence of outflows towards the Tunisian outlet;
- the Western Basin, where all water resources are young. Throughout their trajectory, the CI waters are constantly being renewed;
- the Eastern Basin, where waters are ancient, but, paradoxically, the highest figures are found upstream of the groundwater flow, at the southern edge where the Kiklah is in direct contact with the Paleozoic waters of Djebel Hassaouna. Assuming that these waters are in the "fossil waters" category, the age anomaly can be readily understood: the CI is "recharged" here by ancient waters from the Cambro-Ordovician, and not be present-day waters.

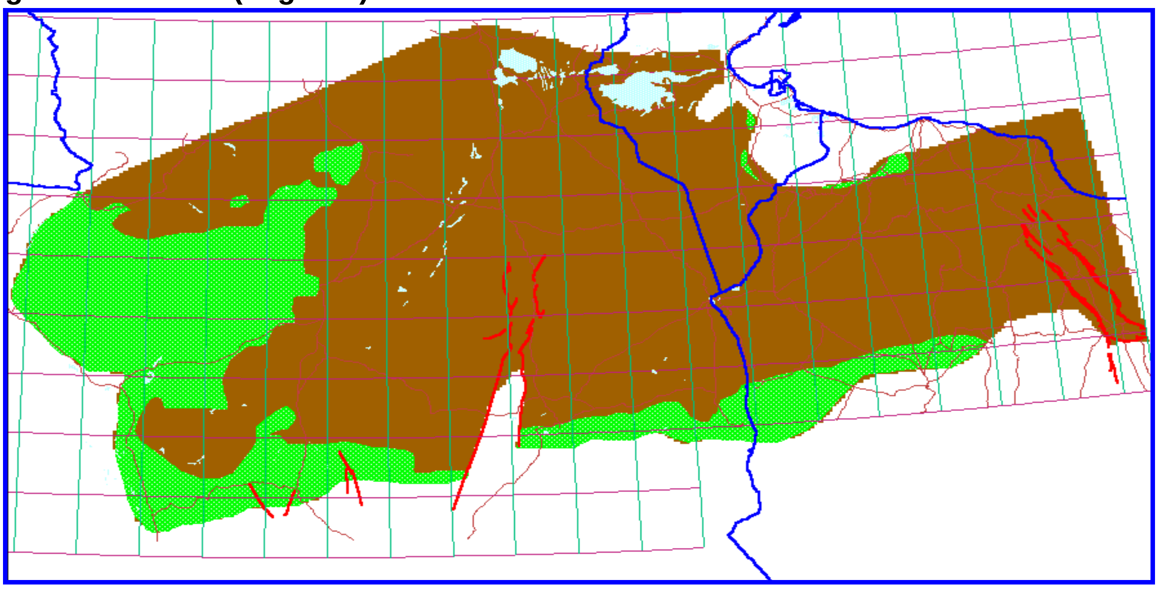
Fig.7 - Age of CI waters according to C14 content



14 – For the CI as a whole, the project collected **140** figures on transmissivity. For the CT, the figure was **302.** For CI, the average for transmissivity is **20.E-3 m^2/s**, while for the CT, the figure is equal to **16.E-03 m^2/s**. The spatial scatter of transmissivity can serve as reference points for calibrating the model in a steady state. Further, and as a model-design aid, the map on extension of the unconfined free level has been drawn up. At all points, it is obtained by taking the difference between the level of the top of the formation and the reference, piezometric level for, respectively, the CI and the CT.

These demarcations provide an initial indicator for assigning coefficients for the storage of unconfined waters when calibrating the model in the unsteady state.

Fig. 8 - Extension (in green) of the unconfined free area of the Continental Intercalary

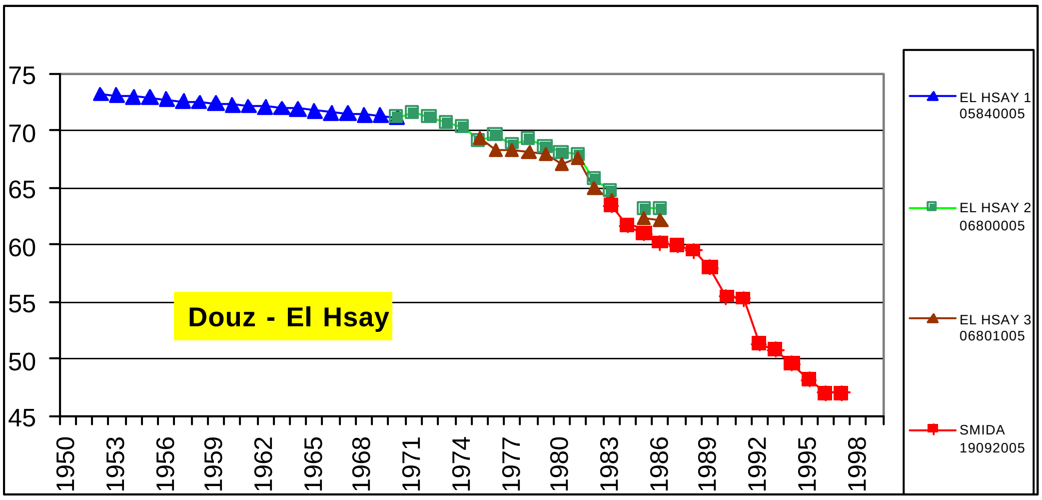


15 – The most significant piezometric evolutions in the CI are grouped into homogeneous, representative geographic sectors: Tamerna for the artesian basin with strong pressure at ground level, Kef No. 27 for the zones near the unconfined aquifer area, Chott Fedjej for the area near the Tunisian outlet, and Djerid for the areas with very strong drawdowns, the Ghadamès basin and the Graben.

For the CT, the presentation of contours showing changes in piezometric values is also based on homogeneous geographic groupings. The CT-Tunisia is confronted with an usual situation: a large number of observed wells, a very large number of measurements, but few series that are sufficiently long to support interpretations based on knowledge of changes in the aquifer system over a long enough period, 50 years, a period that would justify investigation.

Since a large amount of information was available, an attempt was made to facilitate transitional calibration of models, and, for each geographic group, to draw up a standard series, or a "summary contour line" by aggregating measurement data available for the group as a whole.

Fig. 9 - Group of control wells to reconstitute piezometric series



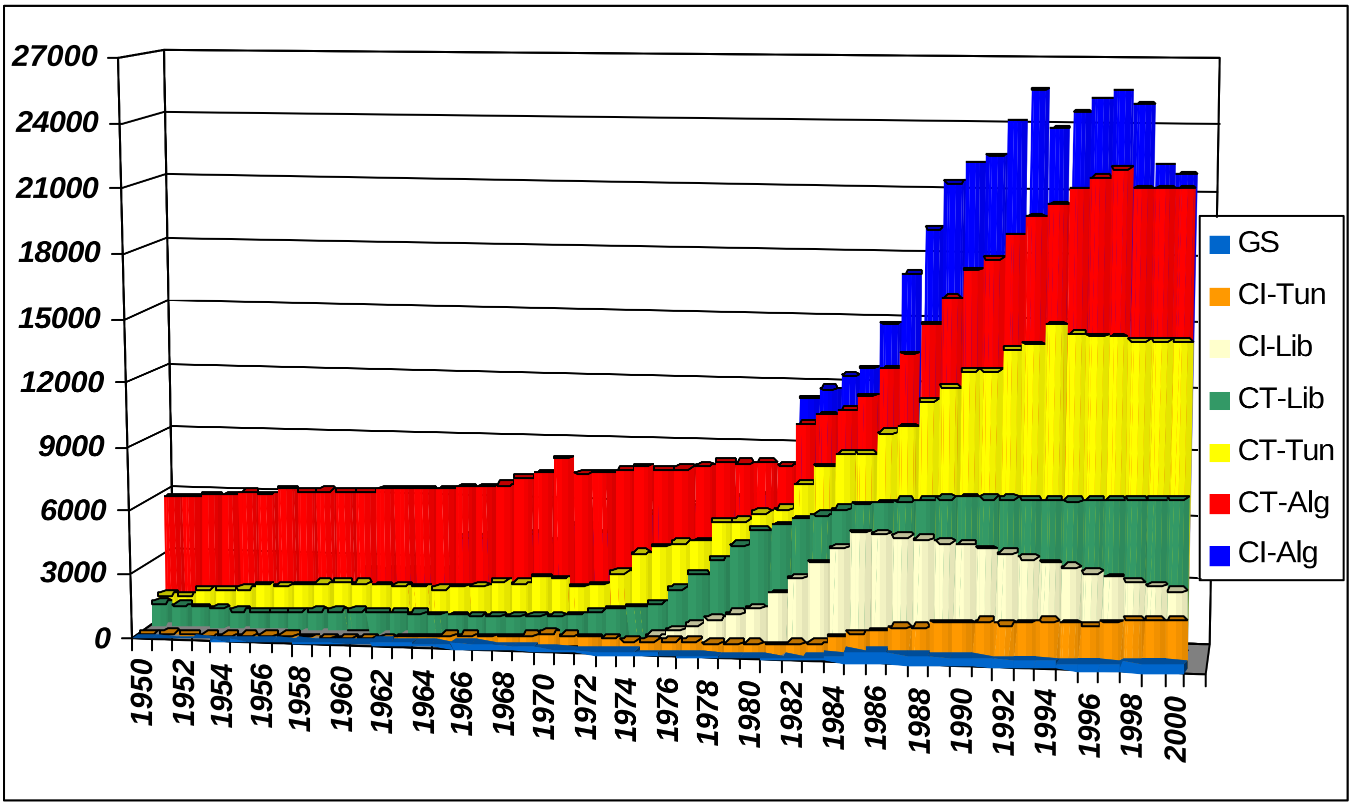
16 – It has been somewhat difficult to reconstitute the history of abstractions. A few rough figures can be used to measure the scope of the task:

- In the CI, an estimated **1200** wells have been permanently or temporarily pumped during the 1950-2000 period;
- During that same period, the figure is **2000** wells in the CT;
- These figures must be increased to include sources in Tunisia and Libya as well as the foggaras d'Adrar, which have close to **1000** wells.

Considering the difficulty of making precise evaluations of withdrawal flows in watertables comprising several thousand wells and the even greater difficulties encountered in reconstituting the history of flows in time, we can expect to encounter a certain number of problems because of differences in calculation methods; this depends on the countries and their evolution in time. Abstractions, per well, in nearly all cases, were kept at a stable level during the 1950s, 1960s and 1970s. There was a **sudden increase in the 1980s,** in all countries and aquifers. In a few cases, a downward trend was recorded towards the end of

the 1990s, but the last phenomenon may have been an artifice, which, perhaps in Algeria was caused by the interruption in the inventory between 1994 and 1998, and in Libya, by the excessive importance given to the operationalisation of the GMRP (Great Man-made River Project).

Fig. 10 - Evolution of abstractions from wells, per aquifer[1] and per country



II - PRODUCTION OF THE MATHEMATICAL MODEL

A – Construction of the model

17 – To optimise the enormous amount of available information, ideas and expertise, and to ensure the harmonious integration of hydro geological representations in the three countries, the overall design of the model(s) must comply with two major concerns, that appear contradictory but are actually complementary.

- Respect the overall pattern of the main past studies, in particular those of ERESS, GEOMATH and GEFLI, in order to integrate the expertise from the system that has been built up over the past thirty years and thus contribute to building up knowledge about the system. This approach involves adaptation and regional matching of the main options regarding the overall distribution of transmissivity and storage, the general appearance and regional-level outflow distribution, the nature and position of conditions at the contours, especially in the recharge and outflow areas, and compliance with orders of magnitude for various terms of the evaluation.

[1] The aquifer of the Upper Sandstone (GS in the chart) is presented in the section on the "production of the model".

- **Replace the ERESS CI vs. CT duality** by a multi-layer representation whose **Conceptual Model** has proven to be capable of combining the three hydro geological options, especially the Algeria-Tunisia system with the Libyan system.

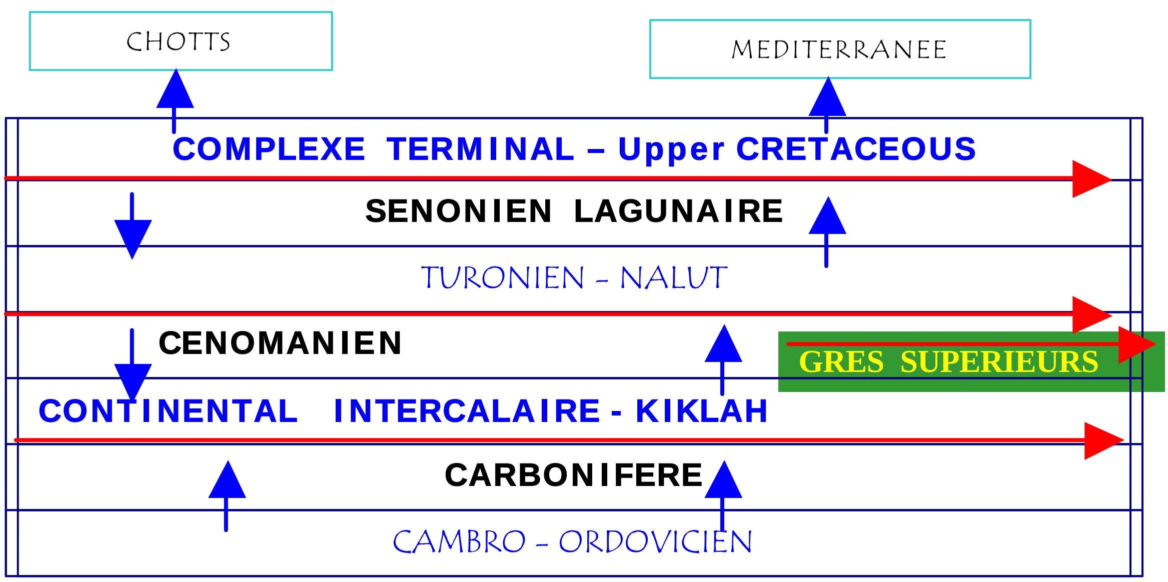
18 – The structure adopted for constructing the Conceptual Model includes four aquifer layers separated by three aquitards. The two main layers are the **Complex Terminal** (sands of the MioPliocene, the Calcareous Eocenes and the Carbonated Senonian) and the **Continental Intercalary**. The **Turonian** is represented in Algeria and Tunisia to ensure the unity and monitoring of the hydrological cycle, and because of its capacity, essentially in the Hassi Messaoud sector, to serve as a possible source of contamination, in the long term. In Libya, it constitutes a good quality aquifer in the northern half of the basin. The **Cambro-Ordovician** (COD), has been introduced as a fixed hydrant head. The representation of COD should help determine the flows that it can contribute to the CI in an equilibrium regime; these flows may be diverted once the Dj Hassaouna wellfields have been brought on stream.

19 – The first model calibration phase clearly showed the need to restructure the model for the south of Tunisia. By processing lithostratigraphic data we collected, we were able to build up a geological data base specifically for southern Tunisia. It covers five geological provinces in the region. Inter-province correlation made it possible to develop a **hydro-stratigraphic** scale composed of six aquiferous entities that are found in all or part of the region. But the representation of the CI in Tunisia is limited to a two-layer structure comprising:

- the **Continental Intercalary** *sensu-stricto,* which in the south is composed of the Wealdien, superimposed by the Albien, and, in the north, by the combination of the Kbar el Haj formation with the sandstone and the chott and the sandstone at Bois;
- the **Upper Sandstone**, which is unique because of its atypical piezometric behaviour in time and space, apparently unconnected to the Continental Intercalary.

The new structural design of the NWSAS model includes an additional aquiferous layer: the aquifer of the Upper Sandstone. Further, the new contour lines of the CI in the Gabès region have a serious gap, which corresponds to the **Mole du Melaab**, which explains why the aquifer is considered non-existent.

Fig. 11 - Structural design of the NWSAS model



20 – The grid in the model covers a square of cells of **12.5 x 12.5 km**, which represents the following: for the CT **4295 cells**, for the Turonian **4295 cells**, for the Upper Sandstone **109 cells**, for the CI **6639 cells**, for the Cambro-Ordovician **1185 cells**. This amounts to **16,523 cells** representing a developed area of close to 2,580,000 km^2. The NWSAS model is almost three dimensional, and is based on the hypothesis of multi-layer outflow that is parallel to the (horizontal) layers in the aquifers and perpendicular to the (vertical) layers in the aquitards.

21 – The simulation software should guarantee that the NWSAS model could be easily used in the three countries. This requires installation on a computer and a Windows operating system. The best tool for these conditions is the PMWIN software, especially **PM5**, which runs on the USGS Modflow code and can be used to model water transfers in a multi-layer aquiferous system through the finite differences method. Data are introduced cell by cell, which causes some problems in entering the history of abstractions when (and this is the case for NWSAS) the history is very long and is expressed in terms of "wells" rather than "cells".

The project had to produce an interface programme between the database and the PM5 per-processor. This software includes other calculation modules: transport of solutions, plotting flow lines, interpolators, etc.

22 – Hydraulic parameters for initiating model calibration especially includes transmissivity data which are derived from:

- the two mono-layer models for the CT and the CI (ERESS);
- the GEOMATH multi-layer model;
- the Algerian-Tunisian CI model (BRL-École des Mines);
- the three mono-layer models representing the watertables of Mizda, Nalut and Kiklah, (GEFLI).

This level of information is further expanded by transmissivity data collected during the NWSAS project, by attention to variations in the facies, and by SONATRACH pumping tests in the Turonian. Further, maps on the depth of the semi-pervious formation and the vertical hydraulic gradients through the layers make it possible to obtain a preliminary estimate of vertical permeability.

B – MODEL CALIBRATION

23 – Traditionally, the **protocol for model calibration** is first carried out in the **steady state**, in order to ensure the coherency of data on the conditions at the confines, the piezometry and the transmissivities. This requires the definition of a permanent reference mode; the reference date will be 1950.

The second model calibration phase entails verification of the **functioning in the transitional mode.** This is to ensure spatial distribution of storage coefficients.

In the case of the NWSAS, a model calibration procedure that went beyond adjustment of parameters was implemented. This involved adjusting transmissivity data during calibration in the transitional mode. In certain cases elements that were thought to be unquestionable were challenged during this operation. The same was done for the evolution of withdrawal rates, the final form of certain contours to the model, and even the structure of the aquifer system. The model had to be revised several times because of the geological complexity of

the system and the difficulty in acquiring precise data on current abstractions and piezometric levels.

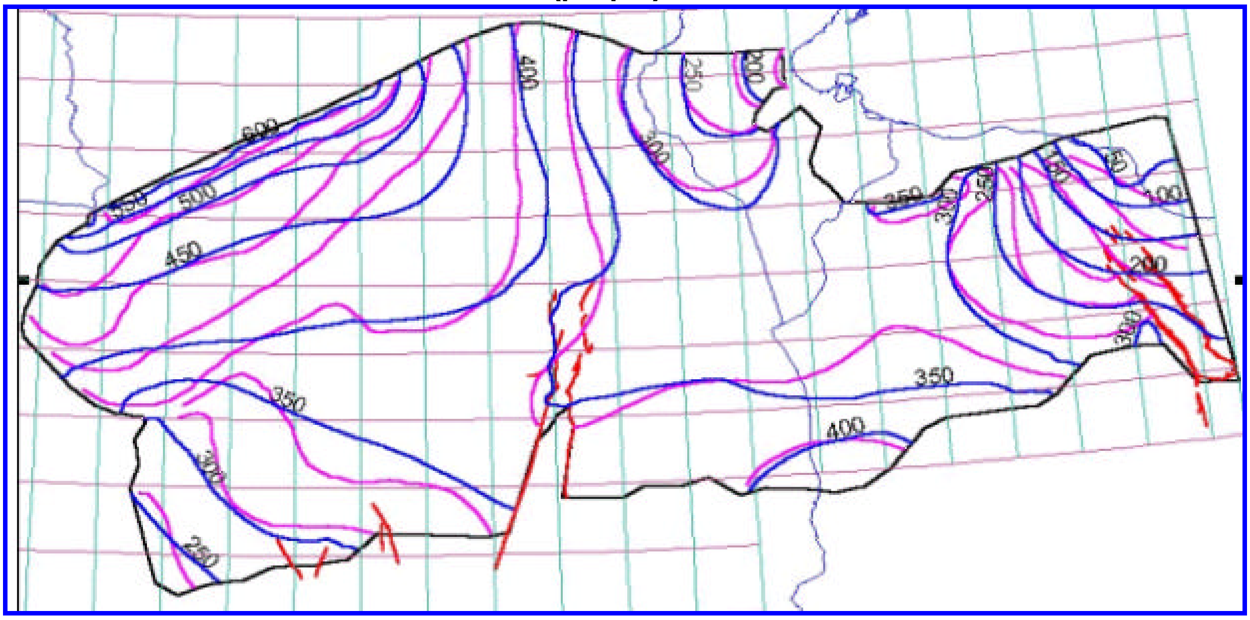
The first version of the model, called the **"Tripoli Model"**, underwent major changes, *inter alia*:

- revision of the history of abstractions in Algeria;
- revision of the Tunisian outlet in the CI watertable;
- reconsideration of the model in the Eastern Basin.

24 – To evaluate the capacity of the model to make the best possible rendition of the regional piezometric reference state, differences in piezometric level **(calculated-observed)** can well be used as an **indicator of the *"regional accuracy"*** of the model, as judged through ground truth; **differences** in **70%** of the aquifer areas in both the CI and the CT, **are under 25m**.

Superimposition of calculated and observed iso-piezometric contour lines also gives an idea of the capacity of the model to "**follow**" the shape of the plotted contour lines. With this in mind, these contour lines can be considered as the **priority reference criterion**; they translate the ***aptitude of the model to respect by the hydro geological angle.***

Fig.12 - CI – Steady state – calculated piezometric curve (blue) and reference curve (purple)



25 – Besides the scatter of horizontal and vertical transmissivity, one of the main results of model calibration in the steady state is the Saharan multi-layer assessment, which essentially includes:

- **evaporation** of the CT water resource in the Algerian-Tunisian chotts and sabkhat, equal to **8.7m^3/s**,
- **flow at the Tunisian outlet: 3.1 m^3/s**,

- **flow rate of the foggaras 3.6m^3/s**,
- Tunisian **sources** at the CT and Ain Tawargha **sources** at the CI, **2 m^3/s each**,
- **Recharge by infiltration**, respectively about **18. m^3/s** and **10. m^3/s** for the CT and the CI, the latter coming essentially (80%) from the Sahara Atlas.

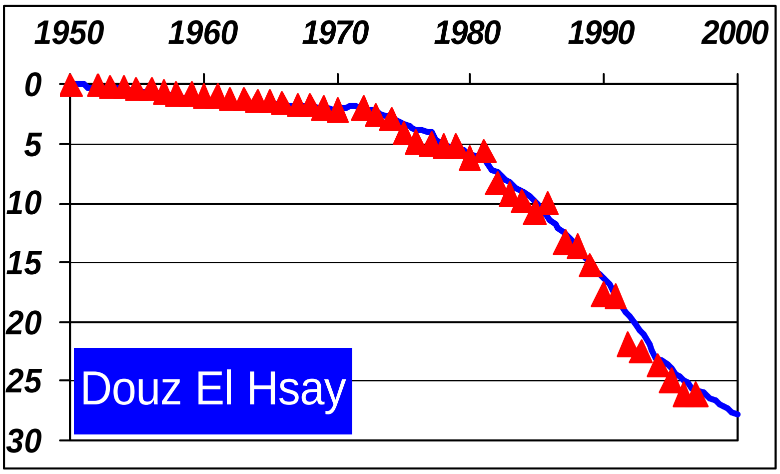
26 – In the transitional mode, the reference period for model calibration ran from **1950 to 2000**. The criteria for calibration were good restitution:

- first of series of historical reference levels,
- then, of flow series measured at the outlets: Djerid and Nefzaoua, Ain Tawargha and Kaam sources, foggara flow rates. The following results were obtained from the model calibration: storage coefficient distribution, piezometric maps **(2000),** draw down maps **(1950-2000)**, the NWSAS performance report **(2000)**

27 – The important calculated (and observed) draw down in **2000** could impel major changes in the hydrodynamic regime of aquifer systems in relation to a known situation in the equilibrium mode, especially as concerns the CT, more specifically as concerns exchanges between the CT and the Algerian-Tunisian chotts.

Studying the 2000 piezometric map of the CT indicates that the main groundwater flow to the Algerian and Tunisian chotts and the Gulf of Sirte have been maintained. Nonetheless, these flows have been seriously affected by pumping at Djérid, Nefzaoua and the Oued Rhir Valley. Since excessive draw down in this area could cause flow reversal, comparisons should be made of piezometric levels calculated in 2000 and chott values. There is a **very clear evolution between 1950 and 2000** in Tunisia, where the watertable was clearly artesian in 1950 and now, in all of the **Nefzaoua** and the Djerid region, as a result of **overall draw down** of about **25 m**, piezometric levels are barely in equilibrium with the level of Chott Djerid. In the future, this situation will get worse unless the abstraction rate is reduced. In Algeria, the situation is even more alarming at **Chott Merouane** where the **piezometric level of the CT** is already below the **level of the chott**, and is being "**drawn on**".

Fig. 13 - Calibration of a historical series of piezometric levels in transitional mode



28 – The following observations can be made from an **assessment of the NWSAS in 2000**:

- **system recharge** (including waters from the COD by deep percolation) amounted to 30.m^3/s, which represents **43% of the total abstractions per borehole** (**70. m^3/s**);
- **contributions from the reserves** ("water from draw down") amount to a total of **46. m^3/s** and represent **66%** of withdrawals from the wells;
- from the above and from a study of the evolution of draw down as a function of time, we can predict that draw down will continue to progress, even if pumping were to be maintained at its present level. Such progression, in time and space, remains to be calculated and is to be the **objective of "predictive simulation zero"**;
- a comparison of 1950 and 2000 figures indicate a **drop of close to 52% in flows at the Tunisian outlet;**
- note should also be taken of the **strong drop in outflow from the CT** to the chotts and the sebkhas: **2.2 m^3/s in 2000 against 8.8 m^3/s in 1950**! This evolution was predictable because of the declared abstractions and observed drawdowns but, were it to continue, would be the prelude to **serious**, perhaps even **irreversible upheavals** in the chotts region.

III – IMPLEMENTATION OF PREDICTIVE SIMULATIONS

A -Definition and implementation of exploratory simulations

29 – The first step is to define a certain number of exploratory simulations designed to evaluate the NWSAS capacity, from the hydraulic angle, to achieve the objectives the three countries set for water resource development. This entails:

- providing details on each of the scenarios or development plans selected (additional abstraction showing spatial scatter and time schedule), with reference to 2000. Each scenario or plan is to be simulated.
- defining the results expected from the simulations;
- defining conditions for computing simulations, i.e. initial state, horizon being predicted, temporal variation in flow, conditions at contours.

30 – The aim of the exploratory simulation is to investigate the system, i.e. how far can it be used in developing resources at this stage? Since there are many uncertainties concerning hydro geological, economic and social parameters that could create unreal data for working hypotheses and results, the calculation period should be:

- sufficiently long so that the impulses whose effects are to be measured have reached their maximum and appear as far as possible out in space;
- not too long so as not to exceed the limit of significance of the tool considering the sources of uncertainty listed above and the length of the history used in calibrating the model.

A simulation period of fifty years seems reasonable. ***The exploratory simulations are conducted over a period of fifty years. The initial reference state is the state of the system in 2000, as reconstructed by the model.***

31 – So that the full reactions and capacities of the aquifer system can be explored, bearing "sustainability" in mind, the simulation assumes constant flow throughout the computed period of time. This flow rate represents the maximum flow envisioned by the plan or the scenario under consideration. Each of the simulated scenarios will include the following results:

- map of draw down 2000-2050;
- contours of draw down (2000 to 2050);
- main elements of the 2050 assessment, especially concerning the calculated flow rate for the three main outlets, *viz.* Ain Tawargha, Foggaras, the Tunisian outlet (*Exutoire Tunisien*);
- evaluation of the impact (in terms of additional draw down) on each of the neighbouring countries;
- depth maps of piezometric level in 2050, in relation to ground level;
- depth maps of piezometric level under the surface of the Algerian-Tunisia chotts, that can be translated into "risk" (of potential Stalinization).

32 – In the reference scenario the present state, i.e. **Zero Simulation** remains unchanged. This scenario is needed to find out whether the scenarios should be compared to each other and to assess, with full knowledge of the facts, the effects of various scenarios on the envisioned development. The purpose is to **maintain the level of abstractions recorded in 2000 constant** and to calculate the corresponding evolution of the system for the next 50 years.

33 – Two scenarios were designed for Algeria:

- **a "High Hypothesis"** with additional abstraction of **101 m^3/s**, which would increase abstractions in Algeria from **42 m^3/s in 2000 to 143 m^3/s** in 2030;
- **a "Low Hypothesis"** with additional abstraction of **62 m^3/s**, which would increase abstractions from **42 to 104 m^3/s**.

In Tunisia, the scenario being considered provides for savings through more efficient irrigation, which would, gradually offset the additional demand for water for new irrigated lands. This is very close to the "no change" scenario.

In Libya, exploratory simulations concern two programmes:

- the Ghadames-Derj pumping field, which is part of the last phase of the GMRP, and where an additional flow of **90. Mm^3/an** is to be exploited;
- the Djebel Hassaounah well field in the Cambro-Ordovician watertable, which is shown through a layer of cells at an imposed level that can vary in time.

Recapitulation of Exploratory Simulations

SCENARIO	Forages CI m3/s	Forages CT m3/s	Total Forages SASS m3/s
Simulation Zero :			
Algérie [1]	**21.2**	**20.9**	**42.1**
Libye [2]	**3.4**	**7.4**	**10.8**
Tunisie [3] *Grès Sup inclus dans CI*	**2.7**	**14.5**	**17.2**
TOTAL SIM-ZERO	**27.3**	**42.8**	**70.1**
Débits_ADDITIONNELS :			
Algérie_Hyp_faible [4]	36.4	26.1	62.5
Algérie_Hyp_FORTE [5]	59.6	41.8	101.4
Libye_Ghadamès field [6]	2.9	0.0	2.9
Libye_Jbel Hassaouna	0.0	0.0	0.0
TOTAUX DEBITS SIMULES :			
TOTAL Hypothèse faible = [1]+[2]+[3]+[4]	63.7	68.9	**132.6**
TOTAL Hypothèse FORTE =[1]+[2]+[3]+[5]	86.9	84.6	**171.5**
TOTAL Ghadames field_Libye = [1]+[2]+[3]+[6]	30.2	42.8	**72.9**

34 – In the **Continental Intercalary**, if present abstraction rates are continued, there will be serious **drawdowns** (over **40 m** in the central region on the El Oued – Hassi Messaoud axis) throughout the Lower Sahara-Algeria by **2050**. Draw down elsewhere in Algeria will remain slight.

- In Tunisia, draw down is above **20 m** everywhere. It exceeds **40 m** in the Ksar Ghilan area and is close to **25 m** around Chott Fedjej.
- In Libya, draw down is around **25 m** near the main exploitation areas: Bani Walid, Wadi Zamzam, Wadi Ninah, Sufajin. Elsewhere, calculated draw down is about **10m** throughout the Hamada El Hamra.

Depths of **piezometric levels** show that the limits to the artesianism calculated for 2050 are not far from current levels. Loss of artesianism is limited to the El Borma and Ghadames areas.

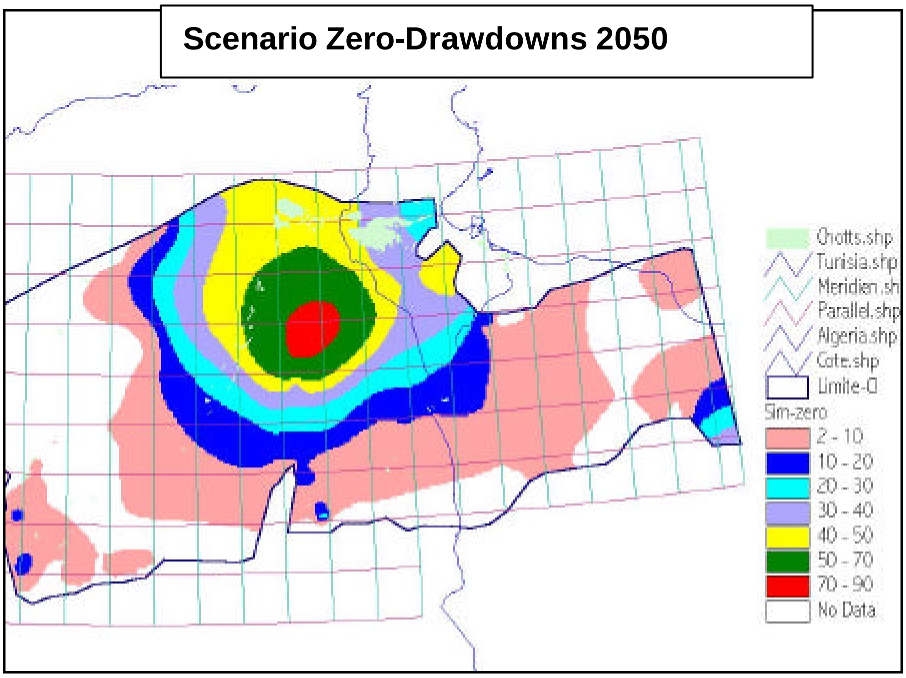
35 – At the **Complex Terminal**, Scenario Zero means:

- in Algeria, draw down would exceed **30 m** throughout the Oued Rhir Valley north of Toggourt and reach **60 m** north of the chotts.
- In Tunisia, draw down would be between **20 and 30 m** throughout the Djerid and Nefzaoua areas.
- In Libya, maximum draw down, i.e. approx. **60 m,** would be found in the south-east near the Soknah, Hammam and Ferjan groupings.

Further, the map of piezometric levels and the map of the depth of these levels in relation to the ground clearly indicate ***total elimination of artesianism through the region of the Tunisian-Tunisian chotts.*** We even see that the Merouane and Melrhir chotts are completely "suspended" over the piezometric surface of the CT. The same applies in the

Djerid and the Nefzaoua regions, with all the attendant risks of chott waters “recharging” the CT watertable because of this unusual, seemingly unprecedented situation in the region.

As concerns the risk of salt contamination, even without additional abstractions, these areas are already serious exposed. *Continuing the present pace of abstraction could potentially be very dangerous*. In Libya, artesianism has decreased, in particular along the coast, which is the area most seriously exposed to the risk of reverse flows.



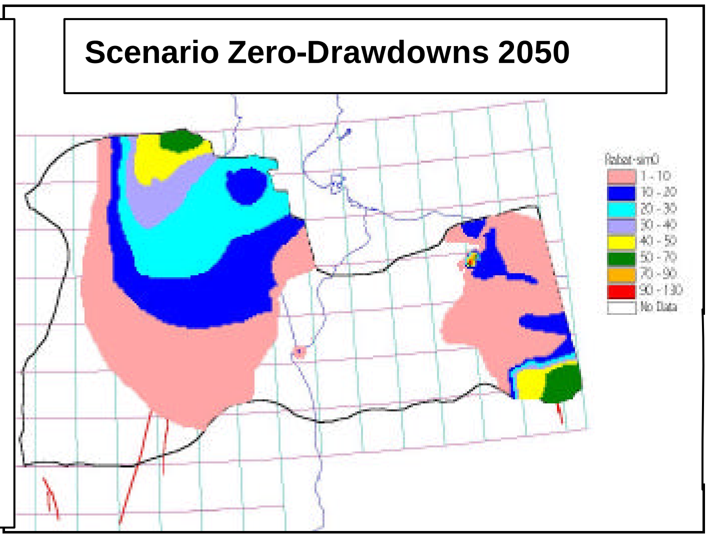


Fig 14 : Drawdowns on CI and CT for Scenario Zero

36 – The **High Hypothesis** affects the CI through **draw down of 300-400 m** at Ghardaia, Oued Rhir, El Oued, and Ouargla. Artesianism in the Lower Sahara-Algeria would totally disappear: throughout the Oued Rhir Valley, pumping depth would be between **100 and 300 m**. Libya would hardly be affected by this scenario, but Tunisia would be, with

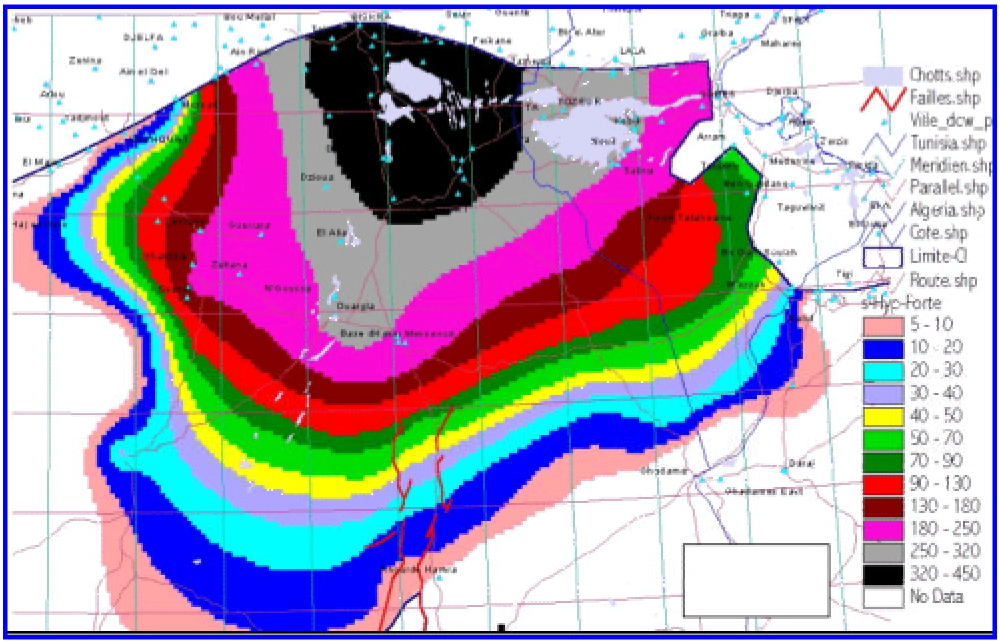
- **draw down of 200-300 m** in the main well fields;
- disappearance of artesianism;
- total elimination of the *Exutoire Tunisien*.

For the Complex Terminal, major additional draw down in the Oued Rhir, Souf, and Ouargla. In Libya, this scenario would have no effect. But in Tunisia, the impact would be considerable:

- additional draw down of about **50 m** at Djerid and **30 m** in the Nefzaoua region;
- the chotts Djerid and Rharsa), because of their position, could recharge the CT. Average differences in level are around 50 m. This difference in level is the main risk indicator. The difference is much greater in Algeria (over **100 m** under the Melrhir and Merouane chotts, **200 m** at Mghaier and Djamaâ).

37 – Draw down affecting the CI in the Low Hypothesis is also very significant, i.e. **250 m** at El Oued-Biskra. **Artesianism has disappeared** from all of the Lower Sahara, and the pumping depth is **100 m.** In Tunisia, **artesianism** has totally **disappeared** and the ***Exutoire Tunisien*** **has dried up**. At the **CT**, drawdowns are very high. This applies to Algeria and Tunisia. The chotts may even, potentially, recharge the CT.

Fig. 14 - CI High hypothesis: net draw down 2050



38 – Drawdowns induced by the Ghadames wellfield on the CT are negligible. As for the CI, drawdowns are around **100 m** in the field. With distance, the figure gradually goes down and at a radius of 200-300 km, no longer exists. All of the far southern part of Tunisia is affected. And in the Debdeb region of Algeria, induced draw down is about **60 m**. Furthermore, the effects of the Djebel Hassaouna field on the CI is limited to the Hamada El Hamra basin and do not reach the Algerian or Tunisian borders. In Libya, the calculated drawdowns form a ring around the well field, with the maximum draw down being 50 m in the south.

Scenario Ghadames field-net drawdown 2050

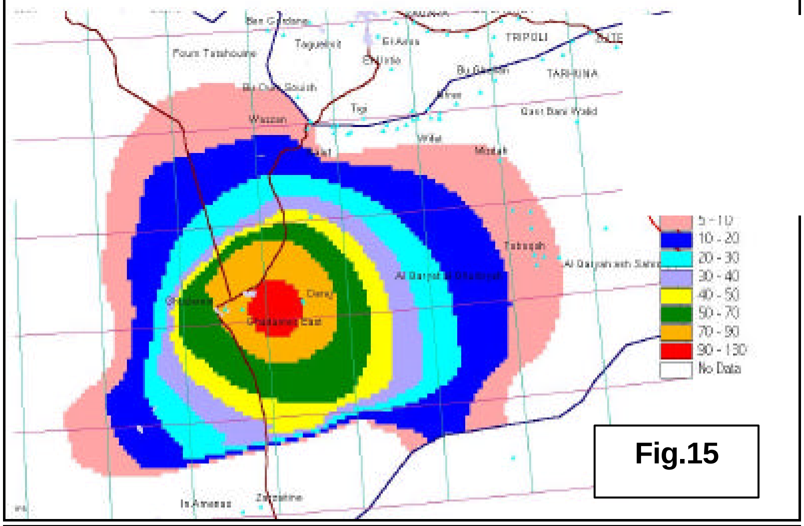


Fig.15

B - Miniaturisation of the model to investigate the reservoir

39 – The exploratory simulations showed that a certain number of harmful consequences and risks are connected to the very efforts to develop the water resources. Increased exploitation of the CI and CT water systems will require considerable risk minimisation and management. Risks include:

- elimination of artesianism,
- excessive pumping depths,
- drying up of the Tunisian outlet,
- drying up of the foggaras,
- excessive interference of draw down from one country to the next,
- potential recharging through the chotts.

Furthermore, results from the "high hypothesis" and the "low hypothesis" have shown the limits to the "pure simulation" approach in defining a development strategy for NWSAS. They show that both of these hypotheses, which at first seemed to provide a setting for decision-makers and possible solutions, would have devastating consequences for the future of NWSAS. Hence it was decided that **another way must be found to define acceptable solutions, using a miniature model.**

40 – The principle of the "**micro-model**" is the following. In **cell i,** an abstraction amounting to a flow unit is applied and maintained constant throughout the simulation. Draw down is calculated for each cell in the model; this calculation can be repeated for all the cells with the result being an **influence matrix** at $\mathbf{n^2}$, **n** being the total number of cells in the model.

In other words, with $\mathbf{a_{ij}(t)}$ as the draw down induced in **j,** at time **t,** [t = 50years] by the unit level of abstraction in **i**, draw down induced in **j** by undetermined pumping, $\mathbf{Q_i}$**,** carried out in **i** is equal to: $\mathbf{r_{ij}(t)=a_{ij}(t)Q_i}$

So it is enough to know the **aij** coefficient in order to determine the draw down corresponding to undetermined pumping within the aquifer system. Defining each aij function requires simulation on a model for a 50 year period; this requires a considerable number of manipulations.

Since all the cells in the model (tens of thousands) are not slated to become pumped cells, calculations will be limited to cells that some day are to be used in pumping sites, or to observe the effects of pumping.

Hence we can produce matrices of influence coefficients that can be readily seen and manipulated, and whose reactions can be measured on a spreadsheet on the screen of a micro-computer.

41 – Considering the results of the exploratory simulations, we adopted the principle that we should **leave aside research on development scenarios** that did not seem to have any direct relation with the properties of the aquifer and were founded exclusively on predicted water demand. We decided, on the contrary, to build up "**hydrology-based**" scenarios, considering the NWSAS production capacities, working in sites that were as close as possible to locations where present or future demand could be expected to be strong, without however ignoring favourable areas that might be far from sites with potential demand but might be well suited for water exportation.

The first step in this process was to make an inventory of all the potential pumping sites. This inventory was made country by country.

42 – There are **89** potential pumping **sites** throughout the NWSAS of which **55** are in the **CI** and **34** are in the **CT.** A "unit" simulation is being made for each of these sites on the digital model. This involves calculating the draw down function or the influence function in each of the control wells over a period of 50 years, starting in the beginning of 2001. For each of the two water systems, the size of the matrix of influence coefficients has become too big. This especially applies to the CI, where the size is 55x55, which is too big to display on a single screen window.

Fig. 16 – The NWSAS discharge-draw down converter

	Ouled-djellal	El-oued	Djemaa	M'ghaier	Taleb-el-larbi	Sebseb	Guerrara	Zelfana	El-alia	N'goussa	Ouargla	H-Mess-nord	Deb-deb	C-F	Bhaier	Sabria	El-gounna	Ghoumrassen	Bordj-Bourguiba	Bir-zar	Tiaret	Borj-el-khadra	Hazoua	Deguache-hamma	PIK	Nalut	Sinawan	Ghadames	Rabattemnt-Total	Hauteur pompage	Etat	Contr-Rabt
POMPAGES	0.0	0.0	0.0	0.0	0.0	5.0	0.0	2.0	1.0	0.5	0.5	0.5	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0	0.0	0.0	0.0	0.0	0.0	3.0	17.0			
Ouled-djellal	0	0	0	0	0	14	0	10	10	4	3	3	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	46	-42	Artésien	
Tolga	0	0	0	0	0	13	0	10	10	4	3	3	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	45	-108	Artésien	
El-oued	0	0	0	0	0	10	0	8	10	4	3	4	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	43	-83	Artésien	
Ben-guecha	0	0	0	0	0	9	0	7	8	3	2	3	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	36	-130	Artésien	
Djemaa	0	0	0	0	0	14	0	10	12	5	4	4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	51	-163	Artésien	<=10
M'ghaier	0	0	0	0	0	13	0	10	11	4	3	4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	47	-197	Artésien	<=13
Taleb-el-larbi	0	0	0	0	0	8	0	6	8	3	2	3	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	34	-92	Artésien	
Douar-el-maa	0	0	0	0	0	8	0	6	8	3	2	3	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	34	-95	Artésien	
Sebseb	0	0	0	0	0	45	0	16	4	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	71	147	0	
Guerrara	0	0	0	0	0	30	0	23	10	4	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	74	98	0	
Zelfana	0	0	0	0	0	41	0	21	8	4	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	80	0	
El-alia	0	0	0	0	0	21	0	16	18	9	6	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	78	-26	Artésien	
N'goussa	0	0	0	0	0	21	0	15	17	12	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	90	-25	Artésien	
Ouargla	0	0	0	0	0	22	0	15	13	12	11	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	85	-21	Artésien	
H-Mess-nord	0	0	0	0	0	17	0	12	13	12	12	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	86	4	0	
Deb-deb	0	0	0	0	0	0	0	0	0	0	0	0	45	0	0	0	0	0	0	2	15	23	0	0	0	0	0	66	151	141	0	
C-F	0	0	0	0	0	4	0	3	4	1	1	1	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	1	19	-62	Artésien	
Bhaier	0	0	0	0	0	4	0	3	4	2	1	2	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0	1	21	-68	Artésien	
Sabria	0	0	0	0	0	5	0	4	5	2	1	2	1	0	0	0	0	0	0	2	1	1	0	0	0	0	0	1	24	-76	Artésien	
El-gounna	0	0	0	0	0	5	0	4	5	2	2	2	1	0	0	0	0	0	0	3	2	1	0	0	0	0	0	2	27	-49	Artésien	
Ghoumrassen	0	0	0	0	0	2	0	1	2	1	1	1	1	0	0	0	0	0	0	6	4	2	0	0	0	0	0	3	24	69	0	
Bordj-Bourguiba	0	0	0	0	0	1	0	1	2	1	0	1	3	0	0	0	0	0	0	11	7	3	0	0	0	0	0	7	37	88	0	
Bir-Zar	0	0	0	0	0	0	0	0	1	0	0	0	10	0	0	0	0	0	0	26	22	9	0	0	0	0	0	22	92	154	0	
iaret	0	0	0	0	0	0	0	0	0	0	0	0	29	0	0	0	0	0	0	11	101	27	0	0	0	0	0	66	235	291	0	
orj-el-khadra	0	0	0	0	0	0	0	0	0	0	0	0	46	0	0	0	0	0	0	5	27	25	0	0	0	0	0	85	190	174	0	
Hazoua	0	0	0	0	0	8	0	6	8	3	2	3	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0	1	37	-57	Artésien	< 50
Deguache	0	0	0	0	0	4	0	3	5	2	1	2	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	20	31	0	< 50
PIK	0	0	0	0	0	3	0	2	3	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	13	-89	Artésien	< 50
Nalut	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	3	281	0	
Sinawan	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	13	30	15	0	0	0	0	0	41	117	237	0	
Ghadames	0	0	0	0	0	0	0	0	0	0	0	0	44		0	0	0	0	0	4	22	28	0	0	0	0	0	65	163	154	0	

Total Algerie 11.5 | Total Tunisie 2.5 | Total Libye 3.0 | Débit exutoire tunisien (m3/s) 0.50

43 - The aim of model miniaturisation is to construct a ***discharge-draw down converter*** on a spreadsheet which has the same format as the matrix of the problem's influence coefficients, and is connected to the coefficients of the matrix. Applying the principle of superimposition of outflows, these coefficients are used to calculate the draw down that corresponds to the pumping discharge rates shown on the converter. The operator can change discharge rates at will and the machine immediately calculates the new corresponding draw down.

One of the main advantages of the converter is its ***interactivity***. But the operator must have the ***data and the results of the problem on the screen at the same time***. Since a table that has more than 25 columns is hard to manipulate on an ordinary screen we have divided the problem into parts. First we will use a ***micro-model* for each country and for each watertable**. It will include the control wells in the border areas so that transborder interference can be assessed. This will make it possible, in the first phase, to seek "acceptable" configurations. We will then compare them using a converter that groups all the NWSAS "interference" fields, i.e. on the one hand, the well fields of the Algerian Sahara,

Tunisia and the Ghadames basin for the CI watertable and, on the other, all the chott basins for the CT.

44 – During the last twenty years, **water abstraction has risen extremely fast**. If this trend, shared by the three countries, were to continue there would undoubtedly be serious reason to worry about the future of the Saharan regions where **early signs of resource degradation are already appearing**. Major draw down may, in the near future, cause **irreversible** salinisation of the CT watertable, which is in equilibrium with the watertables of the Tunisian-Tunisian chotts.

This trend has been strongly confirmed by the results of the first exploratory simulations made on the NWSAS digital model, in particular in the '**high hypothesis**" and the '**low hypothesis**" scenarios.

In the near future, thus, the three countries that are concerned by the future of the system will have to develop a certain type of joint basin management.

What can be done to ensure maximum water abstraction, for optimal regional development without risking resource degradation?

And how can the "best" water utilisation plan be developed?

It was with this in mind that the **NWSAS micro-model** was designed. But first of all, an inventory will have to be made of the risks, and of what constraints must be respected in order to minimise these risks. **This will require risk quantification, which means being able to put risks into a model, which is exactly the function assigned to the NWSAS Digital Model.**

C – Implementation of predictive simulations

45 – The work done on the micro-model during the Tunis workshop (1 and 2 April 2002) led to certain scenarios that meet development goals and, at the same time, by respecting imposed constraints, minimise risks of degradation. These scenarios are presented in detail.

After being identified on the micro-model, they are simulated on the digital model which gives fuller results and, further, makes it possible to measure the extent to which the constraints have been respected.

The results of the predictive simulations are evaluated in the light of the following indicators:

- *net draw down* (draw down minus draw down on Scenario Zero calculated at the same period);
- *interference in drawdowns;*
- *discharge at the outlets;*
- *artesianism for the CI and position of levels in relations to the chotts for the CT;*
- *water balance in 2050.*

Additional abstractions in the Continental Intercalary (m^3/s)								
Scenario	**CI-1**	**CI-2**	**CI-3**	**CI-4**	**CI-5**	**CI-6**	**CI-7**	**CI-8**
Algeria	8.5		2	8.5	38.5	80		118.50
Tunisia		2.2	1.4	2.2				2.20
Libya			2.9	3.6			5.2	8.35
Total	**8.5**	**2.2**	**6.3**	**14.3**	**38.5**	**80**	**5.2**	**129.00**

Additional abstractions in the Complex Terminal (m^3/s)					
Scenario	**CI-1**	**CI-2**	**CI-3**	**CI-4**	**CI-5**
Algeria	14.7				14.7
Tunisia		3.3			3.3
Libya			11		11.0
Algeria-Oued Mya				18.0	18.0
Total	**14.7**	**3.3**	**11**	**18.0**	**47.0**

46 – ***Simulation CI-1; Lower Sahara-Algeria*** [**additional 8.5 m^3/s**]. Drawdowns are concentrated around the Zelfana-Ouargla sections and the Debdeb field. In Tunisia, induced draw down is **25 m** at Tozeur-Nefta, and **12 m** at Fejej chott. In Libya, the effects of pumping at Debdeb led to net draw down of about **40-50 m** in the field as well as in the far southerly part of Tunisia (**50 m** at Bj. el Khadhra and **30 m** at Tiaret). In this simulation, there is no impact on the foggaras

As for the Tunisian outlet, the flow would be **0.6m^3/s** by 2050, while it would be **0.94m^3/s** in the event of Scenario Zero. In Algeria, artesianism at Hassi Messaoud disappears. For the rest, active artesianism is found nearly everywhere: **80 m** at Ouargla, **50 m** at Toggourt and El Oued, **180 m** at Mghaier. In Tunisia, we still have **80 m** at Tozeur and Sabria. The water budget indicates that discharge for additional abstractions comes from:

- 93% from the reserves;
- 4% recovery from the Tunisian outlet;
- 2.5% from leakage.

CI-Simulation n°1- Net drawdowns 2050

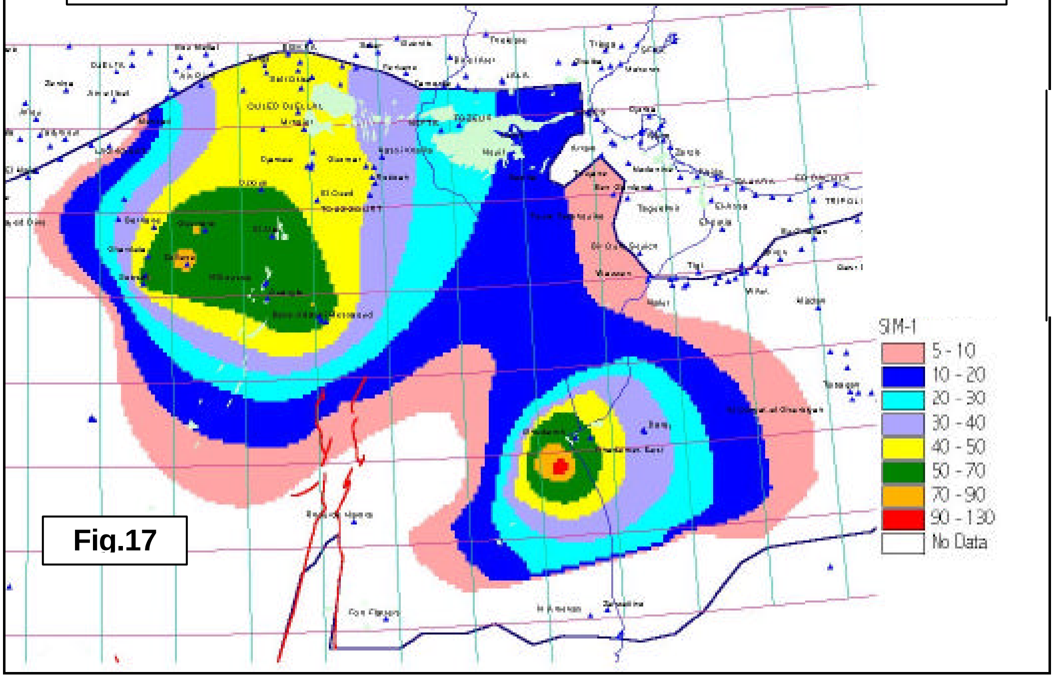


Fig.17

47 – S*imulation CI-2; the CI in Tunisia* [**additional 2.2 m^3/s**].The greatest draw down (approx. **130 m**) occurs in the far southerly area, especially in the Tiaret field. Elsewhere net draw down is relatively slight: **20 m** in the Nefzaoua region and **15** m in Chott Fedjej. In the northern part, the effects on Algeria are slight: **10 m** at Biskra and Mghaier, **8 m** at Toggourt, **13 m** at El Oued, **22 m** at Taleb El Arbi. In the southern part, net draw down is **25 m** at Debdeb in Algeria, and **30 m** in the Ghadames field in Libya. Discharge at the Tunisian outlet is reduced to 0.5 m^3/s. The effects on artesianism are minimal. In comparison with Scenario Zero, we can assume that simulated additional withdrawals (2.2 m^3/s) will come from:

- reserves from the CI watertable **(73%)**;
- the Tunisian outlet **(20%)**;
- leakage **(5%)**.

CI Simulation no. 2 – net drawdowns 2050

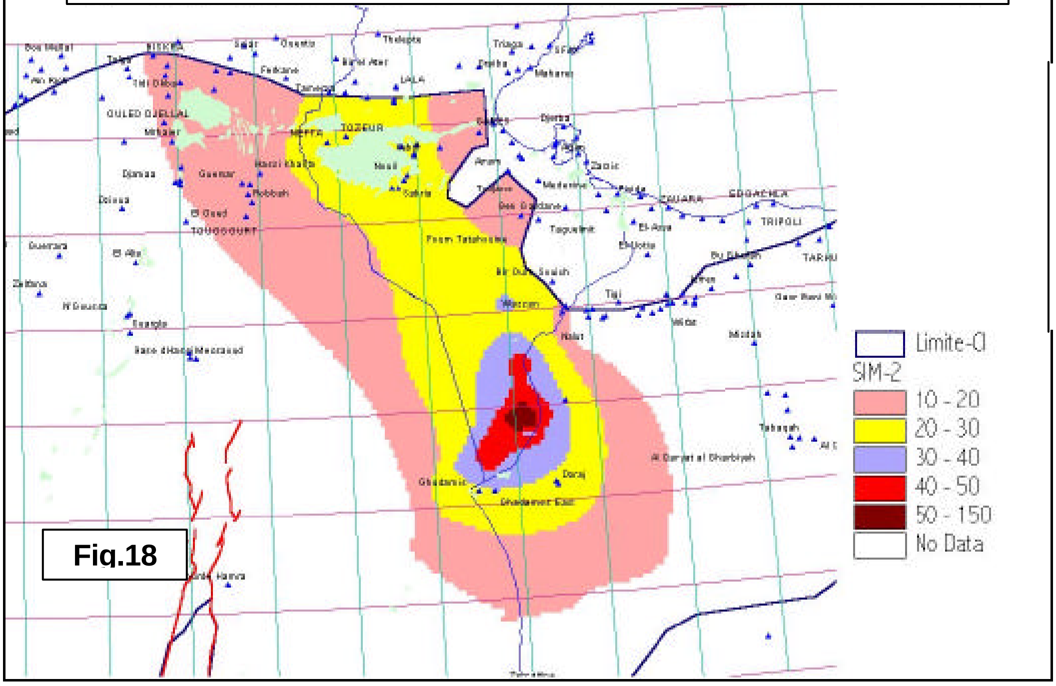


Fig.18

48 – *Simulation CI3; the Ghadames Basin* [**additional 6.3m^3/s**]. In the simulated wellfield areas, the expected drawdowns are very high, i.e. approx. **180-200 m** at Ghadames, Debdeb, Tiaret; and the ring formed at **100 m** draw down has a radius of 100 km. This simulation cannot be used to measure reciprocal influences since the abstractions are made concurrently in all three countries. The Tunisian outlet goes to **0.84m^3/s**. The additional discharge comes from:

- reserves **(86%);**
- leakage from the Turonian aquifer **(8%)**;
- the Cambro-Ordovician **(3%)**;
- the Tunisian outlet (**1.5%)**.

49 – *Simulation CI-4; the CI throughout the Central Basin* [**additional 14.3m^3/s**].

This simulation essentially reflects the accumulation of the discharge shown in the preceding three simulations. Hence, it is normal that the drawdowns represent the sum of the drawdowns in simulations 1, 2 and 3. This simulation cannot be used to measure reciprocal influences since abstractions are made in all three countries. The Tunisian outlet drops to **0.13 m^3/s** under the combined effect of abstractions in Tunisia and Algeria. As concerns artesianism, there is little difference with Simulation I. Total discharge from simulated pumping comes from:

- CI reserves **(87%**),
- the Tunisian outlet **(5.5%**,
- leakage from the Turonian aquifer **(4%)**.

CI Simulation no. 3 – net drawdowns 2050

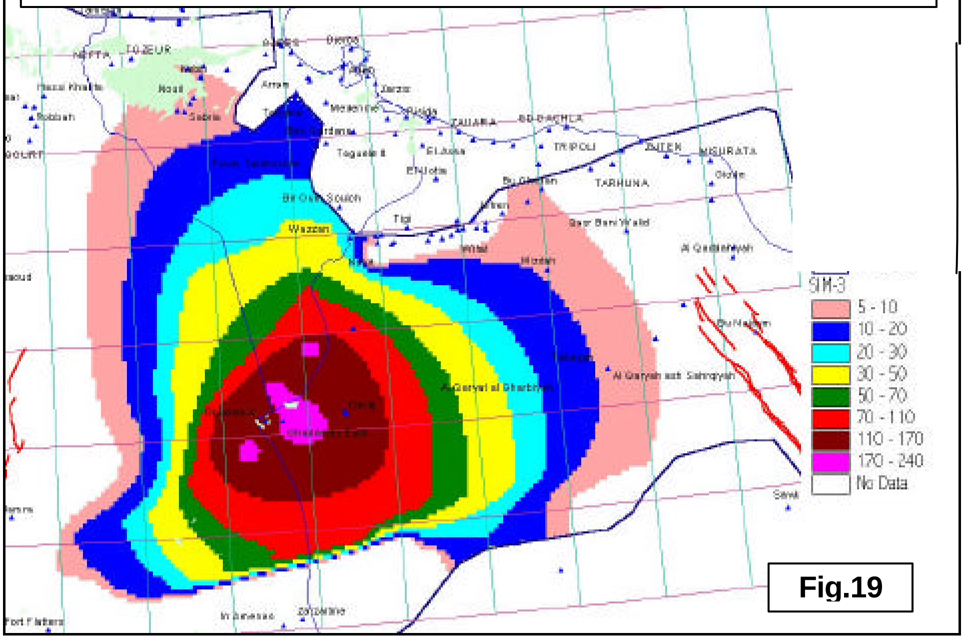


Fig.19

50 – ***Simulation CI-5; Lower Sahara-Algeria, and Adrar*** [**additional 38.5 m^3/s**]. This is like Simulation no. I, plus major abstractions from the Western Basin, in particular Adrar, In Salah and El Goléa. All these new abstractions come from the unconfined aquifers of the CI. The drawdowns are concentrated in cones with very deep centres and very little spread. The effects on Tunisia and Libya and the discharge at the Tunisian outlet are exactly the same as in Simulation no. 1. The discharge in the foggaras drops from **1.95m^3/s** in the simulation of Scenario Zero to **1.32 m^3/s**. Simulated additional discharge comes from: a) CI reserves (**97%**), b) the foggaras (**1.5%**),

51 – ***Simulation CI-6; Exploitation of CI reserves in the Grand Erg Occidental*** [**additional 80. m^3/s**]. This simulation confirms and consolidates the results of the preceding simulation on draw down of the CI in the unconfined area which is concentrated in an area with very little lateral propagation: **1 m** at El Golea which is within a 100 km radius, and practically nothing in Hassi Messaoud and Ouargla after 50 years of pumping. Absolutely no effects on Tunisia and Libya in 2050. The discharge in the foggaras drops to **1.78 m^3/s**, which is 0.17 m^3/s below the reference, i.e. Scenario Zero. This simulation has no effect on artesianism. Additional abstractions come from:

- reserves **(99.75%)**,
- lower discharge rates in the foggaras **(0.22%)**.

52 – ***Simulation CI-7; Deficit resorption in 2030 in Libya*** [**additional 5.1m^3/s**].
Two sectors clearly stand out:

- Soknah-Hun to the south where the net draw down reaches 110 m;
- a 60 m channel stretching between Bani Walid and Bou Nujaymn.

Further, there are **20-25 m** drawdowns in the coastal area; drawdowns gradually decrease towards the west. The effects on Algeria and Tunisia are limited to the far southerly area of Tunisia and the Debdeb region. In the Gulf of Sirte, percolation ranges from **0.6 m^3/s** in Scenario Zero to **0.3 m^3/s**. At the same time, the discharge from the Ain Tawargha source drops from **1.3 m^3/s** (Scenario Zero) to **0.4 m^3/s.** A pocket of artesianism at 30 m still exists in the Graben, everywhere else it has disappeared. Yet all along the coast, the CI watertable is still very slightly artesian, and its PL is systematically well above sea level. Additional abstractions come essentially from:

- reserves **(29%)**;
- leakage from the Turonian aquifer **(41%)**;
- the Cambro-Ordovician **(24%)**.

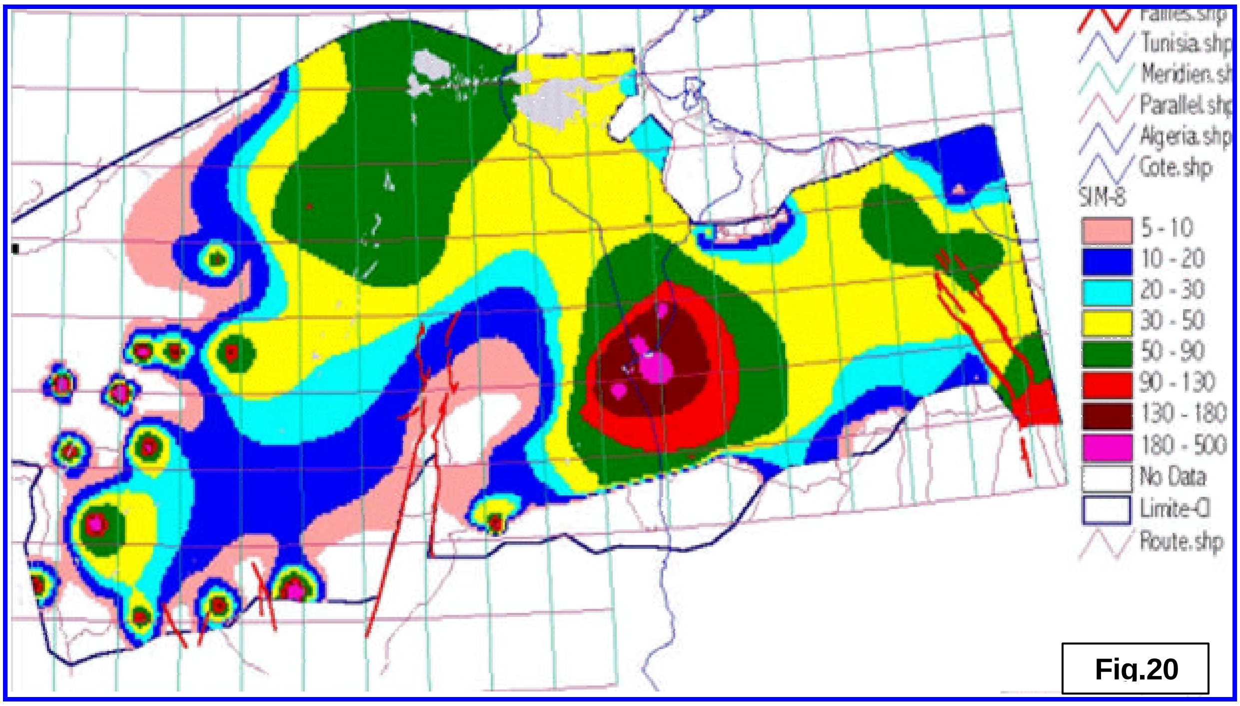


Fig.20

53 – ***Simulation CI-8; Exploitation throughout the CI*** [**additional 129. m^3/s**]. The combination of simulated drawdowns, discharges at the outlets, and artesianism make up the simulation found in C18, in other words, the C12, C15, C16 and C17.

With regard to the water balance for 2050, additional abstractions amount to **129 m^3/s**, of which **118.5** are in Algeria. These supplementary discharges must come from:

- CI reserves (**122.3 m^3/s**, i.e. close to 95%)
- leakage from the Turonian aquifer (**3.2 m^3/s**, i.e. 2%);
- the Cambro-Ordovician (**1.2 m^3/s** i.e. 1%);
- less discharge at the outlets (Ain Tawargha 0.4, Tunisian outlet 0.8, Gulf of Sirte 0.3, foggaras 0.75, which amounts to **2.25 m^3/s**, i.e. 1.5%).

54 – ***Simulation CT-1; Additional abstractions in Algeria*** [**additional 14.7m^3/s**]. The maximum drawdowns in this simulation were around 70-100 m. They came from the Gassi Touil field where most abstractions were made. In other places, draw down was generally low, especially at the level of the Merouane and Melrhir chotts, where they were 10 m. As concerns interference, the 5 m curve more or less follows the Tunisian border. Induced drawdowns are 7 m at Nefta, 5 m at Tozeur and 3 m at Kebili. This simulation has absolutely no effect on Libya. As concerns the position of the PL of the watertable in relation to the

chotts, the piezometric level of the CT is, on the whole, 10 m lower than in Simulation Zero for Melrhir and Merouane, and 5 m lower for Djerid; yet Scenario Zero has already been considered critical. Thus, Simulation CT 1, according the chotts criteria, will created an even more precarious situation. The CT reserves will provide 14.6 m^3/s (i.e. 99.3%) of the additional discharge.

55 – ***Simulation CT2; Additional abstractions in Tunisia*** [**additional 3.3m^3/s**]. North of Rharsa net draw down is 25 m, everywhere else under the Tunisian chotts it is **10 m**, and **5-10 m** in all of the Nefzaoua region. The Algerian border, on the whole, follows the **10 m** draw down curve. Effects of Tunisian abstractions amount to **3 m** at El Oued, and **1 m** at Mghaier. The PL of the watertable in relation to the chotts is 10 m lower than in Scenario Zero. As concerns the water balance in 2050, more than 99% of the additional underground discharge comes from the CT reserves.

Piezometric levels 2050 on the Gulf of Sirte – Sim 3 & Sim 5

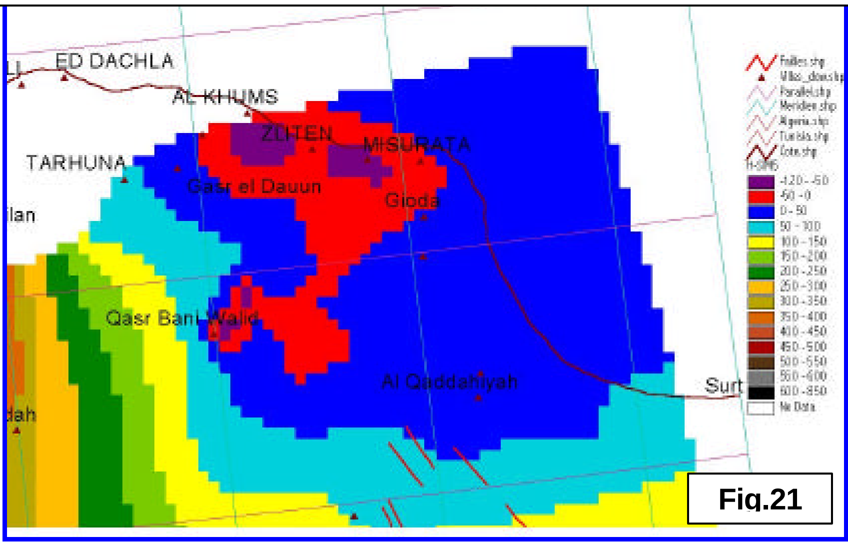


Fig.21

56 – ***Simulation CT3; Deficit resorption in Libya*** [**additional 11.6 m^3/s**]. Net drawdowns are about **100 m** at Soknah and Waddan, **10-20 m** all along the Graben, and **50 m** in the northerly fields close to the Al Khoms-Zliten coast. No interference in Tunisia and Algeria. The discharge at Ain Tawargha drops from **1.3 m** (Scenario Zero) to **0.4** m^3/s; the leakage in the Gulf of Sirte drops from **0.5 to 0.4 m^3/s**. The wellfields in the coastal zone [Al Khums, Zliten, Misurata] have especially low piezometric levels, even below –50 m on the coast !! Additional discharge comes essentially from:

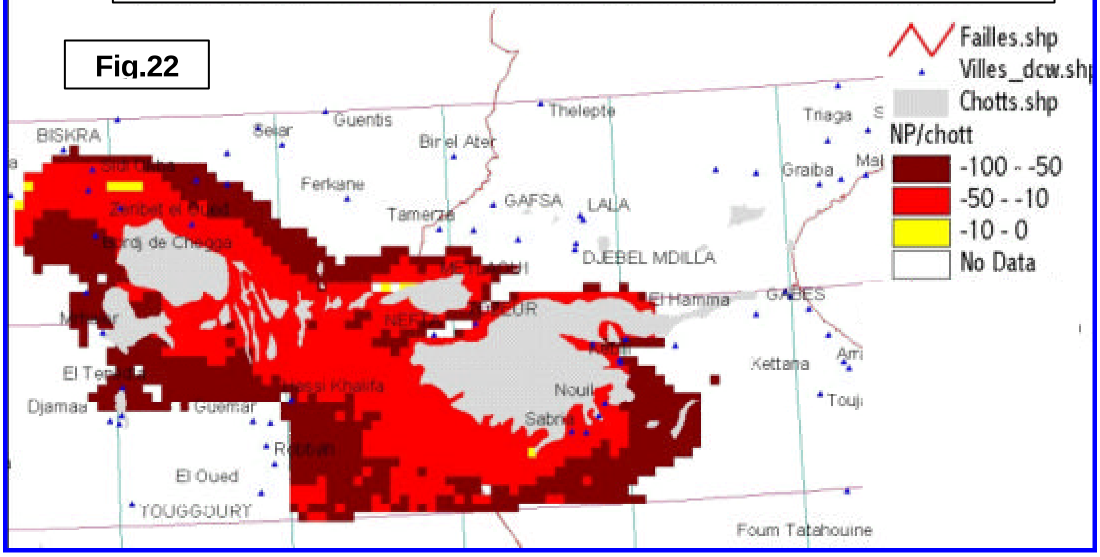
- CT reserves (**6.9 m^3/s**, i.e. 59%),
- leakage from the Turonian aquifer (**3.8 m^3/s** i.e. 32%).

The rest is recovered from discharge at the outlet.

57 – ***Simulation CT4; the wellfield of Oued Mya*** [**additional 18. m^3/s**].
Net draw down is circumscribed around the field with about 150 m in the centre of the field. No effects on Tunisia and Libya. There is practically no draw down(10-20 cm) induced by this simulation in the chotts region (**10-20 m**). In relation to the chotts, there is no difference between this scenario and Scenario Zero. The additional discharge comes from the CT reserves (**17.9 m^3/s**).

Simulation no. 5 – PL of CT in relations to chotts in 2050

Fig.22



58 – *Simulation CT5; Exploitation throughout the CT* [additional 47. m^3/s].

The simulated additional discharge is the sum of the discharges shown in the preceding four simulations. The effects, on the whole, are equivalent to the sum of the effects described previously. The most noteworthy are:

- **10-15 m** draw down under the chotts. This increases risks, although abstractions in the chotts region have almost been stabilised;
- piezometric levels of more than **50 m** below sea level along the Libyan coast, which is very critical;
- and, as concerns the water balance, most of the abstraction comes from the CT reserves.

CT Simulation no. 5 – net drawdowns 2050

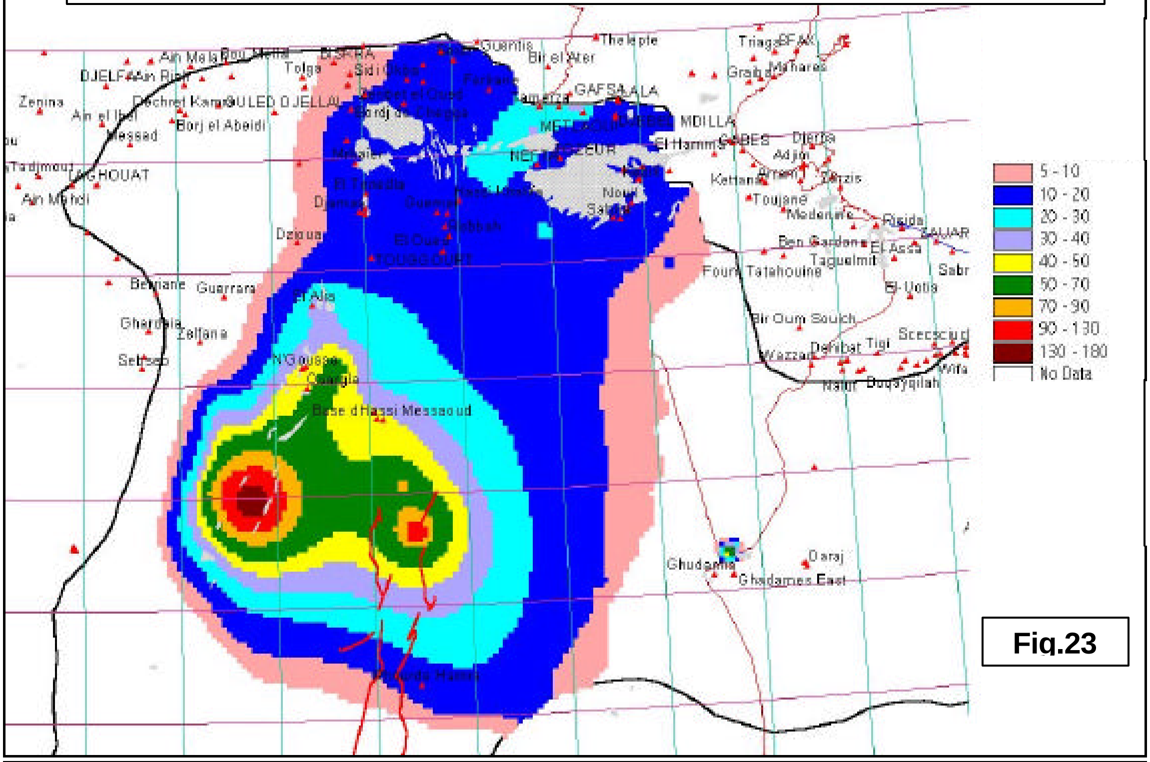


Fig.23

IV - CONCLUSIONS

The purpose of the Study of the North-Western Sahara Aquifer System was to:

- construct, for each of the two main watertables (the Complex Terminal and the Continental Intercalary), a digital simulation model, to "produce a coherent synthesis of data and knowledge acquired on these aquifers;
- make an assessment of water resources of north-western Sahara;
- determine the exploitable resources and work out management schemes for these resources on the basis of development scenarios".

The study was made from January 2000 to June 2002. How well have the objectives been fulfilled?

- **CI model vs. CT model**

At the beginning of the NWSAS project, there were two traditions, two visions, two parallel concepts of Saharan hydrogeology.

- on the Tunisian-Tunisian side, the depth of the semi-pervious inter-formation layers, and the very great difference in loads between the two main watertables supported a well-anchored tradition of treating the CI and the CT separately; models since "Géopétroleé in 1963 have been designed for independent mono-layers;
- on the Libyan side, the separating layers between aquiferous formations are not as deep; since the first regional model by Idrotecneco in 1981, a multi-layer structure has been used.

To ensure the harmonious combination of hydro geological outlooks in the three countries the CI vs. CT duality, adopted by ERESS in the overall design of the NWSAS model, had to be replaced by a **multi-layer representation.** The **"Conceptual Model"** has turned out to be the only one that can bring together Tunisian-Tunisian and Libyan hydro geological systems. The representation of the "Saharan Multi-layer" makes for the best long-term simulation conditions; it includes the Turonian and the Palaeozoic, and gives due attention to outflow from leakage between CI and CT.

- **Synthesis of acquired knowledge**

The first level of hydrodynamic modelling entails cartographic representation of outflow. No map of this sort was ever made for the whole NWSAS territory, although there were representations of parts of the territory, and each one contributed to the knowledge base.

As part of the project, it was necessary to construct a piezometric map in order to make a coherent representation of groundwater flow for the basin as a whole. This map defines groundwater flows in the "natural" state, i.e. little or not affected by pumping.

As concerns the general dynamics of the system, the most significant piezometric evolutions have been grouped per homogeneous, representative geographic sector:

- at the CI: Tamerna for the artesian basin with strong pressure at ground level, Kef No.27 for the areas near the unconfined aquifers, chott Fedjej for the area near the Tunisian outlet, Djerid for the very strong drawdowns, the Ghadames Basin and the Graben;
- at the CT: in Tunisia, a standard-type or "summary contour" had to be established by aggregating measurements that were available for each geographic group.

It was difficult to reconstitute the history of abstractions because of the number of "**active**" water points, the length of the histories and the diversity of counting methods, which changed according to country and successive teams.

- **Exploitable water budget and resources in north-western Sahara (ERESS)**

The ERESS (*Eau et Ressources Exploitables du Sahara Septentrional*) project defined the water resources for the major watertables in the Sahara as follows: "considering the current and future geographical distribution of abstraction points, the water resources of a watertable shall be the discharge that corresponds to a value and to an acceptable increase in investments and operating costs in a given period of time". This "**depletive**" approach to watertables, known to be "**fossil**", has been revised. Exploratory simulations on the NWSAS model have shown that a certain number of harmful consequences and "**risks**" are connected to the very efforts to develop the water resource.

Increased exploitation of the CI and CT water systems will require considerable risk minimisation and management. Risks include:

- elimination of artesianism,
- excessive pumping depths,
- drying up of the Tunisian outlet,
- drying up of the foggaras,
- excessive interference of draw down from one country to the next,
- potential recharging through the chotts.

Furthermore, results from the "high hypothesis" and the "low hypothesis" have shown the limits to the "pure simulation" approach in defining a development strategy for NWSAS. They show that both of these hypotheses, which at first seemed to provide a setting for decision-makers and possible solutions, would have devastating consequences for the future of NWSAS. Hence it was decided that another way must be found to work together on devising acceptable solutions, using a miniature model.

Considering the results of the exploratory simulations, we adopted the principle to **leave aside research on development scenarios** that did not seem to have any direct relation with the properties of the aquifer and were **founded exclusively on predicted water demand**. We decided, on the contrary, to ***build up hydrology-based scenarios founded on the NWSAS production capacities that minimise risks of identified harmful consequences***, working in sites that were as close as possible to locations where present or future demand could be expected to be strong, without, however, ignoring favourable areas that might be far from sites with potential demand but might be well suited for water exportation. The first step in this process, obviously, was to make a country by country inventory of all the potential pumping sites.

What can be done to ensure maximum water abstraction, for optimal regional development without risking resource degradation?

And how can the "best" water utilisation plan be developed?

It was with this in mind that the **NWSAS micro-model** was designed. But first of all, an inventory had to be made of the risks, and of what constraints must be respected in order to minimise these risks. This required risk quantification, which meant being able to model the risks. The NWSAS digital model has been invested with just such a function.

The results of an investigation carried out using this model made it possible to check that NWSAS well exploitation, estimated at **2.2 billion m^3** in 2000 [1.33 in Algeria, 0.55 in Tunisia, 0.34 in Libya], could be raised to **7.8 billion m^3/yr.** by 2030 while giving due consideration to instructions on coping with the risk of resource degradation. Exploitation, per country, would be as follows: **6.1 billion m^3/an in Algeria, 0.72 billion m^3/yr. in Tunisia, 0.95 billion m^3/yr. in Libya**. The possibility (actually it is a hypothesis) of tripling the present abstractions would mean that the NWSAS exploitation regime would move to a level of **eight times** the renewable resource. Such an operation, of course, would require drawing on the system's reserves.