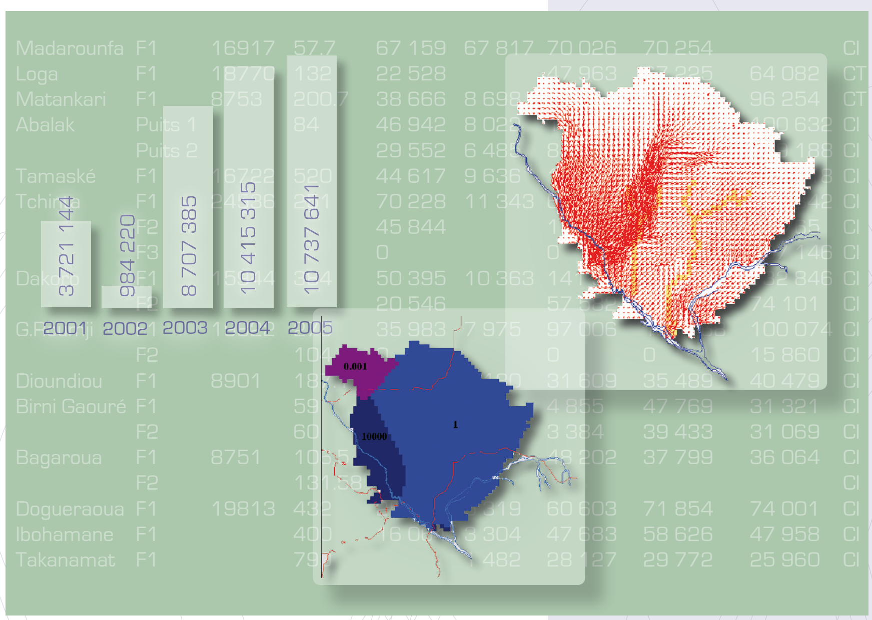
Iullemeden Aquifer System

Mali - Niger - Nigeria

Volume III

HYDROGEOLOGICAL MODEL



III

SAHARA AND SAHEL OBSERVATORY

Iullemeden Aquifer System

Mali - Niger - Nigeria

Volume III

HYDROGEOLOGICAL MODEL

Tunis, 2011

Other documents (IAS)

Volume I : Transboundary diagnostic analysis

Volume II : Common Database

Volume IV : Participatory management transboundary risks

Volume V : Monitoring & Evaluation of transboundary aquifers

Edited in Tunis with the financial suppot of Unesco/IHP and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

ISBN : 978-9973-856-50-0

Acknowledgements

This document was reviewed and edited under the supervision of M. Chedli Fezzani the Executive Secretary of the Sahara and Sahel Observatory (OSS). It emanates from the work lead from January 2004 to June 2009, by the OSS permanent staff of the project "the Iullemeden Aquifer System", in partnership with Mali, Niger and Nigeria, under the scientific and technical coordination of M. Mohamedou Ould Baba Sy, Expert in database, GIS and groundwater modelling, the Scientific advisor M. Ahmed Mamou and regional project coordinator M. Abdel Kader Dodo.

This work is the culmination of their efforts combined with those of experts from three countries (Mali, Niger and Nigeria) in particular through their participation in training sessions in database, GIS and mathematical model facilitated by M. Mohamedou Ould Baba Sy.

We express our deep gratitude to the personalities who contributed in this work, especially:

MALI

- M. Seidou Maiga, Hydrogéologue, point focal national, DNH
- Damassa Bouaré, Ingénieur Hydrogéologue, Responsable Base de données, DNH,
- M. Luc Diakité, Ingénieur hydrogéologue, DNH
- Pr Amadou Zanga TRAORE, Ecole nationale d'ingénieurs

NIGER

- Abdou Moumouni MOUSSA, Hydrogéologue, Point focal national
- Sanoussi RABE, Hydrogéologue
- Hassoumane Hassane, Ingénieur géomètre adj hydraulique
- Hassane Adamou, Hydraulicien
- Bako Mamane Hydraulicien informaticien

NIGERIA

- John Chabo, National focal, Deputy Director, FMWR, Abuja
- M. Stephan Margima Jabo, Hydrogeologist FMWR, Abuja
- M. S. Mukaile Babarinde, Prin. Hydrogeologist, FMWR, Abuja
- M. Hussaini Sunday Ushe, Hydrogeologist, FMWR
- Simon O. Okpara, Hydrogeologist, FMWR, Abuja

INTERNATIONAL CONSULTANTS

- Dr PIZZI Giuseppe, Expert in modelling
- Abdous Belcacem, Expert in database

We express our deep gratitude to our partners for their financial, scientific and technical support:

PARTNERS

- Takehiro Nakamura, UNEP/GEF
- Alice Aureli, Unesco

We also thank the UNESCO/IHP and GIZ for their financial support in publishing this document, as well as France, Switzerland, AWF/ADB and the NBA for their continued support to the Water Programme of OSS.

We are also indebted to Mrs Tharouet Elamri who undertook the design of the model and the finalization of this document not to mention the financial and administrative team have spared no effort for the successful implementation of all activities this project.

Water Programme coordinator

Abdelkader Dodo

Executive Secretary

Dr. Chedli Fezzani

Contents

LIST OF ACRONYMS/ABBREVIATIONS

ABN	Autorité du bassin du Niger
ABV	Autorité du bassin de la Volta
ACDI	Agence canadienne de développement international
ACMAD	African Centre of Meteorological Application for Development
ADB	Banque asiatique de développement
ADT	Analyse diagnostique transfrontalière
AIEA	Agence internationale de l'énergie atomique
AMCOW	African Ministers' Council on Water
ASAR	Advanced Synthetic Aperture Radar
ASTER	Advanced Spaceborne Thermal Emission and Reflection
BAD	Banque africaine de développement
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Institut Fédéral des Géosciences et des Ressources Naturelles)
BRGM	Bureau des recherches géologiques et minières
CCNUCC	Convention-cadre des Nations unies pour les changements climatiques
CCRE	Centre de coordination des ressources en eau de la CEDEAO
CEDEAO	Communauté économique des Etats de l'Afrique de l'Ouest
CEN-SAD	Communauté des Etats sahélo-sahariens
CI	Continental intercalaire
CILSS	Comité inter-Etats de lutte contre la sécheresse au Sahel
CNCS	Comité national de coordination et de suivi des activités
CRA	Centre régional Agrhymet
CT	Continental Terminal
DDC-SUISSE	Direction du développement et de la coopération - Suisse
DSRP	Document de stratégie de réduction de la pauvreté
ENVISAT	ENVIronment SATellite
EBRD	Banque européenne pour la reconstruction et le développement
ERS	European Remote Sensing Satellite
ESA	European Space Agency (Agence Spatiale Européenne)
FAE	Facilité africaine de l'eau
FAO	Organisation des Nations unies pour l'alimentation et l'agriculture
FEM	Fonds pour l'environnement mondial
FFEM	Fonds français pour l'environnement mondial
FIDA	Fonds international pour le développement agricole
GEF	Global Environment Facility
GIRE	Gestion intégrée des ressources en eau
GICRESAIT	Gestion intégrée et concertée des ressources en eau des systèmes aquifères

	d'Iullemeden, de Taoudéni /Tanezrouft et du fleuve Niger
GIS	Geographical Information System
GTZ	Agence de coopération technique allemande pour le développement
IDB	Banque inter-américaine pour le développement
IGAD	Inter Governmental Authority for Development
JRC	Joint Research Center
MCA-WEAP	Multi-Criteria Analysis tool - Water Evaluation and Planning System
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NEPAD	New Partnership for Africa Development
OMVS	Organisation de mise en valeur du fleuve Sénégal
ONUDI	Organisation des Nations unies pour le développement industriel
OSS	Observatoire du Sahara et du Sahel
PANA	Plan d'action national pour l'adaptation aux changements climatiques
PAS	Programme d'action stratégique
PHI	Programme hydrologique international
PNUD	Programme des Nations unies pour le développement
PNUE	Programme des Nations unies pour l'environnement
PO	Programme opérationnel du GEF
SAI	Système aquifère d'Iullemeden
SAR	Synthetic Aperture Radar
SASS	Système aquifère du Sahara Septentrional
SAT	Système aquifère de Taoudeni/Tanezrouft
SEI	Stockholm Environment Institute
SIG	Système d'information géographique
SRTM	Shuttle RADAR Topographic Mission
UMA	Union du Maghreb arabe
UNESCO	United Nations Educational, Scientific and Cultural Organization
WEAP	Water Evaluation and Planning System

I. SCOPE AND LIMITS OF THE STUDY

I.1. Scope of the study

The hydrogeologic modeling activity started in the project «Management of the hydrogeologic risks of the Iullemeden Aquifer System, (IAS)» (GF/2713-03-PMS : GF/1030-03) is part of the «transboundary Diagnostic Analysis activity» (TDA) to better evaluate the water resources of the aquifer system and identify the hydrogeologic risks of their development.

Initially planned as a complementary training in modeling for scientists and technicians of those countries that have to handle water resources, this activity has also led, after the first diagnostic analysis of transboundary hydrogeological risks, to the first modeling of the aquifer system in question for an evaluation of the exploitable resources through the analysis of the available information.

Indeed, these hydrogeological risks that are threatening the water resources of the Iullemeden Aquifer System of those resulting from the use of these resources, can only be identified as long as the hydrodynamic functioning of this aquifer system is well mastered and its exchanges with its environment well-known. The hydrogeological synthesis undertaken until this day in the IAS countries, were carried out within the national frontiers and mainly concern the description/identification of the aquifers rather than their assessments and their constituents.

Thus considered, the conception of the administrators and decision-makers of the future of the IAS water resources in each of the three countries concerned (Mali, Niger, Nigeria), is not necessarily the same, mainly, concerning the hydrodynamic functioning of the aquifers and the links they have with the recharge areas (example of the River Niger suspected as a zone of recharge of IAS groundwaters) and the outlets (Dallols). It is then as much necessary to have a common vision as to the hydrodynamic functioning, as it is to compare the evaluations of the available funds in water.

Thus, the structural configuration of the different aquifer levels is largely influenced, in each of these countries, by the knowledge of the geology information and threw drillings. The relative importance of these aquifer levels from one country to another made the interest given to their water resources variable according to their geographical extension and we are far from having an overall view of the global aquifer system.

The geographical extension of the IAS aquifer formations in each of the three major countries that share this aquifer system (Mali, Niger, Nigeria) can be considered, as an elementary indicator of the importance of the groundwater resources compared to the global water resources of these countries. With the surface of 525,000 km^2, this aquifer system extends over 31,000 km^2 (6%) in Mali, 434,000 km^2 (83%) in Niger, and 60,000 km^2 (11%) in Nigeria. For Niger, the IAS is the major sedimentary structure receiving the groundwaters of the country and concerning a major part of the urban as well as the rural population. This demographic aspect related to the groundwater is also important in the case of Nigeria which basin of Sokoto, concerned by the IAS, is also a zone with a strong population density.

It is within this framework that the Project Steering Committee (Abudja, Nigeria, February 25-26, 2006) has decided the elaboration of the hydrogeological model of IAS. The adequate hydrogeological model is that which explains best the hydrodynamic functioning of all the aquifers and their interaction with their environment (surface waters of the Niger River) and with climatic conditions (viabilities characterized by recurrent droughts).

The OSS offered to carry out with the contribution of the national teams, to give these three countries a performing tool for the management of this shared water resource, while presenting a critical analysis of the available information and showing the practical limits in the improvement in knowledge about the aquifer system performance and the identification of the hydrogeological risks associated with the growing exploitation of groundwater resources.

I.2. Limits of the study

This modeling operation has been conduced within the scope of this study concerning the identification of hydrogeological risks, which threaten its water resources, and answers to the following essential objectives:

- the harmonization of the data of the countries concerned to reach a shared conception about the hydrodynamic functioning of the aquifers of the system;
- the elaboration of a hydrogeological assessment of the aquifer system with a maximum precision about its constituents:
  - inflow : recharge, leakage,
  - hydrogeologic characteristics : structure, piezometry, chemical quality,
  - outflow : exploitation, leakage,
- the use of the model as a simulation tool of the aquifer system in order to elaborate development scenarios of its water resources according to the planning objectives of the three countries and to show the impact of the takings on the aquifer system performance and the risks.

The achievement of these objectives depends on the state of knowledge available in these countries which would help to simulate the real IAS performance. This aspect revealed to be the basis of the Transboundary Diagnostic Analysis (TDA), since each of the specialists of the three countries has, within the limits available data, a particular conception about the importance of the exploitable resources and their geographic distribution, which remains within the countries' frontiers.

None of the three countries was able to present a rational evaluation of the exploitable water resources based on this system and the follow-up data of its performance. None of them was able to show the risks related to the exploitation on the whole basin. Even if the objectives listed above could not be achieved by this modelling operation, this stage of the resources evaluation points to the need for training to implement a performing tool to ensure the evaluation of IAS shared water resources, as well as their management by objectives.

I.3. Approach of the study

This report is the synthesis of the work of the project team and the national experts in charge of the collection and the shaping necessary to the modelling activity. It also gives the results of the collegial efforts of the national experts for the conceptualisation of the functioning of this hydraulic system and its relation with its environment.

On the other hand, this report also accounts for the different stages of the construction of this model, its calibration, the verification of its ability to simulate the natural aquifer system functioning and to be used as an estimation tool for other situations considered within the scenarios developed.

This activity was achieved thanks to a team work, with training sessions in modelling for the technicians of those countries concerned with the IAS program in the future, and two other training sessions about the elaboration and the implementation of a common database[1]. The two training sessions are:

- first training session from April 8th to 19th 2006 (OSS Tunis) grouping two representatives per country[2]. It dealt mainly with the elementary notions of the hydrogeological modelling in order to elaborate the aquifer system and use it as a tool to manage the water table. This session helped the representatives of the three countries to agree on the limits of the aquifers, their vertical extension and their structural configuration. It was also possible to elaborate the conceptual modelling sketch of the IAS and to agree on the data needed by the model. Teams of different countries were asked to contribute to the collecting and the shaping of the data necessary of this modelling activity[3];
- second training session from November 28th to December 9th 2006 (OSS Tunis). During this session which grouped the same participants as in the previous one, the focus was on the practical side of the elaboration of the IAS model and the critical analysis of the collected data. The actual needs in data revealed the limits of the available information for the construction of a multilayer model as wished by the IAS water administrators. The representatives of the three countries had to create a model with a limited number of aquifer layers but still representative of the whole system. Therefore, conditions were decided about the limits of the model and the choice of the calibration period of the steady rate of flow. It was also possible to put forward the gaps in the necessary data[4]. The countries' representatives were asked to do their best to fill these gaps. The project team also bustled on this task. A mission was scheduled to this effect in Niger around mid – December 2006.

Considering these elements and the different modelling attempts mentioned previously in the three countries[5], the elaboration of the IAS model was undertaken in order to simulate the hydrodynamic performance of the aquifer system and to evaluate its results in water as well as the constituents of those results, mainly those influencing the transboundary exchanges.

This model was created as part of an inter-related tools (DB – GIS – Model) helping the administrators of the IAS to make decisions according to the modifications that these ground waters undergo. This model will therefore become – in the long run – a management tool of the IAS.

[1] The two sessions dedicated to the common database are workshops of 04 / 26 – 30 / 2004 (OSS Tunis) and from April 26th to May 05th 2005 (Niamey – Niger)

[2] Mali : S. Maïga and D. Bouaré, Niger : M. Abdou Moumouni and S. Rabé and Nigeria : J. Chabo and S. Jabo

[3] See the workshop report : session of intensification of the capacity of the countries representatives in mathematical modeling of the IAS. OSS – Tunis, April 2006, 13 p

[4] See the workshop report "second session of reinforcement of the capacities of the countries representatives of mathematical models of the IAS" OO, Tunis, December 2006, 16p

[5] Among these modeling attempts, we mention Carmen (2001) and Guero (2003). It is tobe noted that the Carmen works came to nothing

12

II. COLLECTING AND PROCESSING OF DATA

II.1. Work tools

The previous IAS modelling attempts stumbled over the problem of **the unavailability and the inadequacy of the necessary hydro geologic information**. It's the precise knowledge of the geologic structures, the piezometry history, the exploitation and the chemistry of the water, which is enormously lacking. This aspect is even more crucial when the objective is to elaborate a model for the whole sedimentary basin which shows the hydrodynamic functioning of the aquifer system and helps with the quantitative evaluation of its water resources.

The lack of harmonization of geological information relative to the physical aspect of the aquifer system revealed to be, in this case, one of the priorities to consider in order to conceive all the IAS aquifers through their natural links within an entity.

Hence, the availability of data is one of the major problems and the harmonization of these data is a difficulty since few previous hydro geologic studies dealt with lithologic and stratigraphic drilling data in order to process them systematically.

The analysis and interpretation of this geologic information to undertake a structural study, is a necessary element to understand the subsurface structure of the IAS basin.

That is why an IAS common database was elaborated with features and contents largely influenced by the needs of the model. Thus, this database essentially dedicated to hydro geologic data, also includes complementary data such as "geology" which collects lithostratigraphic data of the drilled wells and the "networking" which helps with the direct shift (data transfer from the database to the hydrodynamic model).

On the other hand, this **database** is related to a **Geographic Information System** (GIS) which helps to localise geographically water points, to reflect the space distribution of data and the degree of their homogeneity.

It's obvious that the simulation of the hydrodynamic functioning of the IAS aquifers can't be achieved without the use of a specific software to help the discretisation of the physical space into "domains" of calculation, according to the groundwater hydrodynamic concepts.

The necessary tools for this modelling are mainly:

- database which structure is oriented to the needs of the model (Volume II: Common databases of the Iullemeden Aquifer System);
- the geographical information system which gives the distribution of the information in thematic layers;
- a simulation software for the groundwater hydrodynamic.

II.2. IAS common database

This part points out the highlighting elements of the SAI database which is largely described in a separate booklet.

The IAS common database groups the data collected in the three countries and which concern the climatology, hydrology, geology and the IAS hydrogeology. This database is mainly managed by the software "ACCESS". The processing of the information and its shaping are done through other tools such as "Rockworks" and "Photoshop" for the geological data, "Arcview" and "Mapinfo", for the hydrogeologic data, etc.

The major columns of the common database are the following:

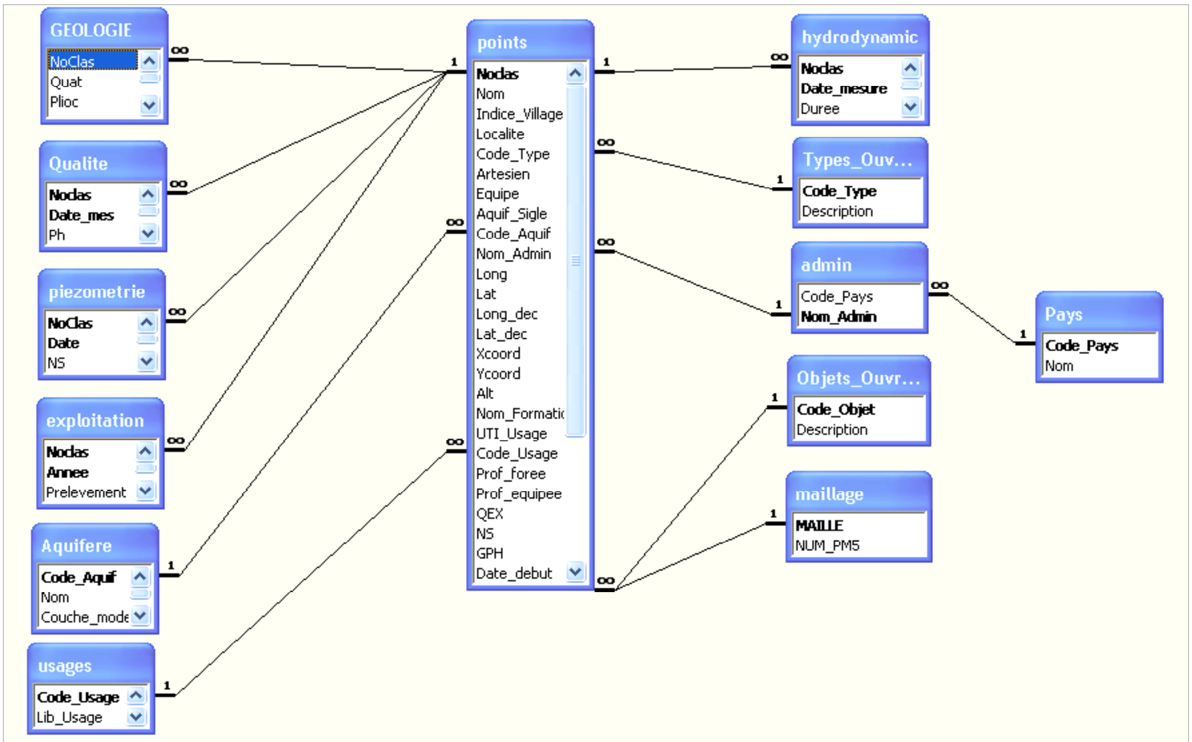


Figure 1 : Diagram of the IAS database

The diagram of the database is a logical representation of data model elaborated during the conception stage. This diagram shows the essential role of the column " (water) points" related on one side to the identification columns (countries, hydrodynamics, work type, admin, work object, networking...) and on the other hands to the columns of variables (geology, quality, piezometry, exploitation, aquifer, uses...). The relation between the column "points" and the other columns can be unambiguous (1 to 1) or multiple (1 to many) (OSS, 2007).

II.2.1. Geological database

The geological database part of the common database, is **specific to drilled wells** database used to study the IAS structural configuration. It groups the lithostratigraphic logs of the existing drilled wells divided into a "lithostratigraphic" log adopted by the three countries and which shows the major IAS aquifers and aquicludes as well as the layers which make up its substratum or basis.

This geological information is used in:

- the elaboration of lithostratigraphic correlations connecting the drilled wells through the IAS basin,
- the elaboration of the major structural maps used to identify the aquifer layers and their vein walls (thickness, bottom and top maps of each layer).

The following software were used : « ACCESS » for the construction of the database, "**Arcview**" and "**Mapinfo**" for the geographical positioning of the drillings across the basin and "**Rockworks**" and "**Photoshop**" for the elaboration of the geological correlations and the structural maps.

The use of Rockworks software helped visualize the geographical distribution of drillings in the IAS and ensure a god representation of lithostratigraphical data. Considering the descriptions of these drillings by different geologists over more than **fifty years** periods, the terminology used as well as geological series are not necessary homogeneous. This resulted in a work of harmonization and criticism of these data (mainly from both parts of the frontiers between the three countries) to show through the established correlations, the depression structure of the basin. Several correlations were thus drawn in all directions before getting to an overall relatively homogeneous diagram.

II.2.2. Climatological, hydrological and hydrogeologic database

The database also includes columns mainly focused on the structures of the water resources management and not on those specific to the analysis of the physical data (hydrology and hydro geology) and the climatological one (rain, infiltration, evaporation), within the scope of the modelling. These data, recovered from the national database and digitalized water resources maps (Niger and Mali), necessitate the geo-referencing of each water points and their integration in the other specific columns. Thus, in its current state, the IAS common database needs a complete restructuring in order to integrate new columns (data) which are relative to the exploitation of the water resources and their uses, in the columns which will add them to the model's historical record. (OSS, 2007).

II.3. Geographical information system (GIS)

This IAS geographical information system is a set of software which helps with a cartographic representation of the data included in the common database. It also helps recover the results of the hydrodynamic model to combine them with the other available data and use them as helpful elements in decision making as to the distribution of water resources and their different uses. The digitalized maps aid necessary to this representation was elaborated within the scope of the project as a separate activity. This activity was considered as a preliminary stage to help the integration of the information.

The GIS used to represent the IAS is thus conceived as an integral part of the global Information System (created for very large needs), so as all the descriptive information of the geographical objects is planned in the database structure. The essential purpose is that each information be stored at one place (no redundancy). This set of tools helps the harmonization of data, their analysis and their shaping.

The second purpose concerns the links between the database and the model on one hand, the GIS and the model on the other. These relations should be clear and automatic for the user. They can be established later, after the implementation of the database, but before supplying the model with specific data. The IAS information system has two major elements: the database and the GIS. This set is added to the model's networking, which is a column of the DB and a layer of the GIS at the same time. This link helps move data from the D in a legible format for the model.

This complementary between the tools developed within the scope of the project for data processing of the IAS water resources, made it possible to ensure the synthesis of the information at the level of the aquifer basin and reach results that would show an overall performance.

II.4. The software used (PM5)

The choice of the IAS hydrogeologic modelling software has the same importance as the software used in the elaboration of the common database or for the management of the GIS. It was very important from the start, to have software with "free" use and no problems of cost to the countries. It was also important to have software which accepts a variable "density" of information, according to a variable-sized networking. This is due to the importance of the IAS and to the fact that the geographical distribution of water points is not homogeneous. Add to this the fact that the aquifer system is a multi-layer system, but with a dominance of horizontal flow on vertical bonds which should be identified and which functioning should be precise.

Hence, the choice of the software simulating the hydrodynamic functioning of the aquifer system should respond to different restraints mainly:

- the availability of this tool in the public property and its large use ensuring periodically the initiation/training of water resources administrators in the three countries;
- the simulation of the aquifer system on the basis of a geographical information heterogeneously distributed;
- the possibility to use only necessary modules at one stage or another (hydrodynamic aspect) with the eventual resort to other modules depending on the density of the information (refill or simulation of the distribution of the solutions).

For many years, the "Processing Modflow" imposed itself as the modelling tool of the subterranean flows helping to understand new constituents specific to surface flows and their connection with the aquifers as well as the processing of some aspects proper to the hydrodynamics of the groundwater such as the transfer of solutions or the distribution of salts. The IAS is particularly rich in bond with the surface flows (drainage of the water table by the Niger River and drainage of the water table in other places by the same river). Particular situations of localized refilling are also to be considered to ensure the impacts of some works or water flows on the behaviour of the water table across the frontier (the Kainji dam in Nigeria and the water table of the Maradi region in Niger). The chemical anomalies considered as localized hydrogeological risks deserve, in the long run, to be studied in order to determine the extent of the phenomenon and its influence zone.

Considering these objectives, the version 5 of the Processing Modflow software (PM5) was chosen. This version, elaborated by W.H. Chiang and W Kinzelbach, is based on the Modflow code implemented by the US Geological Survey[6]. In 1988 and helps the modelling of water transfers in **a multilayered aquifer system**. Other utilitarian codes are incorporated in PM5: PMPATH (layout of electricity cables and water flows speed), the PEST code (optimization program), transport module MT3D. PM5 also includes an integral interpolator of the Shepard's methods (reverse of the distance), of Akima and Renka triangulation, and the krigeage process.

Besides, the conditions to the usual limits (imposed potential, imposed stream and mixed condition of Cauchy), can be schematised: fault, evapotranspiration, and exchange between subterranean water table and superficial flow in a drainage net or canal. Other aspects of the modelling can be processed such as the drainage of some thickness of the aquifer, the shifting of the limits of the water table, the subsidence and the thick flows due to the salinity or to temperature.

This Modflow version previously used in the aquifers modeling in the North-Western Sahara Aquifer System (NWSAS), stood the test. It proved to be friendly and well-adapted to process the

[6] Michael G. McDonald & Arlen W. Harbaugh: a modular three dimensional finite-difference groundwater flow model; USGS, 1988.

simulation of the multilayered aquifers systems of a great extension and a high localized hydro geological information density.

III. CONCEPTUALISATION OF THE MODEL

The hydrodynamic modelling of the hydrogeological functioning of the aquifers system is a several stage process, during which decisions are made according to situations in order to simulate through the functioning of the mathematic model, the physical performance of the aquifer system. Several scenarios were studied to choose the hypothesis which corresponds better to reality.

Hence, the different modelling stages are mainly:

- **the conception of the aquifer system hydrodynamic functioning** as a natural entity submitted to external impacts through the water exchanges (entrances and releases) with its natural environment and the transformations which occur within the aquifer system;
- **the construction of the mathematic model** reproducing the physical functioning of the aquifers and able to simulate projected situations, based on data or hypotheses set by the variables;
- **the preparation of necessary data, their processing, their analysis and their shaping** in order to adapt them to the model's functioning format;
- **the introduction of the necessary data for the functioning of the model** to ensure the similarity of its functioning with the physical reality of the aquifer system (wedging of the model);
- **the analysis and validation of different results**, their releases (results of the model).

It comes out that the conceptualisation of the hydrodynamic functioning of the aquifer system, is a major and decisive stage in the construction and functioning of the model (simulation). It closely conditions the results and helps, by comparing these results to the real behaviour of the aquifer system, to evaluate the representativeness of the model and its sensitivity to each variable. This conceptualisation concerns the physical aspects of the system (structure and extension) as well as its internal hydrodynamics by refining the different aspect to be processed by means of a simplification guaranteeing the similarity of the model's performance with the physical system.

The conceptual model of hydro geologic entity must show the following aspects:

- the structural configuration,
- boundry Conditions (horizontal and vertical)
- transfer functions within the system.

III.1. The structural configuration of the IAS

The structural aspect of the IAS caused disagreement among the three countries' representatives because the extension of the system in each of these countries is variable and that its water resources are not of the same strategic importance. Indeed, the synclinal depression of structure of the system is only perceived at the scale of the whole basin. Whereas, in a country like Mali or Nigeria, the aquifers linked to this depression are a limited extension and sometimes their water resources fulfil only limited sector-related uses (AEP, watering of the livestock, irrigation…). The need for water resources in the three IAS countries was originally much more oriented towards surface water (river Niger) than the IAS groundwaters. The latter became necessary only within the limits of the climatic zone of the Sahel and Sahara.

Based on lithostratigraphical correlations established by reference to geologic layers shown by the drillings and the available geographical studies, it was established that the IAS structural configuration is a sedimentary depression which deepest layers of the Pre-Cambrian Crystalline, are on the borders (Margat, 1982) (Figure 2) Within the limits of this depression, the sedimentary coats expanding between the Lower Cretaceous and the Quaternary, are largely dominated by layers of continental origin, thus showing notable variation of features and thickness.

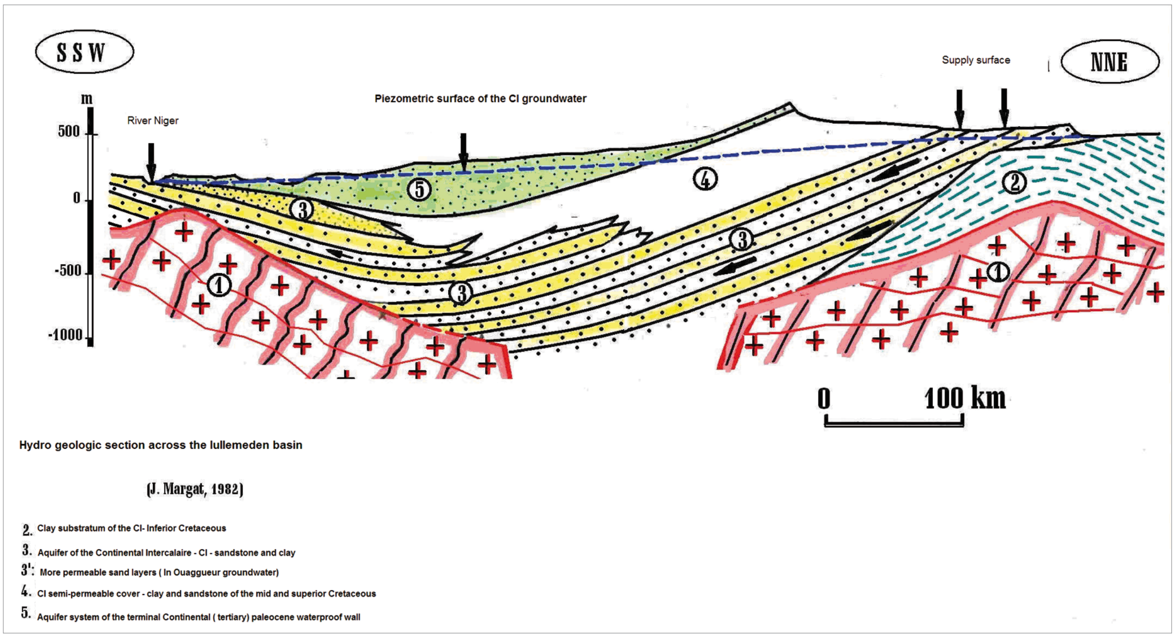


FIGURE 2 : SSW-NNE section across the Iullemeden basin

This structure was accessible to schematisation only through the synthesis of the data of the geophysical prospecting (relatively modest) and hydraulic drillings (numerous, but a limited depth) and oil drillings (unlimited number), because the lateral variation of features and the abrupt tectonics largely influenced the speed of the burying of the geologic layers.

Hence, the drillings data make up the remainder of the geologic maps to clarify the particularities of the structure of the basin, as well as its delimitation.

Indeed, the passage to the two adjacent basins (Lake Chad basin in the East and the Taoudeni basin in the West), is of sedimentary and structural conditions not always evident.

The bottom of the depression, theoretically made up of a substratum in the shape of an insular shelf (primary and Precambrian rocks), does not have well-evaluated depth everywhere. The continental sedimentation constituting the majority of the basins' layers makes the thickness of each of these layers subject to variations, besides the existence of lateral changes of facieses.

Therefore, the geologic database revealed to be a major tool for the conceptualisation of the IAS structure. A particular attention was given to the structural evolution of the basin, particularly to faults of regional extension to better grasp the paleo-geographic evolution of this sedimentary depression well-framed by the insular shelf shields (Ahaggar of Iforas and the Aïr in the North and Noeth-East).

This simplified scheme of a more or less asymmetrical depression is insufficient when it is about the conceptualisation of the aquifer system in multi-layers. Indeed, as these layers do not perfectly overlap over the extension of the whole basin as:

- their thickness varies,
- the geological slope of the layer is not constant,

- only the dense data, relative to the depth and thickness of each of these layers, can account with the maximum precision possible, for the overall structure of the different layers of this structure.

The IAS overall structure is deducted from a fine analysis of the geophysical prospecting data, structural maps and drillings data. It is managed according to an analysis process of the geological data in the three countries in order to establish a "**stratigraphic log type**" which satisfactorily shows the basin's overall structure.

The elaboration of the "stratigraphic log type " is obtained thanks to the harmonization of the IAS geological data mainly those of the drillings.

This harmonization is undertaken according the following process:

- elaboration of a stratigraphic log representative of all the geological layers (designation per geological coat) and lithological ones (designation per lithological layer) on the basis of a stratigraphic log per country in order to adopt it in the description of the drillings records and their divisions into geologically correlative lithologic series,
- description of the totality of the drillings records and the data capture in the database,
- drawing of geological correlations to be completed at a later stage, by hydrogeological data (piezometric level, harnessing, dry residue, ...), as well as structural maps (maps of thickness of the top and bottom of each layer) in order to precise the overall structure of the basin and its conceptualisation for the model needs as a hydrogeologic entity to ensure the hydraulic continuity.

III.1.1. Representative stratigraphic log

On the basis of the lithostratigraphic description adopted in each of the three countries within the limits of the Iullemeden basin, the elaboration of a representative record of the IAS totality is conducted as follows:

- the identification of the aquifers between the basely substratum and the ground surface in each of the three countries,
- the comparison of the aquifers in question as to the general stratigraphic scale,
- the implementation of elementary subdivisions in the major aquifers separated by aquicludes,
- the identification of the substratum and the roof of each layer.

On the basis of this lithostratigraphic log, all of the drillings in each of the major countries that share the basin (Mali, Niger, Nigeria) are analysed in order to implement in each case the corresponding log. In each of these three countries the tradition adopted to describe the aquifers divided by the drillings, is scrupulously respected in order to reflect the specificity of the structure; but the need to treat the whole basin as a structural and hydro geological entity, requires a simplification and harmonization effort supplied later, so as to reach an overall picture.

III.1.2. Stratigraphic log adopted by Mali

The part of the Iullemeden basin belonging to Mali is of **31.000 Km²** (6% of the basin's surface). It is situated in the North and overlaps the Adrar and the Iforas mounts and the Tamesna sub-basin where Primary and Cambrian geological features show. This makes Mali mainly interested in the Iullemeden basin, by the "Gao strait" (or Sudanese ditch) which is the transition zone between the basins of Iullemeden and Taoudeni, and part of the Tenere largely dominated by the continental intercalary outcrops. These typical types of drillings are a reference in this part of a basin:

1. Drilling section of Tahabanat no.1 representative of the Iullemeden basin

This drilling (fig 3) crossed 2011 m of Tertiary and Secondary layers with one part of the basely Precambrian Substratum It gives the following lithological succession:

0 - 70 m : Tertiary (Eocene and Paleocene marine origin): marls with limestone and limestone and grey.

70 - 1965 m : Mesozoic (Cretaceous and Jurassic)

70 - 455 m : Upper Cretaceous (marine origin)

- **Senonian** : Limestone, grey and marls.
- **Upper Turonian**: clay and argilits withe beds of gypsum, grey and marls,
- **Upper Cenomanian – Lower Turonian**: clay and argilits with beds of gypsum and marls,

455 - 1740 m : Lower Cretaceous :

- **Lower Albian** (455 - 760 m): Grey with clay beds,
- **Aptien** (760 - 1140 m) : From top to bottom : hard clay beds, grey beds, grey beds with limestone and calcareous aerolit,
- **Neocomian** (1140 - 1575 m) : : aerolits with grey and limestone,
- **Lower cretaceous member** (1575 - 1750 m) : hard argileous beds calcareous beds of grey and marls,
- **Jurassic** (1750 - 1965 m) : Grey with mica and conglomerate in the bottom.

1965 - 2011 m : Precambrian : Schists with quartz and biotite.

2. Drilling section of Tamat no. 1 representative of the Tamesna sub-basin

For this northern part of the Iullemeden big basin, the Mesozoic and Paleozoic layers are dominating. Only those layers connected to the Mesozoic are taken into consideration. The lithologic succession which was sectioned from top to bottom, by the drilling in this part of the basin is, as shown by the Tamat no. 1 drilling, as follows (figure 4, see page 24) :

0 – 208 m : Lower Cretaceous: Bedded grey and clay (Tégama Grey).

208 – 336 m : Lower Cretaceous – Upper Jurassic: Bedded red and green clay with limestone and siltlys beds (Irhazer Clay).

336 – 451 m : Midly Jurassic: Bedded grey with inclined stratification, changing in the bottom at clay beds with calcarious cement (Agadez Grey).

451 – 544 m : Trias – Permien (?): ArkosiCly grey and clay (Serial of Isegouadane), including a basely conglomerate and brech.

544 – 597 m : Upper Carbonifer: argilits (Tagora Formation)

597 – 631 m : Devonian : grey.

631 – 800 m : Gothlandian : Schists (631- 697m), gry and darkly schists with pyrite and Graptolites.

800 – 1141 m : Cambro-Ordovician: heterogenous white to gry Grey with thin beds of clay silts (Equivalent of the units I and II of the lower greys).

1141 – 1170 m : Precambrian : Cristalline Schists

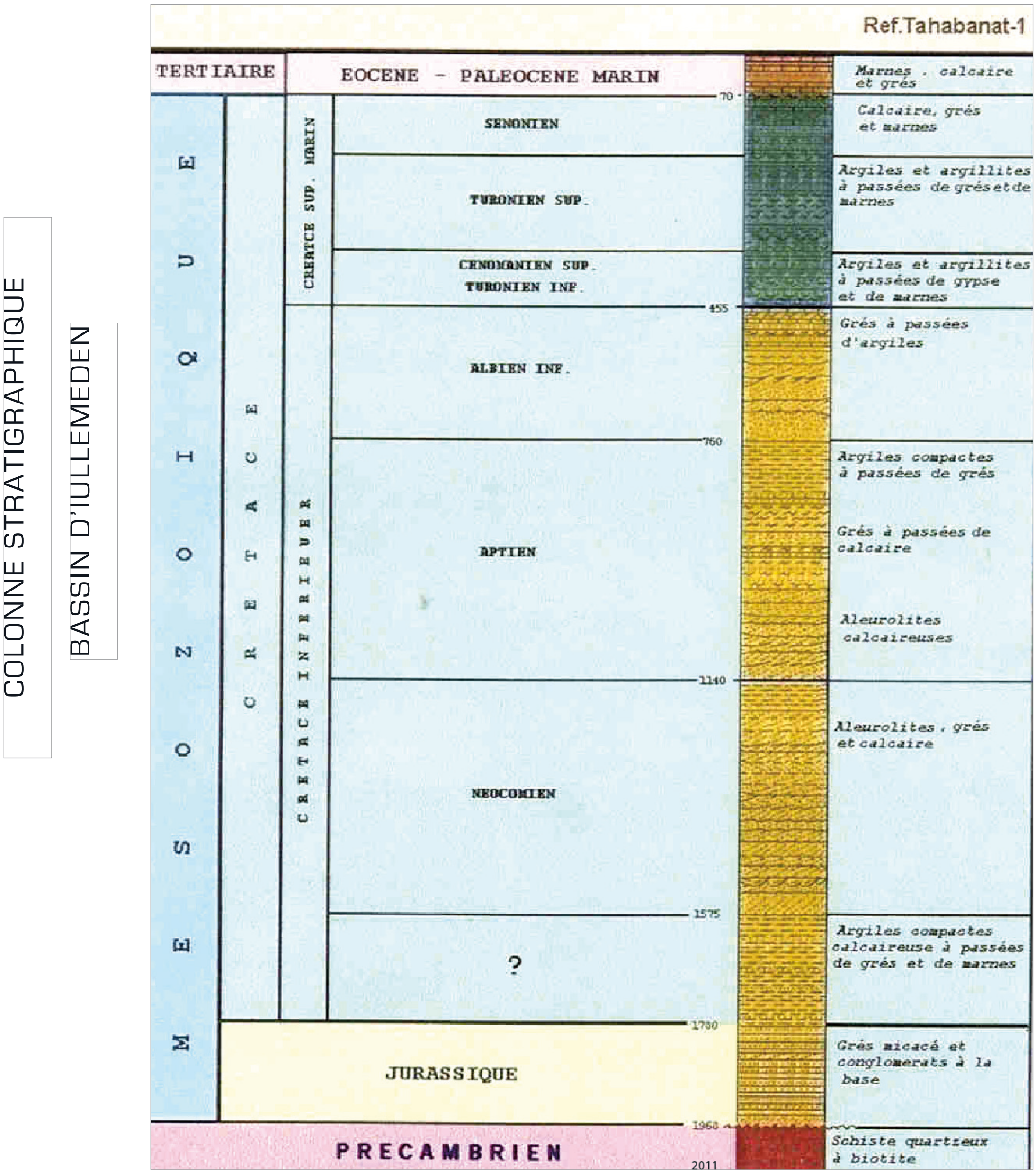


Figure 3 : Tahabanat no.1 drillings section

The Iullemeden aquifer system is mainly concerned with geological types of Lower Cretaceous (Tagama sandstone) and Jurassic (Irhazer clay and Agades Sandstones). All the other aquifer layers situated in lower stratigraphic scale, are of a secondary importance and are frequently connected to substratum which varies between Irhazer Clay and Precambrian Schists.

The aquifers connected to the Cretaceous have two facieses:

- an lower facies, thicker and extending from the upper Jurassic to the Cenomanian base it is mainly Continental and detrital,
- a upper facies extending from Cenomanian transgression to the top of the Senonian; it is typically carbonated with elements deposited in marine environment.

It is this marine facies of the upper Cretaceous which constitutes almost everywhere, wherever it is present, the top of the lower Cretaceous of the Continental intercalaire in the large sense. The development of the marine Cretaceous in the oriental part of the IAS basin (mainly in Niger and Mali), results in aquifers levels within the limestone coats of the Cenomanian, Turonian, and Senonian which importance is very variable.

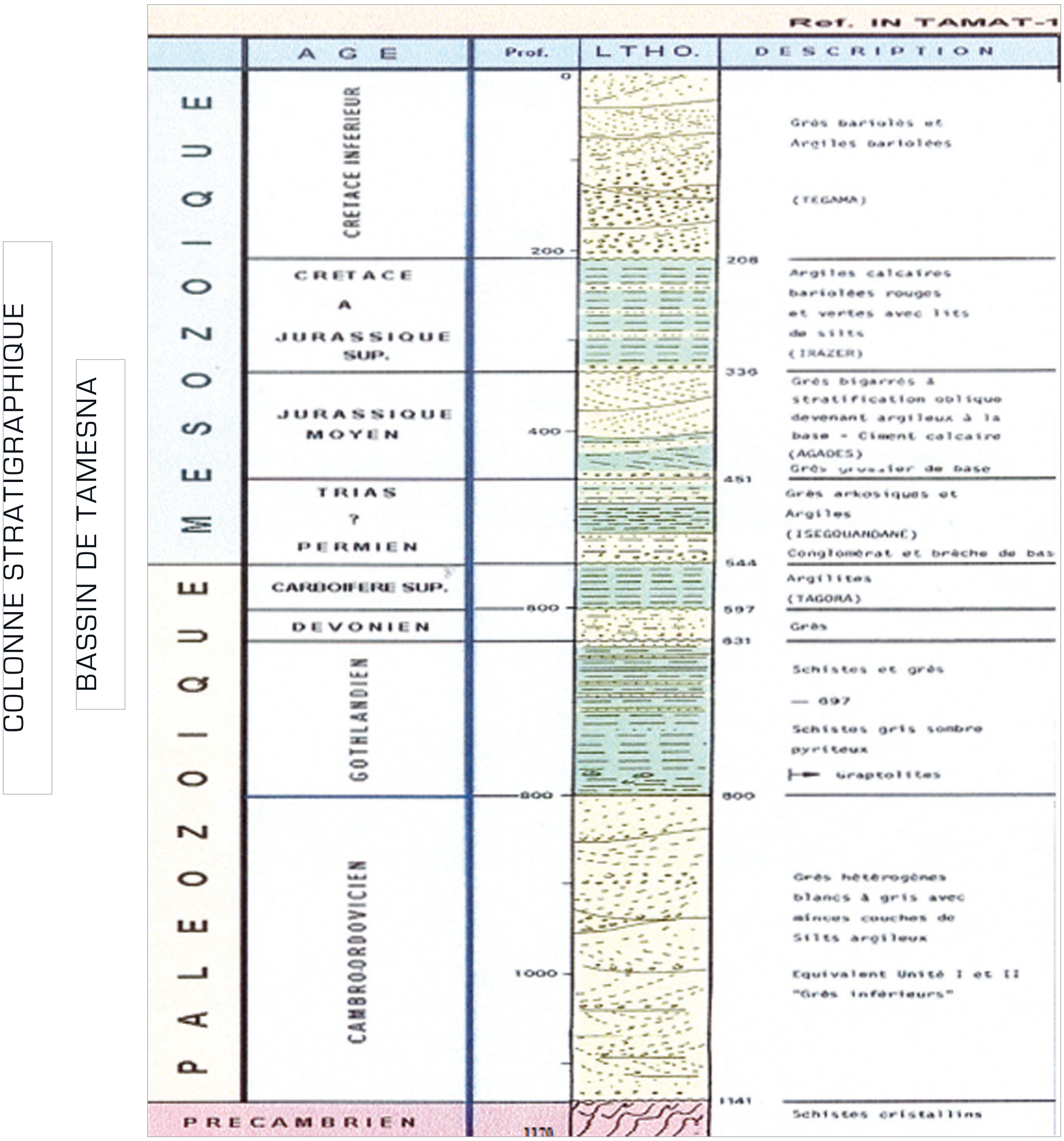


FIGURE 4 : Tamat no. 1 drilling section

3. Drilling section of Ansongo no. 1 representative of Gao ditch

In the Gao ditch which is a transition zone between the Iullemeden basins and the Taoudeni, the geological layers of the upper Cretaceous and the Tertiary undergo a clear redaction in their thickness. Those older than the lower Cretaceous are completely absent and the Continental intercalaire rests directly on the Precambrian Cristalline substratum. The Amsongo drilling section of around 1697 m of depth, illustrates this situation (figure 5). This drilling sectioned – from top to bottom – the following stratigraphic lay:

0 – 56 m : Tertiary: Bedded Argileous with intercalations of grey and mica.

56 – 116 m : Upper Cretaceous : clay

116 – 645 m : Lower Cretaceous : clay in the top changing gradually to sandly and clay in the bottom ; the stratigraphic limits are difficultly precised because there is any fossils in this layer.

The stratigraphic drilled well log premises to define into the Lower Cretaceous the following subdivisions:

116 – 295 m : Albian to Lower Cenomanian: bedded silty argileous changing in silty grey,

295 – 385 m : Albian : bedded silty clay changing to silty grey,

385 – 480 m : azoïc formation: bedded silty clay changing to silty grey,

480 – 815 m : Lower Albian – Upper Aptian: bedded clay with thin beds of grey, sandstone and limestone,

815 – 922 m : azoïc formation: bedded clay with thin beds of grey, sandstone and limestone,

922 – 945 m : Aptian (?) : bedded argileous with thin beds of grey,

945 – 1460 m : azoïc formation: bedded clay with thin beds of grey, sandstone and limestone,

1460 – 1572 m : Barremian (?): Corse Sandstone with beds of argileous and limestone,

1572 – 1645 m : azoïc formation: Corse sandstone with beds of clay and limestone,

1645 – 1697 m : Precambrian : Hard clay and grey.

COLONNE STRATIGRAPHIQUE

BASSIN DE GAO

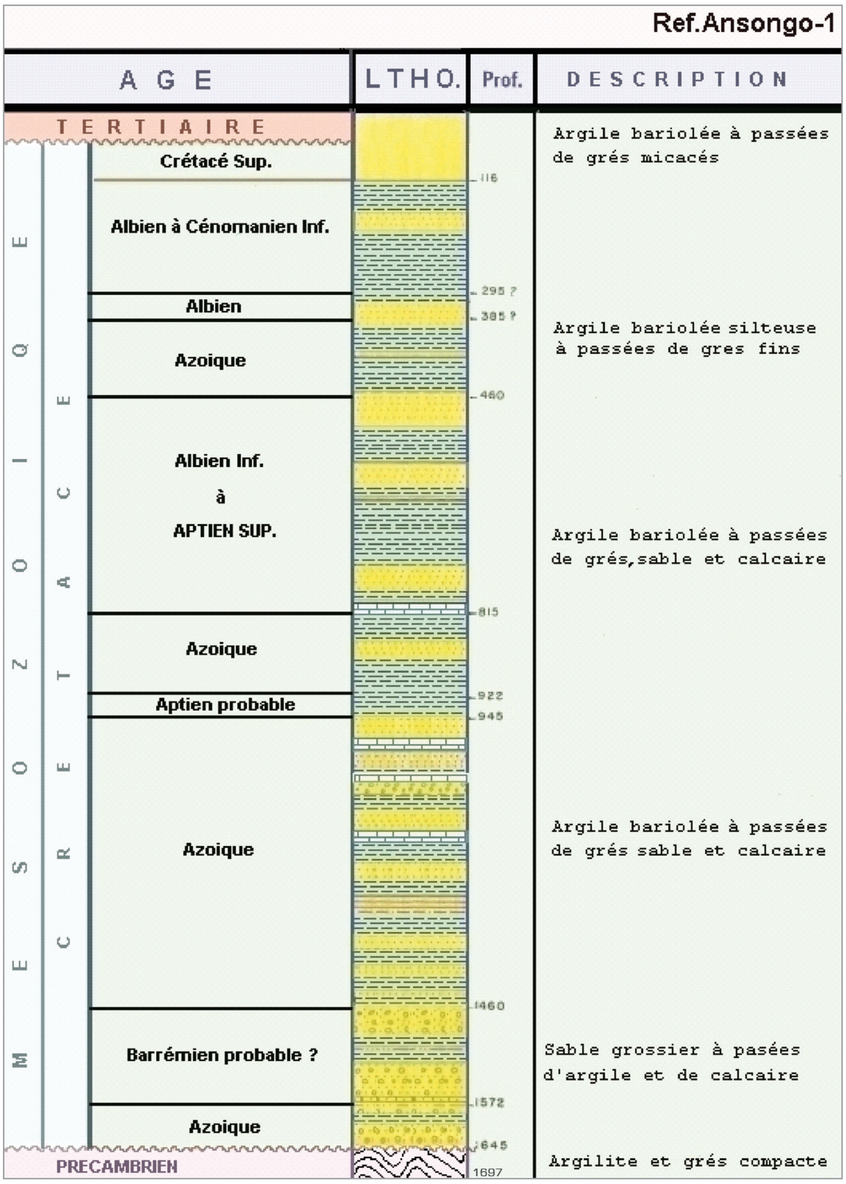


Figure 5 : Ansongo no. 1 drilling section

On the basis of this description adopted in Mali, the stratigraphic log representative of the sedimentary layers taken into consideration within the scope of the structural configuration of the Iullemeden basin, in this country, is from bottom to top, as follows:

- substratum constituted of the Precambrian substratum layers or by the non aquifers layers of the Trias-Jurassic-Lower Cretaceous,
- Continental intercalaire aquifer essentially situated in the Tegama sandstones and sometimes in the sands of the Continental Hamadian,
- a semi-impermeable aquiclude including the Paleocene and the Eocene and separating the aquifers of the Continental intercalary and the Continental Terminal,
- aquifer of the Continental Terminal including the shallow aquifer of the alluvium level.

Age		Mali	
		Groupe	Layers
Quaternary		Quaternary	Alluvium, dunes Aquifers
Tertiary	Pliocene	Continental Terminal	Sandy sandstone clay
			Aquifer
	Miocene		
	Oligocene		
	Eocene	Mid-Eocene	schistes
	Paleocene	Terminal Palaeocene	limestone and sandy marl – with phosphates beds
		Lower Palaeocene	limestone- sand
Cretaceous - Jurassic	Upper Cretaceous	Maestrichtian - Cenomanian	sandstone – clay Aquifers
	Lower Cretaceous	Continental intercalaire	Quartz sandstone, micro conglomerate, arkoses, sand, clay Tégama
			Aquifer
Trias-Jurassic - Precambrian			
Paleozoic		Precambrien	Birrimian

III.1.3. Stratigraphic log adopted in Niger

Almost 83 % of the Iullemeden basin service is inside the Nigerian territory. In this part of the basin, the major lithological layers of the Secondary, Tertiary and Quaternary outcrop locally from the border to the center and from the most old to the most recent. A big number of hydraulic drillings tally these layers in depth, thus underlining the lateral variation of thickness and facieses.

Three relatively deep drillings, were selected to represent the lithological variation of the tallied geological layers. These drillings are: combretoum n°1 (oil drilling, sun oil, Niger), Takanamat and Dogon Doutchi.

- **Combretoum no.1 drilling**:

This 1186m deep drilling tallied lithological layers of the Tertiary, Secondary and Precambrian.

from 0 to 166 m : **Continental Terminal** undifferentiated sandy clay,

from 166 to 198 m : **Eocene –Paleocene (marine origin)**, limestone and clay,

from 198 to 407 m : **Upper Continental Cretaceous** (Continental Hamadian), essentially sandy clay with sandstones, gravels and marls,

from 407 to 1154 m : **Lower Cretaceous to Jurassic** (Continental intercalaire) sands with clay and sandstones.

from 1154 to 1186 m : **Precambrian Substratum**.

- **Takanamat drilling:**

This 850m deep drilling, was continued till the first Continental Intercalaire layers. It tallied the following quotes:

from 0 to 10 m : **Quaternary** sandy clay,

from 10 to 20 m : **Continental Terminal** (CT_1 ?) clay,

from 20 to 100 m : **Continental Terminal**, sedirolithic sand and sandstone layers,

from 100 to 181 m : **Eocene – Paleocene** clay little limestone,

from 181 to 582 m : **marine Facieses of the upper Cretaceous** essentially clay and marl with little limestone,

from 582 to 760 m : **white limestone layers of the upper Cretaceous** essentially **limestone and marl**,

from 760 to 850 m : **Continental intercalaire** sand - sandstone.

This section shows the development within the upper Cretaceous of marine facieses with more and more limestone and marl, moving laterally to the Continental Hamadian with a facieses more sand and sandstone.

- Dogon Doutchi drilling:

from 0 to 9 m : **Quaternary** sandy,

from 9 to 370 m : **Continental terminal** sand – clay, we distinguish:

- 9 to 192 m : CT_3
- 192 to 288 m : CT_2
- 288 to 370 m : CT_1

from 370 to 451 m : **Paleocene**, with:

- 370 to 400 m : clay layer,
- 400 to 432 m : limestone layer (term VII),
- 432 to 451 m : calcareous clay layer (terms VI and V)

from 451 to 753 m : **Continental hamadian** (Continental intercalaire).

In this of the Iullemeden basin situated in Niger, the upper Cretaceous layers, of the Paleocene and the Continental Terminal show a notable thickness development so that they became important with clay and marl facieses with detritus sequences which thickness is variable.

The evolution of the Paleocene from the North to the South of the basin indicates the constancy of the upper terms (terms V to VII) with a progressive transition of marine facieses towards the Continentals (Dogon Doutchi 300 km).

The top of the Continental Hamadian moves progressively from the lower Turonian to the upper Turonian then to Maestrichtian, thus indicating a movement of exondation from south to North and coarser detritus layers around the borders north and south of the basin.

South of the 12th parallel, the Paleocene bedrock is made up of coarse detritus layers (Illo group equivalent to the Rima group in Nigeria). Considering these facieses changes and the attenuations from North to South, and the presence of maritime layers progressively replaced by continental ones, the stratigraphic log in Niger is as follows:

Age		Niger		Simplified layers
		Groupe	Layer	
Quaternary		Quaternary	Alluvium, dunes **Aquifers**	Quaternary
Tertiary	**Pliocene**	Continental Terminal CT_3	Clay and sandstone layers of Mid Niger (**Aquifer**)	CT3
			Aquitard	
	Miocene	Continental Terminal CT_2	Clay sand – lignite layers - **Aquifer**	CT2
			Aquitard	
	Oligocene	Continental Terminal CT_1	Siderolithic layer - **Aquifer**	CT1
	Eocene		Upper papyraced Schists - **Aquitard**	Palaeocene
	Paleocene	Garadawa layer	limestone - **Aquifer**	
		Paleocene marine	Lower papyraced Schists - **Aquitard**	
Cretaceous - Jurassic	**Upper Cretaceous**	Upper sandstone	sandstone of Im Wouagar	Marine Facieses
		Mid-Senonian	Cly of Doutchi Zana - **Aquitard**	
		Mid-Senonian (Lower sandstone)	Bouza Silts	
		Lower Senonian	Lower Sénonien clay - **Aquitard**	
		Turonian	White limestone	White limestone
		Cenomano-Turonian	Senomano-turonian clay - **Aquitard**	
	Lower Cretaceous	Continental intercalaire (Jurassic-Albian)	Continental Hamadien	CH
		Aquifer	Farak clay	
			Tégama sandstone	Ci
Trias-Jurassic – Precambrian		Trias-Jurassic – Precambrian / **Aquitard**	Argile de l'Irhazer / Socle	Substratum
Paleozoic				

III.1.4. Stratigraphic log adopted in Nigeria

The stratigraphic log adopted in Nigeria is described by the Sokoto[7] hydrogeologic map. This log is described as follows:

7 JICA (1990) : The study Groundwater Development in Sokoto State, 1990.

The lithological description of these layers helps to understand their hydro geologic particularities useful for their classification in aquifers layers and in aquitards.

Geological era	Layer	Group	Formation	thickness (m)	Lithology
Quaternary	Actual and Pleistocene			0 - 15	Silts and sands with gravel (valleys)
Tertiary	Post-Eocene et Eocene		Gwandu	0 – 300+	Sands and clay sub-consolidated with clay and black marl
	Palaeocene	Sokoto	Kalambaina	0 – 50+	Clay limestone sub-consolidated with plastic clay
			Dange	0 - 40+	Blue to grey clay with phosphates nodules ans thin limestone shelves
Cretaceous	Upper Cretaceous	Rima	Wurno	0 – 45+	Little consolidated sands stratified with clay and marl
			Dukamaje	0 - 30	Blackish fossilised marl with thin layers of limestone
			Taloka	0 – 200+	Fine to mid-sands sub-consolidated with clay and conglomerate with lignite
	unconformity				
	Lower Cretaceous		Gundumi & Illo	0 – 300+	Sands and sandstones little consolidated with clay and conglomerate
Ante-Cretaceous	unconformity				
	Substratum				Granite-gneiss, phyllithes and quartz

- **Superficial deposits** (Quaternary) correspond to the most recent geological layers. These deposits result from a hydraulic thrusting (river and lacustrian environment) or from local evolution (laterisation).

- **Tertiary** (Paleocene and Post Eocene and Eocene): corresponds to the Continental terminal well-represented by the **Gwandou Layer** which constitutes a sandy aquifer level. These sands are frequently fine to coarse cemented by limonite and in alternation with layers of modules of limonite. These layers show lignite black clay layers. The basis of the Tertiary is constituted of the "Sokoto Group" made up of:

- **Kalambaina Formation** (Paleocene Post) comes as marl limestone semi-consolidated with plastic clay and marl. This layer is aquifer; it is captured by wells and results in sources on the outcrop surface,
- **Dange Formation** (Paleocene) made up of bluish, semi-consolidated sandstone with plastic clay and phosphates nodules and thin calcareous layers. Aquifer level with a specific weak flow.

- **Cretaceous superior** corresponds to **Rima Group** represented by the following three layers:

- **Wurno Formation** (Cretaceous Superior and Maestrichtian?): with a thickness not exceeding 50m, this layer is aquifer and frequently spurting;
- **Dukamje Formation** (Cretaceous superior): blackish fossiliferous marl with thin calcareous layers. Its thickness does not exceed 30m.
- **Taloka Formation** Cretaceous Superior) : fine to mid-sands, semi-consolidated with clay and conglomerate with lignite. Its thickness can reach 200m.

- **Cretaceous Inferior** corresponds to the Continental intercalary/ Continental hamadian constituted of **Gundumi & Illo layer** in the shape of fine to coarse sands with clay and conglomerate towards the basis. Its thickness can reach 300m.

In this sedimentary set – which majority is continental – two groups come out:

- **A basic group** (Cretaceous – Jurassic), within which we find the following three aquifer levels (from bottom to top) : Gundumi and Illo layer, Taloka layer and Womo layer which importance varies according to the extension of the layer and its thickness. In this group, the two aquifer levels Taloka and Womo, together in the "Rima Group" have a particular importance in the Sokoto basin. Hence, the Cretaceous superior, which constitutes in Niger and Mali an aquifer layer of a lesser importance, is vital in Nigeria for the Sokoto region.
- **A superior group** (Tertiary –Quaternary) corresponding to the post Eocene layers, it includes the two aquifer levels of the Gwandu layer and the quaternary Alluvia. This aquifer group is separated from that of the basis by sedimentary layers of the "Sokoto Group" (Paleocene, Eocene).

The two major IAS aquifers (Intercalary Continental and Continental Terminal) are separated in the North of the basin, in Mali, by a thick sedimentary layer mainly marine of the Superior Cretaceous. This layer has in the centre of the basin (Niger) and in the South (Nigeria), intermediary aquifer levels, of a secondary importance as to the major aquifers. As a result, the aquiclude thickness, which is common to the whole basin and which separate these two ground waters, is in some places, relatively reduced to the point of showing in the long term, hydraulic exchanges by drainage.

Stratigraphic log adopted by the IAS

The IAS stratigraphic log type shows notable variations in the thickness and the lithologic nature of the layers constituting the aquifer levels or their aquitards. Because of the need to ensure the hydraulic continuity between the different parts of the basin from one country to another within the IAS, the best plan to represent this aquifer system is to consider the following configuration:

- **A first generalized aquifer level** of the Continental Terminal (CT) grouping the aquifer layers of the Tertiary, (CT1, CT2, CT3) and also integrating the ground waters of the quaternary alluvia (fig. 6),
- **an aquitard** mainly made up of Paleocene and Eocene layers and which includes (in Mali, for example) part of the Superior Cretaceous,
- **a second inferior aquifer level** in the Continental intercalaire (Ci) and grouping locally the superior level of the Inferior Cretaceous (IC3) or Continental hamadian.

Thus, the IAS will be, at a first stage of its conceptualisation, a "bilayer" of a regional extension of a depression structure with a thickening of the layers in the centre and a reduction of the thickness around the borders. This bilayer configuration can be detailed later, in "multi-layer" depending on the availability of data in each country.

The basis of this aquifer system is made up of the Birrimian shelf in Mali, the Irhazer clay (in the North) and the undifferentiated shelf (in the South) in Niger, the Precambrian shelf in Nigeria.

The two major aquifer layers thus individualized, are separated by little permeable layers (schists, marl limestone, clay limestone) of the superior Cretaceous (Cenomanian – Maestrichtian), Paleocene, Eocene and Oligocene which aquifer role is not evident and the lateral continuity is not ensured. Hence the decision to consider them, at a first stage, as a semi-impermeable or aquiclude ensuring the top of the inferior aquifer level and the partition of the superior aquifer level.

Age		Mali Groupe	Mali Formation	Niger Groupe	Niger Formation	Nigeria Groupe	Nigeria Formation
Quaternary		Quaternary	Alluvia, dunes **Aquifer**	Quaternary	Alluvia, dunes **Aquifer**	Quaternary	Alluvium **Aquifer**
Tertiary	**Pliocene**	Continental Terminal	Sand sandstone and clay	Continental Terminal CT_3	Mid Niger sandstone clay layer **(Aquifer)**	Continental Terminal	Gwandu
			Aquifer				**Aquifer**
	Miocene			Continental Terminal CT_2	Sandy clay with lignite layer - **Aquifer**		
	Oligocene			Continental Terminal CT_1	Siderolithic - **Aquifer**		
	Eocene	Mid-Eocene	schists		Schists papyracés supérieurs - **Aquitard**	Sokoto	Kalambaina
	Paleocene	Paleocene terminal	Lime stone marl sandy with phosphates level	Formation of Garadawa	limestone - **Aquifer**		
		Paleocene inferior	Limestone sand	Marine Paleocene	Schists papyracés inférieurs - **Aquitard**		Dange **Aquitard**
Cretaceous- Jurassic	**Upper Cretaceous**	Maestrichtian - Cenomanian	Sandstone clay **Aquifer**	Superior Sandstone	Im Wouagar sandstone	Rima (Mæstrichtian)	Wurno **Aquifer**
				Mid-Senonian	Doutchi Zana clay - **Aquitard**		
				Mid-Senonian ((inferior sandstone)	Bouza silts		Taloka
				Inferior senonian	Inferior Senonian clay - **Aquitard**		**Aquifer**
				Turonian	White limestone		
				Cenomano-turonian	Senomano-turonian clays - **Aquitard**		
	Lower Cretaceous	Continental intercalaire	Grès quartzitique, micro-conglomératique, arkoses, sable, argiles Tégama	Continental intercalaire (Jurassique-Albien)	Continental Hamadian	Continental intercalaire / Continental Hamadian	Gundumi & Illo
			Aquifere	**Aquifer**	Farak clay		**Aquifer**
					Tegama sandstone		
Trias-Jurassique - Précambrien				Trias-Jurassic – Pre-Cambrian / **Aquitard**	Irazer clay/Shelf	Precambrian	
Paléozoïque		Precambrian	Birrimian				

In the same direction as the simplification of the overall structure caused by the lack of specific data, it was decided to integrate the Maestrichtian in Niger (Rima Group), (which has two aquifer levels (Wurno and Taloka) separated in places by the Dukamaje lenticulary clays) in the intercalary continental, as it is the case of the Continental hamadian in Niger.

This need for simplification also concerns the continental Terminal which is subdivided in Niger into three aquifer layers and into one aquifer layer in Mali and Nigeria (Gwandu).

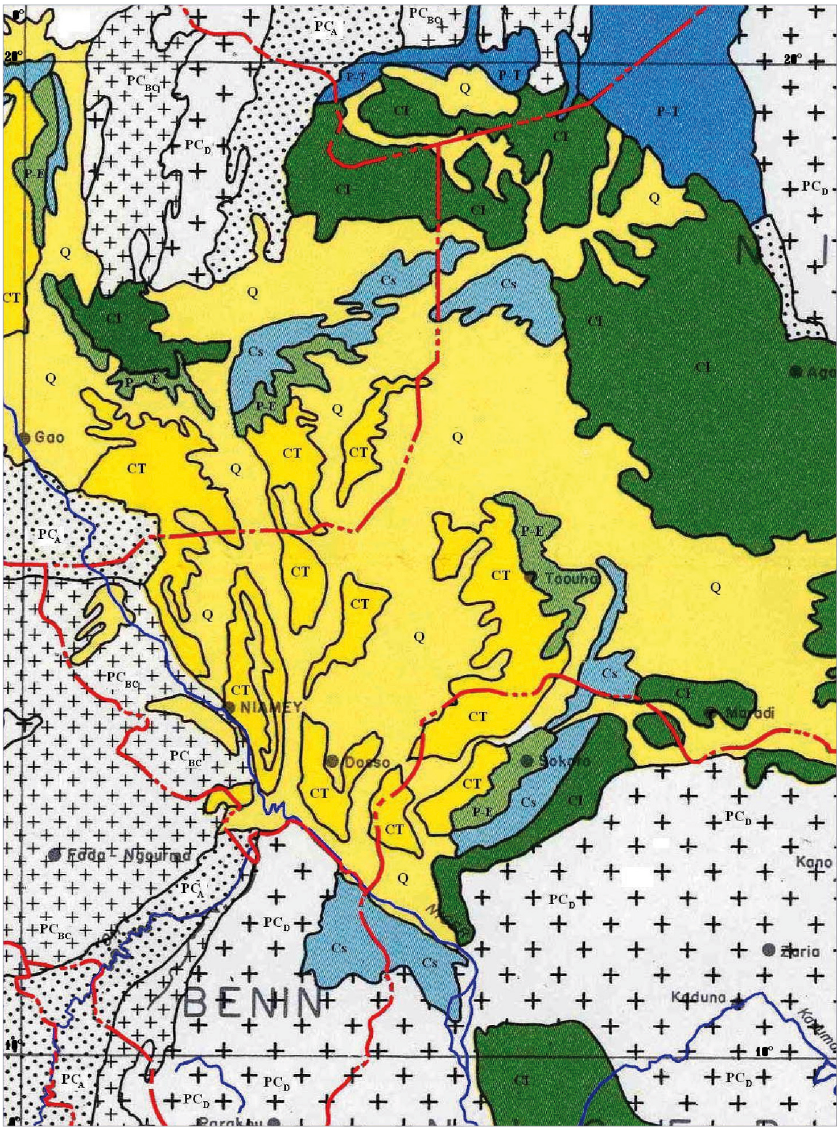


FIGURE 6 : Affleurement des principales formations géologiques du SAI

ORIENTATION FOR IAS MODELING

Due to the limited availability of specific data for each IAS aquifer lave land to the need to be at that stage, on the scale of the whole basin, the IAS hydro geologic pattern was conceived as follows:

- **FIRST STAGE**: a global bilayer model (Continental intercalary and Continental terminal) which continuity is ensured in the three countries. This model will serve as a basis to the implementation of the hydrodynamic assessment of the system and the inter-influences on each side of the frontiers. It will be the reference for the local models concerning limitation conditions, as much as needed.
- **SECOND STAGE**: multi-layer local models to take into consideration the aquifer specificities in each country. Thus, the Continental terminal will be detailed in Niger, the secondary aquifers of the superior Cretaceous will be considered in Mali, Niger and Nigeria.

In the Sokoto basin, the option to individualise the aquifer levels (Gundumi, Rima and Gwandu) is largely dependent on the availability of specific information at each aquifer level.

It is clear that this process of the IAS hydraulic schematisation is induced by the insufficiency of information necessary to the realization of a multilayer hydrodynamic model which highlights the specificities of each level in the three countries. This very objective does not seem practicable as far as the continuity of the layers is not ensured and we have to go through a certain joint schematisation.

At this stage of the study, the schematisation adopted ensures the achievement of a rather reliable hydro geologic outcome which shows the major variables of the system, namely: the entrances, the releases and the theoretical reserves. Now the precision of those elements of the assessment is itself a very important objective to show the distribution of the aquifer system resources among the three countries.

On the other hand, the model thus elaborated can provide with an acceptable precision, the major element other assessment In a way to better understand the weakness of the model as to the variations of each element of the assessment. This aspect is also very important and helps appreciate the tendencies of the terms evolution due to the development of the takings.

These data helped define the aquifers geometry and the IAS conceptual model. The general structure of the model adopted at the end of the conceptual elaboration (Fig.7) has two aquifer layers separated by an aquitard.

Figure 7 : General structure of the IAS model

With this overall structure relatively simple and realistic conditions of exchange between the model an its environment, remain to be specified. These conditions are mainly linked to the geographic extensions of each of the aquifer layers and aquicludes, to the system's entrances, mainly its localized supply (river Niger and Dallols), its natural releases represented by the exchanges with the river Niger and those within the aquifer system under the influence of the drainage and the differential pressures. These different aspects were largely discussed with the hydro geologists of the countries; they were also subjected to several wedging attempts in order to end up in the most realistic situation.

III.2. Extension and delimitation of the layers

The delimitation of the geological layers in the Iullemeden basin is carried out on the basis of their extension on the geological maps representing the outcrop zones of these layers. In case the layer's limits are not outcropped, or their continuity is interrupted by a fault, the appeal to geological correlations is very frequent to make plausible hypotheses about this delimitation.

This spatial expansion also contains the dimension "thickness" of the layer and its "lateral passages of facieses". For this, the structural maps (roof, wall and thickness of layers) are of a great use. They help to show the thickness variations as well as the extension limits.

This spatial delimitation was not carried out only on the basis of the lithological criterion, but also of that of the differentiation of the layer in "aquifer" or "aquiclude". This is mainly the case of the individualized intercalary continental layers in the study zone of the following three major layers:

- Agadès sandstone (Ci 1) which extension is limited to the oriental part of the basin,
- Irhazer clays (Ci 2) considered as the stratum of the intercalary Continental in the oriental part of the basin (Niger),
- Tégama sandstones (Ci 3) constituting the aquifer layer of the intercalary Continental in the Iullemeden.

Delimitation of the extension of the major aquifer levels

This delimitation is analysed with the lithostratigraphic correlations moving through several drillings having tallied water grounds in the IAS sedimentary layers. This analysis is carried out thanks to the geological sections we realized (Fig.8) and those presented in the earlier studies.

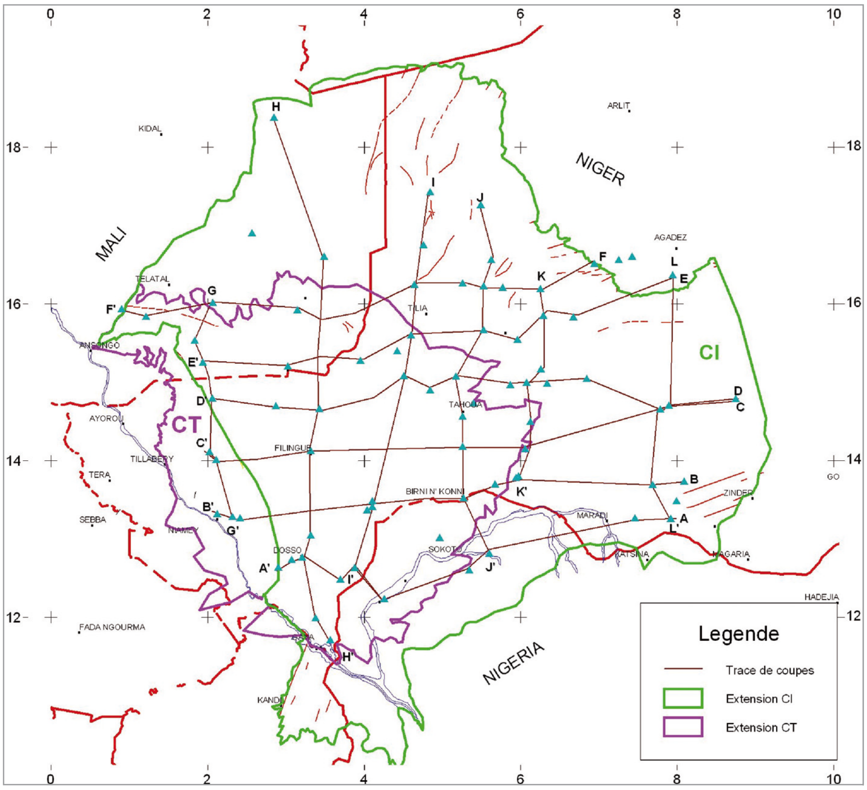
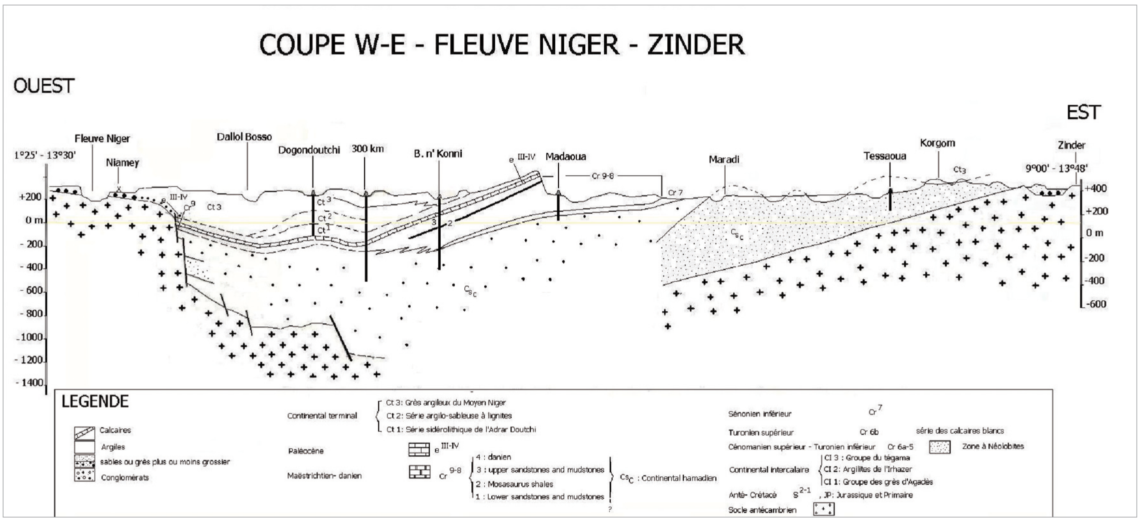


Figure 8 : drawing of the geological sections

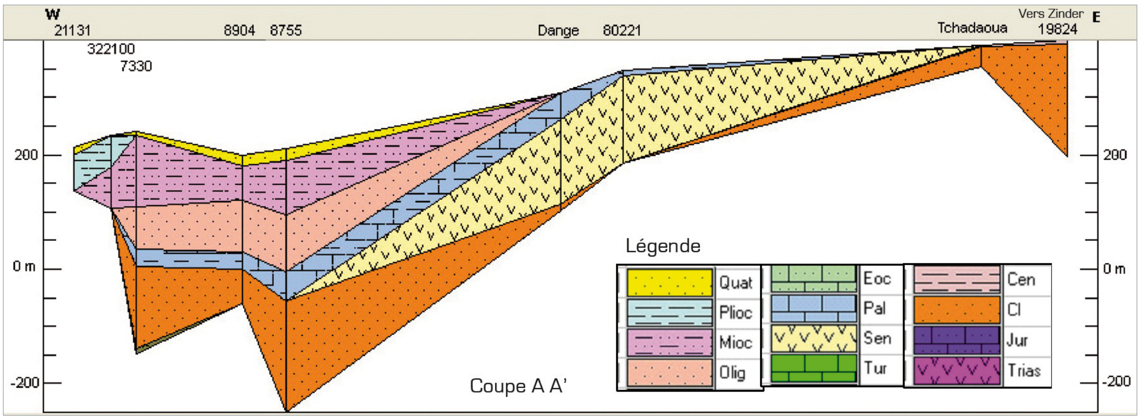
W-E litho-stratigraphic correlations between river Niger and Zinder

These correlations starting from the West of the shelf's outcrops (Fig.8), opens up in the East on the widening surface of the intercalary Continental outcrops (mainly the Agades sandstones and the Irhazer clays, between Maradi and Zinder) (Fig 8a, b, and c). The Abrardoutch cliff shows the northern and oriental limits of the terminal Continental (Fig 8a). This section shows the role of the sedimentation of the different IAS levels as well as the difficulty to estimate the thickness of the Continental intercalary (Tegama sandstone) in the centre of the basin (Fig.8a, b and c) where the drillings do not cross all its thickness.

a



b



c

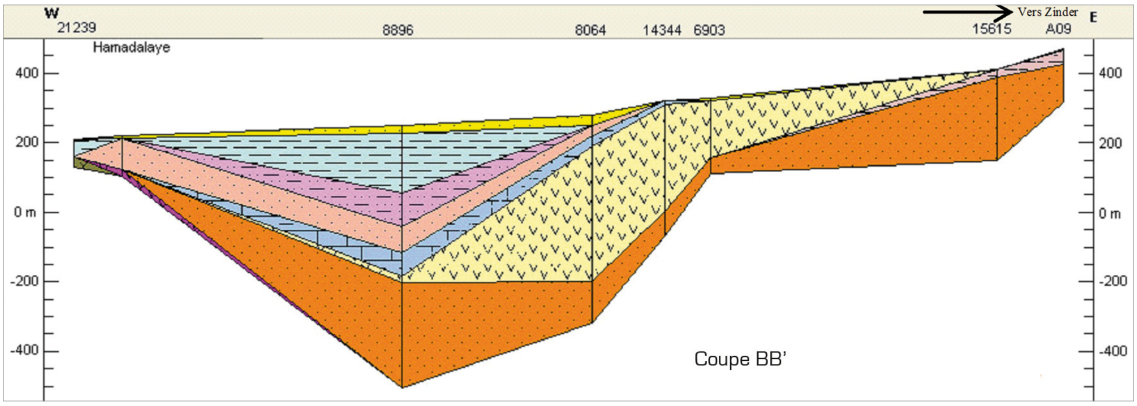


Figure 9 : (a, b, c) W-E section between river Niger and Zinder

⏩ SW-NE litho-stratigraphic correlations between river Niger and Agades

This correlation explains at best the depression aspect of the IAS and shows that the Superior Cretaceous develops in the centre of the basin, but is non-existent in the occidental part. The Continental Terminal is lenticulary and develops between the two Dallols Maouri and Bosso (fig. 10).

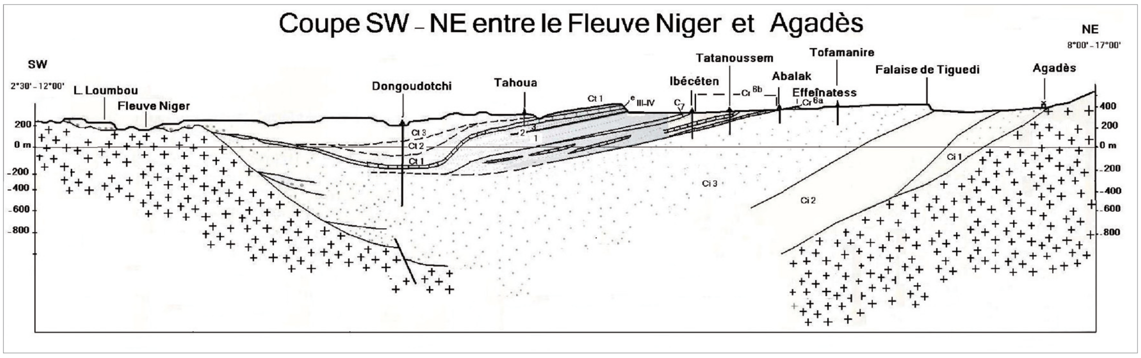


Figure 10 : SW-NE section between river Niger and Agades.

⏩ W-E litho-stratigraphic correlations between the river Niger and Gournache (drilling 23882)

These two sections also illustrate the IAS depression morphology in Fig. 10. the Superior Cretaceous layers disappear in the East of the basin where the Continental Intercalary is in outcrop (Fig.11a and b). The recent data clarifies the thickness of the Continental Intercalary in the western part of the basin, the combretom Cenomanian crossing the Ci in all its thickness (fig.11b).

The Cenomanian and Turonian layers, absent in the South (fig.11a), appear in the North, from the drawing of the scion W-E3 (fig.11b).

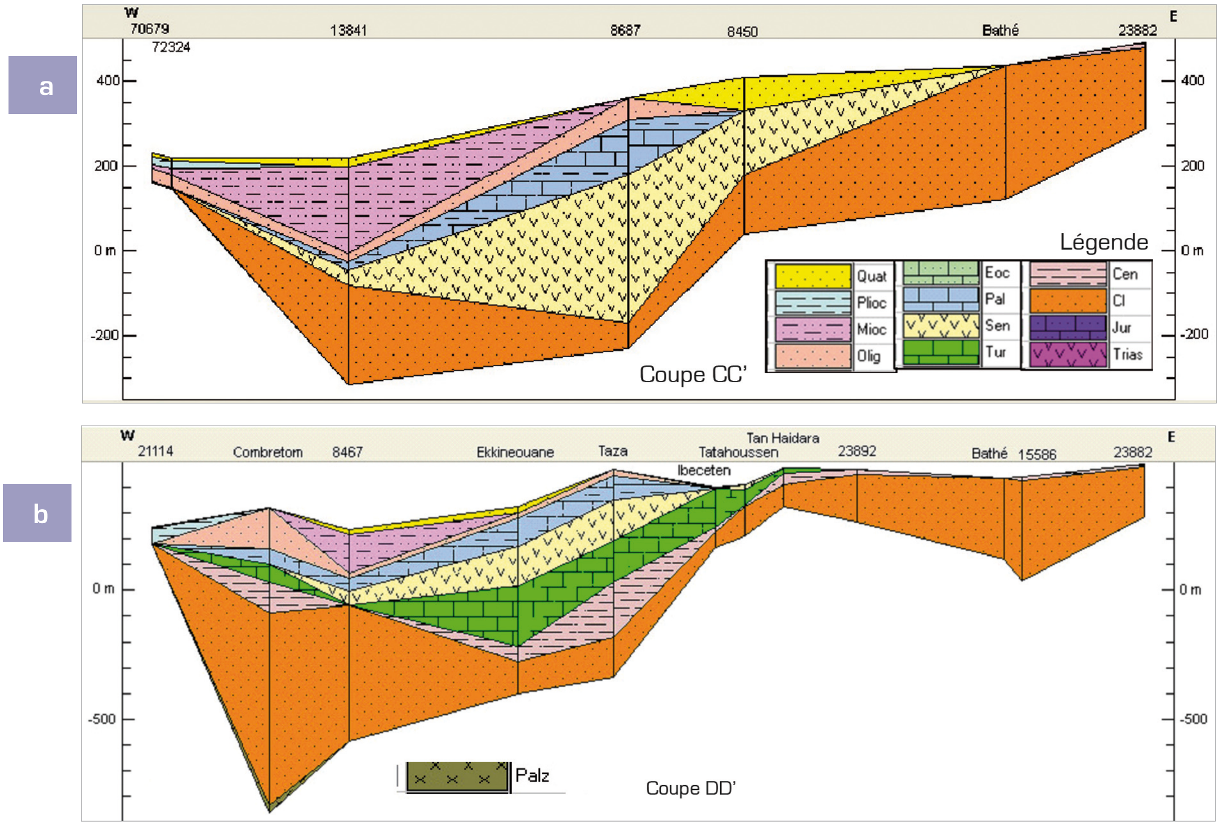
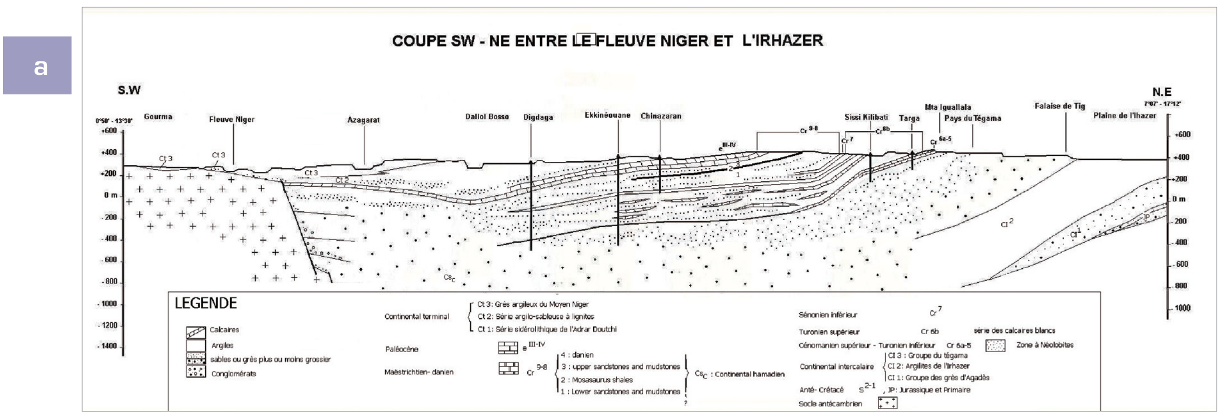


Figure 11 : (a & b) W-E section between the river Niger and Agades

SW-NE and W-E litho-stratigraphic correlations between the river Niger and Irhaze

These correlations confirm the IAS depression structure and show that the Tegama sandstones, considering their thickness, made up the majority of the aquifer sedimentation of the aquifer (fig.12a, b and c). It also underlines the relative importance of the marine sedimentation of the superior Cretaceous (Continental hamadian) between the two cliffs of Tigueddi and Abrar Doutchi (fig.12a). The effect of the regional fault parallel to shelf outcrop in the occidental part of the basin results in a waterproof limit between the IAS aquifer and this shelf (fig.12a). The basin is limited in its eastern part by the Jurassic outcrops (fig.12b and c).



b

c

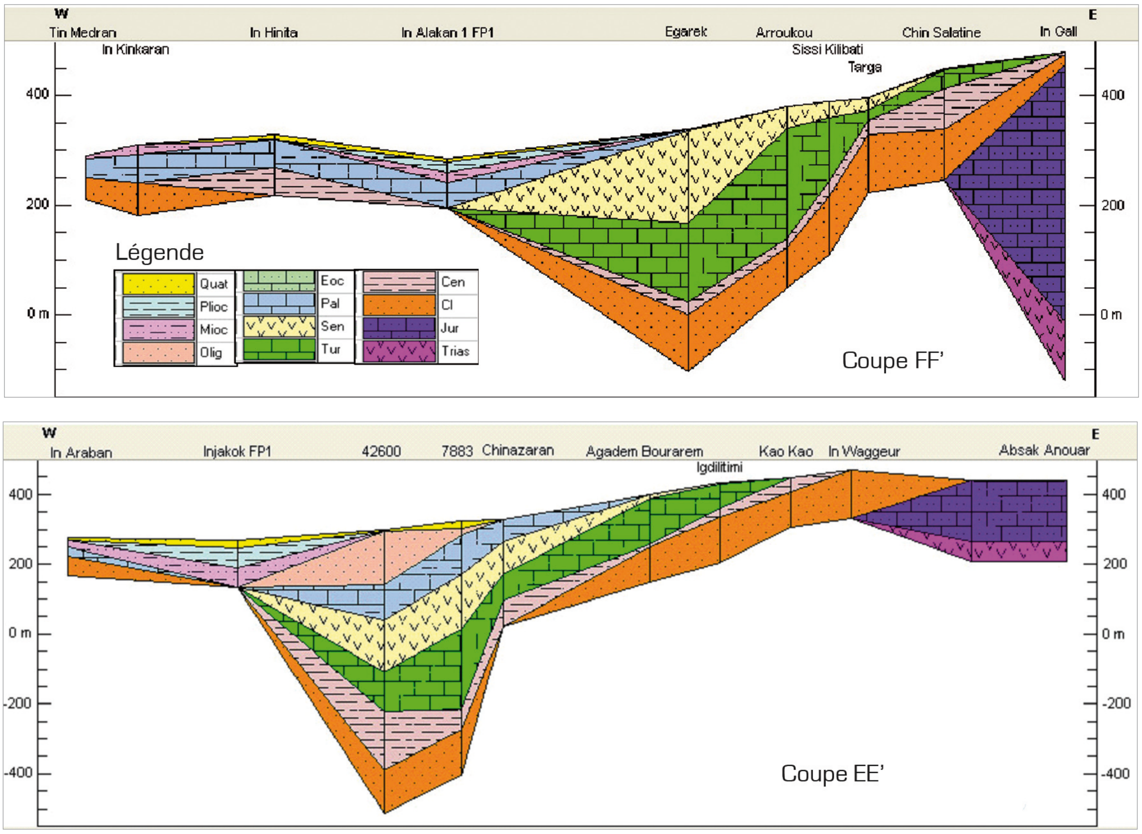
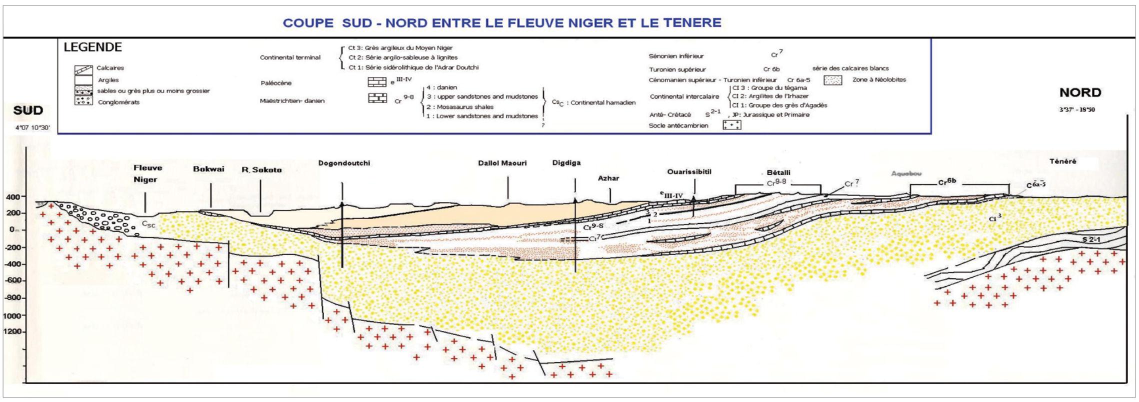


FIGURE 12 : (a; b & c) SW-NE and W-E section between the river Niger and Irhazer

⏩ S-N litho-stratigraphic correlations between the river Niger and the Tenere

These correlations underline the continuity of the Intercalary Continental (Tegama sandstones) on the circumference of the basin and they also show the disappearance of the Superior Cretaceous layers in the South and their thickening in the North (fig.13 a, b, c). The plans of fig.12a and the N-54 and N-55 sections show perfectly well the depression structure of the aquifer. In the occidental part of the basin, the limit between the intercalary Continental and the Continental Terminal is marked on the N-56 section by the disappearance of the Ci layers in the South, where the CT layers are stacked in the Precambrian shelf (Fig. 13d).

a



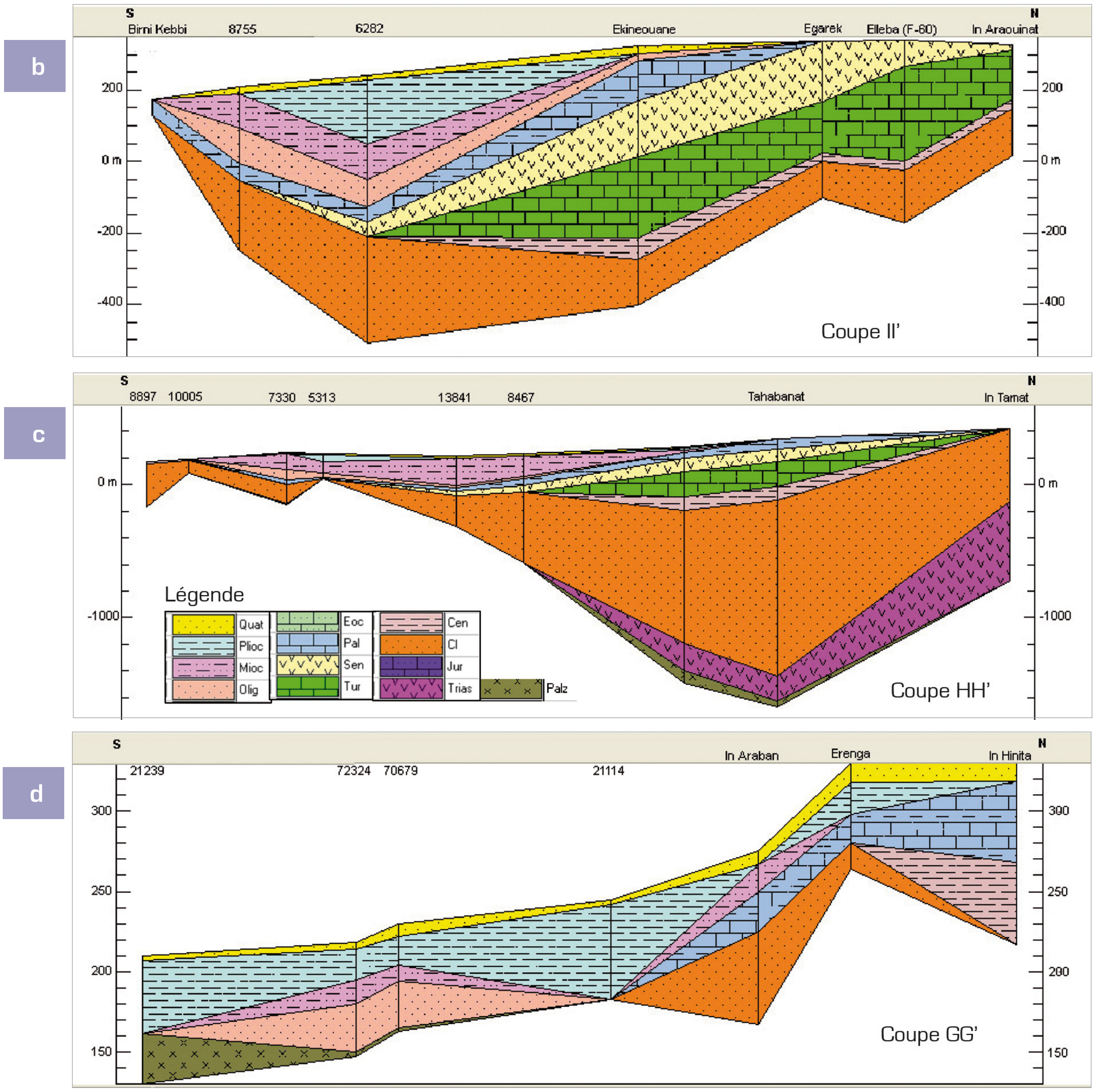
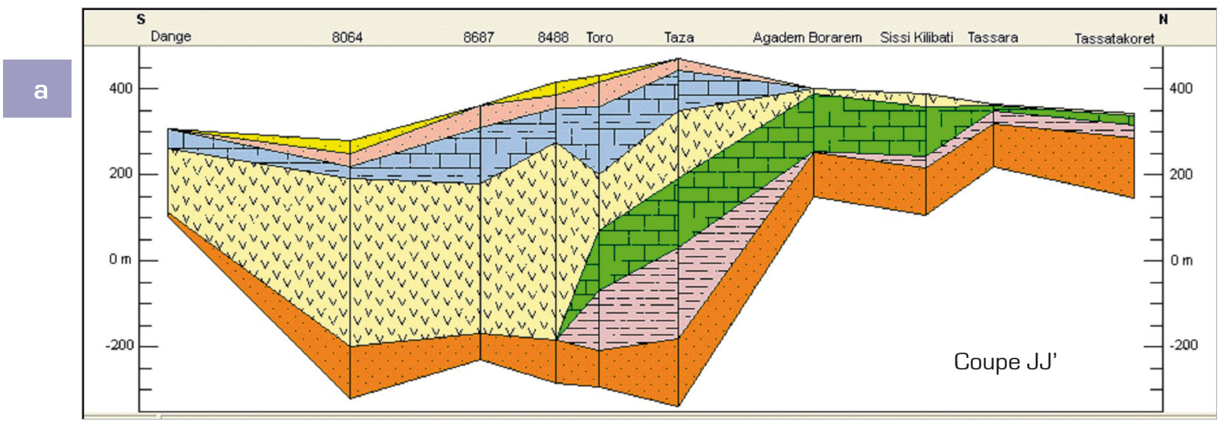


Figure 13 : (a, b, c & d) S-N sections between the river Niger and the Tenere

S-N litho-stratigraphic correlations between the river Rima and the Tessatakoret Chin Salatine villages

The depression structure is also highlighted in this part of the basin (Fig.14a).The limits between the intercalary Continental layers and those of the Continental Terminal are marked by the exten-



sion limits of the Continental Terminal in the North (Fig.14a and b). In the Eastern part of the basin, the CT layers are absent. The extension limits of the Ci are marked by the outcrops of the Jurassic layers (Fig.14c).

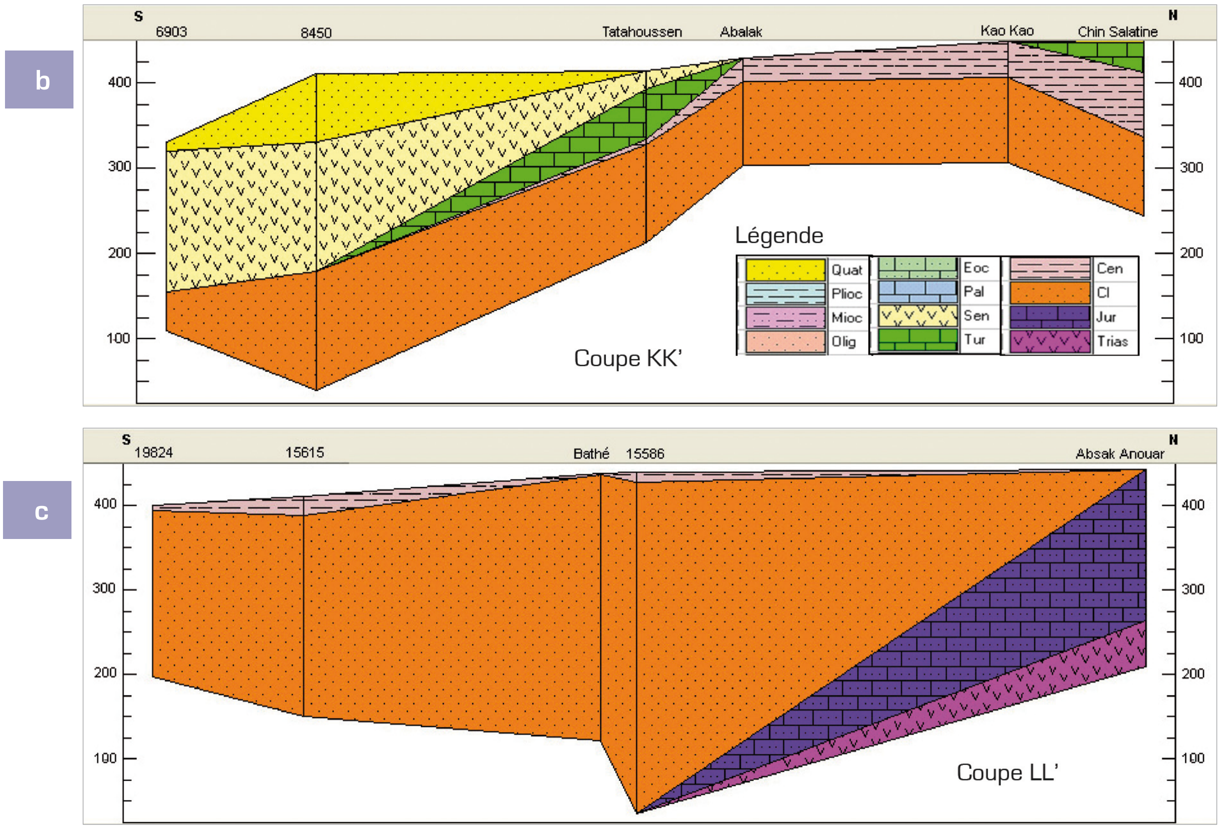


Figure 14 : (a, b & c) S-N sections between the river Rima and the Tessatakoret and Chin Salatine

It is clear, from all these correlations that the synclinal depression is a tectonic one, which occidental side largely affected by a regional fault with a plan parallel to the river Niger stream. The three Lower Cretaceous layers (Agades sandstones, Irhazer clays and Tegama sandstones) contribute to the groundwater flow of the intercalaire Continental aquifer only through the Tegama sandstones. Under the oriental part of the basin, the Irhazer clays make up the substratum of the Iullemeden aquifer system. The upper Cretaceous layers (Continental hamadian) have some hydrogeological importance only in Niger and in Mali where they thicken and expand. In the South (Nigeria), they do not have any hydrogeological role. Similarly, the Continental Terminal aquifer layers have a limited role to the central part of the basin (Niger) and if necessary in the North (Mali).

Figure 15 : extension of the two Ci and CT layers

On the basis of this structural analysis, the geographical extension of the both major IAS aquifers is represented on a map (Fig.15).The **CT extension** is about **203 000 km²** and that of the **Ci** is of **500 000 km²**. In the occidental part of the basin, the CT layers are directly stacked in the Pre-cambrian shelf (Gourma).

III.3. Calculation of CT and Ci reserve

On the basis of a hundred geological sections selected in the geological database, it was possible to estimate the CT and Ci thickness layers. The CT thickness results the substraction of the partition slopes from the CT roof, read on stratigraphic logs. Hence, the average **thickness of the CT** layer was evaluated to **130m** and that of the **Ci** layer to **200m**.

Knowing that the CT surface is of 203 296 km², the product of the average thickness and of the surface supply a volume of 2 64285 x 10^{13} m^3 (2600 billions m^3). The Ci surface being of 484 443 km², the volume of water contained in this aquifer is of 9 72886x10^{13} m^3 (9700 billions m^3).

The efficient porosity remains an unknown facto rand apparently highly variable, at least in the Kori-Dantiandou, aquifer system in the East of Niamey. The only two efficient measures of porosity, are of 1% in Banikane (2°37'29"E,13°35'10"N) and 15% in Banizoumbou. These values allow some freedom of appreciation of an efficient porosity. It is thus difficult to decide if this is an expression of the extreme variability of the aquifer or just wrong measures (Massuel 2006).

Besides "the estimation of the reserves can be achieved through the destoring calculation by reduction: expressed by the flow equations and the assessment of the term [S.dh/dt] in confined aquifers, or [e.dh/dt] in the condition of free aquifers. The contribution of the reserves is thus proportional to the reduction speed, and with equal reduction it depends on the storage coefficient. We can easily understand that the contribution of the reserves be dominating in the regions where the aquifer contains a free surface groundwater: indeed, the ratios of importance of the captive storage coefficients and the porosities is generally between 1 and 500 or even more" OSS (2002).

It is hence considered that in a free water table, the storage coefficient amounts to the efficient porosity. The map of the storage coefficients of the IAS models shows – in the free water table parts- a ratio of 4% in the CT and Ci aquifers (Fig. 16a and b); we will adopt in our calculation this ratio of 4 % as that of the efficient porosity.

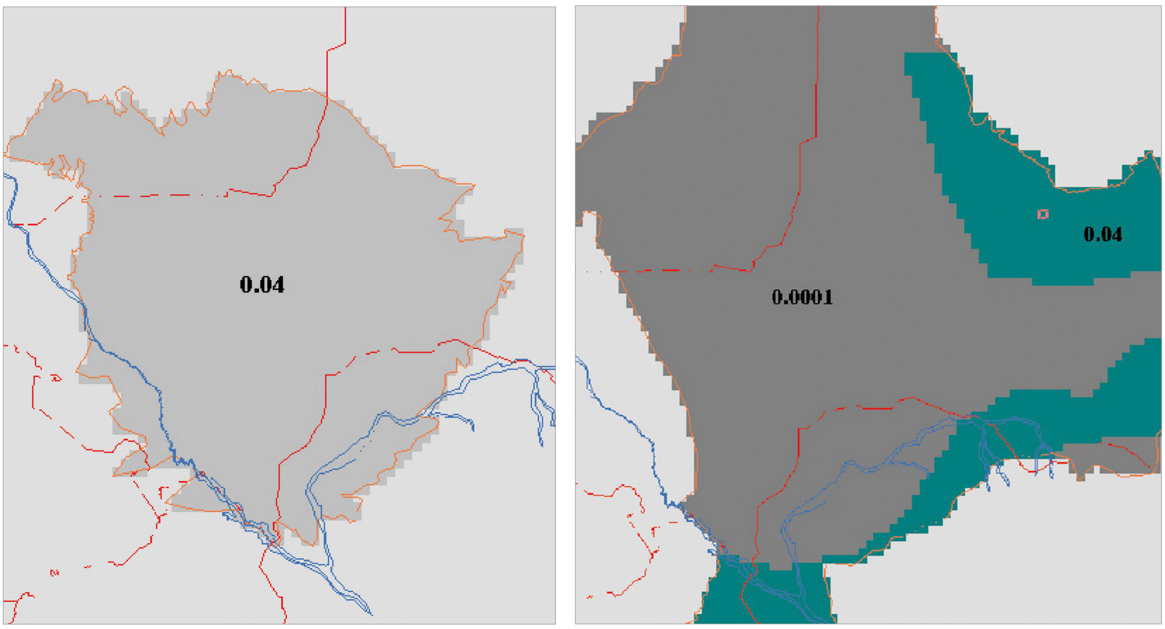


Figure 16 : Storage coefficients of CT(a) and Ci(b) after calibration

Considering an efficient porosity of 4%, we can estimate the Ci reserves at ($9,72886\times10^{13}$ m^3 × 4/100) = 3891x109m^3. With an average annual flow of natural refill of 0,05x109 m^3/year, the Ci groundwater renewal rate is of 1 28.10-5; or a duration of about 77820 years

For the same efficient porosity ratio (4%), the CT reserves are estimated at ($2,64285\times10^{13}$ m^3 × 4/100) = 1057x$10^9$$m^3$. With an average annual flow of natural refill of 0,103x109 m3/year the renewal rate of the Ci water table is of 9,74.10-5; or a duration of about 10262 years.

These results were summed up in the chart 1 below:

Aquifer reservoir	Average water volume (10^9 m^3) S	Mid-flow (10^9 m^3) Q	Renewal duration (years) S / Q	Renewal rate Q / S
Continental intercalaire	3 891	0.05	77 820	$1,28 .10^{-5}$
Continental terminal	1 057	0.103	10 262	$9,74 .10^{-5}$

Table 1 : reserves calculation of the IAS

.

IV. CONSTRUCTION OF THE MODEL

The construction of the mathematical model for the simulation of the groundwater aquifer development is a process based on the following steps:

- discretisation of the space to be simulated and the construction of a representative structure;
- definition of the physical data (layers, conditions to limits, connections...);
- preparation of the hydrogeologic data (supply, piezometry, exploitation).

The discretisation of the space is in accordance with the procedure imposed by the software "PM5", by referring to a geo-referential map which helps to distinguish the model's structure of the map grid.

The preparation of the physical and hydro geological data is undertaken following the "PM5" procedure which specifies the format of each parameter. The shaping of this information is undertaken within the database. The passage from the database to the model is governed by the connection of the data importation and the release of results.

IV.1. The hydrogeological scheme of the model

The general structure of the model adopted after elaboration of the conceptual model (Fig.1) has two aquifer layers (the Continental Terminal and the Continental intercalaire) separated by an aquiclude. The extension of the layers is defined within the hydrogeological limits of the aquifer layers. The geometry of the model's entity is defined by the sub-permeable and the roofs and partitions of the aquifers.

IV.2. Discretisation of the space and construction of the model's grid

The field of study was discretised in a pattern representing a regular square cells of 10x10 km, representing for each layer:

Continental Terminal :	2 030 mailles
Continental intercalaire :	4 860 mailles

Or a total of 6890 cells over a modelised surface of almost 689 000 km^2. The meshing of the two layers of the model is represented in Fig.17 and 18 (page 44).

As to the sub-permeable layers, they are represented by the vertical flows which cross them under the effect of the difference of charges between the aquifer layers: the drainage flows. We use an almost three-dimensional model with the "multi-layer hypothesis" according to which the flows of the sub-permeable (aquiclude) are strictly vertical , when we consider that the flows in the major aquifers are horizontal. We demonstrate that this hypothesis is largely verified when the contrast of permeability between adjacent layers (aquifer/aquiclude) is important: a ratio of 104 is sufficient. This is the case in the IAS where the studies achieved (Niger) set the Cenomanian vertical permeability- Mid Eocene around 2.5*10-10 m/s(ETH,1999). In these conditions,

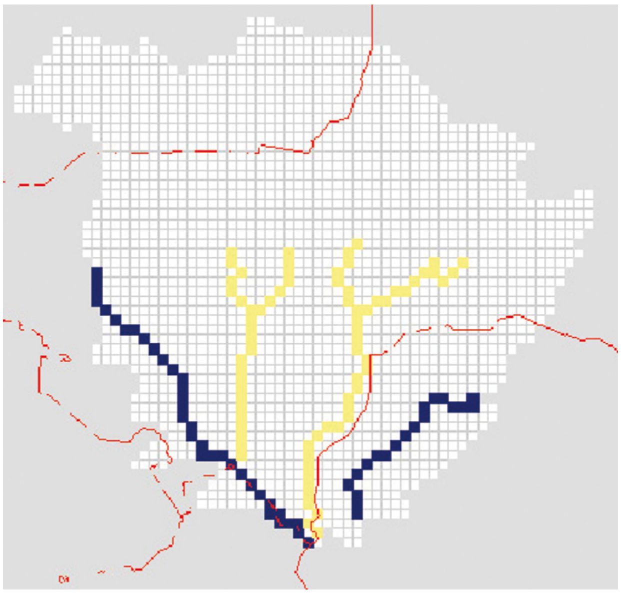


Figure 17 : the CT meshing

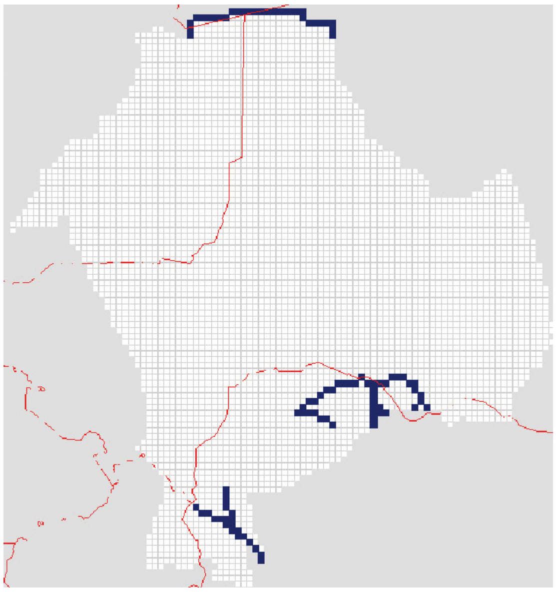


Figure 18 : the Ci meshing

the general equation of the flow in the multi-layer, which makes up the IAS mathematical model-is broken down as follows:

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial h}{\partial x}\right)\frac{\partial}{\partial y}\left(T_y\frac{\partial h}{\partial y}\right)+q_H+q_B=S\frac{\partial h}{\partial t}+q$$

$$q_H=K_v\frac{H_H-H_C}{e_H}$$

$$q_B=K_v\frac{H_B-H_C}{e_B}$$

Tx is theTransmissivity of the l'aquifer according to Ox
Ty is the Transmissivity of the aquifer according t Oy
Ox and Oy are the major axes of t anisotropy
Qh is the major specific drainage flow towards the top
qB is the specific drainage flow towards the bottom
h is the hydraulic charge in the aquifer
HH is the hydraulic charge in the superior aquifer
HB is the hydraulic charge in the inferior aquifer
Kv is the vertical permeability of the semi-permeable layer

IV.3. Boundary Conditions

According to the modeling of their hydrodynamic functioning, the groundwater aquifers are conceived as in contact with their environment through exchanges. These exchanges are either "inflow" (recharge, leakage) or "outflow" (exploitation, evaporation, evapotranspiration). The transfers within the system are also lateral and vertical exchanges (leakage) of flows or solutions. Boundary Conditions which characterise the aquifer system, are defined through the totality of these exchanges.

The three classical boundaries conditions adopted in our model are:

- the fixed heads (Dirichlet condition);
- the fixed flow, nil or otherwise, (Neumann condition);
- the drain or the fixed potential through a resistance (Caushy condition).

In this perspective, the condition of the fixed potential in the IAS in the river Niger where the hydraulic charges were fixed to evaluate the exchanges between the river and the aquifers. This condition is also applied in the North of the basin in the Ci aquifer to evaluate the inflow from bordering Paleozoic aquifers.

- The condition of “drain“ or “the fixed potential through a resistance“ quite frequently concern emergences on the surface resulting from the hydrodynamic development of the aquifer. In case of the IAS, the condition of drain was applied in the Dallols which drains the CT underlying aquifer, which piezometry coincides –at their level- with the water table.
- The condition of the “fixed flow equal to zero ” is used along the impermeable limits of the aquifer system where it do not receives lateral flow. This is also the case of the Ci and the CT which receive no flow from the substratum (Substratum, Irhazer clays and Paleocene for the Ci and Substratum, Paleocene-Eocene for the CT).
- The condition of the ”non nil fixed flow“ is used in the case of the IAS, on the recharge areas of the Ci, as a device of recharge estimation. These flows were calculated using the fixed potentials in these areas during its calibration..

IV.3.1. The aquifers recharge

The aquifer recharge is a major characteristic of the ”inflow” of the aquifer. It must be specific according to its mode (natural by infiltration or artificial by induction) and its duration (continuous, sporadic or temporary).

In the case of the IAS, the recharge of the different aquifer layers is to be considered in its geological dimension to account for the great climatic changes having contributed to the implementation of big water reserves in the system during periods characterized by rainier climates than nowadays.

The current recharge of this system is achieved in two paces:

- a sporadic recharge during rainy and streamely periods which result in the overall outcrops of the permeable aquifer levels and at the level of the temporary puddles.
- a permanent supply along the permanent water courses (River Niger, River Rima an its tributaries which are in a permanent flow).

The evaluation of the IAS aquifers recharge is estimated from recorded rainfalls and the extension of the permeable infiltration areas. The ”climatology“ database is sought through available rainfall records to clarify this aspect. The recharge by direct infiltration of rain water was imposed in the CT layer.

IV.3.2. The natural outlets

The natural outlets of the groundwater aquifers included natural emergences (springs) and permanent water stretches with a hydraulic bond with the water table. In the IAS case, the re is not natural emergences in the basin and the permanent water stretches are limited to the surface water streams (River Niger). It is at this level that we should study the natural ”outflow” of the aquifer system.

IV.3.3. The artificial abstractions (withdrawals)

The artificial abstractions points include water points which tap the aquifers. In the case of the IAS, these sources are:

- traditional dag wells,
- drilled wells with ‘extraction well’,
- boreholes.

Each of these sources has a specific exploitation regime which must be studied and adopted in each of the three countries to evaluate their exploitation.

This aspect has a particular importance in the case of the IAS because of the lack of surveys and follow up chronicles of the exploitation. Only basic statistics relative to the water sources and the pace of their execution are available. The evaluation of this exploitation was achieved according to sections which consider the number of the water sources and the need for water per sector (water supply, livestock watering, irrigation,...). Total withdrawals are represented, in the model, as fixed potential.

IV.4. Hydrodynamic Data

Initial Horizontal Transmissivity values

The transmissivity values which served to initialize the calibration of the model were taken from the rare published documents or extracted by the technicians of the countries from their national databases.

We According to Massuel (2005) the few pumping tests executed in the boreholes tapping the aquifers in the sector of Kori-Dantiandou in the East of Niamey, are to be considered with reserve. Generally the boreholes tap only the first 10m of the aquifer and the duration of the pumping test immediately achieved after the drilling operation, is frequently insufficient. It is usual to observe an auto-development of the borehole during his testing period. We must add to these considerations, the extremely variable lithology of the aquifer.

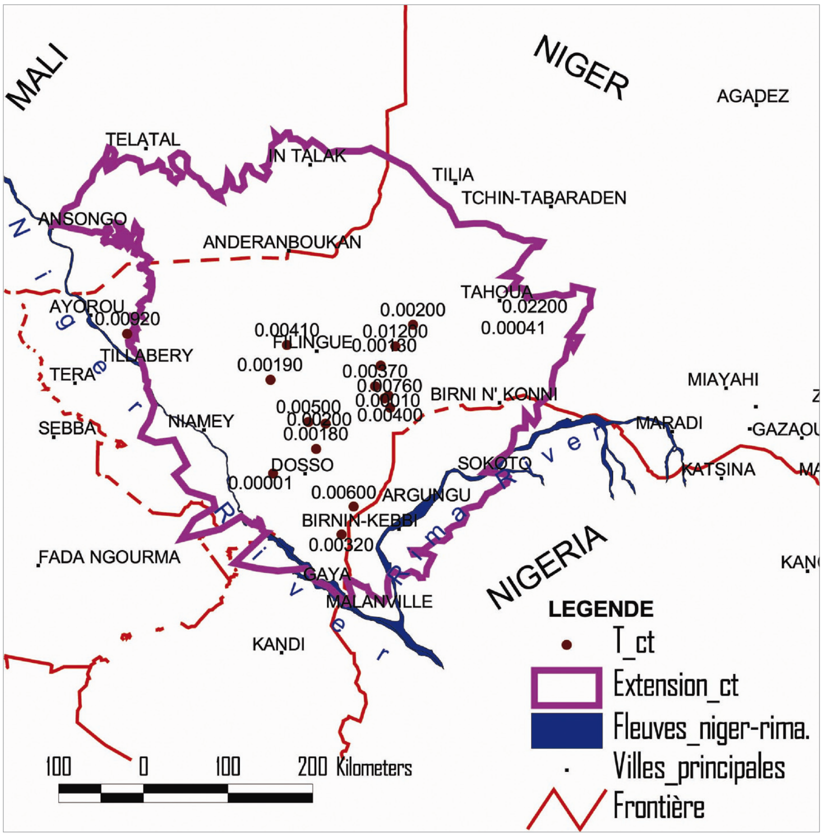


Figure 19 : CT initial transmissivities map

If these sedimentary layers can be considered in some regions as homogeneous, at the local level the presence of clay or sandy lemna can considerably modify the punctual lithological description (unique representatives of the peculiarity). The transmissivity values obtained during the testing flow with no apparent development of the well, vary between 5.10-4 and 1.10^{-3} m²/s. The **transmissivity values** which we have collected in this sector show a proportion of **10^{-3} m²/s**. These same proportions are displayed in the Birnin Kebbi and Filingue zones (Fig. 19).

Concerning the wells, the analyse of the recent pumping tests attempts of longer duration, show that the transmissivity values obtained according the Theis/Jacob' method merge about **6.10^{-5} to 1.10^{-3} m²/s** for deducted permeability of about 10^{-5} to 10^{-4} m/s (Favreau, 2000). With a saturated thickness varying from 10 to 90 m on the Kori – Dantiandou zone, the **permeability** can be evaluated by **available** data between **10^{-6} to 10^{-3} m/s** (Massuel, 2005).

These different transmissivity values added to the database, served as initial ratios for the calibration of the model (Fig. 19 & 20).

Vertical permeability of the aquicludes

The initial vertical transmissivity value of the Cenomanian – Mid-Eocene aquitard is of **10^{-12} m²/s**.

IV.5. Data about the piezometric levels

The hydraulic charge (piezometric level) constitutes the Variable of status of the aquifer system, which the model is to reconstitute at the best of its performance. A good knowledge of this proportion, its distribution in space and its evolution in time is hence elementary for the implementation of the model and the quality of its calibration (OSS, 2003).

The oldest piezometric levels values (dated) are those published by K.F Saad (1969) and FAO (1970). Many other values date from the end of the 1970's (Greigert, 1979) and the 1980's (BRGM, 1988).

To elaborate a piezometric map that we will call « Piezometric map 1970», we studied all the pre-1970's piezometric values, but also those measured at the beginning of the 1970's, even though the precise concordance of this date is not ensured everywhere.

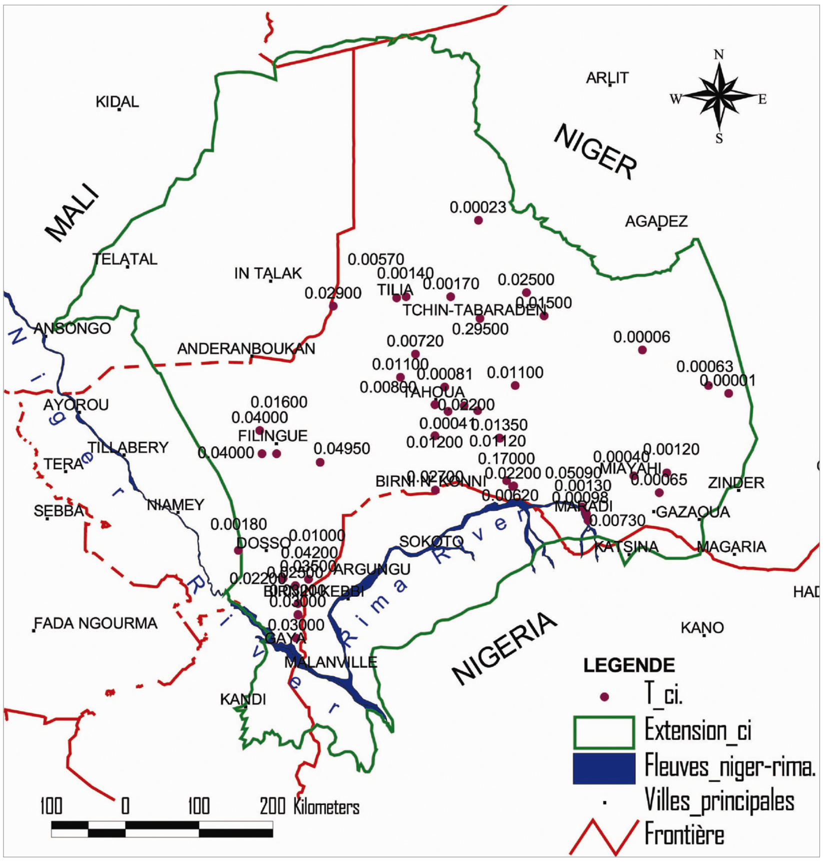


Figure 20 : Ci initial transmissivity values map

The temporal evolution of the piezometric heights, from 1970 up to now, is not well known. Hence, in the IAS database, the observed points giving two or more piezometric measures at two different dates are rare.

IV.6. Data on the withdrawals and their variation

IV.6.1. In Mali

Direct calculation method

This method is based on the calculation of volumes exploited per village and per year from cumulated accounts of water sources tapping the CT/Ci aquifers per village and per year (Table 2).

The mean of storage applied per water source is of 1m3/hour during 8 hours of pumping per day, or 8 m²/day.

The calculated withdrawals values were balanced to the average rate of the water sources functionality (70 % in 2005).of the concerned zones.

Only the water sources tapping the CT/Ci aquifers were taken into consideration.

Because of the interdependence of problems of availability of pasture and livestock pressure on the groundwater resources, the residence time (month/year) of the livestock in the pastures zones as to the years of great droughts, was taken into consideration as indicated on Table 2.

	1955	1959	1961	1966	1968	1974	1978	1980	1985	1990	1995	2000	2004	2005
existent MWS														
MWS_CT	0	3	3	7	9	9	10	11	29	84	99	185	196	196
MWS_Ci	1	3	6	7	7	8	9	9	19	38	55	113	133	139
BF_AEP												24	31	53
Tot_MWS_inv*	22	27	30	35	37	38	40	41	69	143	175	343	381	409
MWS required														
Pop_sed_pem	53	57	60	66	69	78	85	89	98	109	121	135	147	150
Pop_nomad_pem	42	44	45	48	49	53	55	57	60	64	68	72	76	76
Chep_pem	1298	1350	1377	1448	1477	1097	1142	1165	1041	1094	1150	1208	1257	1270
Tot_MWS_required	1393	1452	1483	1562	1595	1228	1282	1310	1199	1267	1339	1415	1480	1496
Takings rate (%)	2	2	2	2	2	3	3	3	6	11	13	24	26	27
Funct_rate_MWS (%)	98	98	98	98	95	95	95	90	85	85	80	70	70	70
Livestock res.time (month/year)	7	7	7	7	7	3	4	5	5	5	6	6	6	6

* There are 21 equipped drillings without date of creation which were integrated to the total accumulation here.

Table 2 : rate of potential coverage of the needs per existent MWS

- The modern water sources (MWS) required to meet the needs were calculated following the norms:
  - 1 MWS for 400 sedentary inhabitants or 20l/inh/day;
  - 1 MWS for 533 nomadic inhabitants or 15l/inh/d;
  - 1 MWS for 200 livestock units (lsu) or 40l/lsu/d;
- the ratio (number of existing water sources)/(number of water sources required to satisfy the needs) is a line of potential taking on the basis of the norms mentioned above (Fig. 21) ;
- the calculated needs of the sedentary populations, the nomads and the livestock were balanced to the line of potential taking and the residence time of the livestock in the pasture sites.

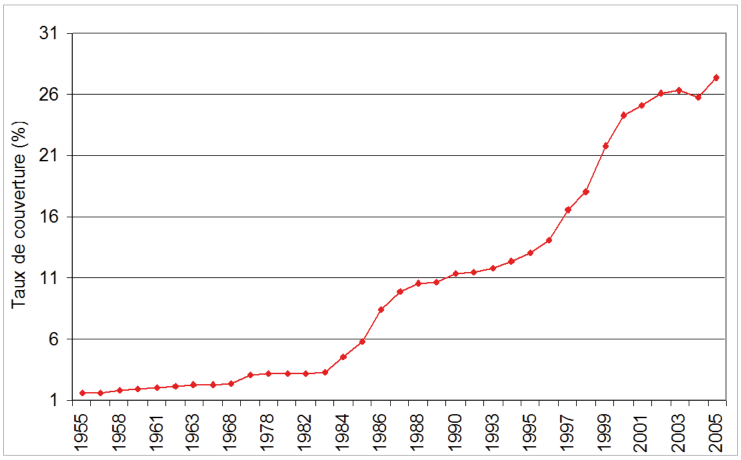


Figure 21 : rate of potential coverage of the needs per existing MWS

- the calculated takings per CT/Ci were balanced to the functionality rate of the MWS and to the residence time of the livestock in the pasture sites.

Indirect calculation method

Calculation of the sedentary population per village and per year

The rates were extrapolated as to the data of the 1998 general census. The annual growth rates applied are:

- 2,4% for the villages of 2 000 and pore inhabitants
- 1,2% for the villages of less than 2 000 inhabitants.

Calculation of the nomadic population per village and per year

The rates were extrapolated as to the data of the 1998 general census. The annual growth rate applied is of **1,2 %**.

Calculation of the livestock per village and per year

The available gross data about the livestock are those issued from the 1998 general census.

With no real data for the other years, an annual growth rate of 1% was applied to calculate the other ratios by extrapolation. Hence, abrupt decrease rates of the livestock of about 30% and 15% were noticed respectively for the years 1974 and 1984 to reflect the impact of the great droughts of those years on the livestock.

Calculation of the sedentary population needs per village and per year

The consumption norm applied is of 20 litres/person/day. The number of accumulated water sources per aquifer (CT/Ci) and per village, is indicated for 2005.

Calculation of the nomadic population needs per village and per year

The consumption norm applied is of 15 litres/person/day. The proportion of pasture sites equipped with water sources capturing the CT/Ci is indicated.

Calculation of the livestock needs per village and per year

The consumption norm applied is of 40 litres/livestock unit/day. The proportion of pasture sites equipped with water sources capturing the CT/Ci is indicated. The calculated ratios are balanced as to:

- the representative coefficient of water sources capturing the Ci as to the total number of water sources per village.
- the average rate of effective coverage of the sedentary populations' needs in water in the zones concerned (Table 3).

Because of the interdependence of problems of availability of pasture and pressure of the livestock in the subterranean water resources, the residence time (month/year) of the livestock in the pasture zones as to the years of great droughts was taken into consideration as indicated in table 3.

Calculation of the sedentary population needs served from water sources capturing the CT or the Ci per village and per year

The consumption norm applied is of 20 litres/person/day. Only villages with at least one water resource tapping the CT or the Ci, were taken into account. The annual withdrawals are mentioned in figure 22.

Year		1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005
DIRECT METHOD												
CT	MWS_takings	0	5008	12877	15719	8322	13578	31439	91214	119136	195202	207466
	Prod_AEP										54355	127550
Ci	MWS_takings	2862	6200	14785	15951	15951	19053	42815	81286	116800	183960	221774
	Prod_AEP										16180	26744
TOTAL CT+Ci		2862	11208	27662	31670	24273	32631	74253	172499	235936	449697	583534
INDIRECT METHOD												
CT	Sed_ pop_need	2225	2915	3920	4499	6653	7470	15291	33411	43117	89175	112075
	Nomadic_pop_need	1824	2279	2922	3204	4535	4869	9504	19790	24326	47899	57284
	Livestock_need	32819	40606	51547	55954	23529	41692	68485	141203	206235	402083	476139
Tot CT		36868	45801	58389	63656	34717	54032	93279	194404	273679	539157	645498
Ci	Sed_ pop_need	180	230	300	333	472	508	1004	2120	2642	5279	6411
	Nomadic_pop_need	116	145	187	204	289	311	607	1263	1553	3057	3656
	Livestock_need	2095	2592	3290	3572	1502	2661	4371	9013	13164	25665	30392
Tot Ci		2391	2967	3777	4109	2263	3480	5982	12396	17359	34002	40459
TOTAL CT+Ci		39259	48768	62166	67764	36980	57512	99262	206799	291038	573159	685958
	SED	2405	3144	4220	4831	7125	7978	16295	35530	45760	94455	118486
	NOMAD	1941	2425	3109	3408	4824	5180	10110	21053	25879	50956	60941
	LIVESTOCK	34914	43198	54837	59525	25031	44354	72856	150216	219399	427748	506530

Table 3 : Withdrawls calculations (m^3/year)

The calculated ratios are balanced as to the:

- representative coefficient of water resources tapping the CT or the Ci as to the total number of water resources per village,
- average rate of effective coverage of the sedentary populations' needs in water in the zones concerned (table 2).

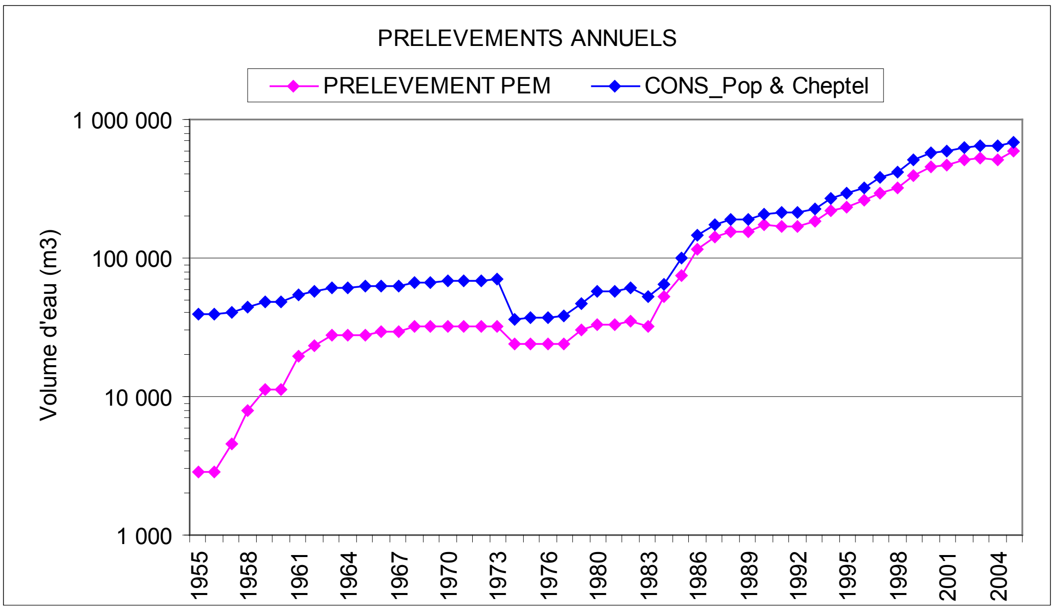


Figure 22 : Annual withdrawas

The withdrawals curve on the basis of water consumption reflects the needs covered from groundwater sources as to the production potential of the existing water sources compared to the needs of the moment and of the residence time of the livestock on the pasture sites.

The withdrawals curve based on drawings per groundwater sources reflects the production potential of liable water sources as to their functionality and the residence time of the livestock on the pasture sites.

The general increasing withdrawals starting from 1998 reflects the accelerated rhythm of the creation of the modern wells and boreholes (Fig. 23).

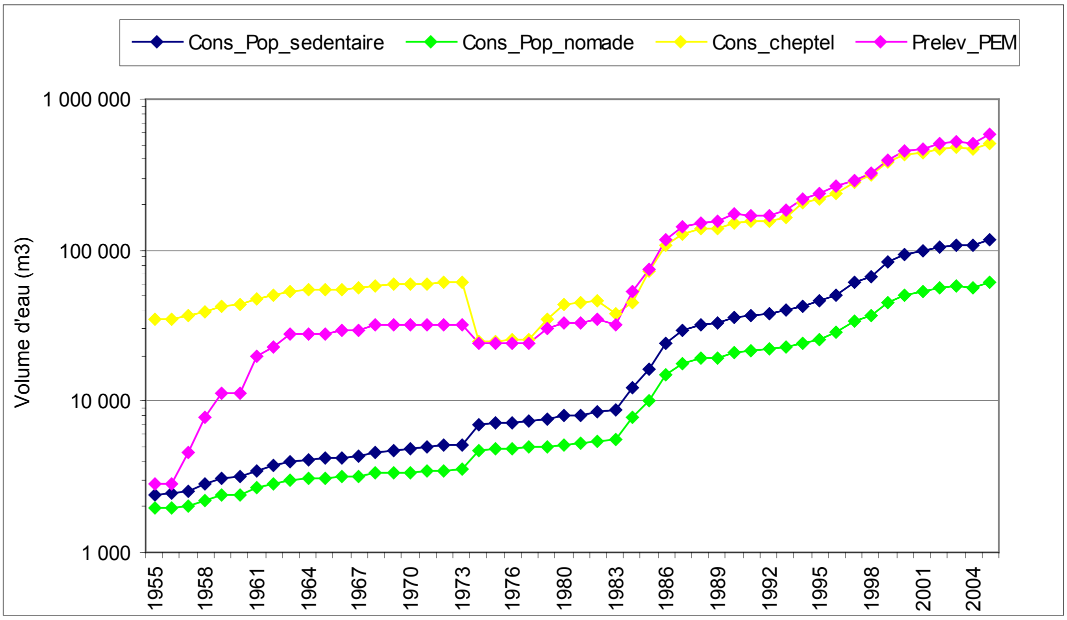


Figure 23 : General increase of withdrawals

The total withdrawals from water sources seems to be controlled by the livestock consumption. The abrupt decrease noticed in 1974 and 1983-1984 on the consumption curves of the livestock and taking per MWS reflect the decimation of the livestock and the reduction in the time of pasture these years in relation to the rainfall deficits.

Withdrawls on the basis of the different uses consumption increase, more or less constantly, according to the demographic growth and the increase of the water sources.

IV.6.2. In Niger

There is no exhaustive withdrawals record in Niger. Only few water sources were followed up during five years (2001 – 2005) by the National Society of Water Exploitation in Niger (NSWEN).

▶▶▶ Water abstraction determination from modern water sources by the Village Hydraulics

This is about built wells and boreholes with counter-wells and drillings equipped with human motivity pumps. In rural zones in Niger, the majority of water drillings are equipped with human motivity pumps with a pumping flow of about 1 m^3/hour and exploited for almost 8 hours per day.

Knowing that the majority of the database hydraulic wells are made up of drillings and basing on the exploitation flow of 1 m^3/hour during 8 hours by day, the water exploited from each water source can be estimated to 8 m^3/day. The evolution of needs in the MWS in rural environments in Niger is mentioned on Table 4.

Regions	Total needs in MWS 100%			Existing MWS 2000	Coverage rate 2000 (%)	MWS to be achieved to reach	
	2000	2004	2010			70 % en 2004	100 % en 2010
Agadez	820	993	1323	418	51	277	628
Diffa	714	746	796	700	98	0	96
Dosso	5781	6659	8233	3212	58	1449	3572
Maradi	7437	8567	10592	3540	48	2457	4595
Tahoua	7335	8483	10549	2923	40	3015	4611
Tilabéri	6935	7685	8964	3969	57	1410	3585
Zinder	7183	8147	9842	4606	64	1097	4139
Niger	36166	41181	50038	19468	53	9459	21211

TABLE 4 : Evolution of needs in MWS in rural environments in Niger

Water withdrawals determination from water sources of Urban Hydraulics

It is about the boreholes exploited by the National Society of Water Exploitation in Niger (NSWEN). These drillings are exploited for the water supply in urban and semi-urban centres are equipped with water meters which show the quantity of water pumped during a given pumping time.

Hence, the daily withdrawals of each well is calculated as being the product of schedule flow by the pumping time. Since the statements are monthly, the annual accumulation is determined by the sum of the 12 water production per year for each harnessing zone. Corrections were made to the exploitations in need of several aquifer systems.

The different annual productions corrected by the different centres managed by the NSWEN recorded in the following table 5. Figure 24 is the total annual productions of all the centres (Ci and CT). *Let's however note the weakness of the water production in 2002 which unmistakably results from an error of reporting data. This 2002 ratio will be corrected with the agreement of the* NSWEN *management.*

Determination of the water demand

The daily needs in water "B" (daily demand) are defined by applying the following hypotheses:

Specific consumption equal to 15 l/inh/day (Kollo meeting);

5% loss in the distribution and water supply nets;

A nil growth and consumption rate to avoid the over sizing of the works;

Animal consumption of 40 l/livestock unit/day.

Hence: $\mathbf{B = 1{,}05\,[P_{2003} \times Cs + CH_{2003} \times Ca]}$

With:

B: Daily demand in m^3/day;

P_{2003}: population censed at the end of 2003;

Cs: specific consumption in l/inh/day;

CH_{2003}: livestock accounted for at the and of 2003*;

Ca: animal consumption in l/livestock unit/day.

** The livestock is only accounted for when the available water resources are sufficient and/or the will to pay is confirmed.*

Source : CIMA International 2003 : study of a rural hydraulic program in Niger

These needs in water of the pastoral zone (strict sense) in Niger in 1997 are broken down in Table 6 (page 56).

N°	Centre	Drilling	N° IRH	Depth (m)	2001	2002	2003	2004	2005	Aquifer
					Volume of takings	Volume of takings	Volume of takings	Volume of takings	Volume of takings	
1		F1		160	16 496	0	67 683	143 821	116 648	Ci
2		F4		155	46 796	14 805	178 209	220 031	226 940	Ci
3		F5			122 513	13 335	175 240	183 832	141 307	Ci
4		F6			93 580	22 015	249 911	238 957	257 691	Ci
5		F7		160.25	0		117 384	155 346	213 066	Ci
6	Maradi	F8		159.9	34 648	36 859	310 432	411 698	362 121	Ci
7		F9		159.65	142 630	21 132	239 544	335 568	333 366	Ci
8		F10		196.4	36 366		32 955	65 249	0	Ci
9		F11		192	128 310	43 423	427 488	360 408	469 133	Ci
10		F12		201.5	173 020	33 226	351 300	515 720	634 619	Ci
11		F13		190	186 314	32 448	380 580	496 489	463 220	Ci
12		F14		191.02	0		0	0	3 514	Ci
13		F1	14101	700						Ci
14		F2			203 298	39 220	380 530	329 114	154 987	Ci
15		F3	18769	686.2	159 561	31 184	339 826	364 289	374 358	Ci
16	Tahoua	F4	24885	688	141 864	31 063	382 249	191 296	70 782	Ci
17		F5	80003	690	75 003	14 768	146 019	162 853	167 675	Ci
18		F6		700	0		0	443 450	622 983	Ci
19		F7		701	0		0	37 471	157 715	Ci
20		F2	16721	133.4	0		0	0	0	CT
21		F4	15713	126	0		0	23 001	152 692	CT
22		F5	16895	128	58 244	9 390	47 012	0	19 423	CT
23		F6		132	107 802	17 682	188 123	240 888	242 475	CT
24	Dosso	F7		135	103 833	16 725	180 192	108 302	55 417	CT
25		F8		132	107 517	18 134	197 459	198 705	227 530	CT
26		F9		129.5	0		47 031	65 145	62 685	CT
27		C1			24 391	13 795	222 968	307 956	261 890	Ci
28		C2			93 972	12 476	145 398	220 046	267 827	Ci
70		A01		158.39	0		0	0	25 516	Ci
71		A02		142.9	0		0	0	32 650	Ci
72		A03		153.18	0		0	0	24 079	Ci
73		A04		134.1	0		0	0	50 777	Ci
74		A05		123.65	0		0	0	0	Ci
75		A06		113.9	0		0	0	33 461	Ci
76		A07		158.9	0		0	0	34 129	Ci
77		A08		127.24	0		0	0	42 146	Ci
78		A09		150.7	0		0	0	30 206	Ci
79		A10		136	0		0	0	23 460	Ci
80		18783		168.1	0		0	0	36 205	Ci
81		Secours 1			0		0	0	31 490	Ci
82	Filingué		13851	529	36 292	13 928	162 847	196 187	177 508	Ci
89		F2	80.64	600		57 765	673 811			Ci
90	Konni	F3			290 128	57 765	0	761 329	623 351	Ci
91		F4		569	0			0	123 095	Ci
92		F1	6903	227.88	8 042	98	71 802	0	0	Ci
93	Madaoua	F2	13740	259						Ci
94		F3bis			109 943	21 065	178 207	323 562	323 562	Ci

N°	Centre	Drilling	N° IRH	Depth (m)	2001	2002	2003	2004	2005	Aquifer
					Volume of takings	Volume of takings	Volume of takings	Volume of takings	Volume of takings	
95	Tessaoua	F1		140.4	56 638	14 525	169 126	196 063	152 293	Ci
96		F2	14655	152.02	72 656	12 229	150 609	178 425	235 096	Ci
97		F3		154.47						Ci
98	Doutchi	F1	6882	366	83 665	21 164	221 166	199 828	199 828	CT
99		F2	24183	339.51	30 442	6 725	89 165	55 006	55 006	CT
100		F3	321768	163.09	0		0	100 234	100 234	CT
106	Ouallam	F1	14013	72.95	42 288	8 338	95 664	104 210	115 162	CT
112	Tanout	F1	4367	404.5	19 520	3 532	26 710	32 608	17 617	Ci
113		F2	14547	505	16 735	9 221	22 656	0	0	Ci
114		F3	27016	931	29 023		87 715	129 996	111 608	Ci
115		F4			0		0	0	9 631	Ci
121	Bouza	F1	8460	374	33 035	8 038	99 003	108 707	115 251	Ci
122	Keita	F2 Italy	25799	480	31 120	7 652	91 271	103 643	103 278	Ci
123	Gazaoua	F1	19824		81 914	75 283	87 740	84 964		Ci
133	Aguié	F1	19823	173	39 904	8 582	103 943	125 205	133 163	Ci
134	Illela	F1	8687	603	67 898	67 198	75 518	75 503		Ci
135	Madarounfa	F1	16917	57.7	67 159	67 817	70 026	70 254		Ci
136	Loga	F1	18770	132	22 528		47 963	67 225	64 082	CT
137	Matankari	F1	8753	200.7	38 666	8 698	89 368	95 323	96 254	CT
138	Abalak	Puits 1		84	46 942	8 022	100 370	109 881	100 632	Ci
139		Puits 2			29 552	6 485	81 449	118 489	119 188	Ci
140	Tamaské	F1	16722	520	44 617	9 636	121 893	138 848	133 418	Ci
141	Tchinta	F1	24536	251	70 228	11 343	69 308	142 157	103 342	Ci
143	Dakoro	F2			45 844		134 013	86 536	42 765	Ci
144		F3			0		0	57 853	107 146	Ci
145		F1	15944	384	50 395	10 363	141 522	95 135	132 846	Ci
146		F2			20 546		57 582	79 983	74 101	Ci
147	G.Roumji	F1	19822	270	35 983	7 975	97 006	132 168	100 074	Ci
148		F2		104.1	0		0	0	15 860	Ci
161	Dioundiou	F1	8901	187.1	12 718	3 180	31 609	35 489	40 479	Ci
162	Birni Gaouré	F1		59			4 855	47 769	31 321	Ci
163		F2		60			3 384	39 433	31 069	Ci
167	Bagaroua	F1	8751	106.5	19 127	4 167	48 202	37 799	36 064	Ci
168		F2		131.58						Ci
169	Dogueraoua	F1	19813	432	25 283	5 319	60 603	71 854	74 001	Ci
170	Ibohamane	F1		400	16 064	3 304	47 683	58 626	47 958	Ci
171	Takanamat	F1		799		1 482	28 127	29 772	25 960	Ci
172	Gazaoua	F								Ci
173	Illéla	F								Ci
174	Madarounfa	F								Ci
175	Tassara	F1		147	6 835	3 719	49 230	54 805	67 082	Ci
176	Tillia	F1		760	5 586	6 494	63 677	84 981	102 729	Ci
Volume total annuel					3 663 474	972 792	8 562 356	10 249 485	10 566 237	

TABLE 5 : Annual productions corrected for the different centres managed by the NSWEN

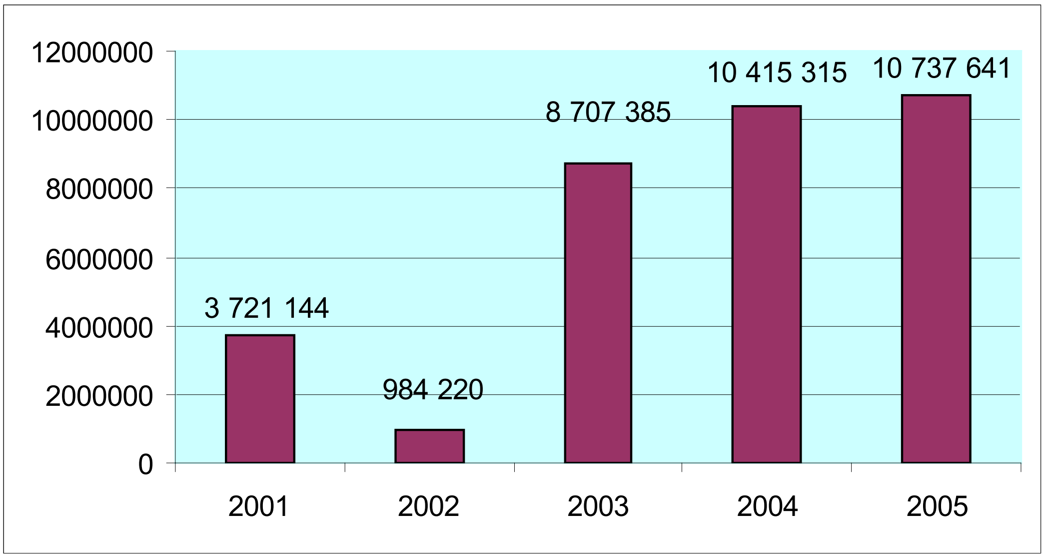


Figure 24 : Annual total productions of all the centres (Ci & CT)

Department	Borough	Thousand of livestock units	Needs in water (m^3/day)
Tahoua	Tchintabaraden	251	7530
Agadez	Tchirozérine	134	4020
Diffa	Diffa	243	7290
	Maïné Soroa	162	4860
	N'guigmi	125	3750
Maradi	Dakoro	62	1860
Zinder	Gouré	192	5760
	Tanout	116	3480
Tillabéri	Filingué	97	2910
	Ouallam	66	1980
	Tillabéri	52	1560
TOTAL		1500	45000

Table 6 : Needs in water daily Maxima in 1997 of the Pastural Zone livestock in Niger

IV.6.3. In Nigeria

There are no records of withdrawals. We had to make an estimation from a 2004 population census of the major localities situated in the sokoto basin [Kebbi, Sokoto, Zamfara (State of Sokoto) and Katsina] (table 7).

The urban and rural population estimations (in the Iullemeden basin) of the 4 states above are obtained (table 8) by considering the following hypotheses:

S/N°	State	Total Population
1.	Katsina	5,479,413
2.	Kebbi	3,019,971
3.	Sokoto	3,499,538
4.	Zamfara (Sokoto)	3,026,68
Total		**15,025,602**

Table 7 : total population of the Sates of Nigeria in the basin

- State of Sokoto: 100% of the total population lives in the basin: 20% is urban and 80% is rural.

- State of Kebbi: 70% of the total population lives in the Iullemeden basin, 20% in urban zones and 80% in rural zones.
- State of Zamfara: 20% of the population lives in the basin, 20% is urban and 80% is rural.
- State of Katsina: 10% of the population lives in the Iullemeden basin, 20% in urban zones and 80% in rural zones.

S/N°	State	Urban Population	Rural Population	Total
1.	Kebbi	602 194	2 416 977	3 019 171
2.	Sokoto	599 908	2 799 630	3 399 538
3.	Zamfara (Sokoto)	605 535	726 345	1 331 880
4.	Katsina	109 588	438 363	547 951

TABLE 8 : Urban and rural population in the basin

As to the livestock, the total population estimation is shown in table 9 below:

S/N°	State	Total livestock population
1.	Sokoto	6 311 184
2.	Kebbi	5 716 500
3.	Katsina	3 621 800
4.	Zamafara (Sokoto)	5 716 000
Total		**21 365 484**

TABLE 9 : total livestock population in the states

The livestock population estimation in the basin is obtained (table 10) by considering the following hypotheses:

- The total livestock population in the state of Sokoto lives in the Iullemeden;
- 70% of the total livestock population of the state of Kebbi lives in the Iullemeden basin;
- 1% of the total livestock population of the state of Katsina lives in the basin;
- 20% of the total population of the state of Zamfara lives in the basin.

The types of the livestock considered are the following: sheep, goats, camels and donkeys.

S/N°	State	Total livestock population in the Iullemeden basin
1.	Sokoto	6 311 184
2.	Kebbi	4 001 550
3.	Katsina	36 218
4.	Zamafara (Sokoto)	1 143 200
Total		**11 818 114**

TABLE 10 : livestock population in the Iullemeden basin

For the calculation of the abstractions, the consumption norm applied is of 20l/person/day for the urban population, 15l/person/day for the rural population and 20l/livestock unit/day for the livestock (table 11).

State	Urban population	Rural population	Livestock	Exploitation (Urban) (l/day)	Exploitation (Rural) (l/day)	Exploitation (livestock) (l/day)	Exploitation (Urban) (m³/year)	Exploitation (Rural) (m³/year)	Exploitation (livestock) (m³/year)
Kebbi	602194	2 416 977	4 001 550	12 043 880	36 254 655	80 031 000	4 396 016	13 232 949	29 211 315
Sokoto	599908	2 799 630	6 311 184	11 998 160	41 994 450	126 223680	4 379 328	15 327 974	46 071 643
Zamfara (Sokoto)	605 535	726 345	1 143 200	12 110 700	10 895 175	22 864 000	4 420 406	3 976 739	8 345 360
Katsina	109588	438 363	36 218	2 191 760	6 575 445	724 360	799 992	2 400 037	264 391
Total	1 917 225	6 381 315	11 492152	38 344 500	95 719 725	229 843040	13 995 743	34 937 700	83 892 710

Table 11 : Estimated withdrawals in Nigeria

IV.7. Conclusion

There exists in the three countries a lack of records of storage or exploited volumes for specific uses (water Supply, irrigation, livestock, industry). This major gap in the IAS aquifers follow up makes the model calibration relatively difficult, since we have to use sectioning methods to evaluate this exploitation.

It is then a sectioning based on the **number** (population or animals) and the sector "**need**" (needs in water/inh/day, needs in water/TB, needs in water/irrigated ha, etc.), or the **number** and the "**production** in water" (daily production of the common centres) that this exploitation in studied in an improvised way. Other hypotheses are into consideration in this evaluation whenever elements of appreciation are available in order to present plausible estimation of exploitation per aquifer and per country.

V. CALIBRATION OF THE MODEL IN A STEADY STATE

V.1. Definition of a reference state

The analysis of data collected from diverse contributions : data sent by the countries, National Database, bibliography (Boeckh, 1965, Saad, 1969, FAO, 1970, Gregeirt, 1978, Margat, 1982, BRGM,1988, JICA, 1990, Bonnier, and al., 1992, Dodo, 1992, Favreau, 2000, BCEOM, 2000, Guéro, 2003) helped to choose **1970** as a state of Piezometric reference or "**initial state**" characterised by an equilibrium state of the aquifer system undisturbed by the abstraction.

In fact, that year can be considered as the end of a period and the beginning of another, since it coincided with the generalisation of the droughts in all Western Africa thus reducing surface waters and obliging the populations to use the groundwaters. That date is, thus, the date of the implementation of the major village hydraulic projects in the region.

On the basis of anterior works and recent data, the piezometric maps of the initial state (1970) of each of the two CT and Ci layers were established (figures 25 & 26).

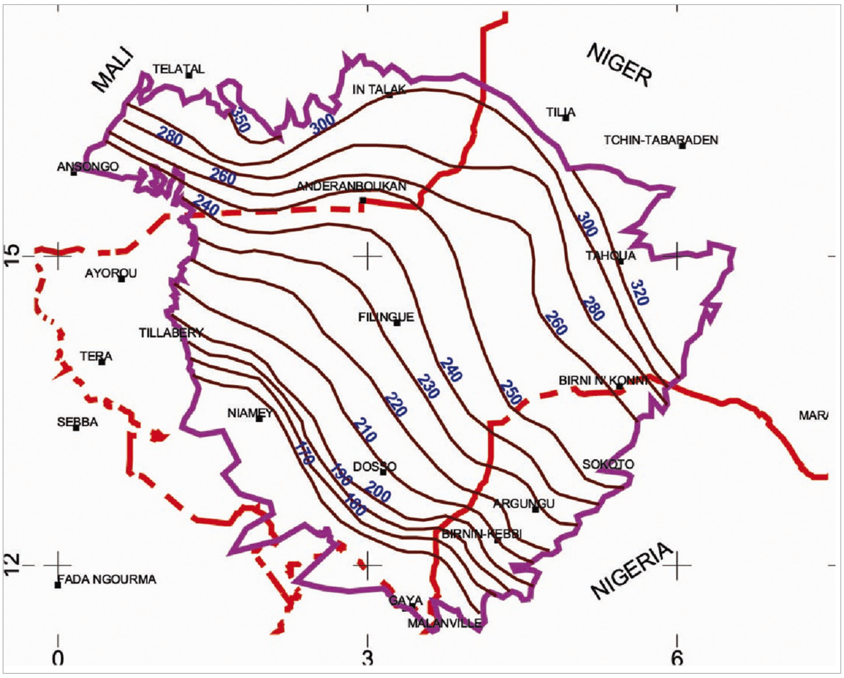


FIGURE 25 : The CT piezometric map (initial state 1970)

The study of the CT piezometric map (Fig. 25) shows the major axes of drainage of the NW-SE and NE-SW oriented water tables. The module of spacing decreases from the NE to the SE. The supply zones of the CT ground waters are in:

- the North-East suburb;
- the North West suburb;
- some villages of the Rima river.

The exit zones are mainly the river Niger and the river Rima.

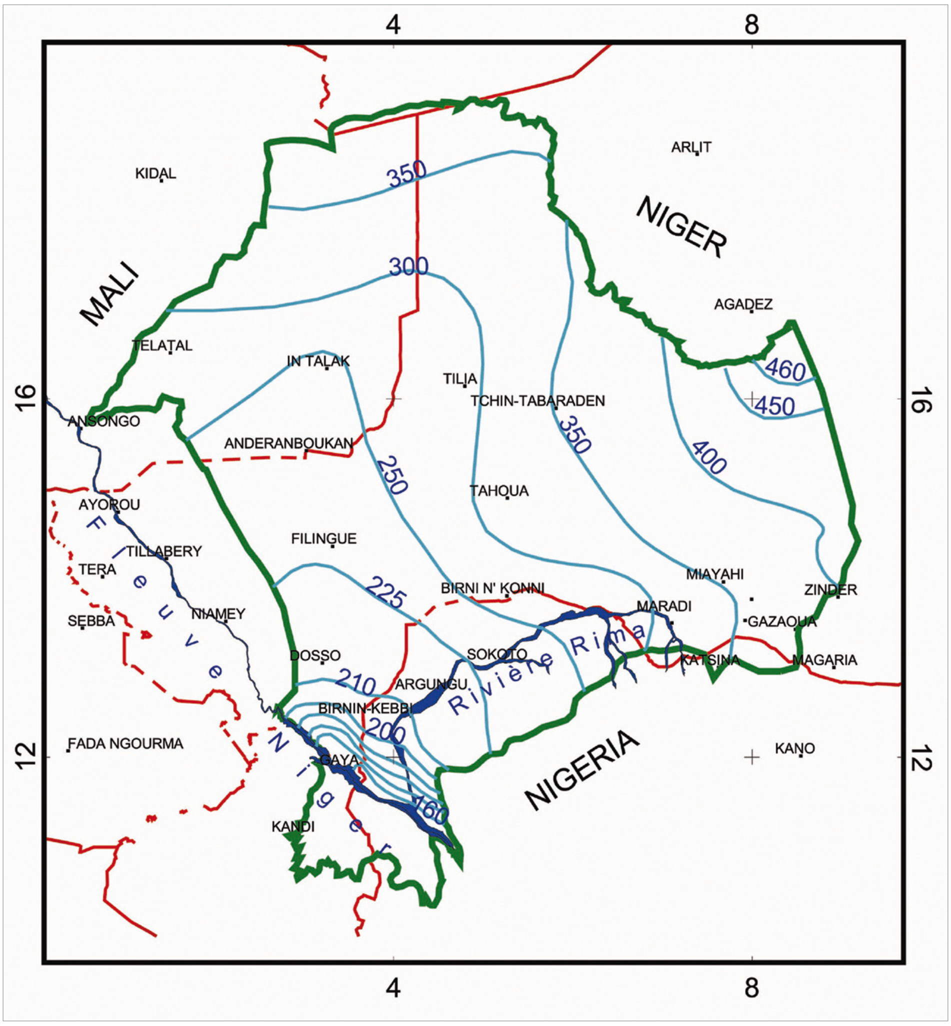


Figure 26 : The Ci piezometric map (initial state 1970)

The study of the Ci piezometric map (Fig.24) shows that the major supply zones of the Ci ground waters are:

- the Hoggar massif in the North;
- the river Rima.

The major natural exit of the Ci water table is made up of the river Niger which is draining and towards which waters converge. Some meshes located under the river Rima also serve as drains to the Ci.

V.2. Definition of the reference criteria for the calibration of the steady state

The calibration criteria as specified, try to constitute as exact as possible:

- the piezometric reference maps of Ci and CT corresponding at an equilibrium state near 1970,
- the collected piezometric locally values observed or evaluated from bibliographical references,
- the storage of the system at the outlet (Niger and Rima rivers) at the same date.

V.3. Calibration steps

The major stages of the calibration and the modifications of the calibration model in relation to the initial rates adopted can be broken down as follows:

- the condition of river initially fixed on the river Rima was replaced by the condition of imposed potential;
- on the border of the Ci aquifer, corresponding to the line of division between the Iullemeden basin and that of the lake Tchad, the condition of fixed potential was replaced by a condition of a nil flow;
- the horizontal transmissivity values were increased along the Dallols, in the Ci ground waters, thus creating a drainage corridor;
- the reference piezometric map of the Ci aquifer shows a weak hydraulic slope in the South-West and the North-East. The horizontal transmissivity was increased in this sector;
- a recharge comprised between 0.1 to 0.6 mm/year was fixed in the parts where aquifers (CT and Ci) were phreatic;
- the vertical transmissivity of the upper Cretaceous, initially equal to 10^{-12} m^2/s, was slightly decreased in the centre and in the East of the basin, (10^{-15} m^2/s), strongly decreased at the level of the Gao detch, in the East (10^{-18} m^2/s) and very slightly increased in the West of the basin. (10^{-11} m^2/s);
- the calculation of the refill rate and the water assessment of the system (4.8 m^3/s) looked weak at first. Consequently we proceeded to some attempts to increase it. But the results revealed to be incompatible with the observed piezometry and the transmissivity values. Moreover, this refill rate is comparable with the infiltration of rain water (Dodo, 1992).

V.4. Evaluation of the steady state calibration

V.4.1. Reconstitution of the overall piezometric maps of the Ci and the CT

The evaluation of the model's ability to reproduce quite faithfully, piezometry of reference, is done by comparing the piezometry observed to that calculated by the model. The superimposing of the iso-piezometric curves observed and calculated helps to measure the ability of the model to reproduce the look of the curves drawn by the hydrologist.

V.4.2. Reconstitution of the piezometric levels at the control points

▸▸▸ Distribution of the control points:

The piezometry control points are fairly well distributed in the Ci aquifer domain, in the centre of the basin in the East and the North; we note gaps due either to an absence of record or to the non-availability of observation data (Fig. 27). For the CT ground water, (Fig.28), the piezometric observation points are mainly in the exploitation zones (Dallols , River Niger, River Rima).

▸▸▸ Temporal dispersal of record:

In the IAS, the first piezometric records started at the beginning of the 1950'sand extended over the period 1950-1970, whereas the model was supposed to reconstruct an observed state in 1970. At that period, the takings on the CT and the Ci ground waters were almost inexistent. 1970 was then wisely considered as representative of the state of balance of the ground waters.

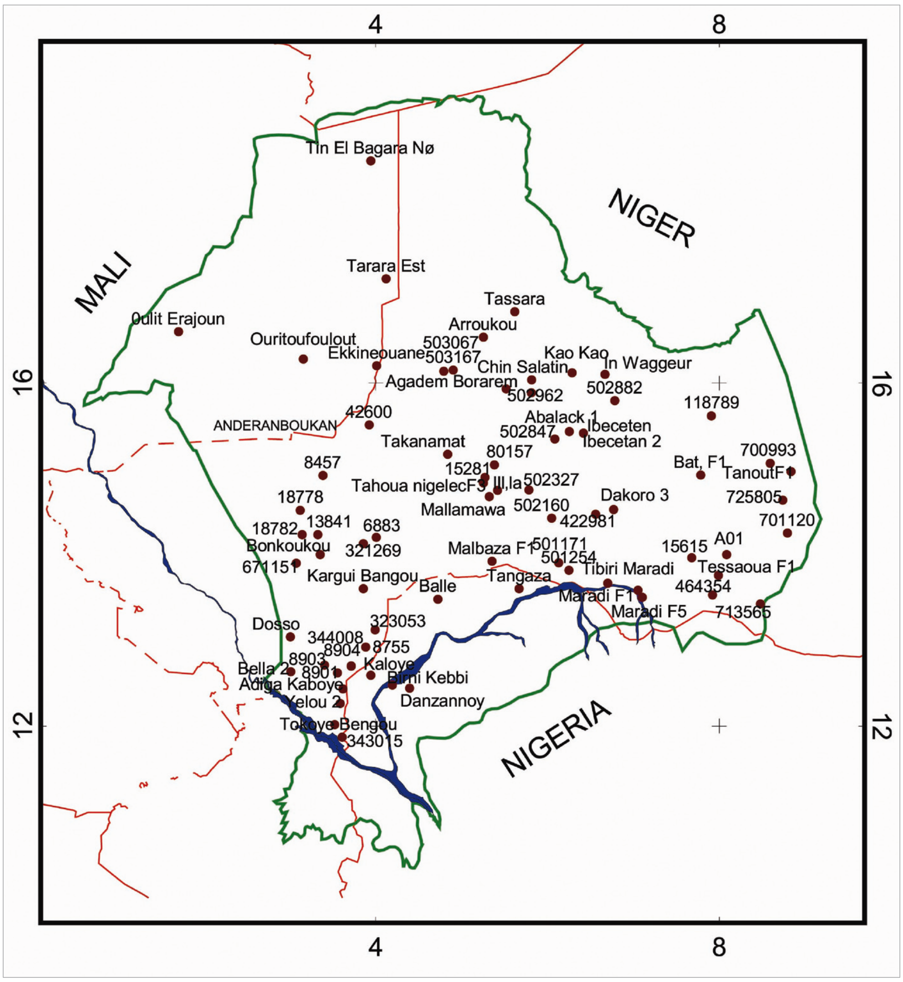


FIGURE 27 : the Ci control points

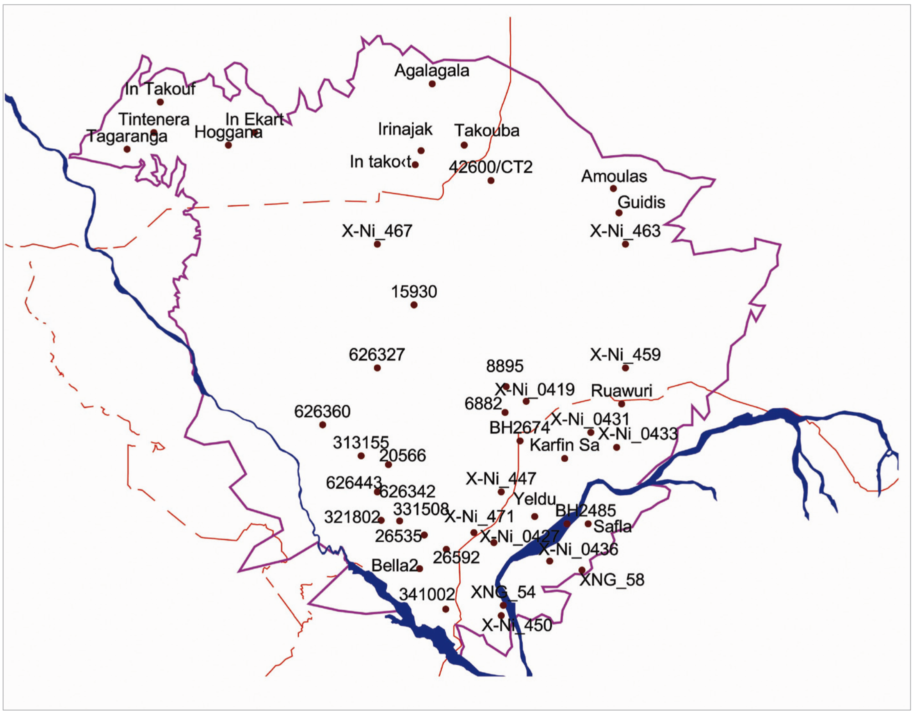


FIGURE 28 : the CT control points

▸▸▸ Analysis of the differences on the piezometric levels:

Generally, the piezometric differences between calculated and measured values are weak. The study of the maps (Fig. 29 and 30) show that the measured punctual rates correctly fill into the recorded curves.

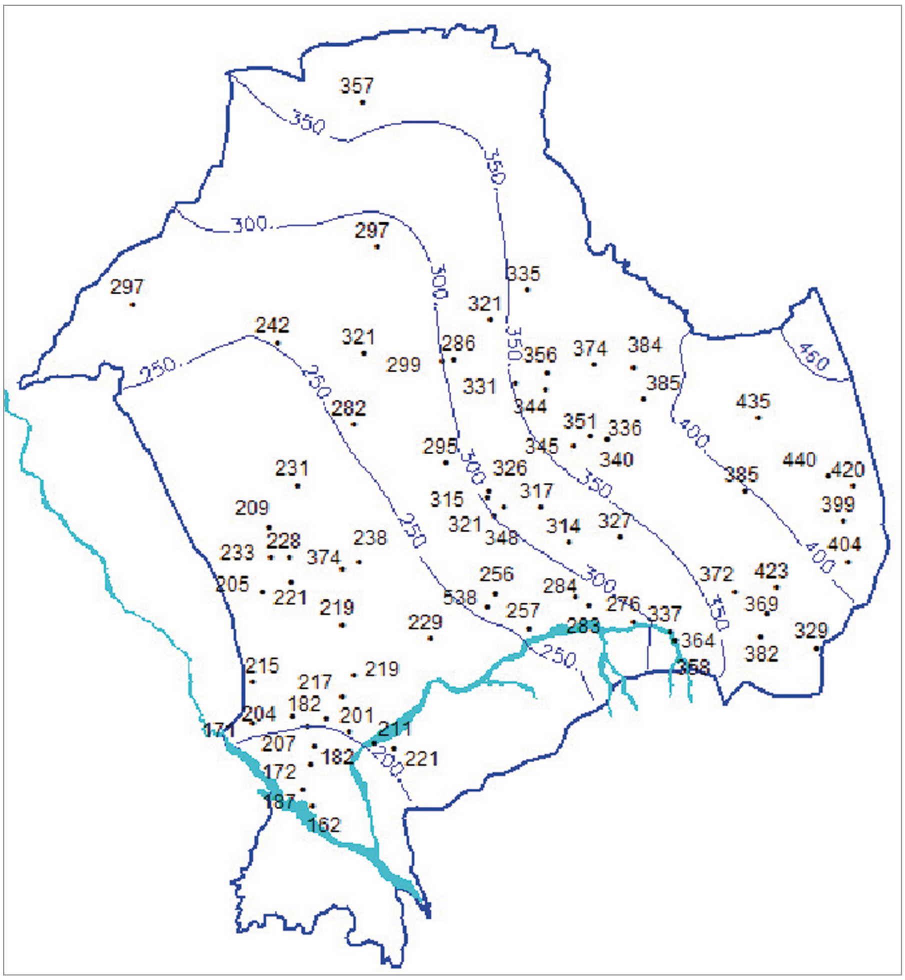


Figure 29 : Calibring gaps on the Ci piezometric levels

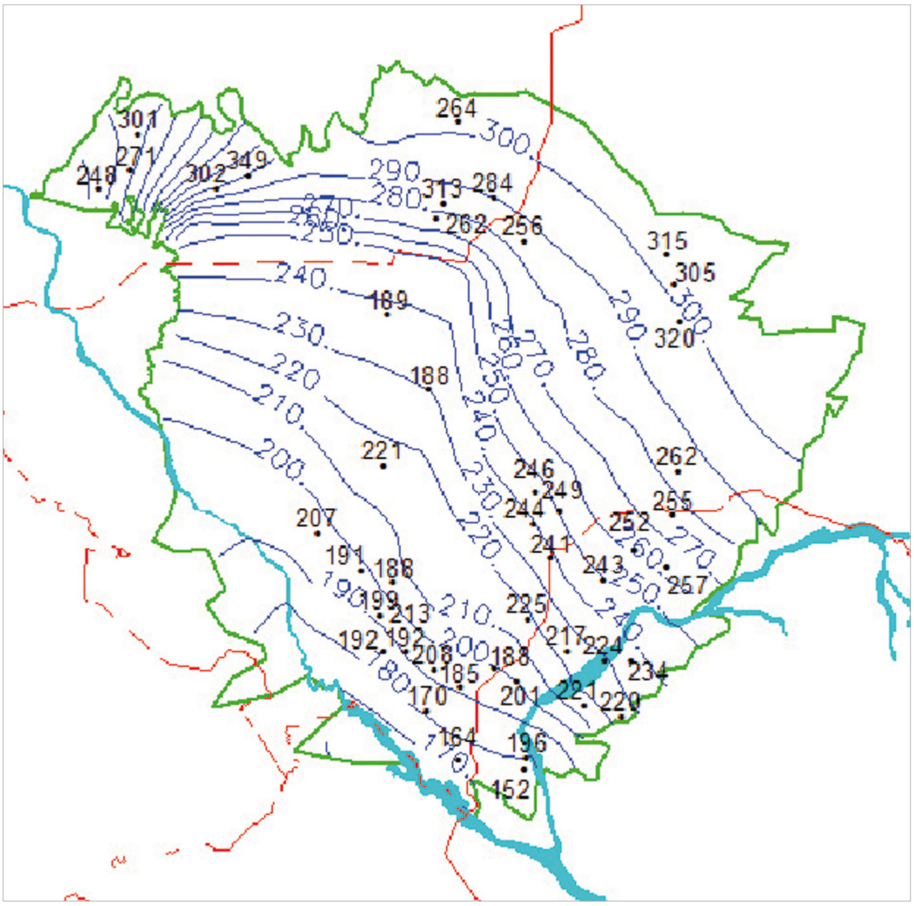


Figure 30 : Calibring gaps on the IC piezometric levels

V.5. Calibration results in a steady state

V.5.1. The general look of the flows calculated by the model

Figures 29 and 30 present the general look of the piezometric curves calculated for the Ci and the CT. Figures 31 and 32 show the speed vectors of the flows, deducted from the map above, which direction and size indicate the way and the importance of the flows.

For the Ci as well as for the CT, we were able to reconstruct the general look of the flows observed. The study of the maps shows that the waters converge to the river Niger which drains the ground waters. The river Rima is another drain for the ground waters of the system.

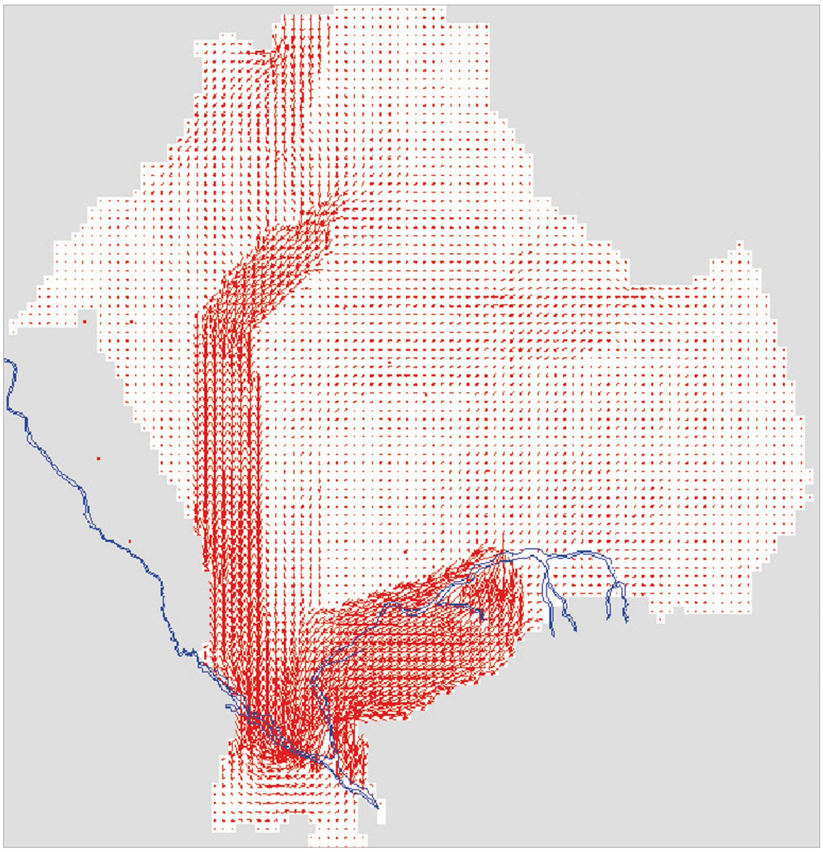


Figure 31 : The Ci flow speed

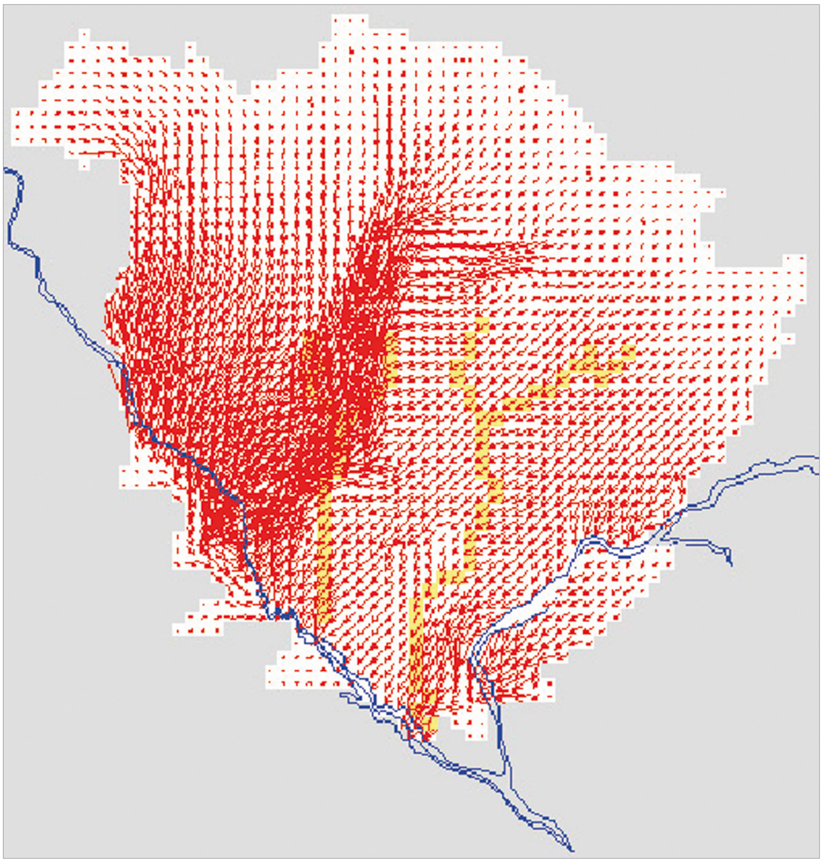


Figure 32 : The CT flow speed

V.5.2. The hydrodynamic Parameters of the Model

The transmissivity distribution after the calibration of the model is shown in figures 33 and 34. They are generally of the same importance as the recorded transmissivity.

Figures 35 and 36 indicate the distribution of the drainage coefficients (Kv/thickness of the sub-permeable) through the sub-permeable.

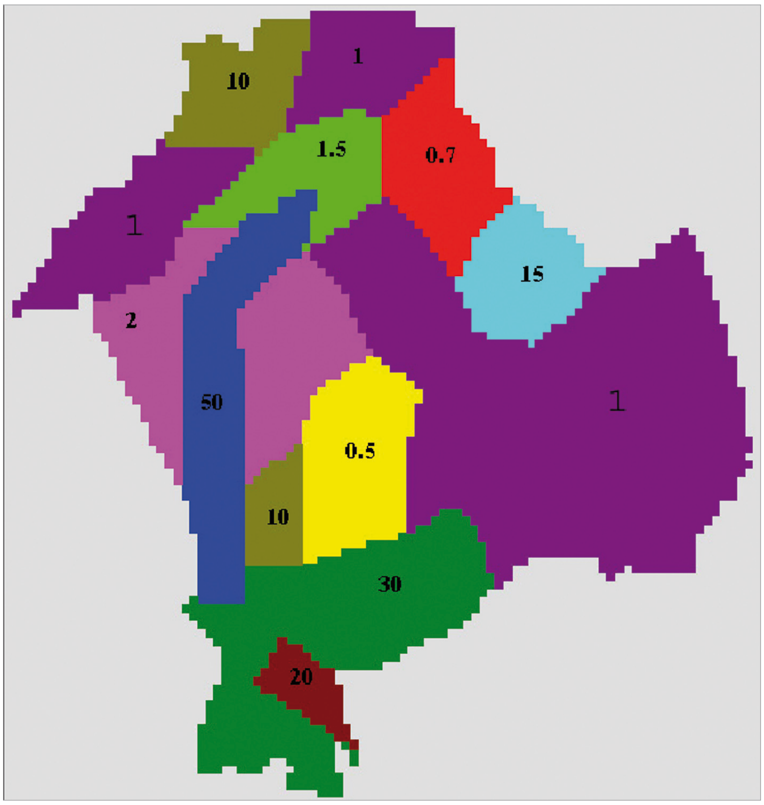


Figure 33 : Transmissivity in the Ci after calibration (10^{-3} m^2/s)

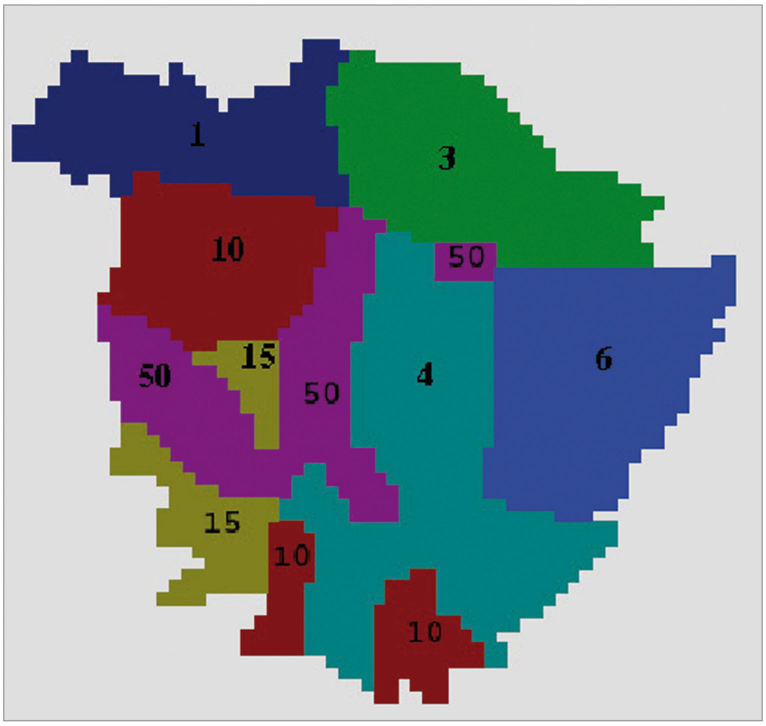


Figure 34 : Transmissivity in the CT after calibration (10^{-3} m^2/s)

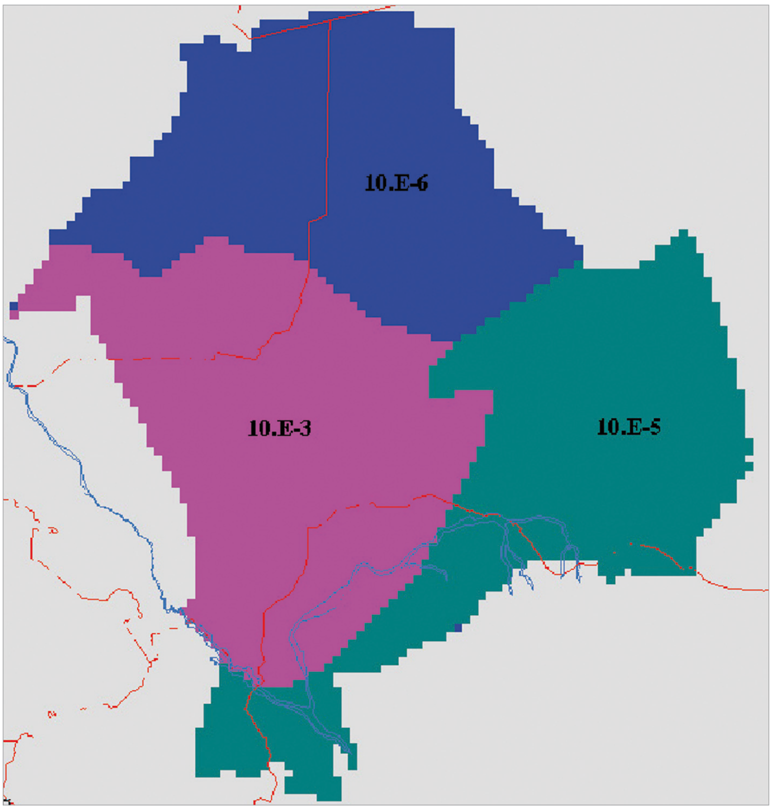


Figure 35 : Vertical trasmissivity in the CT after calibration (m^2/s)

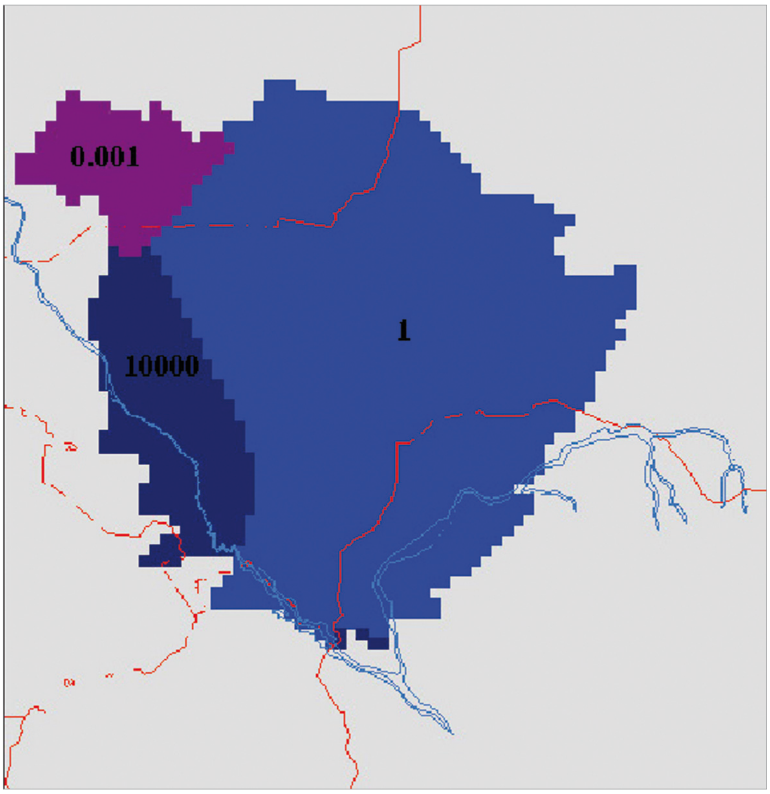


Figure 36 : Horizontal transmissivity in the Ci after calibration (m^2/s)

V.5.3. Water assessment in the Saharian multilayer

The table 12 above shows the detailed water assessment of the system, calculated by the model at the end of the calibration in steady state. The study of this chart shows that the majority of the supply results from the direct infiltration of rain waters. The river Niger constitutes a drain system with flows evaluated at 2.5 m^3/s for the CT and1.6 m^3/s for the Ci. The river Rima functions as a natural exit of the CT, but supplies the Ci with a flow of 770 l/s. The global resources of the system is of almost 5 m^3/s, or 150 millions of m^3/an, of which 82% support the flows of the river Niger.

In first estimate, this volume was considered weak, compared to the 70 m^3/s recommended beforehand as an IAS resource (in the document of the project), an estimate which was not founded on a precise study. Several tests conducted. During the calibration led to the conclusion that the IAS could not contain such a volume. The evaluation of the resource given by the model (5 m^3/s) seems plausible compared to that of the NWSAS (30 m^3/s), which is a system twice as big (1.000.000 km^2), whith an average layers thickness (350 m) are more important than those of the IAS (75 to 200 m) and which permeabilities are also more important than those observed in the IAS.

Continental terminal			
Inflow (m^3/s)		Outflow (m^3/s)	
Direct Infiltration of rain waters	3.29	River Niger	2.50
Drainage of the Ci	0.013	Dallols	0.45
		River Rima	0.35
TOTAL Inflow	**3.30**	TOTAL Outflow	**3.30**
Continental intercalaire			
Inflow (m^3/s)		Outflow (m^3/s)	
Direct infiltration of rain waters	0.55	River Niger	1.60
Contributions of the northern border	0.29	Drainage CT	0.013
Rivier Rima	0.77		
TOTAL Inflow	**1.61**	TOTAL Outflow	**1.61**

TABLE 12 : Assessment of the system in a steady state

V.5.4. Distribution of the flows per section along the rivers Niger and Rima

La figure 37 above shows the villages along the rivers Niger and Rima whose populations exploit those water streams. The flows calculated by the rivers Niger and Rima meshes (Fig. 38 for the CT and Fig. 39 for the Ci), as well as those calculated per section between villages along the water streams (Fig.37, in blue), are shown in table 13 and 14.

Table 13 shows that for the CT ground waters, the flows are globally exiting (2.5 m^3/s) for the river Niger and 0.35 m^3/s for the river Rima. But, when detailed, some of the meshes of the river Rima are supply meshes (positive rates).

On the other hand, for the Ci, all the flows are outgoing at the level of the river Niger (1.6 m^3/s) and globally incoming for the river Rima (0.77 m^3/s) (table 14).

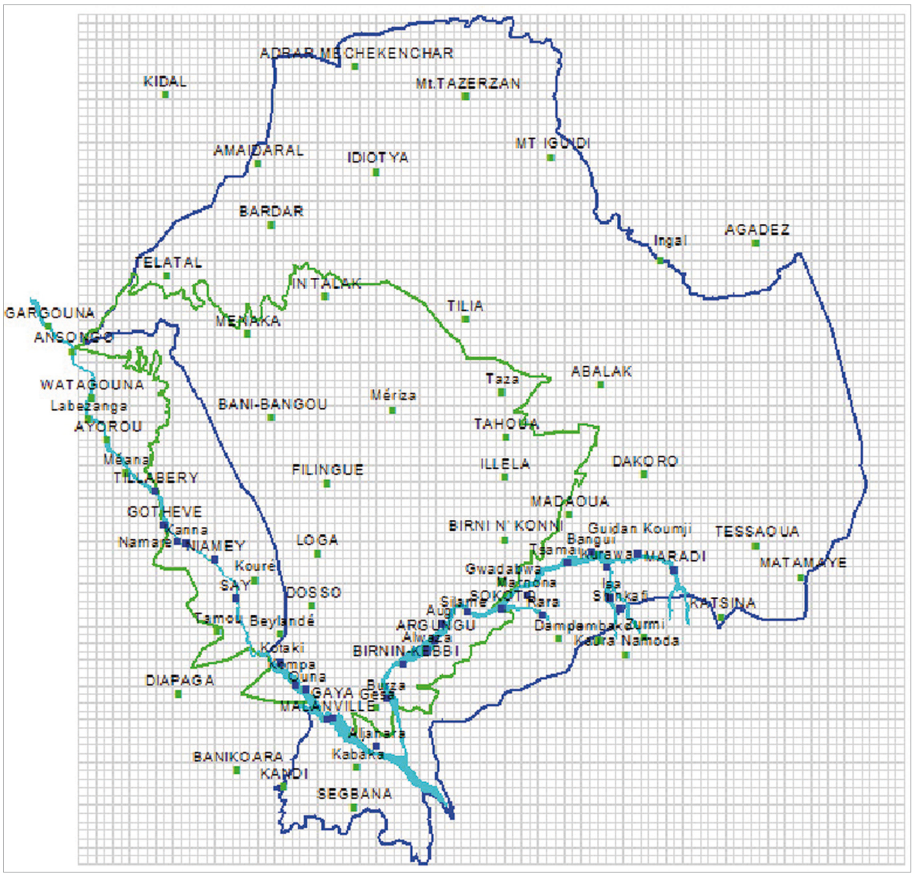


Figure 37 : Villages Along the rivers Niger and Rima

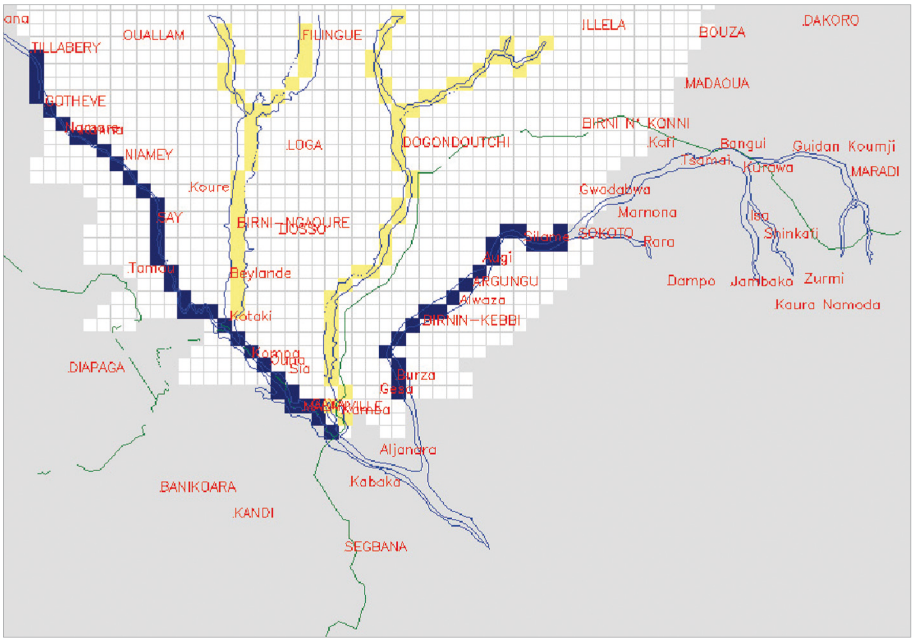


Figure 38 : Drain meshes with an imposed potential in the CT

69

Mesh	Flow per mesh river Niger	Village	Flow per section	Mesh	Flow per mesh Rima	Village	Flow per section
1	-1.607E-01	Tillabery		1	-7.240E-02	South Burza	-7.240E-02
2	-3.500E-02			2	-4.651E-02	Burza	-4.651E-02
3	-2.608E-02			3	-1.110E-01		
4	-1.635E-02			4	-6.798E-02		
5	-5.768E-02	Gotheye	-2.958E-01	5	7.165E-02		
6	-1.023E-01			6	2.231E-02	West Birnin kebbi	-8.501E-02
7	-8.084E-02	Namaré	-1.832E-01	7	2.505E-02	North Birnin kebbi	
8	-9.689E-02	Kanna		8	1.969E-02		
9	-1.153E-01			9	-4.540E-03	Alwaza	4.020E-02
10	-7.125E-02	Niamey	-2.834E-01	10	-2.001E-02	Argungu	-2.001E-02
11	-1.542E-01			11	-2.937E-02		
12	-2.603E-01			12	1.529E-02	Augi	-1.407E-02
13	-3.030E-01			13	-1.366E-02		
14	-6.693E-02	Say	-7.844E-01	14	-3.683E-02		
15	-7.473E-02			15	-6.232E-02	Silame	-1.128E-01
16	-6.659E-02			16	1.526E-02		
17	-6.331E-02			17	-6.694E-03		
18	-8.928E-02			18	4.537E-03		
19	-2.397E-02			19	-5.018E-02	West Sokoto	-3.707E-02
20	-8.728E-02						
21	-2.561E-02						
22	-3.657E-02						
23	-5.545E-02						
24	-5.787E-02	Kotaki	-5.807E-01				
25	-5.748E-02						
26	-3.655E-02	Kompa	-9.403E-02				
27	-3.721E-02	Ouna	-3.721E-02				
28	-3.426E-02						
29	-1.800E-07						
30	-2.919E-02						
31	-1.600E-07						
32	-1.738E-02	Malanville	-8.082E-02				
33	-6.733E-02	Gaya	-6.733E-02				
34	-1.983E-02						
35	-8.191E-02		-1.017E-01				
Total	**-2.509E+00**		**-2.509E+00**	**Total**	**-3.477E-01**		**-3.477E-01**

TABLE 13 : Flows per meshes of the rivers Niger and Rima for the CT (m^3/s)

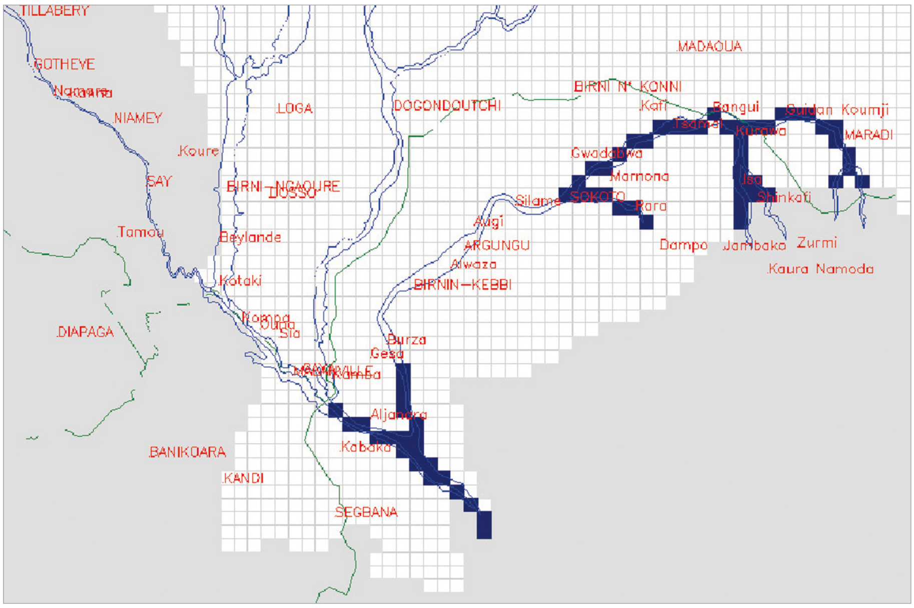


FIGURE 39 : Drain meshes with an fixed potential in the Ci

Mesh	Flow per mesh Rima (Sokoto-Maradi)	Village	Flow per section	Mesh	Flow per mesh Rima (Sokoto-Rara)	Village	Flow per section Sokoto-Rara	Mesh	Flow per mesh Rima (Kurawa-Sud Isa)	Village	Flow per section Kurawa-Sud Isa
1	2.507E-02	Sokoto		1	2.159E-02	Sokoto		1	-9.324E-04	Kurawa	
2	-4.690E-02			2	-4.906E-02			2	4.052E-04		
3	1.102E-01			3	-4.744E-02			3	3.904E-03		
4	1.031E-01	Nord Marnona	1.915E-01	4	8.942E-02			4	9.407E-03	Isa	1.278E-02
5	-4.961E-03			5	-3.788E-02	Rara	-2.336E-02	5	-8.504E-03	Est Isa	-8.504E-03
6	5.302E-02			6	-3.257E-02		-3.257E-02	6	0.000E+00		
7	3.330E-02							7	-5.719E-03	Shinkafi	-5.719E-03
8	2.557E-01							8	1.033E-02	Sud Isa	
9	2.190E-01	Tsamai	5.560E-01					9	1.304E-02		
10	2.610E-02							10	1.857E-02		4.194E-02
11	9.427E-03										
12	-4.277E-03	Bangui	3.125E-02								
13	-3.722E-04										
14	-5.675E-03	Nord Kurawa	-6.047E-03								
15	-6.259E-03										
16	-1.380E-02										
17	-1.217E-02	Guidan Koumji	-3.222E-02								
18	-1.366E-02										
19	-2.045E-02										
20	8.213E-03										
21	-1.313E-02										
22	-1.165E-03	Ouest Maradi	-4.019E-02								

TABLE 14 : flows per meshes of the rivers Niger and Rima for the Ci (m^3/s)

Mesh	Flow per mesh Rima (Sokoto-Maradi)	Village	Flow per section	Mesh	Flow per mesh Rima (Sokoto-Rara)	Village	Flow per section Sokoto-Rara	Mesh	Flow per mesh Rima (Kurawa-Sud Isa)	Village	Flow per section Kurawa-Sud Isa
23	-4.393E-03	Sud Maradi	-4.393E-03								
24	-4.477E-04										
25	8.791E-03										
26	-1.278E-02		-4.433E-03								
Total	**6.915E-01**		**6.915E-01**		**-5.593E-02**		**-5.593E-02**		**4.050E-02**		**4.050E-02**

Table 14 : flows per meshes of the rivers Niger and Rima for the Ci (m^3/s)

Mesh	Flow per mesh river Niger	Village	Flow per section	Mesh	Flow per mesh Rima South of Burza	Village	Flow per section
1	-4.954E-01			**1**	-9.224E-02	South Burza	
2	-2.164E-01			**2**	6.524E-02		
3	-2.202E-01	Aljanara		**3**	1.021E-01		
4	-1.169E-01			**4**	4.623E-02		
5	-1.227E-01			**5**	4.297E-02		
6	-1.475E-01			**6**	-7.215E-02		
7	-2.519E-02						
8	-4.715E-02						
9	-2.302E-02						
10	-7.726E-02						
11	-2.918E-02						
12	-5.203E-02						
13	-2.452E-02						
14	-3.276E-03						
15	-1.583E-04						
16	0.000E+00						
Total	**-1.601E+00**		**-1.601E+00**	**Total**	**9.217E-02**		**9.217E-02**

Table 14 (continuation) : Flows per meshes of the rivers Niger and Rima for the Ci (m^3/s)

VI. CALIBRATION OF THE MODEL IN A UNSTEADY STATE

VI.1. Definition of the reference records and calibration criteria

VI.1.1. Initial condition and reference records

The initial conditions correspond to the calculated piezometric state in 1970, situation assimilated to a permanent regime. On the Ci supply limit, in the North of the basin, the conditions of the fixed potentials were replaced with equivalent flows calculated at the same meshes

As for the period of reference adopted for the calibration of the model in an unsteady state, we simulated the performance of the system over the period covering the initial situation of 1970 (reference year) to 2004 because the data of the withdrawals of the countries (Mali, Niger Nigeria) are limited to 2004. Now, it would have been desirable for this simulation to cover the period from the reference year to the year of the implementation of the model(2006) if the necessary and sufficient data were available, which was not the case; the countries decided **to stop the simulation period relative to the takings at the year 2004**.

VI.1.2. The structural parameters of the initialisation of the calibration

The distribution of the initial storage coefficients was based on the limits « free aquifer – confined aquifer», and relied on the rare punctual rates given by the drillings. These data are issued from records or files supplied by the countries. .

The outcrops maps of the CT and Ci geological layers were also of a great use in the distribution of the initial storing coefficients. Hence, in the zones where the aquifer is free, a porosity of 10% was initially fixed. In the zones where the water table is captive, an initial ratio of 1.10^{-4} was adopted..

VI.1.3. The criteria of the calibration in the unsteady state

It's the case here of a good restoration of the reference levels. Since we are interested in the variations of the ground waters levels, we will compare the reductions observed at the control points, to the corresponding calculated reductions.

The calibration criteria would then consist of resituating the series of measured flows to the outflow (Rivers Niger and Rima and Dallols), but we do not dispose of any records.

VI.2. Knowledge of the withdrawals records

Because of the absence of records in the three countries, we had to elaborate hypotheses based on the existing data with the help of the technicians of the countries.

VI.2.1. Exploitation record in Mali

For Mali, the calculation result by the direct method was judged closest to reality (cf. Chapter IV, section 6.1) and which was used for the wedging of the model. (Table 15).

	Year	1970	1975	1980	1985	1990	1995	2000	2005
CT	MWS takings	15719	8322	13578	31439	91214	119136	195202	207466
	Prod_AEP							54355	127550
Ci	MWS takings	15951	15951	19053	42815	81286	116800	183960	221774
	Prod_AEP							16180	26744
TOTAL	31670	24273	32631	74253	172499	235936	449697	583534	

TABLE 15 : Record of withdrawals in Mali (m³/year)

VI.2.2. Exploitation record in Niger

The data of the five years (2001-2005) were considered insufficient to reconstruct the records of the withdrawals (cf. Chapter IV, section 6.2).this record was calculated from integrated exploitation points within the IAS database. Considering that the average unitary flow is of 1 m³/hour with 8 pumping hours/day - 8 m³/hour/day – the record calculated within the database is shown in the table16 below.

Aquifer	1970	1975	1980	1985	1990	1995	2000	2004
Ci	23 855 271	28 605 820	33 046 606	39 393 934	49 569 672	57 167 479	65 290 015	72 729 834
CT	26 556 271	30 919 658	36 143 021	44 356 116	81 371 668	94 753 742	105 019 515	112 902 876
Total	50 411 542	59 525 478	69 189 627	83 750 050	130 941 340	151 921 222	170 309 531	185 632 710

TABLE 16 : Record of withdrawals in Niger (m³/year)

VI.2.3. Exploitation record in Nigeria

The calculation of the exploitation record in Nigeria is based on the state of the withdrawals in 2004 (cf. Chapter IV, section 6.3) and by considering growth rate of the population from 1970 to 2004 is of 3% (Table17).

As a conclusion, the hypotheses expressed in agreement with the technicians of the countries led to the graph in page 75 (Fig.40) which clearly shows that starting from 1995, the takings estimated at **152 millions m³** exceed the average refill (red line) evaluated by the mathematical model **150 millions m³** in 1970.

Exploitation (Urban) (m³/year)	1970	1975	1980	1985	1990	1995	2000	2004
Sokoto	1844628	2148079	2501448	2912949	3392143	3950167	4599989	5196009
Kebbi	1554700	1810455	2108284	2455107	2858984	3329301	3876988	4379328
Katsina	1569282	1827437	2128059	2478136	2885801	3360530	3913353	4420406
TOTAL	**4968610**	**5785971**	**6737791**	**7846191**	**9136928**	**10639998**	**12390330**	**13995743**

Exploitation (Rural) (m³/year)	1970	1975	1980	1985	1990	1995	2000	2004
Sokoto	5549846	6462823	7525989	8764051	10205781	11884682	13839771	15632987
Kebbi	5441564	6336728	7379151	8593057	10006658	11652802	13569745	15327974
Katsina	1411777	1644021	1914471	2229410	2596159	3023240	3520578	3976739
TOTAL	**12403186**	**14443572**	**16819610**	**19586519**	**22808598**	**26560724**	**30930094**	**34937700**

TABLE 17 : Exploitation record in Nigeria

Exploitation (live-stock) (m³/year)	1970	1975	1980	1985	1990	1995	2000	2004
Sokoto	19318508	22496498	26197283	30506864	35525394	41369496	48174982	54417003
Kebbi	10370270	12076231	14062830	16376235	19070206	22207349	25860567	29211315
Katsina	93861	109302	127283	148221	172604	200999	234064	264391
TOTAL	**29782640**	**34682030**	**40387395**	**47031321**	**54768204**	**63777843**	**74269613**	**83892710**

Exploitation (Total) (m³/year)	1970	1975	1980	1985	1990	1995	2000	2004
Sokoto	26712982	31107399	36224719	42183864	49123317	57204345	66614741	75245998
Kebbi	17366534	20223414	23550265	27424400	31935848	37189452	43307300	48918618
Katsina	3074920	3580760	4169812	4855767	5654565	6584769	7667995	8661536
TOTAL	**47154436**	**54911573**	**63944797**	**74464031**	**86713730**	**100978566**	**117590037**	**132826152**

Table 17 (continued) : Exploitation record in Nigeria

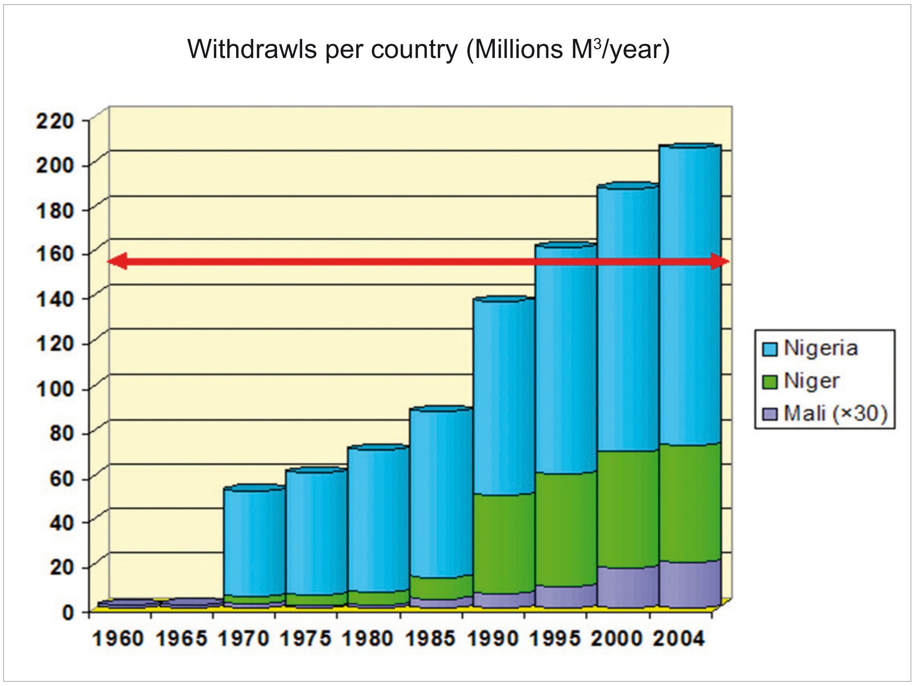


Figure 40 : Evolution of the withdrawals in the IAS

VI.3. The reports of the piezometric levels of refer

We do not have at our disposal any water sources with an exhaustive record of piezometric level, because of a lack of follow up in the countries. In the IAS data base, there is almost no water source with more than two piezometric records in Mali and in Nigeria. However in Niger some piezometric records are available in the Dallols region. The series selected for the wedging of the model are shown in annexe.

VI.4. The stages of unsteady state calibration

VI.4.1. Adjustment of the model's parameters

The major modifications carried out during the calibration concerned the passage of the initial storage coefficient to those retained at the end of the calibration. They are:

- the progressive decrease of the CT storing coefficient from 10 to 4%
- the increase storing coefficients in the free parts of the Ci aquifer from 1.10^{-4} to4.10^{-2}. The ratios of 1.10^{-4} initially adopted were kept because compatible with the captive part of the water table.

VI.4.2. Evaluation of the unsteady state calibration

The restitution of the piezometric records and of the flows to the releases of the system constitutes calibration criteria in unsteady state. The lack of data limits us to the presentation of the results of the evolution of the piezometric heights and the flows at the outflow.

Evolution of the piezometric records

There is no piezometric supervision records in the database that could be used as a control point of the piezometric evolution in the system of the final unsteady state calibration. However, the evolution of the piezometric heights calculated by the model, in some villages.

Evolution of the flows at the outflow

Because of the lack of available records, there are no elements of comparison of the outgoing flows at the releases. Those calculated by the model are shown in figures 41 (a, b and c) below to understand their evolution in time. This is about the flow at the level of the Dallols and the rivers Niger and Rima.

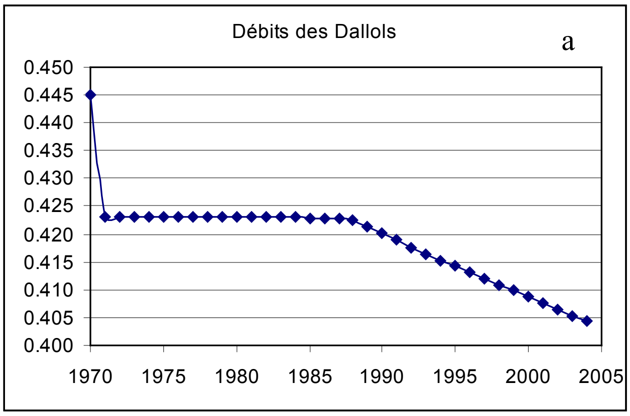
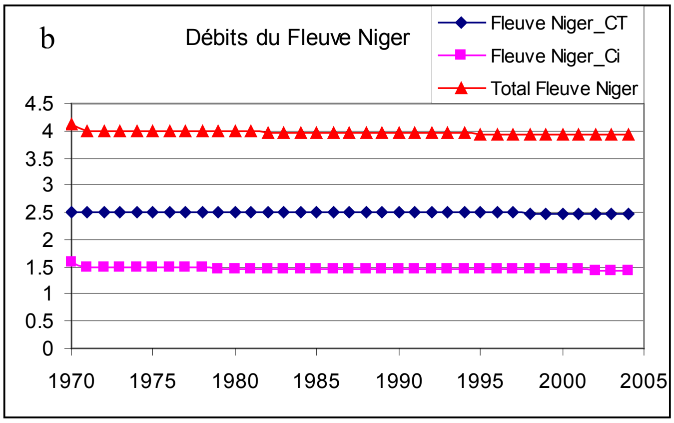
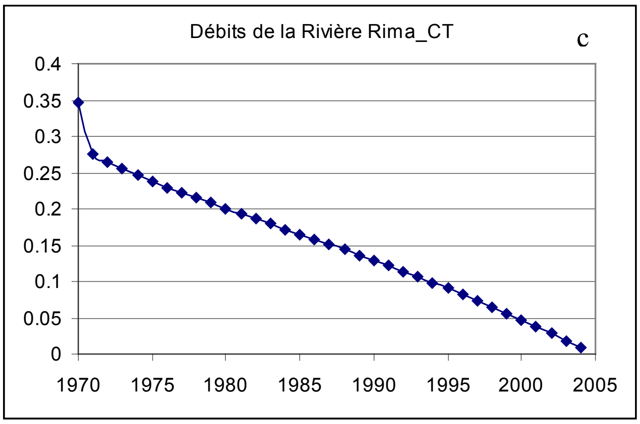


Figure 41 : (a, b & c) Evolution of the flows at the releases of the system





VI.5. Results of the unsteady state calibration

VI.5.1. Distribution of the storage coefficients

The storage coefficient after calibration are generally distributed as follows:: 1.10^{-4} in confined aquifer and 0.04 in free aquifer (Fig.42 a & b). This distribution was considered representative to better reconstruct the evolution of the piezometric levels at the level of the natural outflow.

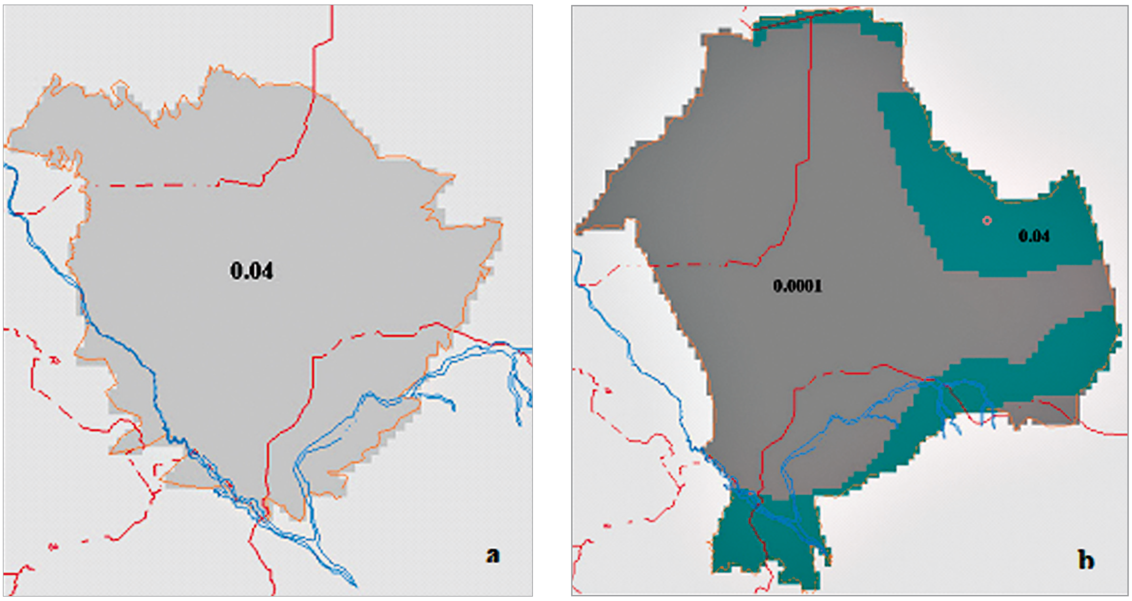


FIGURE 42 : (a & b) The CT(a) and the Ci (b) storage coefficients after calibration of the model

VI.5.2. The Map of reductions 1970-2004

The elaboration of an exploitation record helped to construct a mathematical model and the simulation of the system's performance over the period 1970- 2004. These simulations gave the following results:

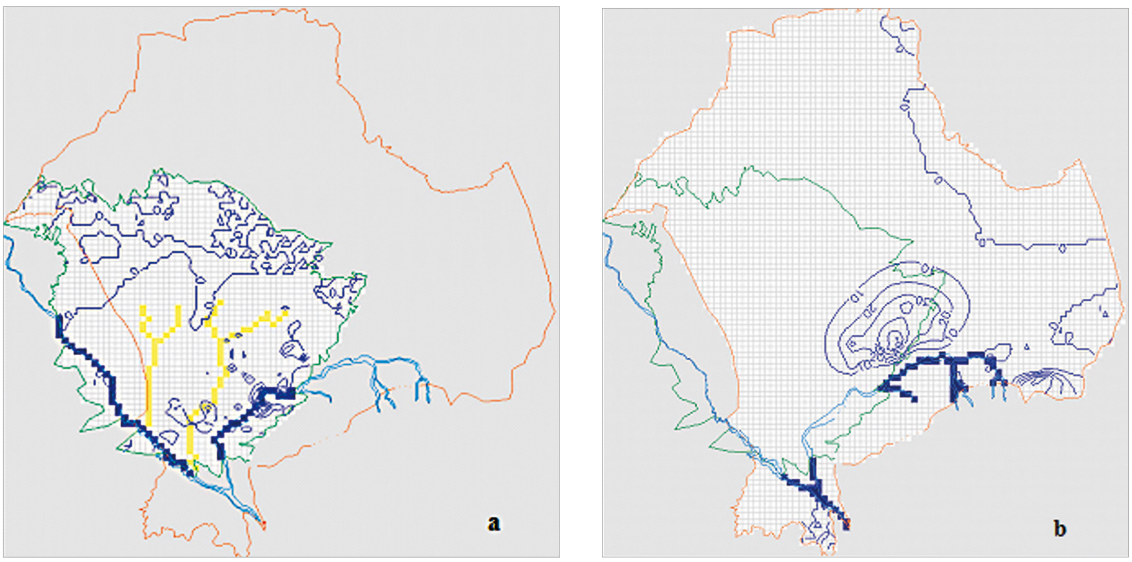


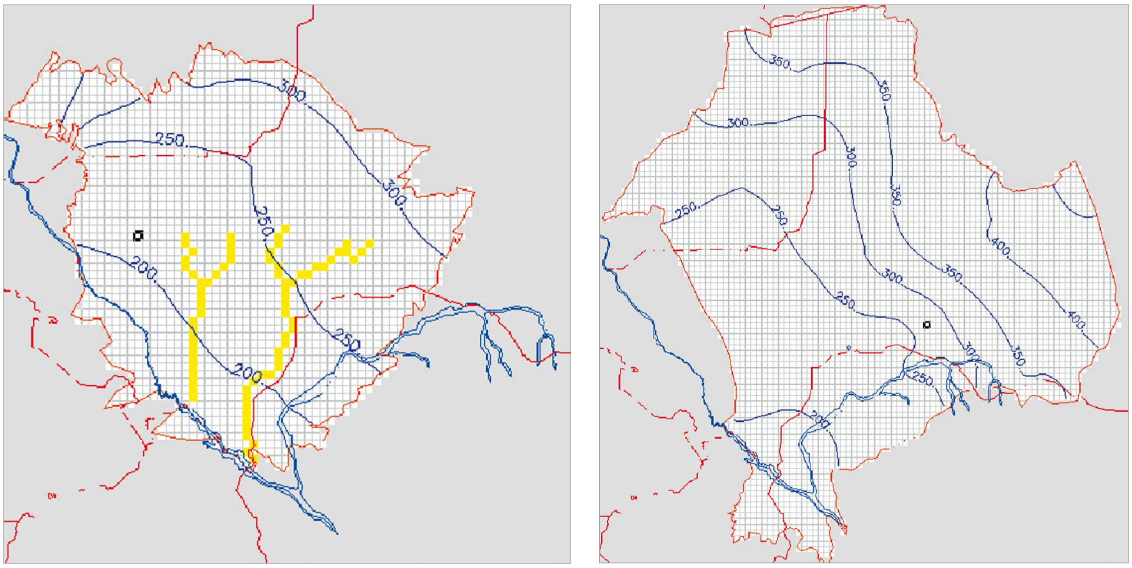
FIGURE 43 : The CT (a) and the Ci (b) reductions in 2004

- For the Continental Terminal, the reductions were unimportant with a maximum of 5 metres in the Goulbi sector of Maradi (Fig.43a).these weak reductions are explained by the direct infiltration of rain waters and the supply from the hydrological net.
- For the Continental Intercalaire (Ci), the most important reductions are in the oriental part of the basin centred in the village Birni N'Konni (in Niger) with a maximum reduction of 62 metres over the same period (Fig.43b). the resources of this confined water table are little renewable, it is thus threatened by mining.

VI.5.3. The calculated piezometric maps in 2004

The study of figures 44(a and b) below show that the general speed of the isopiezes curves is preserved. However, in the region of Birni Konni (Ci), in Niger, the flows are strongly marked by the supposed takings where we observe maximum flows.

a



b

Figure 44 : The CT(a) and the Ci(b) piezometric maps calculated by the model in 2004

VI.5.4. The 2004 assessment

The assessment of the system in 2004 is shown in the chart 18 below.

Continental terminal			
Inflow (m^3/s)		Outflow (m^3/s)	
Refill	3.294	**River Niger**	2.477
Drainage Ci	0.011	**Dallols**	0.404
Reserves	2.092	**Rivier Rima**	0.008
		Pumping	2.516
TOTAL Inflow	**5.397**	**TOTAL Outflow**	**5.405**
Continental intercalaire			
Inflow (m^3/s)		Outflow (m^3/s)	
Refill	0.548	**River Niger**	1.438
Ratios North border	0.298	**Drainage CT**	0.011
River Rima	1.576	**Pumping**	1.979
Reserves	1.302		
TOTAL Inflow	**3.724**	**TOTAL Outflow**	**3.428**

Table 18 : Water assessment in 2004

The study of the results shows that:

- the sum of the refill of the system is 4.15 m^3/s, or 92% of the total of the withdrawals per drilling (4.49 m^3/s)
- the contribution of the reserves (« ratio per reduction») is evaluated at 3.39 m^3/s or 75% of the withdrawals per drilling.

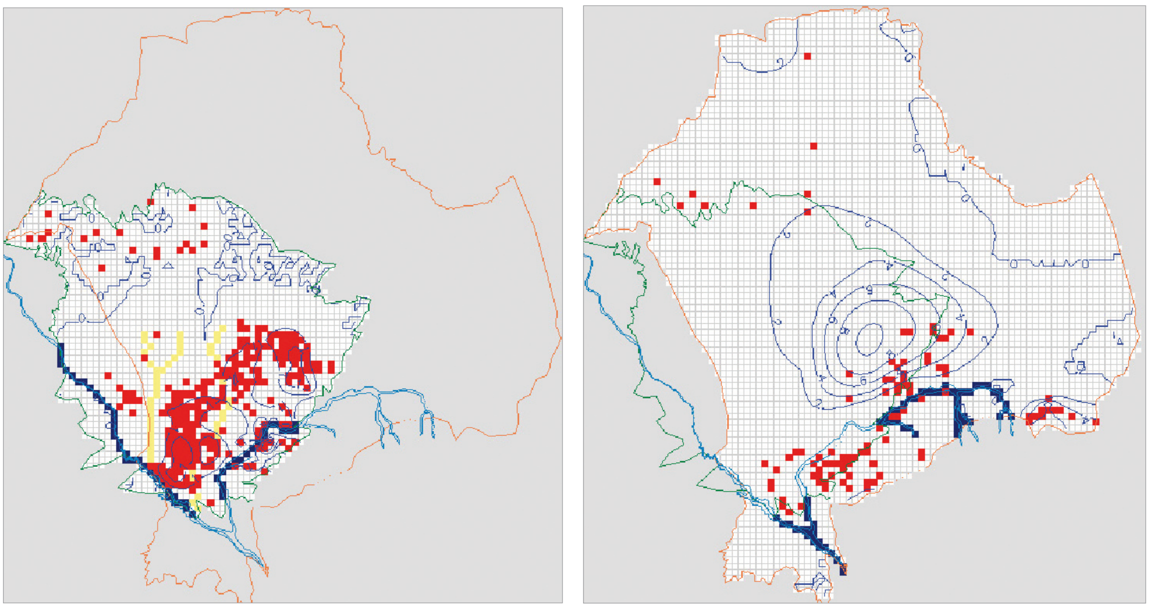
Basing on these results, we can already anticipate will keep increasing even if we decide to keep the pumps at their present level. The importance of this progress, in time and space, remains to be clarified. This calculation will be the object of a projected simulation zero, the first to be considered by the model.

VI.5.5. Exploratory Simulations

Following these results, the performance of the system was simulated over the period 2004-2025, on the basis of a hypothesis called «hypothesis zero». This hypothesis consists in maintaining the 2004 withdrawals constant and simulating their impact on the resource in the year2025. The estimations of the model in 2025 state a maximum of 2 meters additional reductions for the CT and 10 meters for the Ci (Fig.45b).

This helped to identify the vulnerable zones characterised by important reductions caused by a growing exploitation. These risky zones are situated in the region of Birni N'Konni (Factory of Malbaza), in Nigeria in the region Sokoto and in Mali in the northern part (figures 45a and b).

a



b

Figure 45 : Additional reductions in the CT(a) and the Ci(b) in the year 2025

For the same period (2025), the simulation above was reused by dividing the refill by 3. The estimates show, roughly, the same reductions- a maximum of 2.25 meters additional reductions for the CT (Fig.46a) and of 10.8 meters for the Ci (Fig.46b). We must however note that for the Ci where the impact of the decrease of refill is more significant, the disappearance of the isoratio 0 curve in the North-East and an opening of the curve iso-ratio 2, show a general increase of the reductions.

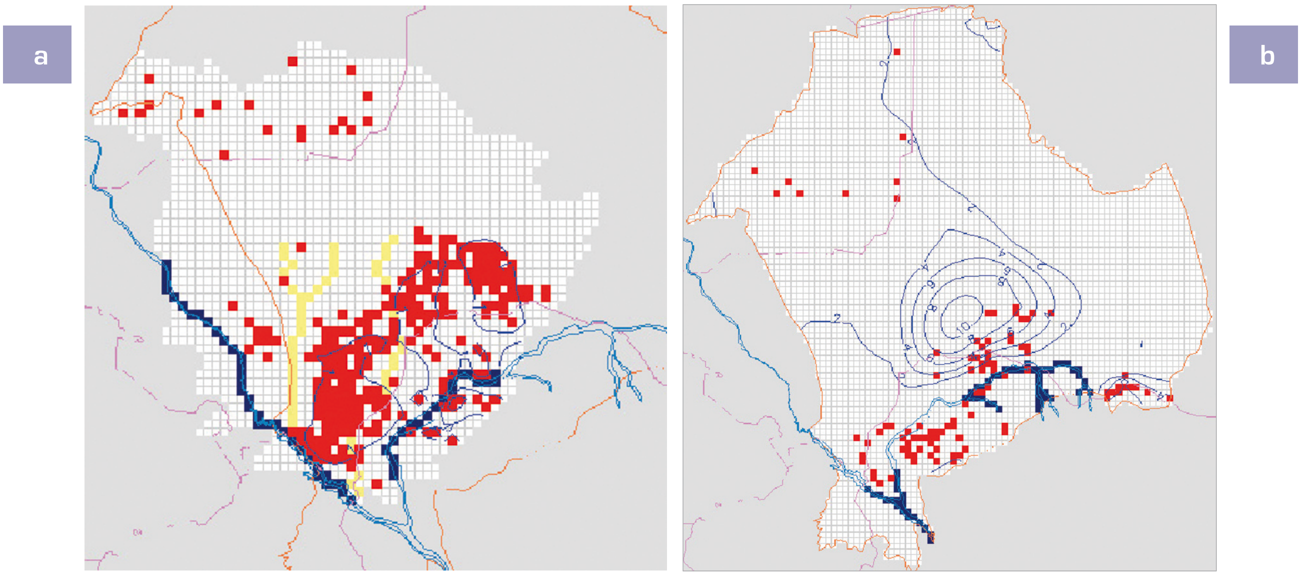


Figure 46 : Additional reductions in the CT (a) and in the Ci (b) in the year 2025, with a refill divided by 3

VII. CONCLUSION

The Iullemeden Aquifer system is a sedimentary depression which different aquifer layers, situated between the Precambrian shelf at the basis and the surface of ground, are sought differently in the three countries (Mali, Niger and Nigeria) which share this system.

The conceptualisation of the hydrodynamic functioning of this multilayer system was undertaken on the basis of a good synthesis of the geological data available – mainly the geological map of the outcrops and tens of oil and hydraulic drillings.

The elaboration of correlations between the different drillings based on this volume of geological data helped to set an acceptable schematisation of the extension of the aquifer layers separated by aquicludes and ensuring the continuity of the underground flow in the whole aquifer system.

On this basis, and with the help of maps of the roof, the wall and the thickness of each layer, it was possible to refine the physical structure of the aquifer system and to adopt a bilayer configuration in order to group the different aquifer levels.

The calibration of the hydrodynamic functioning of the aquifer system is achieved by reference to its piezometric situation of **1970**, period considered the best to explain, through available piezometric information, the state of the aquifer system not yet influenced by the exploitation. This date coincides with the beginning of great droughts in the Sahel till mid 1980's.

A lack of records of the flows or exploited volumes for specific uses (Water Supply, irrigation, livestock, industry), was observed in the three countries. The records obtained were elaborated on the basis of hypotheses expressed with the help of the countries. This major gap in the follow up of the IAS aquifers made the calibration of the model relatively difficult.

With the acquisition of new data, the model was reorganised to integrate all the new information. This necessitated, during the elaboration of the model, a reorganisation of the limits of the system and of some conditions to limits and a "re-calibration" in a steady state, then in a unsteady one.

The calibration of the model highlights a water assessment of **5 m^3/s** (CT: 3.3 m^3/s and Ci: 1.6 m^3/s). This ratio shows the important entrances of the system in the shape of infiltration. The drainage within the system was at the period relatively weak. In this assessment a particular importance was given to the exchanges between the river Niger and its tributaries (river Rima).

The calibration of the aquifer system functioning in a transitory regime, during the period 1971-2004, referred to an acceptable piezometry and an exploitation record which was constructed with a lot of difficulties because of the lack of sufficient measures punctuating the exploitation during that period.

The aquifer system assessment shows, starting from the mid 1990's, a sensible growth of the withdrawals which exceed the regulatory resources. The reductions ratios calculated (maximum 62m in the Ci) are to be considered with reserve, because they are induced by the withdrawals which remain hypothetical. This exploitation has to become more reinforced and to entail more and more important piezometric drops within the IAS aquifers. This is mainly the case of the CT which is artesian in the Dallols and where this drop results in a weakening of the artesianism.

The estimated simulations of the development of the exploitation mainly based on some hypotheses advanced by the countries, confirm this tendency towards the decrease and show influences overflowing the frontiers of the countries. This is particularly the case between Niger and Nigeria.

Thanks to these first modelling results we can say that the IAS has water resources relatively more modest than supposed previously on approximate hypotheses. This system began with the overexploitation of these geological reserves, phenomenon to be more accentuated with time.

Considering the state of the IAS exploitation and the conditions of elaboration of this model, it is highly recommended, to reach a good management tool of the aquifer system, to consider the elaboration of a hydrogeological model which will clarify its structural construction and more databases relative to the piezometry and to the water withdrawals.

BIBLIOGRAPHY

BOECKH E. (1965). Contribution à l'étude hydrogéologique de la zone sédentaire de la république du Niger. Ministère des Travaux publics et des Mines de la république du Niger. Rapport technique BRGM / BFBH, DAK 65-A 20. Dakar, Sénégal ; in GUERO (2003).

BCEOM-CE, (2000). Etude complémentaire de vulnérabilité à la pollution des aquifères et des mesures de préservation de l'environnement dans les communes de Maradi et de Zinder. Hydro-conseil, BCEOM, CEH-Sidi ; DRE.

DRE/MH (1999). Schéma Directeur de Mise en Valeur et de Gestion des Ressources en Eau- Ministère de l'Hydraulique et de l'environnement. Niamey, Niger, Juin 1999.

DODO A. (1992). Etude des circulations profondes dans le grand bassin sédimentaire du Niger : Identification des aquifères et compréhension de leurs fonctionnements. Thèse, Université de Neuchâtel, 101p. 44 fig., 14 tabl., 15 ann.

ETH (1999). Evaluation des Ressources en Eaux Souterraines et Risques de Pollution dans le Dallol Maouri.

FAO (1970). Etudes en vue de la mise en valeur du Dallol Maouri, Niger : les eaux souterraines. Rome, Italie - 162p. ; cart., graph.. PROJET FAO/SF: 281/NIR 8, 1970.

FAVREAU G. (2000). Caractérisation et Modélisation d'une nappe phréatique en hausse au Sahel dynamique et géochimie de la dépression piézométrique naturelle du kori de Dantiandou (sud-ouest du Niger. Thèse de doctorat Univ. Paris XI, Orsay, France.

GREIGERT J. (1978). Atlas des eaux souterraines de la République du Niger. Etat des connaissances. Rapport BRGM, 79 AGE001. Orléans, France.

GUERO A. (2003). Etude des relations hydrauliques entre les différentes nappes du complexe sédimentaire de la bordure Sud-Ouest du bassin des Iullemmeden (Niger) : Approche géochimique et hydrodynamique. Thèse de Doctorat. Univ. Paris XI. 257p.

JICA (1990). The Study Groudwater Development in Sokoto State.

MARGAT J. (1982). Aquifère du Continental intercalaire du bassin sédimentaire du Niger (Mali, Niger, Nigeria). Bull. BRGM, Hydrogéologie, n°2.

OSS (2002). Système aquifère du Sahara Septentrional : De la concertation à la gestion commune d'un bassin aquifère transfrontière. Projet SASS. Rapport interne. Tunis, Tunisie. 58p.

OSS (2003). Modèle mathématique du Système aquifère du Sahara Septentrional.

OSS (2006A) Première Session de Renforcement des capacités des représentants des pays en modélisation mathématique. Système aquifère d'Iullemeden (SAI). Atelier ; OSS-Tunis, Avril 2006, 13p.

OSS (2006B) Deuxième Session de Renforcement des capacités des représentants des pays en modélisation mathématique. Système aquifère d'Iullemeden (SAI). Atelier ; OSS-Tunis, Décembre 2006, 16p.

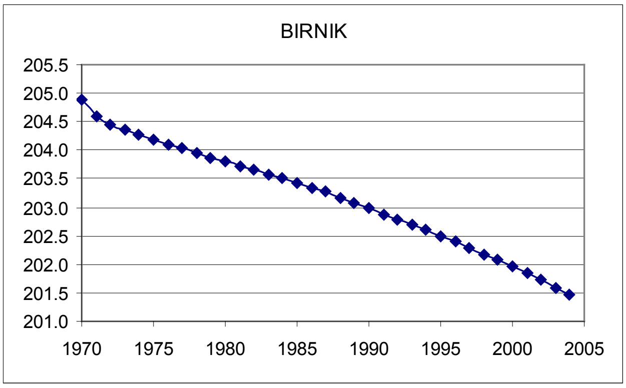
OSS (2007). Base de données du Système aquifère d'Iullemeden.

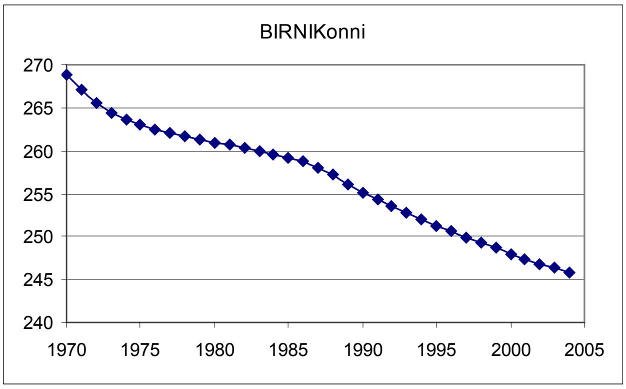
SAAD K. F. (1969). Étude hydrogéologique de l'est du Mali, Rapport 1856/BMS.RD/SCF, 55 pp., UNESCO, Paris.

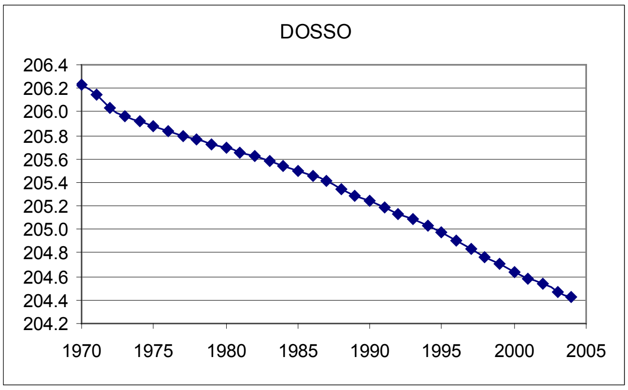
USGS (1988). Michael G. McDonald & Arlen W. Harbaugh: A modular three dimensional finite-difference ground water flow model

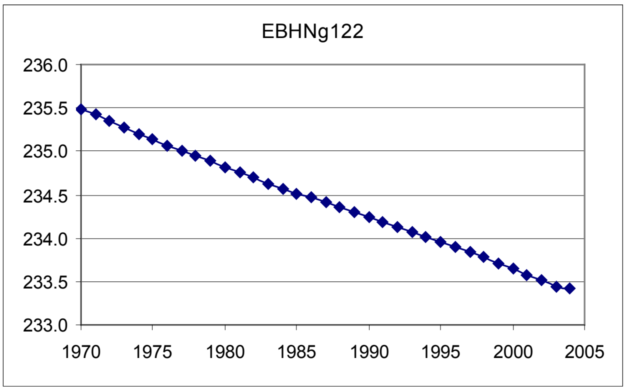
Annexe

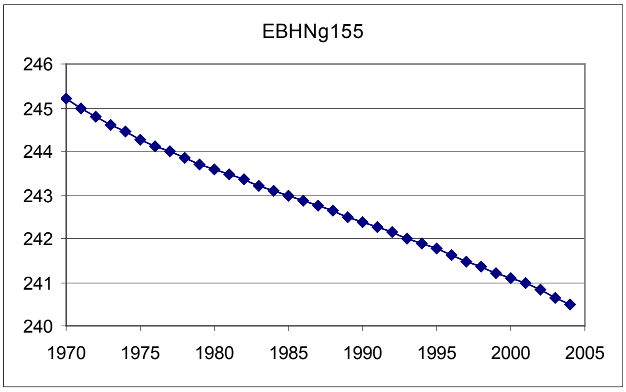
REFERENCE PIEZOMETRIC LEVELS

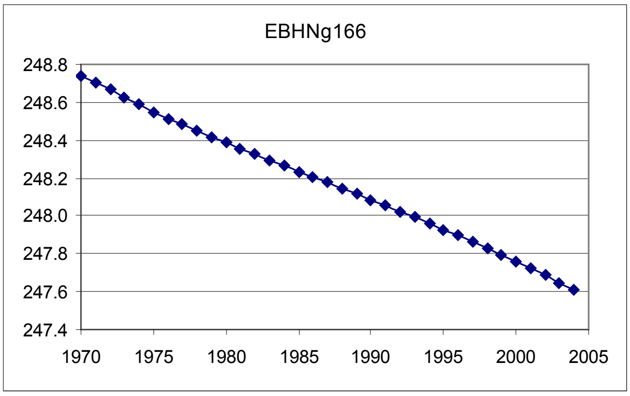


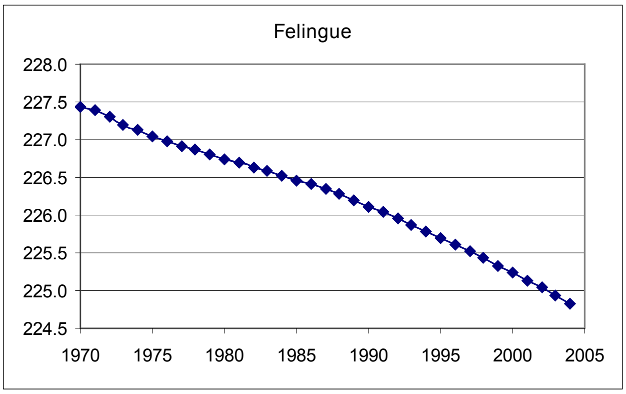


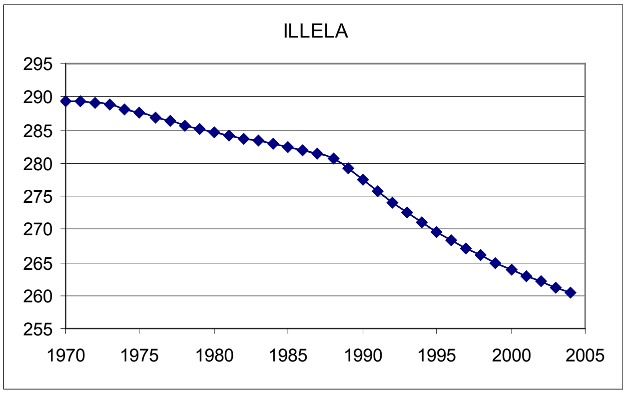


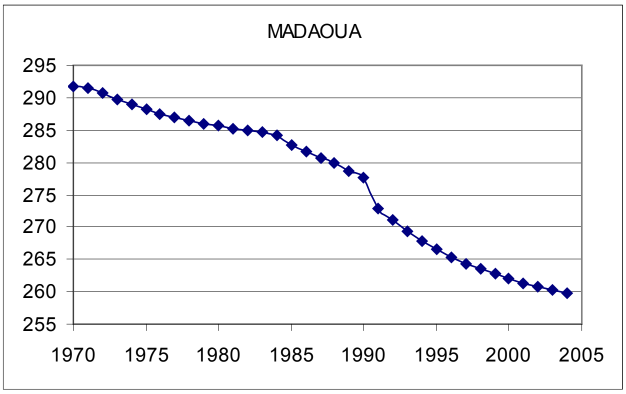


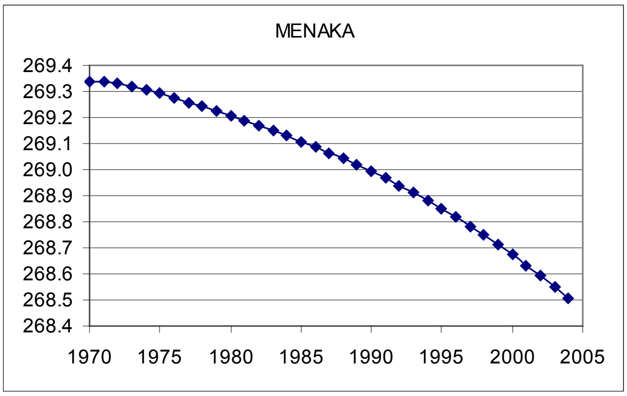


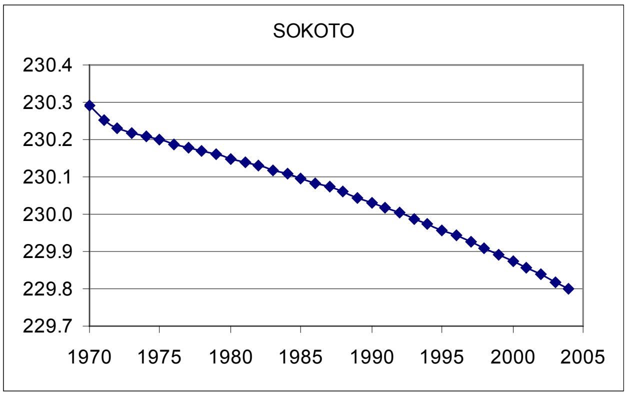


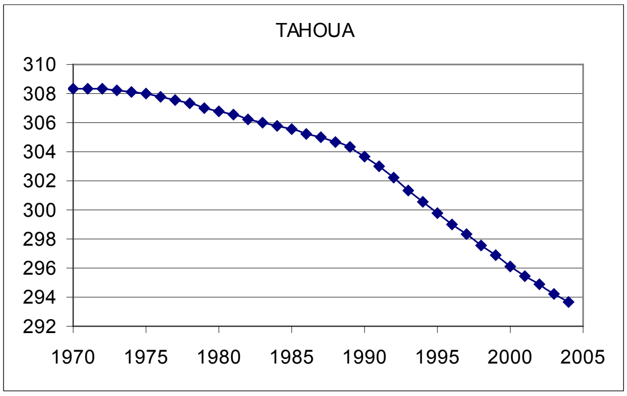

Felingue
228.0
227.5
227.0
226.5
226.0
225.5
225.0
224.5
1970 1975 1980 1985 1990 1995 2000 2005


ILLELA
295
290
285
280
275
270
265
260
255
1970 1975 1980 1985 1990 1995 2000 2005


MADAOUA
295
290
285
280
275
270
265
260
255
1970 1975 1980 1985 1990 1995 2000 2005


MENAKA
269.4
269.3
269.2
269.1
269.0
268.9
268.8
268.7
268.6
268.5
268.4
1970 1975 1980 1985 1990 1995 2000 2005


SOKOTO
230.4
230.3
230.2
230.1
230.0
229.9
229.8
229.7
1970 1975 1980 1985 1990 1995 2000 2005


TAHOUA
310
308
306
304
302
300
298
296
294
292
1970 1975 1980 1985 1990 1995 2000 2005

Iullemeden Aquifer System

Volume III – Hydrogeological Model

The hydrogeological modelling undertaken under the project "Managing hydrogeological risks in the Iullemeden Aquifer System (SAI)" is part of the Transboundary Diagnostic Analysis (TDA). His goal is to better assess water resources of this aquifer system and to identify hydrogeological risks associated

OSS has proposed to carry out this model with the national team's contribution in view to provide to the three countries a powerful tool for managing the shared water resources. This is a critical analysis of available information and identifying its practical limitations in improving knowledge about the behaviour of the aquifer system and the identification of hydrogeological risks associated to the water resource abstraction increasingly intensive.

This document presents a hydrogeological water balance of the aquifer system with its different components: recharge, hydrogeological characteristics (structure, hydraulic head, and water quality), abstraction and seepage.

Using the model as a tool for simulation of the aquifer system can develop scenarios for developing its water resources. It allows to reach the planning goals in the three countries and to identify the impact of withdrawals on the aquifer system behaviour and risks trends.

This document is a summary of the effort made by the project team at OSS and national experts associated in the collection, formatting relevant data for modelling and conceptualization of the hydrodynamic behaviour of this system, and its connections with the environment ●

- Volume I: Transboundary Diagnostic Analysis
- Volume II : Common Database
- Volume IV: Participatory management of transboundary risks
- Volume V: Monitoring & Evaluation of transboundary aquifers

Partners

Mali
Niger
Nigeria
IAEA
ESA
FAO
GEF
UNESCO
UNEP

Edited with the financial support of

Organisation des Nations Unies pour l'éducation, la science et la culture
Programme Hydrologique International
giz

Sahara and Sahel Observatory
Bd du Leader Y. Arafat, BP 31, 1080 Tunis Carthage, Tunisia
Tel. : (+216).71.206.633 - Fax : (+216).71.206.636
URL : www.oss-online.org - Email : boc@oss.org.tn