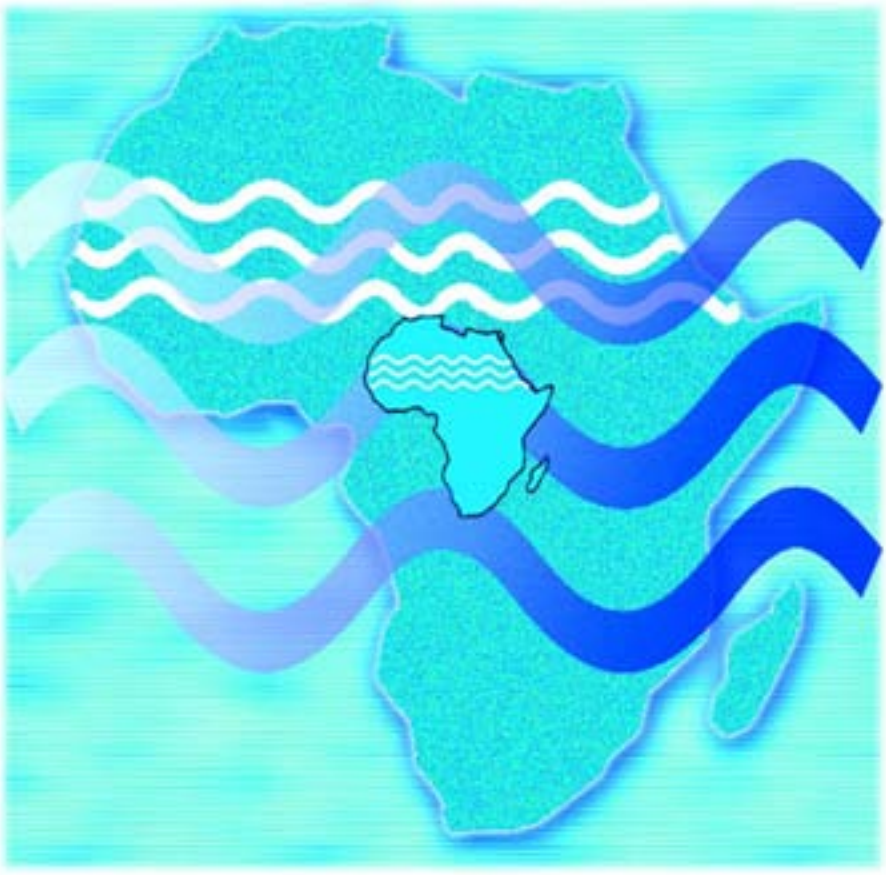
ISARM-AFRICA

Managing Shared Aquifer Resources in Africa



United Nations Educational, Scientific and Cultural Organization

International Hydrological Programme

General Water Authority of the Libyan Arab Jamahiriya

Edited by Bo Appelgren

IHP-VI, Series on Groundwater No. 8

The designations employed and the presentation of material throughout the publication do not imply the expression of any opinion whatsoever on the part of UNESCO concerning the legal status of any country, territory, city or of its authorities, or concerning the delimitation of its frontiers or boundaries.

CO-SPONSORS:

International Organisations:
FAO, IAEA, IAH, IDB, UNECE

Regional Organizations:
SADC, CEDARE, CENSAD, OSS and OACT

National Organisations:
GWA, GMRA, GMRWUA (Eastern, Western and Central Zones), GCMAP, LIBYAN ARAB AIRLINES, WWIP, NSRSC, GCAS

Published in 2004 by the United Nations Educational,
Scientific and Cultural Organization
7, Place de Fontenoy, 75352 Paris 07 SP (France)
Composed by Marina Rubio, 93200 Saint-Denis

© UNESCO 2004

Printed in France

ISBN 92-9220-028-3

Acknowledgments

These proceedings were prepared within the framework of the UNESCO-IHP/ISARM Programme. The proceedings were compiled and edited by Dr Bo Gunnar Appelgren, Senior Consultant UNESCO Division of Water Sciences, with the support of Ms Raya Marina Stephan, Consultant, UNESCO Division of Water Sciences.

Preface

The International Workshop on 'Managing Shared Aquifer Resources in Africa', held in Tripoli, 2–4 June 2002 was hosted and supported by the General Water Authority of the Libyan Arab Jamahiriya and jointly convened by the UNESCO International Hydrological Programme under the Internationally Shared Aquifer Resources Management (ISARM) initiative. ISARM is an inter-agency initiative launched by the Intergovernmental Council of the International Hydrological Programme of UNESCO at its 14th Session (June 2000) (ISARM framework document http://unesdoc.unesco.org/images/0012/001243/124386e.pdf). The Council, having recognized that transboundary aquifer systems are important sources of fresh water in some regions of the world, particularly under arid and semi-arid climatic conditions adopted Resolution No. XIV-12. UNESCO has therefore initiated the inventory of the main transboundary aquifers in different regions of the world.

The International Workshop marked a key activity for the follow-up of the landmark Tripoli Statement in November 1999 (International Conference on Regional Aquifer Systems in Arid Zones – Managing Non-Renewable Resources)[1] and represented a principal step forward for implementing and putting into practice a regional ISARM strategy for the management of internationally shared aquifers in Africa.

The launch of the ISARM Strategy in Africa will lead in particular to establish an inventory of African transboundary aquifers, and drawing a regional map accordingly, and also to create a regional center for the management of shared groundwater resources under the auspices of UNESCO and WMO.

The International Workshop and its sponsorship gave recognition to a notable experience and involvement in international groundwater management and development of the host country under the programmes on the Nubian Sandstone Aquifer and the North-West Sahara Aquifer Systems that Libya shares with the neighboring countries.

The meeting was co-sponsored and attended by the representatives of international and regional organizations including FAO, IAEA, IDB, UNECE, UN-WWAP and IAH together with SADC, CEDARE, CENSAD, OSS and OACT and Libyan government and non-public private sector organizations. More than 200 experts of different disciplines from more than 25 African States participated in the workshop that was held in Tripoli, 2–4 June 2002. The workshop included opening addresses from excellencies and representatives of participating international and regional communities and programmes, presentations of keynote papers and case studies from the host country and 18 African countries, as well as contributions from regional scientific and basin organizations.

In the workshop recommendations the participants gave high priority to the conclusion of the inventory of African shared aquifers, preparation of policy guidelines for sustainable development of shared aquifers, and timely involvement and action for the implementation of an African ISARM Programme, drawing on the support of existing and new partners.

Andras SZÖLLÖSI-NAGY
Deputy Assistant Director-General for Natural Sciences
Secretary International Hydrological Programme (IHP)
Director, Division of Water Sciences

1. Proceedings of the International Conference, Tripoli, Libya 20–24 November 1999, International Hydrological Programme, IHP-V/Technical Documents in Hydrology/No. 42, also available on-line http://www.unesco.org/ihp_db/publications.

CONTENTS

Workshop summary report 9

Tripoli Workshop Recommendations 15

Introductory and keynote papers 17

GWA - Libya
O. Salem, P. Pallas
The Nubian Sandstone Aquifer System 19

UNECE
G.E. Arnold
International initiatives on monitoring and assessment of transboundary groundwaters – implementation of the UNECE groundwater guidelines in a broader perspective 23

World Bank (GWMATE)
M. Nanni
An introduction to the Groundwater Management Advisory Team (GWMATE) 29

SADC
P. Molapo, S. Puyoo
Transboundary aquifer management in the context of integrated water resources management in the SADC region 31

IAH - ISARM
S. Puri
Management of transboundary aquifers: contribution to the water needs of Africa 39

UNESCO/FAO
P. Pallas, J. Margat
Transboundary aquifers – Scientific-hydrogeological aspects 41

UNESCO - ISARM
B. Appelgren
Scope of the International Workshop on Transboundary Aquifers in the African Region 47

Country contributions and technical papers 53

Algeria
A.S. Moulla, A. Guendouz, M.E.H. Cherchali
Contributions des isotopes à l'étude des ressources en eau souterraines transfrontalières en Algérie 55

Benin
F.V. Azonsi
Utilisation des aquifères du bassin sédimentaire côtier entre le Bénin et le Togo dans un contexte de variabilité climatique; problèmes émergeants 69

Botswana
C.J. Chilume
Shared knowledge, a key to equitable utilization of transboundary aquifers 75

Ghana
W.A. Agyekum
Groundwater resources of Ghana with focus on Internationally Shared Aquifer Systems 77

Côte d'Ivoire
J.P.R. Jourda
Les ressources en eau souterraine de la Côte d'Ivoire et le cas de l'aquifère transfrontalier de la Côte d'Ivoire et le Ghana 87

Kenya
F.K. Mwango, B.C. Muhangú, C.O. Juma, I.T. Githae
Groundwater resources of Kenya 93

Malawi
P. Mkandawire
Groundwater resources of Malawi 101

Mali
M. Alhousseini
État de la connaissance des eaux souterraines au Mali 105

Mauritania
B. Diagana
État des connaissances des aquifères Grands bassins sédimentaires au sud du Sahara : approche stratégique 109

Mauritius
R. Pokhun
Groundwater management in Mauritius 113

Namibia
S. Ndengu
The Southeastern Kalahari Karoo Aquifers System 117

Niger
A. Dodo
Caractéristiques des Aquifères du Niger 123
B. Ousmane
La gestion et l'exploitation des eaux souterraines au Niger 129

Nigeria
C.M. Maduabuchi
Case studies on transboundary aquifers in Nigeria 135

Sudan
A.A. Mohammed
Sustainable management of shared aquifers 143

Swaziland
O.M. Ngwenya
Groundwater assessment in the transboundary aquifer at Mhlumeni Border Post Area, Eastern Swaziland 155

Tanzania
S. Mapanda
Transboundary aquifers of Tanzania 161

Tunisia
M. Besbes, M. Babasy, S. Kadri, D. Latrech, A. Mamou, P. Pallas, M. Zammouri
Conceptual framework of the North Western Sahara Aquifer System 163

Uganda
J.A. Kitakarugire
Managing shared aquifer resources in Africa – Uganda case 171

Regional and basin organizations 175

Center for Environment and Development for the Arab Region and Europe (CEDARE)
M. Bakhbakhi
Hydrogeological framework of the Nubian Sandstone Aquifer System 177

Lake Chad Basin Commission (LCBC)
J. A. Oguntola
Management of transboundary aquifer systems in Africa – A case study of the Lake Chad Basin Commission 203

Niger Basin Authority (NBA)
I.A. Olomoda
Impact of climatic change on river Niger 209

Organisation Africaine de Cartographie et de Télédétection (OACT)
M.S. Zitoun
Le Système d'Information sur les Ressources en Eau des Pays de l'Afrique du Nord (SERIPAN) : un outil de gestion concertée des ressources en eau 217

Appendices 223

1. **Table 1**
   Transboundary aquifers in Africa referred to in the Workshop 225
2. **Table 2**
   Transboundary aquifers in Africa Cross-reference between African countries sharing individual aquifer systems 229
3. **Map**
   Transboundary aquifers in Africa 231
4. **List of Workshop participants** 233

Workshop summary report

The event took place at a critical turning point in time, when important global and regional water initiatives are opening the opportunities to raise the role of groundwater and shared aquifer resources in resolving Africa's and the world's water crisis. Water is at the top of the agenda in Africa and the workshop focused on mobilizing and initiating a regional ISARM network in Africa and drawing up the lines for a continental survey of transboundary aquifers in the continent. The workshop is also expected to help in defining the substance and raising the profile of shared aquifer resources and groundwater in general under the recently initiated NEPAD and the African Ministerial AMCOW processes. The recommendations of the workshop provided powerful messages on shared aquifers to the World Summit on Sustainable Development in Johannesburg in September 2002 and to the 3rd World Water Forum in Kyoto in March 2003.

At the commencement of the 21st century water scarcity is taking a dimension of growing global risk. The concern is becoming most evident in the arid and semi-arid areas of Africa, where shortage and lack of access to water form a main cause for poverty, dwindling public health and food insecurity. In Africa groundwater represents a main water resource and a strategic source of freshwater essential to supplement the surface water resources and enhance water security in a region that is increasingly affected by recurrent drought. The African region is endowed with large and in many parts unutilised aquifer resources dominated by the large shared sub-regional sedimentary systems of Sahara and Central and Southern Africa but also including significant shared coastal aquifer resources used to supply concentrations of large urban populations in rapidly growing coastal areas and mega-cities. The aquifer resources in Africa are to a large extent transboundary and shared between two or more countries. There is so far a scarcity of regional hydrogeological information and gaps in the understanding of the role of groundwater in supporting socio-economic development and food security, in sustaining livelihood and welfare and in protecting freshwater, dryland and humid ecosystems. Differently from surface waters, groundwater is not directly visible to the decision makers and the public and scientific evidence is often insufficient to identify and agree at a political level on the perceived transboundary attributes of an aquifer. A situation of high current scientific and policy uncertainty is not only a threat to water security and a constraint to the management of regional and local water risks but also a potential cause for growing international pressure and water conflict.

Many countries and large urban conglomerations in Africa depend to a major extent or entirely on groundwater and the large shared aquifer resources represent often the only source for drought security and life sustenance of large populations in semi-arid areas. The groundwater-land linkages are critical to aquifer recharge and humid zones, and interdependent shared aquifers and land and eco-systems in Africa are threatened from the impacts of accelerated land degradation and desertification, from reduced seepage or from water logging and salinization. These threats, which impact on very large land areas, have reached a sub-regional and transboundary scale in Africa.

Workshop objectives

Within the overall objective to guarantee sustainable utilization, management and protection of internationally shared groundwater resources in the African region, the specific objectives of the international workshop were to evaluate the scope and the conditions and mobilize the countries in Africa and their external development partners to:

1. Initiate an appropriate framework for studying and assessing shared groundwater resources in African countries,
2. Present and discuss case studies on African Regional Aquifer Systems,
3. Identify needs and provide support to the

African countries for improving cooperation to study and assess groundwater resources,
4. Prepare an inventory of the existing African Transboundary Aquifers, and
5. Launch a Regional ISARM Africa Programme.

Workshop contributions and documentation

The groundwater specialists from African countries and from regional, basin and international organisations and associations presented technical papers and country statements, including reports on bilateral and sub-regional cases and background information for development of regional guidelines for management and monitoring of the shared resources. The material presented in the workshop represents a valuable baseline to identify gaps and define the scope for the assessment of shared aquifers in Africa under the ISARM-Africa programme

The workshop included opening and closing ceremonies together with introductory and technical sessions.

Opening ceremony

The addresses delivered in the opening ceremony of the International Workshop included The General Manager of the General Water Authority of the Libyan Arab Jamahiriya, Mr. Omar A. Salem, The Secretary-General of the Saharan Sahelian Group of African Countries, Dr. Mohamed Al-Madani Al-Azhari, Dr. A. Aureli, UNESCO/IHP, The Director of UN-WWAP, Dr Gordon Young and The Executive Secretary of OSS Dr. C. Fezzani.

H.E. Dr. Trekki, Minister of African Unity, opened the International Workshop.

Introductory session

The presentation of relevant programmes and activities of the participating international organizations and regional institutions included FAO, IAEA, UN-ECE, UNESCO-IHP, UN-WWAP, ISARM- IAH and GWMATE/ Word Bank. The participants were briefed on the processes leading to the Johannesburg World Summit on the Environment in 2002 and the 3rd World Water Forum in Kyoto 2003. Assessment of the shared aquifer resources in Africa, including demands and uses and mitigation of risk, forms a high priority for the implementation of the UN World Water Assessment Programme (UN-WWAP, www.unesco.org/water/wwap/). The UN-WWAP has prepared and published for the Third World Water Forum (Kyoto, March 2003) the World Water Development Report, *Water for People, Water for Life*. Assessment will now proceed at a regional level to culminate with a planned UN-sponsored Regional Conference on Water in Africa. The participants were further briefed on the ongoing NEPAD-AMCOW process and the African Ministerial Conference on Water recently launched in the Abuja Ministerial Meeting in April 2002.

Technical sessions

The sessions were initiated with an outline of the scope of the workshop and guidance for a focused debate. The sessions included country presentations, a sub-regional presentation by the SADC Water Sector and case studies by African basin organizations. The presentations and the discussions identified priority management issues as well as examples and requirements, including: a) the importance of joint monitoring of recharge areas in neighbouring countries; b) the importance of shared groundwater in situations of extreme water scarcity, formed by infiltration of surface waters in the neighbouring country; c) shared aquifers left without joint monitoring; and d) the high dependence on shared coastal aquifers for supply of large cities.

The country papers provided overviews of the national groundwater resources and technical presentation of aquifer systems shared with neighbouring countries.

As a result of the workshop a list of identified transboundary aquifers in Africa, with the countries sharing each system, is presented in Table 1 (Appendix 1).

In Table 2 (Appendix 2), the aquifers have been organized for riparian countries, summarizing the number of countries sharing one aquifer as well as the number of shared aquifers in each country. The Table provides the indication of interest for a strategic programme and priorities for action on transboundary aquifers in Africa. One country shares as many as 7 aquifers and several others share 6 aquifers with neighbouring countries. While a few large regional aquifers have up to 6 riparian countries, in most cases only 2–4 countries share the same aquifer sys-

tem. In this situation, similar to transboundary surface water resources, it is observed that a regional capacity building approach to promote bi-lateral cooperation on smaller border aquifers and sub-basins shared by 2–3 countries would be more effective and less complicated than to impose large cooperative frameworks between as much as 5–6 participating countries.

The location and approximate extension of the aquifers are indicated in Map 1 (Appendix 3).

The presentations, and suggestions made by the participants in the sessions, included a list of relevant observations on the shared aquifer systems in the region:

- while the region is endowed with large and often under-utilised shared groundwater resources, water scarcity and lack of access to water in the region form major constraints to socio-economic development,
- groundwater forms the principal water supply for urban agglomerations, and is also often the only source for accessible and safe supply to rural populations in Africa,
- the region is increasingly dependent on shared groundwater for water security,
- the immediate need for safe quality water to support priority initiatives on improved drinking water supplies in Africa,
- the groundwater resources in Africa are to a large extent shared between two or more countries, while the many and large shared aquifer resources in Africa are not well identified or known,
- the shared transboundary aquifer systems, renewable and non-renewable, represent an invaluable social and cultural inheritance and are of strategic importance for socio-economic and agricultural development, improved welfare and public health, alleviation of poverty and improved food security for the present and current African populations. These shared groundwater resources, as well as the related land resources suffer from growing pressure and lack of proper management, which result in losses in water resources, productive land and life-supporting eco-systems,
- the shared aquifer resources are left to country based management and use, therefore there is risk to impose high social and economic cost and incur loss of resources and benefits both at country and regional level, and therefore,
- scientific data and analysis of shared aquifers are needed to form the basis for national and/or joint decisions on the development, conservation and protection of groundwater resources and of the interdependent land-based resources,
- the implications of national and/or joint decisions for an aquifer need to be assessed, and mitigating measures taken, based on current available knowledge and data,
- the need for an effective cooperative framework for groundwater assessment and water conflict resolution,
- scientific and policy uncertainty and gaps in awareness and understanding of the significance and the role of the shared groundwater in supporting socio-economic development, sustaining livelihood and welfare and protecting life-supporting ecosystems in the Region,
- the gap in the manpower and human resources capacities for joint management of the shared transboundary aquifers,
- the lack of frameworks and institutional mechanisms for joint management of shared groundwater resources as a first prerequisite for cooperation on shared groundwaters,
- the several on-going and planned initiatives on management of shared aquifer resources, water resources assessment and data management in the region including in North Africa, the Sahara-Sahel and the SADC sub-region.

The participants made detailed suggestions related to technical and institutional aspects of management of shared aquifer resources in Africa. The recommendations were organized under four categories: a) inventory and assessment of shared aquifers in Africa; b) policy guidelines for sustainable development; c) activities and requirements under the ISARM Africa Programme; and d) regional cooperation frameworks.

Inventory and assessment of shared aquifers in Africa

- Prepare a regional inventory of the existing, known shared aquifer systems in Africa, based on updated rapid country assessments of groundwater resources shared with adjacent countries, by
  - Identifying shared aquifers and assessing the importance of current and future transboundary issues,
  - Jointly collect and exchange information and establish common knowledge and data bases on shared aquifer resources,
  - Identify and establish a regional centre and focal point responsible for the mana-

gement of a regional data base and other research on the African shared aquifer systems,

- Establish common guidelines for monitoring and assessment of shared aquifers in the Region,
- Improve communications between nearby countries sharing groundwater resources by creating a regional WEB-site where countries could deposit and access basic data related to shared aquifers as one temporary measure prior to formal consultations and data exchange mechanisms,
- Give priority attention to improve assessment of demands as present water abstractions and future water demands from shared aquifers in Africa establishing: water abstractions and contamination by a) sectors (agriculture, industry, water supply), by b) national use of shared aquifers, and c) predict future water demands based on national water policy and reasonable assumptions on population dynamics, consumption patterns and socio-economic development. Establish joint demand–related information systems for shared groundwaters at regional/sub-regional level,
- Use modern methodology for hydrogeological investigations of the shared aquifer resources, such as isotope hydrology studies, in a multi-disciplinary context of shared aquifers to, provide information for sustainable management of shared aquifer system, assess potentials and support the development of guidelines for management of non-renewable groundwaters.

Policy guidelines for sustainable development

- Manage shared aquifer resources, jointly with surface water resources, in an integrated manner based on defined hydrological units and water bodies and considering risk and uncertainty,
- Utilize shared aquifer resources efficiently and equitably for socio-economic development for optimal joint benefits, minimizing social, economic and environmental risk,
- Identify opportunities for development and investments for socio-economic development with poverty alleviation and institutional and manpower capacity building,
- Attend to environmental risk, including impacts of land degradation and threats to terrestrial and freshwater eco-systems,
- Develop regional policy guidelines for management of shared aquifer systems, incorporating aspects of development, protection and control, institutional mechanisms and definition of appropriate hydrological units
- Establish regional agreements and frameworks providing for institutional arrangements, rights and obligations and for continuity and stability of the cooperation on the shared aquifers. Countries sharing one or more aquifers are encouraged to forge international cooperation in the management of such groundwater basins by establishing commissions or other frameworks. As and when States establish an agreement this should be substantiated in appropriate bi- or multi-lateral instrument on sharing the aquifer. Available examples of state practice and recommendations need to be inventoried and studied for the guidance of states in particular in relation to non-renewable shared aquifers
- Initially, prior to the establishment of formal framework for cooperation, states contemplating development and management decisions on a shared aquifer should assess transboundary impacts and inform other states concerned taking into account the impacts in their development and management decisions. Operational EIA procedures for protection and monitoring of shared aquifers should be developed and applied.

Activities and requirements under the ISARM Africa Programme

- Review capacities for joint management of shared aquifer resources in the region and establish and implement a regional programme to strengthen manpower and institutional capacities at regional and national level,
- Build on and further develop the experience and the manpower resources within the region and, in particular to draw from the experience from the aquifer studies in the North African sub-region and transfer and apply this knowledge to other African sub-regions including CILSS, SADC and IGAD,
- Build on and use established networks and UNESCO supported university water resources chairs in the region for dissemination and exchange of information and experience,
- Implement, draw on and disseminate mana-

gement experience from case studies of selected, representative shared aquifer systems in the Region. The following sub-regional aquifer systems have been proposed to provide representative sites for case studies under the ISARM African Programme:

- The Iullemeden system shared by Mali, Niger and Nigeria,
- The SASS aquifer shared between Algeria, Tunisia and Libya,
- The Karoo-Kalahari systems shared by Namibia, Botswana and South Africa and by Angola and Zambia respectively,
- The Chad Aquifer systems shared between Chad, Cameroon, Central African Republic, Libya Niger, Nigeria and Algeria,
- The Nubian Sandstone aquifer shared by Egypt, Libya and Sudan,
- The Benin- Togo Coastal Aquifer,
- The basalt aquifer shared by Djibouti and Ethiopia,
- The common Kenya-Tanzania basalt aquifer,
- The Merti aquifer shared by Kenya and Somalia.

■ Exchange international experience from outside the African region on studies and project on the management of shared aquifer systems including transboundary aquifers in Europe, the Guarani aquifer in Latin America and others,

■ Identify and formulate project activities to develop methodology for support joint management, harmonized development and resource protection of shared aquifer systems in Africa. The project on the shared Iullemeden aquifer, formulated and endorsed by the Governments of Mali, Niger and Nigeria, represents a first priority case under the ISARM African programme,

■ The UNESCO/IHP under the current IHP programme (IHP VI) will take the lead on and spearhead a regional programme of groundwater studies and development of decision support tools for the management of the resources,

■ The workshop participants called on the UN agencies, in particular UNESCO/IHP, FAO, IAEA, UNECE, UNESCWA, UNECA, and the UN-WWAP, together with international and regional funding institutions and bilateral donors and other external development partners to identify and provide the necessary assistance and resources for the implementation of the ISARM African Programme. The level of knowledge of the aquifers and water resources varies in Africa, which should be considered when allocating and distributing scientific and technical assistance in the region.

Regional cooperation frameworks

■ Promote and develop the appropriate level of awareness and emphasis on shared ground waters in Africa, under the AMCOW process, and in close contact with related activities of regional institutions and centres, including AU, CENCAD, CILSS/ECOWAS, EAC, IGAD, SADC, UMA, and OSS, and others, and

■ Promote global recognition and awareness of the social, cultural and environmental values of shared aquifers. It is proposed that one or more of the large sub-regional aquifers in the semi-arid regions of Africa that serve as the only available source for water supply, drought security and life sustenance be recognized as UNESCO World Heritage sites.

The findings and recommendations identified in the workshop were reconciled and summarized in the *Tripoli Workshop Recommendation,* and are attached to the workshop proceedings as presented and adopted in the closing session of the workshop.

Tripoli Workshop Recommendations

More than 200 participants from 30 countries, regional and international organisations and associations attended the

International Workshop on Managing Shared Aquifers Resources in Africa

2nd to 4th June 2002

Considering the Statement of the Tripoli International Conference 1999, related to the management of shared aquifers, we the participants of this Workshop recognise that:

- Water scarcity in most African countries implies a serious threat to sustainable and balanced socio economic growth. However, the region is endowed with shared, large, and for many parts under-utilised groundwater resources, often the only source for fresh water,
- There is growing demand for water resources but there is limitation of current management, arising from limited financial resources, lack of awareness and inadequate appreciation of the role of groundwater in national and regional development,
- This workshop marks a clear milestone, demonstrating the extent to, which shared aquifers resources are able to contribute to human development, alleviation of poverty and improved food security.
- The Internationally Shared Aquifer Resources Management initiative with the objective of coordinating efforts on shared groundwater resources will be beneficial.

We the participants consider that, to benefit from the value of these resources:

- Sharing countries should be encouraged to implement joint management, through the strengthening of their respective institutions and supportive legal frameworks, building capacities and drawing on the existing experience at regional and national levels, raising awareness, and encouraging investments,
- Regional integrated water resources policy and international basin programmes should include groundwaters and give attention to shared aquifers.

We recommend that:

A. inventories of African shared aquifers, following the guidance of the ISARM Framework Document be conducted,

B. policy guidelines for sound and sustainable development of shared aquifers be prepared,

C. following the launching of an African ISARM Programme, activities drawing on support from existing partners and seeking support from others should be initiated, and that

D. the above recommendations should be brought to the attention of the African Ministers through the NEPAD and AMCOW process.

We further recommend that:

- a message of the value of shared aquifers be presented to all participants at the World Summit on Sustainable Development, Johannesburg, September 2002 and at the 3rd World Water Forum, Kyoto, March 2003,
- the assessment of the shared aquifer resources in Africa including demand, uses and mitigation of risk be incorporated in the UN World Water Assessment Programme.



Introductory and keynote papers

The Nubian Sandstone Aquifer System (NSAS)

Omar Salem

General Water Authority, Libya

Philippe Pallas

UNESCO-FAO, Consultant

Background

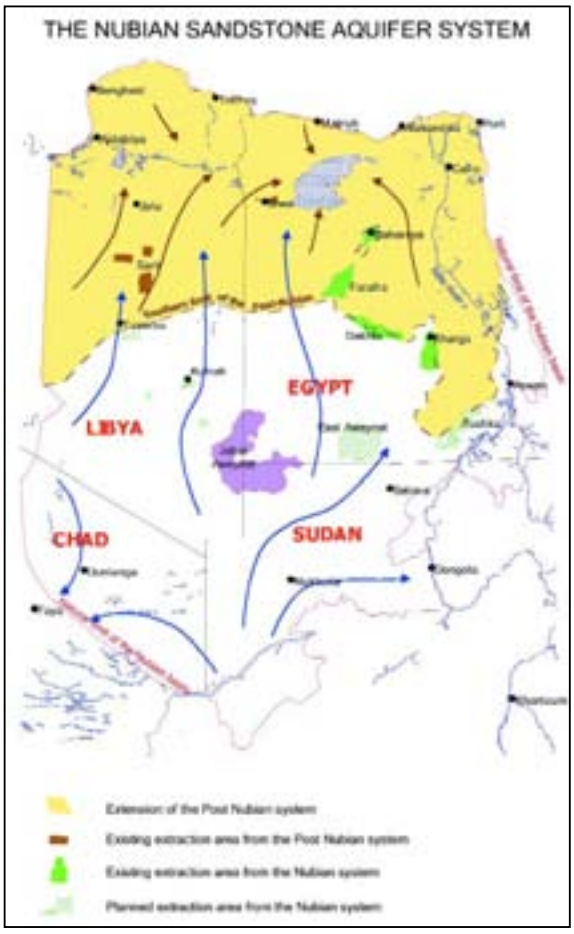
The NSAS consists of a number of aquifers laterally and/or vertically interconnected, extending over more than 2,000,000 km^2 in East Libya, Egypt, North-East Chad and North Sudan. The main components of the NSAS include:

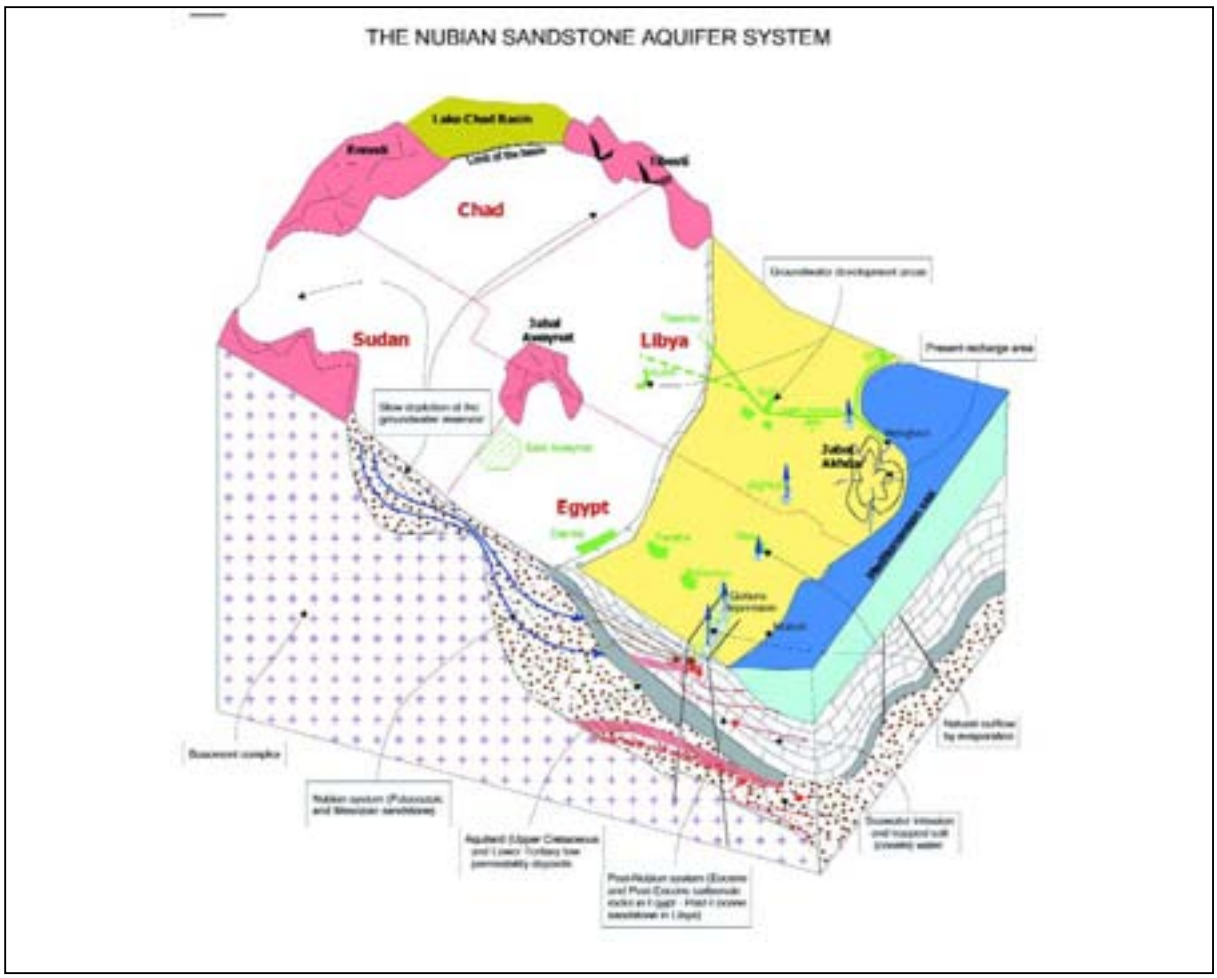
- Palaeozoic continental deposits (mainly sandstone),
- Mesozoic continental deposits, pre-Upper-Cenomanian (Nubian Sandstone *sensu stricto*),
- Post-Eocene continental deposits (mainly sandstone) in Libya, equivalent to carbonate rocks aquifer in Egypt. This component communicate with the underlaying Mesozoic or Palaeozoic aquifers through Mesozoic-Cenozoic low permeability formations.

The **Nubian aquifers** including the Palaeozoic and Mesozoic deposits older than the Pre-Upper Cenomanian extend over the whole Nubian Basin, although becoming very saline in the northern part. The Nubian deposits are outcropping or sub-cropping in all that part of the basin located south of the 26th parallel, in which the aquifer system is under unconfined condition. The unconfined part of the Nubian aquifers includes the most important groundwater potential of the whole basin: the extension of the cones of depression resulting from the water abstraction in existing and planned well fields in that part of the Nubian domain is always limited and makes it possible to multiply the centres of extraction.

The **Post Nubian reservoir** corresponding to the Post Eocene deposits exists only in Egypt and Libya but it is definitely more important in Libya in term of development potential.

The aquifer systems are not in equilibrium: the observed groundwater flow from South to North and the present natural outflow in the large and deep evaporative areas between Ajdabyia and Cairo are not due to present recharge but instead to the slow depletion of the groundwater reservoirs filled up during the pluvial periods of the late Quaternary.





Water resources and beneficial uses of the water resources

Data collected in the framework of the IFAD funded programme on the NSAS made it possible to estimate the amount of fresh water stored in the two aquifer systems. The main results of this fresh water resources assessment are shown on Table 1.

Most of the present water extracted from the NSAS is used for agriculture, either for large development projects in Libya or for private farms located in old traditional oasis in Egypt (New Valley). However, an important project designed for transporting water to the coast from the NSAS is under development in Libya and is already supplying some 70 Mm^3/yr of water to Benghazi and to the major coastal cities west of Ajdabyia. From the figures displayed on the above table it appears that the present extraction represents only some 0.01% of the estimated total recoverable freshwater volume stored in the NSAS.

Significant issues concerning the NSAS

The large groundwater development projects planned in the southern part of Egypt and Libya within the Nubian basin are not expected to induce any significant effect beyond the common border between the two countries. The different options of water resources development can influence the amplitude of the cone of depression, such as the cone of depression that may extend beyond the Egyptian-Sudanese border over several tens of kilometres if particularly intensive water extraction is realised in the South-western part of Egypt.

In the North, the groundwater development in Siwa oasis from the deep aquifer (Nubian) is close to the fresh water/salt water interface and increasing the present abstraction may draw saline water into the fresh water aquifer. The development of a well field in Jaghbub area, located in Libya in a symmetric position of Siwa referred to the border line, would probably augment the risk of deterioration of the water quality in the Nubian aquifer.

TABLE 1. Essential data of the Nubian Sandstone Aquifer

Country	*Nubian system (Palaeozoic and Mesozoic sandstone aquifers)*		*Post Nubian system (Miocene aquifers)*		*Total volume of fresh water in storage (km^3)* (1)	*Total recoverable groundwater volume (km^3)* (2)	*Present extraction from the Post-Nubian system (km^3)*	*Present extraction from the Nubian system (km^3)*	*Total present extraction from the NSAS (km^3)*
	Area (km^2)	*Fresh water volume in storage (km^3)*	*Area (km^2)*	*Fresh water volume in storage (km^3)*					
Egypt	815,670	154,720	426,480	97,490	252,210	5,180	0.306	0.200	0.506
Libya	754,088	136,550	494,040	71,730	208,280	5,920	0.264	0.567	0.831
Chad	232,980	47,810	NA	NA	47,810	1,630	NA	0.000	0.000
Sudan	373,100	33,880	NA	NA	33,880	2,610	NA	0.840(3)	0.833
Total	2,175,838	372,960	920,520	169,220	542,180	15,340	0.570	1.607	2.170

NA: Not applicable.
(1) Assuming a storativity of 10^{-4} for the confined part of the aquifers and 7% effective porosity for the unconfined part.
(2) Assuming a maximum allowed water level decline of 100 m in the unconfined aquifer areas and 200 m in the confined aquifer areas.
(3) Most of this water is extracted in the Nile Nubian Basin (833 Mm^3/yr) which is not considered to be part of the Nubian Basin.

Source: CEDARE/IFAD Programme for the development of a Regional Strategy for the Utilisation of the Nubian Sandstone Aquifer System.

An IFAD funded project[1] is assessing the regional implications of various groundwater development scenarios based on the NSAS and will propose consultation mechanisms for a joint management of the water resources including the systematic data exchange on groundwater extraction and on water level and water quality fluctuations.

1. Programme for the development of a Regional Strategy for the Utilisation of the Nubian Sandstone Aquifer System operated by CEDARE.

International initiatives on monitoring and assessment of transboundary groundwaters

('Implementation of the UNECE groundwater guidelines in a broader perspective')

Geo E. Arnold

Institute for Inland Water Management
and Waste Water Treatment, RIZA
The Netherlands

Abstract

An important contribution to the improvement of knowledge about transboundary waters has been made by UNECE, which has developed Guidelines on Monitoring and Assessment of Transboundary Waters. In the past few years, guidelines have been developed for transboundary rivers, groundwaters and international lakes. The preparation of guidelines and accompanying background reports are activities of the Working Group on Monitoring and Assessment under the 1992 UNECE Convention on the Protection of Transboundary Watercourses and International Lakes (Water Convention). The groundwater guidelines were endorsed by the Parties to the Convention at their second meeting in The Hague (March 2000). The UNECE experience and the documents (Groundwater guidelines and the Inventory of transboundary groundwaters) proved to be very important for the ISARM programme and were a reason for a close co-operation among UNESCO, IAH, FAO and UNECE. Another important development in relation to the Water Convention is the European Water Framework Directive, which came into force in December 2000. The Water Framework Directive will provide the legislative framework for water protection and management in a major part of the UNECE region.

This paper describes the activities undertaken in relation to the European transboundary groundwaters.

Introduction

Groundwater supports various important functions some of which, like nature and agriculture, are directly related to the occurrence of groundwater. For other functions, such as drinking water and industrial water supply, groundwater is used as a production factor, because of its normally good and constant quality. However, high and increasing population density, continuously growing industrialisation and intensive agriculture will have a negative effect on the quality of soil and groundwater. Over-abstraction of groundwater results in declining groundwater tables. In recent times, soils have become increasingly polluted by private and public waste dumps, air pollution, agricultural chemicals (fertilisers, pesticides, herbicides). In shallow groundwaters this pollution can easily be transported to locations where it may be harmful to one or more of the functions referred to above. These problems do not occur only within countries, but can also have transboundary impacts. Then there is a requirement for agreed and consistent cross-border monitoring and assessment activities to identify the origin of the pollution and evaluate its current extent and future evolution. Furthermore, measures may be needed to avoid these undesired developments and monitoring to assess their effectiveness, within, as well as between countries through joint groundwater bodies. The integral basin area approach, or ecosystem approach, which was adopted as a guiding principle in the Convention on the Protection and Use of Transboundary Watercourses and International Lakes, was also the basis for structuring the guidelines on monitoring and assessment of transboundary groundwaters [1].

The groundwater guidelines are supported by supplementary documentation. An inventory, based largely on questionnaire responses, was made of transboundary groundwaters in the ECE region and their current monitoring and assess-

ment practices. Background reports were produced on the inventory and on the present approaches to monitoring which contributed to the drafting of the guidelines. Additional activities included work to identify indicators for groundwater assessment and a review of the use of models.

In this way, four supporting technical reports have been produced:

- Inventory of transboundary groundwaters [2],
- Problem-oriented approach and the use of indicators [3],
- Application of models [4],
- State of the art on monitoring and assessment of groundwaters [5].

Inventory of European transboundary groundwaters

In Europe, a relatively long history exists for the management and international co-operation on rivers (Rhine and Danube). The existence and importance of transboundary groundwaters as a hidden resource were not yet known and generally recognised. After a first quick scan transboundary groundwaters proved to be more important as it was generally recognised. Based on this quick scan a comprehensive inventory of transboundary groundwaters in Europe has been set up. For the inventory a questionnaire has been drafted and was circulated among the ECE members. From the 37 countries 25 countries responded to the questionnaire and 89 transboundary aquifers were indicated (Figure 1).

The inventory gives information on the following items:

- the location, extension and type of transboundary groundwaters;
- the monitoring activities, pollution sources and contamination of transboundary groundwaters;
- the uses, problems and trends in the state of groundwater according to the observations up till now;
- institutional aspects and international aspects in their management in the EC-region;
- the position and significance of groundwaters;
- the legal and administrative background; and
- bilateral agreements.

Lessons learned

Despite the fact that the questionnaire was drawn up very carefully some deficiencies were found after receiving the answers and verification of the results.

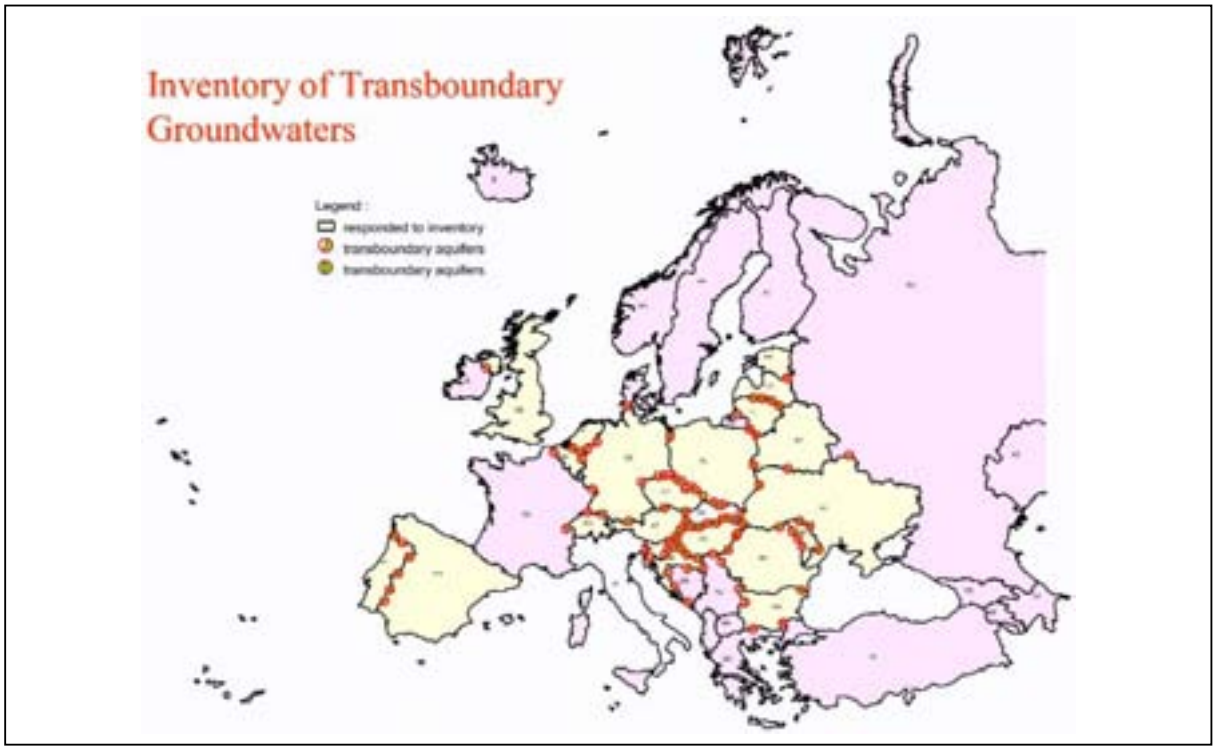


FIGURE 1. Map indicating the countries that responded to the inventory and the indicated transboundary aquifers

The most serious problems came up when trying to compare data communicated by two or more countries on the same aquifer. The identification of (invisible) transboundary aquifers proved to be very difficult and is therefore much more difficult than a (visible) transboundary river. Another additional problem is the wide range of scales of the maps and the list of symbols that are in use between the different countries.

Guidelines for transboundary groundwaters

The main goal of the UNECE groundwater programme was the drafting of guidelines for monitoring and assessment of transboundary groundwaters. These guidelines are based on the background studies published as technical reports (see above).

The groundwater guidelines are intended for decision makers and planners in ministries, organisations and institutions responsible for environmental, water or hydrological issues and all those who are responsible for managing transboundary groundwaters. They also aim to provide advise to those who are responsible for and those who are involved in the development of sustainable water management schemes. So, the character of the guidelines is more strategic than technical. For technical information a lot of information already exists and in the guidelines reference is made to these information.

The UNECE guidelines and also the groundwater guidelines follow the general approach of the monitoring cycle (Figure 2). The cycle can be seen as a sequence of related activities that starts with the definition of information needs and ends with the use of the information product. It can be used as a readers' guide and is a valuable approach when drawing up programmes for the monitoring and assessment of transboundary groundwaters.

Special attention has been given to the aspects of groundwater monitoring because of its special characteristics. Other aspects are the *integrated approach,* like the integration of data gathering and storage, the interaction of groundwater and surface water and the relation between groundwater quantity and groundwater quality.

A first step in groundwater management is the *identification of groundwater management issues.* Core elements in (ground)water management are the functions and uses of the groundwater bodies (aquifers), the problems and pressures (threats) and the impact of measures on the overall functioning of the water body. Examples of functions and uses are the conservation of wetlands (function) and drinking water or irrigation (use). Problems can arrive when due to overabstraction the groundwater table declines. Another problem is pollution with hazardous substances. Possible measures to be taken are

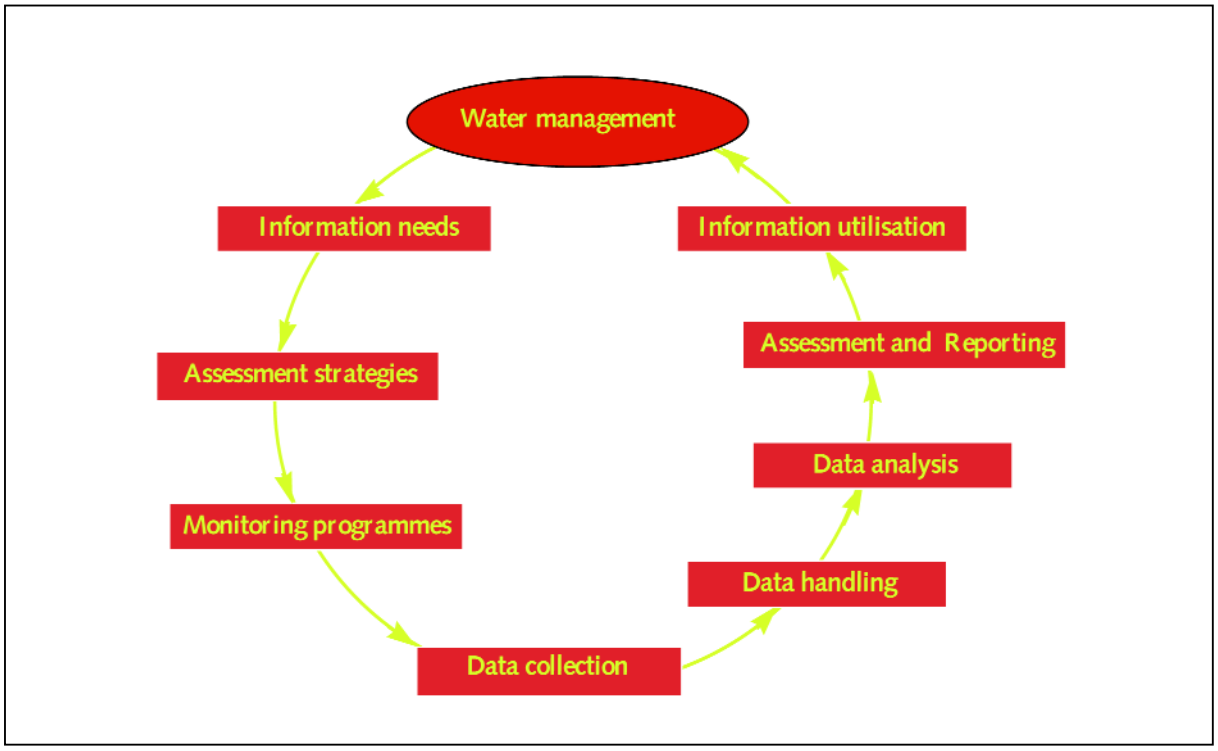


FIGURE 2. Monitoring cycle

reduction in groundwater withdrawal and/ore artificial recharge (infiltration) or in the second case control or remediation of pollution.

Information needs deals with questions *why* and *how* information is needed. That can be illustrated by the so-called policy-life-cycle (Figure 3) and the DPSIR (driving force-pressure-state-impact-response) concept.

The information required for monitoring and assessment should be structured on the basis of issues and on the stage the issue has reached in the policy-life-cycle. In the first stage, the question is whether there is a true environmental problem. When admission of the issue grows, a policy will be formulated. In the 2nd stage, the focus of the public on the problem-solving capacity of decision makers is high, which is reflected by the political weight. In the 3rd stage, the policy is being implemented and measures are taken to solve the problem. The 4th stage is focussed on the nearly solved environmental problem. The first and 2nd stage require rough data and research to recognise the problem and causal coherence. The 3rd and 4th stages require more precise data to select most effective measures and to quantify their effect. In all stages some type of monitoring is required but in the 1st and 2nd stages it will be more on surveys, whereas in the later stages the focus shifts to compliance monitoring and to a lesser extent to surveillance, remediation and restoration monitoring.

Information on transboundary groundwaters can be obtained from primary sources, such as monitoring programmes, computations and predictions with models and other sources (e.g. databases) containing statistical or administrative information. Ultimately, monitoring networks will collect not all information. When specifying information needs (in which process indicators can be very helpful) the specific collection method will be made clear and documented in the information strategy. Using these information sources, in combination with each other, offers optimal conditions for *cost-effectiveness.*

In these guidelines special attention has been given to the use of indicators. Indicators are descriptive and linked to certain issues. They provide means to communicate monitoring results with decision makers since they are closely linked to relevant recommendations for management action.

The Convention distinguish three *types of monitoring:* basic/reference monitoring, monitoring linked to functions and uses or specific purposes and early warning and surveillance monitoring. Each type of monitoring has special requirements in relation with density, location, parameters, frequency, etc.

Important questions for the determination of a *strategy for monitoring and assessment* are: what do we want to know, how do we measure, who does it and who is responsible and finally, how much does it cost.

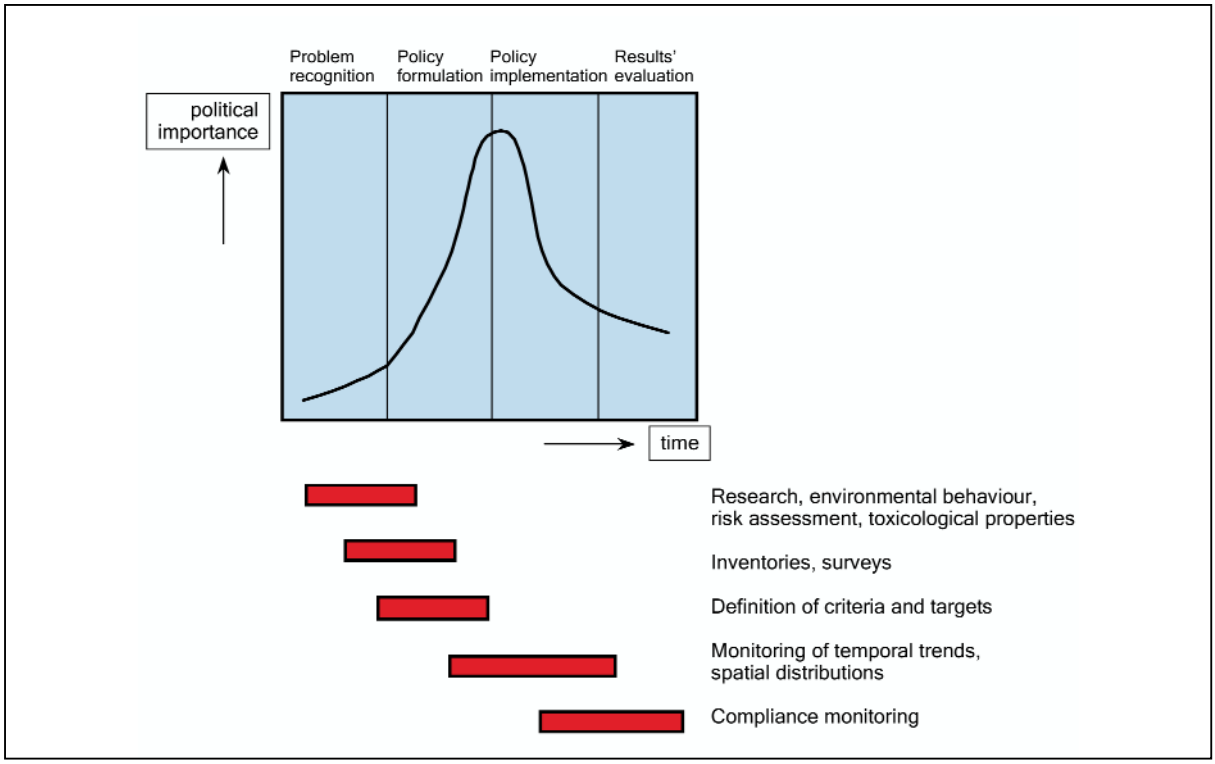


FIGURE 3. Policy-life-cycle

Different strategies often mean different *monitoring programmes.* In developing monitoring programmes for transboundary aquifers the purpose and the requirements of each monitoring programme should be established and agreed upon by the riparian countries.

Data management includes the activities data handling up to and including information utilisation. It is very important that monitoring data that are collected by riparian countries should be comparable, available for integration with information from a variety of sources and easily integrated both in space and in time. Data produced by groundwater monitoring programmes should be validated, stored and made accessible. For modelling purposes of transboundary aquifers, the standardisation of the accessibility of data (interfaces to databases and GIS) is more important than the standardisation of the accessibility of the software that is used. If both the conceptual model and the basis data are reliable, the results will be comparable even when the software used is not the same.

Quality management comprises the definition of a quality policy and a quality system. The harmonisation of methods and the use of international standards are essential for a useful exchange of information.

The successful drawing-up and the implementation of policies, strategies and methodologies on groundwater management are crucial and depend on *institutional aspects*. These include the organisation, the structures, arrangements for *co-operation* and the responsibilities of institutions involved. In these guidelines special attention has been given to the tasks of the *joint bodies* and their activities

Implementation of the groundwater guidelines

Since the endorsement of the groundwater guidelines by the Parties to the Convention (The Hague, March 2000) different actions have been started to implement and test the groundwater guidelines.

a) Pilots

A first activity was to implement and test the guidelines in so-called pilot projects. The objective of pilots is threefold:

- to demonstrate the application and to illustrate from experiences the process and difficulties of implementation;
- to assist countries in the implementation of the guidelines and
- to identify gaps and incompleteness and to propose improvements.

For the selection of pilots some criteria have been defined:

- groundwater body of a 'manageable' size;
- existence of groundwater problems;
- monitoring network should exist;
- participation of 2 or 3 countries;
- existing (i.e. signed or ratified) bilateral or multi lateral agreements and a joint body;
- willingness of countries to implement the guidelines;
- workload should be reasonable;
- workload has to be borne by riparian countries with financial/scientific support by possible donor organisations.

Since 2002, two pilot projects have been initiated. For both pilots, one between Hungary and Slovakia and another between Poland, Belarus and Ukraine, an inception report (project programme document) has been drafted.

b) ISARM

Since March 2000, a co-operation has been established between UNESCO, IAH and FAO and UNECE on the ISARM programme [6] for the implementation of the UNECE groundwater guidelines on monitoring and assessment of transboundary groundwaters and the setting-up of training and exchange of information with the other regions. Some objectives of the ISARM programme are the preparation of inventories defining the main transboundary/regional aquifers in the world and to investigate the existing legislation concerning regional aquifers (to identify possible gaps which may affect good hydrogeological resource management.

As a result of this initiative regional workshops are organised in order to start regional transboundary co-operation (e.g. International Workshop on 'Managing Shared Aquifer Resources in Africa', Tripoli, June 2002). For the implementation of the groundwater guidelines this initiative and the co-operation with UNECE is very important. This means that the groundwater guidelines and the supporting background documents will not only be used in the ECE countries but are also recognised as basic documents for UNESCO-IAH-FAO worldwide.

c) Water Framework Directive

The Water Framework Directive (WFD), 'the European Parliament and Council Directive establishing a framework for Community action in the field of water policy', came into force on 22 December 2000. This Directive is setting the objectives for water protection, including the protection of transboundary watercourses (Helsinki Convention), which should be obtained by a certain deadline.

It forms the needed legal framework to enable (and force) the national authorities to make the necessary arrangements and budgets for the implementation of the Directive (and through the Directive also for the application of the Guidelines) available. One of the obligations is the monitoring and assessment of data in order to generate the required information. This obligation forms one of the most important applications of the guidelines, like the set-up, strategy development and establishment of the required monitoring programmes and monitoring networks. Important actions for the implementation of the EU Water Framework Directive are:

2004 Analysis of the characteristics of the River Basin Districts, review of of the Environmental impact of human activity and economic analysis of water use (article 5).

2006 Establishment of monitoring programmes (article 8).

d) IWAC

Another initiative is the International Water Assessment Centre (IWAC). IWAC [7] is an initiative under the Convention on the Protection and Use of Transboundary Watercourses and International Lakes. IWAC (established in September 2000) will support and facilitate the activities of the Working Group on Monitoring and Assessment by organising training courses and workshops and giving assistance to (UNECE) countries and joint bodies in conducting events to improve monitoring and information systems for decision-making. IWAC can play an important role in supporting special knowledge and training facilities.

References

[1] UN/ECE (2000)
Guidelines on Monitoring and Assessment of Transboundary Groundwaters. UNECE Task Force on Monitoring and Assessment.
ISBN 9036953154.
Lelystad, March 2000.

[2] Almássy, E. and Zs. Buzás (1999)
Inventory of transboundary groundwaters (background report, volume 1).
ISBN 9036952742.

[3] Grift, B. van der, and J.G.F. van Dael (1999)
Problem-oriented approach and the use of indicators (background report, volume 2).
ISBN 9036952751.

[4] Arnold, G.E., R. Chriastel, V. Novak, N.S. Ognianik and Z. Simonffy (1999)
Application of models (background report, volume 3).
ISBN 903695276X.

[5] Uil, H., F.C. van Geer, J.C. Gehrels and F.H. Kloosterman (1999)
State of the art on monitoring and assessment of groundwaters (background report, volume 4).
ISBN 9036952778.

[6] UNESCO-IAH-FAO-UNECE (2001)
Internationally Shared (Transboundary) Aquifer Resources Management, their significance and sustainable management – A framework document.
UNESCO-IAH-FAO and UNECE, Paris, 2001.

[7] IWAC-brochure and website (http://www.iwac-riza.org).

An introduction to the Groundwater Management Advisory Team (GWMATE)

Marcella Nanni

GWMATE

The one outlined below is, in brief, a description of the Groundwater Management Advisory Team (GWMATE) and of its objectives and activities.

Definition and objectives

What is GWMATE?

Within the World Bank-Netherlands Water Partnership Program, the World Bank established the Groundwater Management Advisory Team (GWMATE) in 2000.

GWMATE is a team of experienced specialists in the multidisciplinary area of groundwater management. The team will act globally over a period of 3–5 years to develop capacity and capability in groundwater resource management and quality protection. The strategy is to use World Bank project activities, together with the Global Water Partnership (GWP) regional networks, as the points of entry to achieve this goal.

The objectives of GWMATE are to:

- Support and strengthen the groundwater components of World Bank projects and operations at country or regional level.
- Advise on resource management and protection issues during project identification and implementation (including the definition of key government functions and policy options).
- Facilitate (at least at pilot level) the emplacement of management systems, including the mobilization of stakeholders, to address groundwater resource management and protection needs.
- Harvest and evaluate global experience, taking account of hydrogeologic and socio-economic diversity.
- Disseminate best-practice elements internationally through the provision of briefing guides and short courses.
- Develop a network of specialists in groundwater management and protection on both regional and sub-discipline basis.

Activities and products

Briefing Note Series

The Briefing Notes Series on Groundwater Management: Key Concepts & Tools, was launched in the spring of 2002 by the GWMATE in an effort to provide an overall and reader-friendly information on key groundwater topics ranging from resource management to abstraction rights. The Series is expected to be completed and available on the GWMATE web site in early 2003, but the following issues are already available:

Briefing Note No. 1:
Groundwater Resource Management, An Introduction to its Scope and Practice.

Briefing Note No. 5:
Groundwater Abstraction Rights, From Theory to Practice.

Briefing Note No. 8:
Groundwater Quality Protection, Defining Strategy and Setting Priorities

Briefing Note Series:
Scope and Titles.

Further issues will shortly be available, as follows:

Briefing Note No. 2:
Groundwater System Characterisation, Key Concepts and Frequent Misconceptions.

Briefing Note No. 3:
Key Elements of Groundwater Management Strategy.

Briefing Note No. 4:
Groundwater Legislation and Regulatory Provisions, from Customary Local Rules to Integrated Catchment Planning.

Briefing Note No. 6:
Stakeholder Participation in Groundwater Issues.
Briefing Note No. 7:
Economic Instruments for Groundwater Management.
Briefing Note No. 9:
Groundwater Management Monitoring Requirements.
Briefing Note No. 10:
Implementation of Groundwater Management Schemes.

Technical Papers

The World Bank Technical Papers (WBTP) listed below were prepared in collaboration with the British Geological Survey (BGS) and involved in-depth consultation with numerous World Bank staff and groundwater specialists around the world.

WBTP No. 390:
Groundwater in Urban Development (in English).
WBTP No. 390:
Las Aguas Subterraneas en el Desarrollo Urbano (in Spanish).
WBTP No. 463:
Groundwater in Rural Development (in English).

Case Studies

GWMATE members have been, are and will be involved in World Bank projects in the following regions/countries:

■ In Africa

Kenya:
National Integrated Water Resources Management Strategy.
SADC:
Protection & Strategic Use of Groundwater in Drought Prone Areas (especially Limpopo Basin).

■ In Asia

Cambodia:
Groundwater Quality Hazards.
China:
Water Resources Conservation for North China Plain Aquifer.
Nepal:
Groundwater Quality Considerations in National Water Law.
Philippines:
Groundwater Resources Management and Allocation Review.

■ In the Americas

Argentina:
Groundwater Concerns of the Pampa Humeda; Mendoza Piedemonte Basin Water Resources Management.
Brazil:
Aquifer Storage Augmentation by Underground Dams.
Dominican Republic:
Review and Analysis of Water Legislation.
Mexico:
CNA Pilot Aquifer Stabilisation Programme.
Paraguay:
Water Resources Management Capacity Building; Asunción Groundwater Pollution Control Strategy.
Venezuela:
Quibor Valley Aquifer Management and Artificial Recharge.
Sustainable Management and Use of the Guaraní Shared Aquifer System.

■ In the Middle East

Syria:
Barada-Awaj Basin Integrated Water Management.
Yemen:
Sana'a Groundwater Supply and Demand Management.

Other activities

In consideration of the fact that scant attention is being paid to the management of fossil aquifers, GWMATE, together with UNESCO, will undertake a review of case studies relating to selected aquifers with a view to finding a common scientific approach to their management. The review will serve to formulate a set of management guidelines for the exploitation of fossil aquifers (mining of groundwater storage). National focal points for this exercise are being identified, and a first country representatives workshop will be held in Paris early September 2002.

Website

GWMATE is accessible on the web at http://www.worldbank.org/gwmate.

Transboundary aquifer management in the context of integrated water resources management in the Southern African Development Community (SADC) region

Palesa Molapo

Senior Engineer, Groundwater

Serge Puyoo

French Technical Assistance to SADC WSCU
(Water Sector Coordinating Unit), Maseru, Lesotho

Abstract

The Southern African Development Community is the grouping of 14 Member States.

SADC has established a Water Sector in 1996 and developed a Regional Strategic Action Plan for Integrated Water Resources Development and Management. A Protocol on Shared Watercourses has been signed by SADC in 1995 and was recently revised. The Protocol establishes rules and procedures to implement joint management of Water Resources between countries. Several International River Basin Commissions are being put in place. A Programme for Groundwater Management in the SADC Region is currently being implemented. One of its objectives is to integrate Groundwater issues in the joint management of International River Basins. Some aquifers in SADC are distributed across river basins. Their joint assessment, development and management should be considered as well. The presentation highlights the progress and challenges SADC is facing to better manage groundwater resources.

Introduction

The Southern African Development Community (SADC) is a regional grouping of 14 sovereign states: Angola, Democratic Republic of the Congo, Botswana, Lesotho, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe, with the main purposes of fostering co-operation and mutual benefit from the resources of this region. The SADC region is characterised by very arid conditions in the south-centre and south west of the continent, and is subjected to high climatic variability increasing the vulnerability to floods and droughts.

Adequate integrated water resources management and strengthened cooperation among SADC Member States are considered as key factors for development in the region. Joint management is necessary to optimise the use of available regional water resources: major river basins and some large aquifers are shared by several SADC member States. Therefore, there is a strong convergence between in the one hand, the need for sound management of regional water resources and in the other hand the economical integration within SADC. Groundwater contributes very significantly to existing water supply in the region. Aquifers need to be protected and strategically used and managed as part of the Integrated Water Resources Management Approach.

After reviewing briefly some central aspects of SADC activities in the field of water and presenting the main issues related to Groundwater in the Region, the paper considers the responses that have been developed by the SADC Institutions and describes the available tools and projects, which could contribute to the joint management of Shared Aquifers and Aquifers located in Shared River Basins. The shortcomings and challenges are underlined and consideration is given to interaction between SADC and ISARM initiative.

SADC and Water

The population of the SADC region, estimated at 193 million people is expected to double in 25 years and major water and environment crisis will occur if decisive actions are not taken towards sustainable and integrated water resources management. At present, about 40% of the population have no access to safe water supply and more than half do not have safe sanitation. Average annual rainfall varies from 4,000 mm in the Northern part of the region to less than 50 mm and high evaporation. Rainfall pattern is characterised by seasonal distribution and high variability, resulting in high vulnerability to floods and droughts. The water resource is unevenly distributed in time and space amongst surface and groundwater bodies. There are sixteen major shared rivers in the area covered by the 12 continental States. The Congo river basin includes SADC and non SADC Countries, while other major river basins like the Zambezi, Orange River, Limpopo, and the endoreic basin of Okavango, are shared by SADC member States. The critical importance of water to regional integration and economic development was recognised by the Member States and the SADC Water Sector was established in August 1996. The Water Sector was previously under the responsibility of the SADC Environment and Land Management Sector. The SADC Water Sector Coordinating Unit is based in Maseru (Lesotho).

A SADC Protocol on Shared Watercourses was adopted in 1995 and revised in 2000, to set the rules for joint management of water resources. The definitions and principles of the Protocol are of relevance for managing shared aquifers in the region:

- The Protocol stipulates that 'Watercourse means a system of surface and ground waters consisting a unitary whole flowing into a common terminus',
- It establishes the principles of coordination and co-operation between riparian States regarding equitable and reasonable water use, balance between social development and conservation of environment, and involves compulsory information of the riparian States about the plans and projects occurring in one single country,
- Shared management may include the establishment of joint management mechanism,
- The Protocol gives specific responsibilities to SADC organs and Shared Watercourses Institutions.

This regional agreement fosters the development of co-operation at the River Basin Level and promotes the concept of Integrated Water Resources Management.

River Basin Commissions, in which each riparian State is represented, are being created. Two Commissions already exist: The Orange-Senqu River Basin Commission (ORASECOM), between Botswana, Namibia, Lesotho and South Africa and the Okavango Commission (OKACOM), between Angola, Botswana and Namibia. Discussions about the Zambezi River Basin Commission (Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe) and the Limpopo River Basin Commission (Botswana, Mozambique, South Africa and Zimbabwe) are at an advanced stage. They institutionalise and broaden the scope of joint management activities previously undertaken mainly by bilateral technical committees.

A Regional Strategic Action Plan for Integrated Water Resources Development and Management has been compiled by the SADC Water Sector and is being implemented to address key water management issues, concerning surface water bodies and aquifers (groundwater).

The Concept of Integrated Water Resources Management (IWRM) emerged from the Dublin Principles, in 1992. IWRM looks at the entire hydrological cycle and the interaction of water with other natural and socio-economic systems.

The Agenda 21 of the World Summit on Environment and Development (Rio, 1992) mentioned that IWRM, including land-and-water related aspects, should be carried out at the level of the catchment basin or sub-basin.

Four principal objectives should be pursued as shown in the Box No. 1, Agenda 21, IWRM.

These objectives apply to the development and management of all freshwater resources, including aquifers. IWRM considers the whole water cycle. The assessment, development, protection and management of aquifers as unitary water bodies, should be part of an IWRM approach. Where applicable, interaction between groundwater and surface water, should be addressed at the river basin level.

The 'Regional Strategic Action Plan for Integrated Water Development and Management for the SADC Region' (RSAP) includes seven areas of intervention identified as key issues for the Region: Legal and regulatory framework; Institutional strengthening; Linkages with sustainable development policies; Data collection, mana-

Box 1

Agenda 21, IWRM : Four Principal Objectives

- Multi-sectoral approach including identification and protection of potential sources of fresh water supply and integrating technological, socio-economical, environmental and human health consideration,
- Sustainable planning and rational utilisation protection, conservation and management of water resources based on communities needs and national priorities in terms of economic development policy,
- Design projects and programmes that are both economically efficient and socially appropriate within clearly defines strategies with full public participation, including that of women, youth, indogenous people and local communities in water management policy making,
- Develop appropriate institutional, legal and financial mechanisms to ensure that water policy and its implementation are a catalyst for sustainable social progress and economic growth.

gement and dissemination; Awareness building, education and training; Stakeholder participation; and Infrastructure Development.

The 31 priority interventions, programmes or Projects, have been elaborated into fully fledged project documents. Some of them are ready for implementation, or are being implemented. The Groundwater Management Programme for the SADC Region is one of these priorities, but groundwater issues are or should be addressed as well by other thematic projects, which are not resource specific, such as the development of river basin organisations, capacity building or human resources development in the realm of IWRM.

The groundwater issue in SADC

Groundwater development in the region is influenced by the general stress on water resources resulting from the high spatial and temporal variability of the resource, increasing water use and water demand, economical development and urbanisation, which all impact on the quantity and quality of available resources. In the same time, there is a growing concern on protection of a precious and fragile environment in the Region.

Groundwater resources are strategic in SADC

The Groundwater Resources play a major role in urban and rural water supply (Figure 1) and as such they must be protected and developed in the best sustainable way. In some parts of the region, groundwater is the only reliable source of water. As shown in Figure 1, which relates to the situation in 1998–1999, about 40% of the total population and about 50% of the rural population are not supplied with acceptable water supply systems.

Groundwater is likely to be the key resource to improve the water supply coverage in many rural areas and, to a lesser extent, in urban areas. It has proved as well to be a reliable source of water to mitigate the effects of drought. Countries show varying development levels and appreciation of sustainable groundwater development, depending on various natural and economical factors.

The most arid countries like Botswana, South Africa, Namibia have devoted understandably the most attention to groundwater resources exploration, assessment, development and monitoring.

The region includes several marine and continental sedimentary basins constituting large shared aquifers (Figure 2):

- Coastal marine sedimentary basins between DRC and Angola, Angola and Namibia, South Africa and Mozambique, Mozambique and Tanzania.
- Intra-cratonic and mainly continental basins, such as the Congo basin, involving DRC and Angola, the Northern Kalahari/Karoo basin including Angola, Zambia and Namibia, the

Proceedings of the International Workshop
Tripoli, Libya, 2–4 June 2002

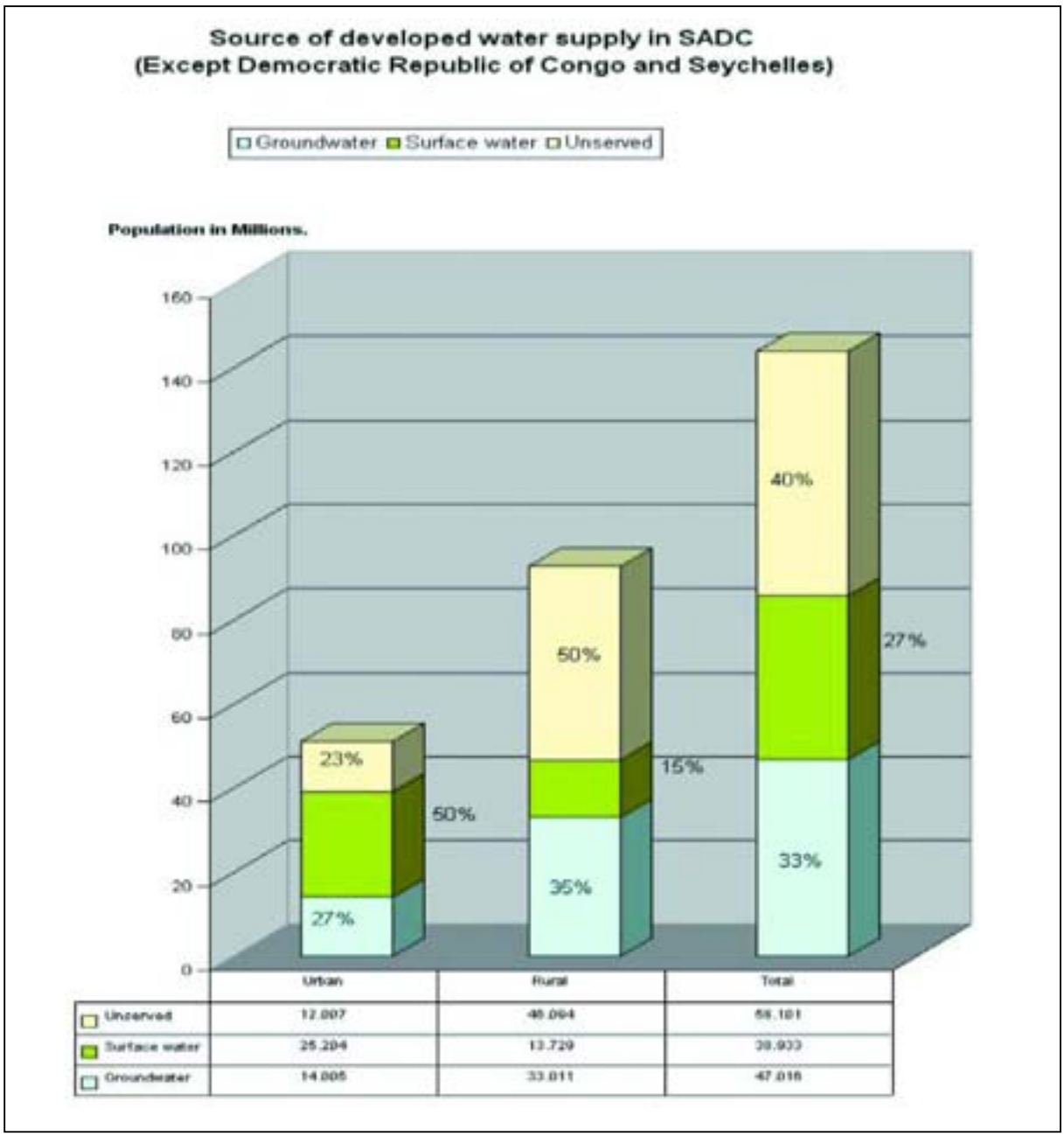


FIGURE 1. Water supply coverage and source of water

Southern Kalahari/Karoo basin including Namibia, Botswana and South Africa, the Karoo sediments between South Africa and Lesotho.

In most of these large basins, aquifer characteristics, direction and continuity of groundwater flow, recharge mechanism and possible cross border impact of abstraction, are 1generally not well identified, except in cases where exploration has been conducted along international borders.

The region also shows a number of shared river basins in which complex relations between surface and groundwater are observed. They include alluvial aquifers, and various compartmented aquifers such as old sedimentary formations and basement rocks. Examples are the high potential alluvia aquifer of the Shire Valley, between Malawi and Mozambique, and the complex suture zones of the medium Zambezi valley and the Limpopo River basin. Aquifers of limited extend or located within national boundaries contribute to the river base flow. Groundwater use in such aquifers may have an impact downstream across international boundaries. Aquifer development and management should therefore be addressed in the context of international river basin management.

The strategic planning in relation to the mobilisation of Groundwater resources has to take into account the international scope of the resource to meet existing and future water demand. The management of shared aquifers should therefore be addressed both at the national and regional planning level.

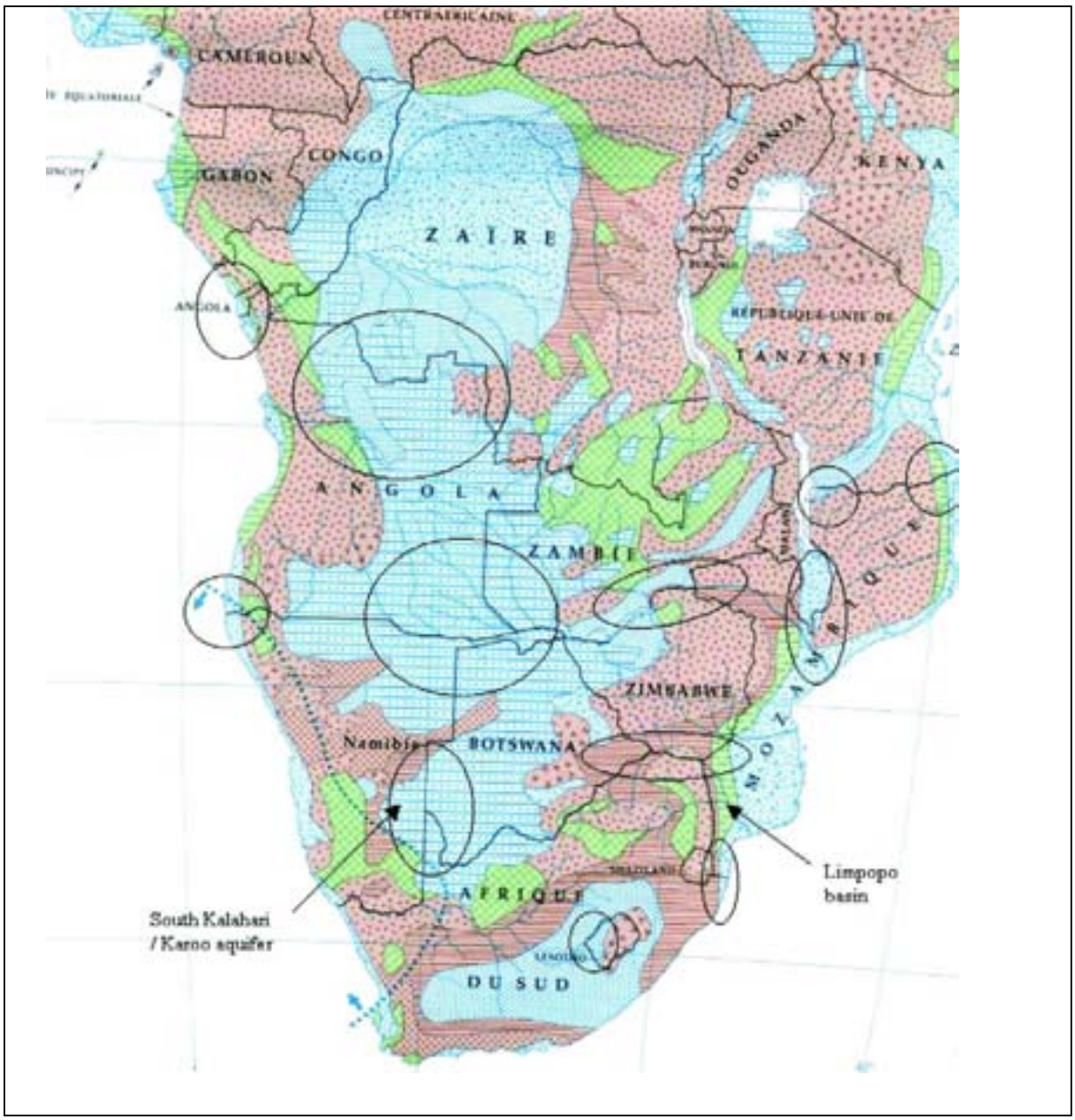


FIGURE 2. Potential shared aquifers in SADC
(from the map: 'Large Hydrogeological systems of Africa',
in *Groundwater in Eastern, Central and Southern Africa,* UN Water Series No. 19, 1989).

The SADC response

Despite the present and future eminent socio-economic role of groundwater, regional water resources programmes in SADC have been in the past dominated by surface water management issues. However, the SADC institutions, i.e. the Water Resources Technical Committee (WRTC), the Sectoral Committee of Senior Officials and the Sectoral Committee of Ministers of Water, have acknowledged that more attention should be given to groundwater development and protection. They established a Sub-committee for Hydrogeology, in which each Member State is represented. The Sub-committee for Hydrogeology serves as supervisor or steering group for the implementation of projects of regional magnitude in the field of Hydrogeology. It may call specific national and regional institutions, experts and consultants for implementation and guidance of these projects.

The establishment of multi-national committees for consultations and project development is a first step to shift from a purely technical approach to a participatory management approach, in line with the IWRM principles.

The case for regional intervention

Some aspects of Exploration/Development/Management in selected aquifers should be addressed at the regional (SADC) level because it would create synergies between countries and optimise scarce human and financial resources. There are mutual benefits to be gained from an improved joint consideration and protection of groundwater, through exchange of information, harmonisation, shared research, development and management activities. The increased demand and pressure on international transboundary water resources create a need for a better joint understanding and adequate shared management. The existing regional framework is well established. Progress in regional cooperation in the water sector is commended. The international nature of water is now considered through IWRM.

The Groundwater Management Programme for the SADC Region

The Water Sector developed a 'Groundwater Management Programme for the SADC Region'. The Programme is part of the Regional Strategic Action Plan for Integrated Water Resources Development and Management in the SADC Region, undertaken with the support of many cooperating partners

The Programme includes 10 projects listed in order of priority (Box 2).

The main objectives of the programme are to:

- promote sustainable development of groundwater resources at regional scale,
- assess groundwater management issues in member states and Provide technical support for their assessment and management programmes,
- develop the groundwater component in the regional integrated water resources development and management approach, with a particular emphasis on the role of groundwater in drought management issues and
- intensify links between national and regional levels of activities within a general framework of regional economical integration.

Tools for shared management of shared aquifers and aquifers contributing to shared river basins

Plans to develop exchange of information and consultation regarding Shared Aquifers in SADC are still in their infancy. The Groundwater Management Programme for the SADC Region creates an enabling environment for joint management by putting in place a framework and specific tools, which are a prerequisite for the management of Shared Aquifers, in particular:

- *A good knowledge base:* Understanding of aquifer characteristics, geometry, limits, amount and location of recharge, direction

Box 2

Groundwater Management Programme for the SADC Region

1) Capacity Building within the Context of Regional Groundwater Management Programme.
2) Develop Minimum Common Standards for Groundwater Development in the SADC Region.
3) Development of a Regional Groundwater Information System.
4) Establishment of a Regional Groundwater Monitoring Network.
5) Compilation of a regional Hydrogeological Map and Atlas for the SADC Region.
6) Establish a Regional Groundwater Research Institute/Commission.
7) Construct a Website on Internet and publish quarterly News letters.
8) Regional Groundwater Resource Assessment of Karoo Aquifers.
9) Regional Groundwater Resource Assessment of Precambrian Basement Aquifers.
10) Groundwater Resource Assessment of Limpopo/Save Basin.

of groundwater flow, vulnerability, prediction on impact of abstraction,

- *A network of institutions,* which create interaction between local, national, regional, global levels: Examples are the Sub-Committees at the SADC regional level and river basin organisations, which can address issues of transboundary nature and could be adapted to large shared aquifers, some of them extending across River basins,
- *A network of experts* from countries involved, as custodians of the technical knowledge,
- *A network of decision makers and NGOs,* facilitating or developing dissemination of information, awareness building, public participation in water management issues,
- *Tools* such as Harmonised Procedures, Code of good practice, Regional Hydrogeological map, models, etc.
- *Training and capacity building* to develop national groundwater management structures, including community participation.

The SADC Sub-Committee for Hydrogeology, so far has established a full situation analysis in the 14 SADC Countries regarding groundwater management setting and standards and pro cedures for Groundwater Development, and prepared a 'Regional Code of Good Practice for Groundwater Development'. The Document includes eleven sections on: Groundwater Project Implementation, Reconnaissance, Borehole Siting, Drilling, Borehole Construction and Development, Groundwater Sampling, Pumping Tests, Production Pumping, Borehole Equipping, Hand Dug Wells and Springs, and Reporting. This code of good practice initiates harmonisation and improvement of practices, serves as guideline and is on the SADC Agenda for implementation, through the SADC project on Standardisation (SADCSTAN).

The SADC Sub-Committee for Hydrogeology also developed an initiative related to management of groundwater resources in the context of drought mitigation, with piloting in the Limpopo River Basin. The project intends to implement some components of the Groundwater Management Programme for the SADC Region and get support from Global Environment Facility, World Bank, and the French Government: '*Protection and strategic uses of groundwater resources in the transboundary Limpopo Basin and the Drought Prone Areas of the SADC Region.*'

The project is an attempt to develop international cooperation at the regional (SADC) and river basin levels. Its general Objective is to protect, develop and manage Groundwater Resources in an integrated manner, taking into account its regional dimension, as a valuable resource to meet human and ecosystem needs.

in drought prone areas. It develops a strategic regional approach to support and enhance drought management policies in relation to magnitude, recharge and supply potential of groundwater resources.

The project includes two components:

- *Regional component:*
  The development of regional information and decision support tools for integrated groundwater management in drought prone areas, comprising Hydrogeological maps, Information systems and monitoring networks, capacity building, institutional strengthening, including the formation of regional groundwater research/management institute or commission.
- *Pilot River basin component:*
  The development of a groundwater resource assessment with focus on interaction between GW and SW, for effective drought management response at the scale of the river basin, demonstration on the ground of the optimal use of GW and combined GW and SW, engaging key stakeholders.

  The project implementation brings groundwater issues in the arena of international river basin management, with a focus on sustainable use of water resources in arid environment. Lessons will be learned for international management of shared water resources, including aquifers.

Shortcomings, challenges

Despite the efforts undertaken by the SADC and national groundwater managers to strengthen international cooperation on a common issue, the Region is facing a number of challenges, in order to convert good will and good principles into practical implementation on the ground of sustainable, joint management of shared groundwater resources.

Some issues have been identified in SADC, as indicated below:

- *Variable level of groundwater need, understanding, development*
  SADC Countries well endowed with surface water have usually lower consideration of groundwater resources than arid countries, relying mainly on groundwater for their water supply.

- *Poor consideration given to groundwater resources*
  In many areas, groundwater is not considered because it was not used in the past, or present water use is limited, or the drilling industry is not developed, or groundwater potential is believed to be poor. This results in neglecting the potential use of groundwater as a valuable alternative to surface water and neglecting its protection.
- *Poor reliance on groundwater resources from water developers and planners*
  In many cases, resource evaluation and prediction of aquifer behaviour are not provided with a sufficient accuracy. The amount of water that can be reliably abstracted in the future being too vague, water planners are not considering the groundwater option, even if it is economically attractive in the short term.
- *Low human and financial resources*
  This is not a groundwater specific issue, but it does affect the groundwater sector as well.
- *Low understanding of transboundary impact of abstraction and low understanding of interaction between surface and groundwater*
  International impact of Groundwater abstraction/degradation has been in the past neglected against the focus on national water resources planning, because there was no evidence of potential competition across the border. However, the increase stress on water resources raises these issues as a component of long term planning.
- *Need for harmonization of water strategies and policies between riparian states*
- *Implementation mechanisms*
  They are still to be put in place. The River basin organisations have to play a role as well as the regional technical committees, to address the identification and institutional setting for shared aquifer management, as some of the aquifers extend across river basins.

The way forward

A greater consideration to groundwater is required, in order to put into practice the concept of Integrated Water Resources Management at river basin and regional level, with the appropriate tools in place. A move towards enforcement of agreed procedures, guidelines or standards is certainly one of the components to develop joint management of shared aquifers, along with the harmonisation of concepts concerning the sustainable use of groundwater, encompassing technical, legal, regulatory, social and financial aspects.

What can be shared between SADC and ISARM?

From the perspective of SADC, the ISARM initiative gives opportunities to exchange experiences, develop awareness on groundwater issues, promote multi national transboundary management concepts/guidelines, make progress in assessing groundwater resources in shared aquifers (Case Studies) and help mobilising financial resources.

Management of transboundary aquifers: contribution to the water needs of Africa

Shammy Puri

Chairman, IAH Commission on Transboundary Aquifers

In common with many parts of the World, Africa too is endowed with transboundary aquifers, as can be eloquently noted from the case studies included in the present publication. While they are comparatively large, they have not as yet been completely investigated for their sound and sustainable management for the needs of the populations. Figure 1 shows some of the major transboundary aquifers of N Africa. No continent wide surveys have been carried out and it is unclear how many are significant. In comparison the UN ECE, in a pioneering survey of transboundary aquifers in Europe, has identified almost 80 transboundary aquifers. The lessons learnt from this survey, and from the guidelines for their monitoring, provide an excellent platform for development of similar approaches in other parts of the world.

While approaches for such a survey in Africa, will vary from those developed by the ECE, due to local constraints, the Internationally Shared Aquifer Resources Management (ISARM) Programme[1] seeks to harmonise, and where practical, find synergies for the sound management of these aquifers using the ECE overview. An excellent start point could be the SADC Water Protocol, which suggests the establishment of 'basin wide' management.

Transboundary aquifers are not well known or understood by decision makers and policy developers, because they are hidden from view and their hydrogeological functioning is often difficult to explain to the non specialist. Unlike, the more obvious functioning of surface water systems, development and other pressures on groundwater produce a slow response, which can be widespread in space and subtle to observe without good monitoring. Policy decisions on conservation of transboundary aquifer resources, appreciation of their role in hydro-environmental support and their sustainable management, need to be made on sound scientific information. Since they are transboundary in nature the information from either side of the boundary has to be gathered, so that an integrated appreciation can be formulated.

For the sound management of transboundary aquifers, science in isolation is insufficient. The ISARM Programme suggests four additional focus areas that have to be addressed to the same level of detail as the scientific base line. The four focus areas include, the legal frameworks, the socio-economics, the institutional issues and the environmental issues. Case studies incorporating the above focus areas have been suggested for interested Member States to implement, with the support from the ISARM Programme. Networks for multi disciplinary working groups can be facilitated by the partners of the ISARM Programme.

The SADC Water Protocol provides a good start point for the sound management of transboundary aquifers. However, there remain many gaps, especially in the development of legal frameworks that can correctly be applied for aquifers. The six year work plan initiated and underway in the ISARM Programme will contribute to the final aim of improving existing conventions and implemented more in other regions of the world.

In May 2002 Members of the Steering Committee for the MSP on the Environment Component of the New Partnership for Africa's Development were briefed and requested to

1. ISARM is a cooperative programme sponsored by the IAH, UNESCO, UN ECE and FAO as the core agencies, with support from interested agencies such as IAEA, ESCWA, OAS and others.

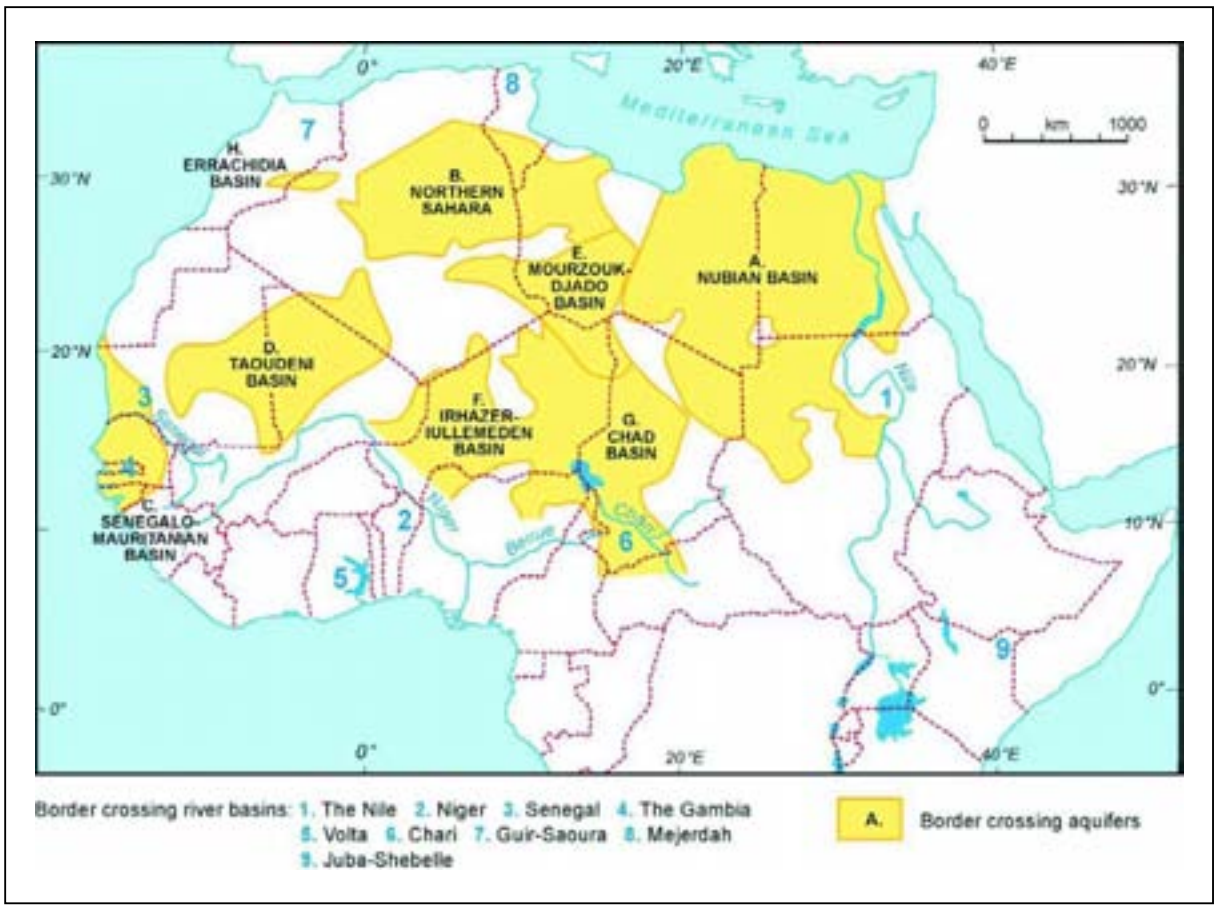


FIGURE 1. Transboundary aquifers in N Africa

incorporate the sound management of transboundary aquifers as one of the important issues for consideration. The Tripoli Conference marks an important milestone in bringing this important issue to the attention of the African water community.

Transboundary aquifers Scientific-hydrogeological aspects

Philippe Pallas
Consultant, UNESCO-FAO

Jean Margat
BGRM

Characterisation of a transboundary aquifer

The objective of analysing the status of transboundary aquifers is essentially to identify the international implications of an effective and equitable management of the groundwater resource among the sharing countries. The first factor influencing the management conditions is a clear definition of the resource boundary in order to identify the nations and users groups involved in the resource development. In the case of groundwater, resource boundaries are often very poorly known because of its invisible and three dimensional nature. However, when analysing the issues related to transboundary aquifers, it is essential to consider the whole aquifer system, including one or several aquifers hydraulically interconnected either directly by lateral or vertical contact or through fractures and low permeability formations (aquitard) allowing water and piezometric changes to be transmitted from one formation to another.

Spatial distribution of factors governing the dynamics of an aquifer

A number of factors affect the behaviour and the development potential of any aquifer, be it transboundary or not:

- The distribution of the main hydraulic parameters affecting the groundwater flow and storage in the different aquifers of the system as well as the productivity of groundwater development structures (wells, drains…),
- The extension of the recharge areas and their location in relation to the rainfall distribution pattern,
- The extension and distribution of confined and unconfined areas, being the unconfined

Box 1

The Nubian Sandstone Aquifer System (NSAS): a large transboundary aquifer system

The NSAS consists of a number of aquifers laterally and/or vertically interconnected extending over 2,000,000 km^2 in East Libya, Egypt, North-East Chad and North Sudan. Main components of the NSAS include:

- Palaeozoic continental deposits (mainly sandstone),
- Mesozoic continental deposits, pre-Upper-Cenomanian (Nubian Sandstone sensu stricto),
- Post-Eocene continental deposits (mainly sandstone) in Libya, equivalent to carbonate rocks aquifer in Egypt. This component communicate with the underlaying Mesozoic or Palaeozoic aquifers through Mesozoic-Cenozoic low permeability formations.

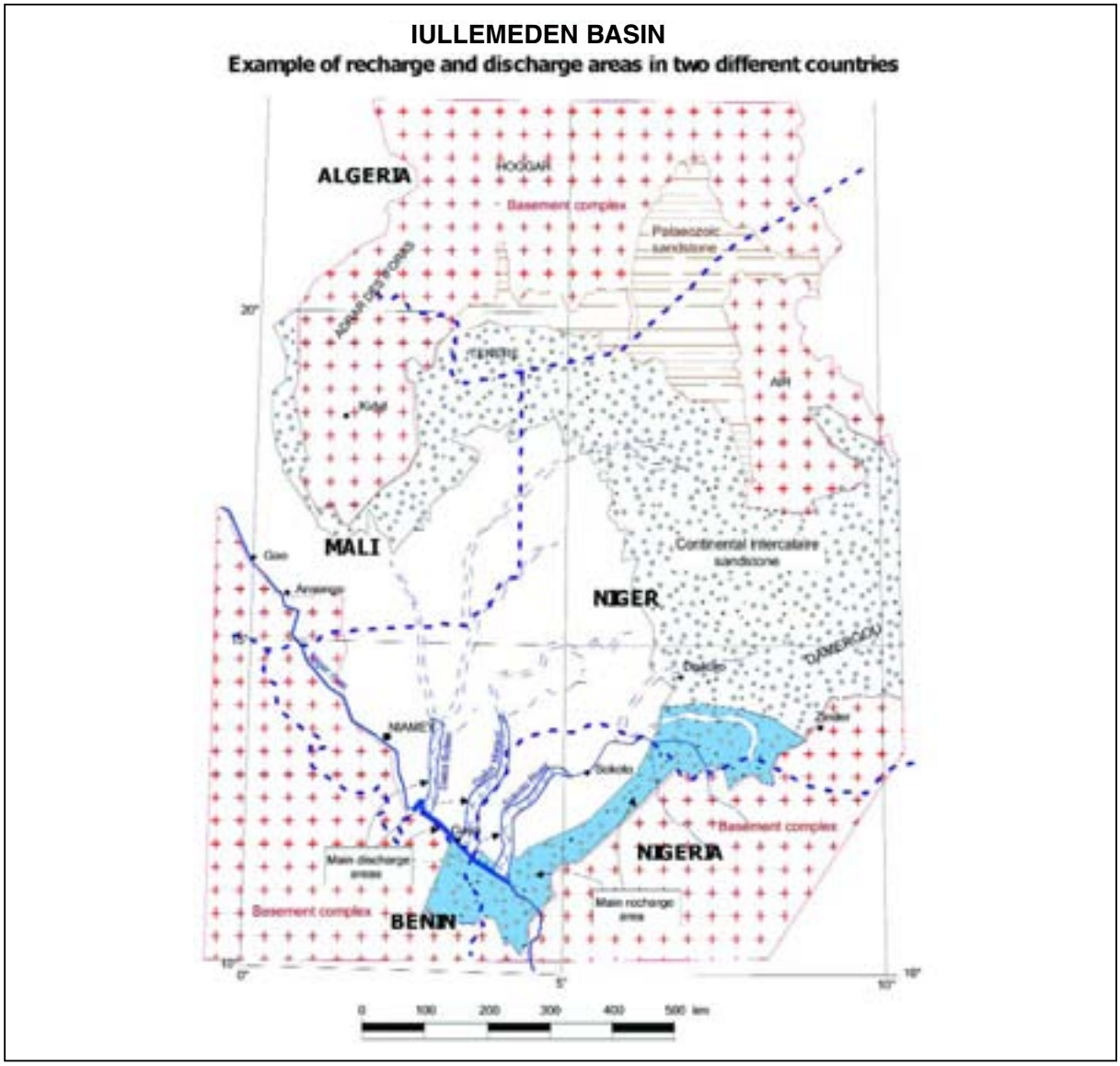
The Palaeozoic and Mesozoic aquifers extend over the whole Nubian Basin, although becoming very saline in the northern part. The other components of the system occur only north of the 26th parallel.

areas an essential component of the groundwater storage in the aquifer system,

- The location and magnitude of the natural discharge areas: springs, draining streams, diffuse outflow in evaporative areas (sebkhas, chotts…) as well as their implication in sustaining natural aquatic ecosystems,
- The location and importance of the present and planned groundwater development,
- The distribution of the different classes of water quality as well as the distribution of the potential risks of deterioration of the water quality in relation to water abstraction,
- The pollution vulnerability and the present and planned distribution of polluting agents such as intensive agricultural schemes, highly polluting industries, important urban development.

In the case of transboundary aquifers, each of these factors may have a different weight in each of the countries sharing the resource:

- It may happen for example that the recharge areas stay in one country while the natural outflow or the most accessible groundwater resources occur in another country. This is the case of the Mountain Aquifer extending over Israel and Palestine, where an estimated 83% of the recharge from rainfall take place in the West Bank, while the springs and the high yielding potential areas are located in Israel. Another example is illustrated by the opposite map and concerns a large African groundwater basin called the Iullemeden extending over Niger, Nigeria, Mali, Benin and Algeria. The main aquifer consists of Mesozoic continental deposits outcropping along the northern and eastern periphery of the basin. Recharge area is almost entirely located in the south-eastern outcrops in Nigeria where the rainfall exceeds 500 mm per year. A significant part of the discharge area is located in Niger in humid valley bottoms and in the Niger river itself.
- It may also happen that within the same aquifer system, one country has already developed the groundwater resources while,



on the other side of the border, the other country does not consider groundwater development as a priority in that area or does not have the financial resources to undertake that development. This is the case for example of Libya and Chad, sharing part of the Nubian Sandstone Aquifer System: since the early 70s, Libya started extracting water from the ground in the Kufrah sub-basin and is even planning to increase the water production in that area for transporting it to the coast, while Chad, on the other side of the border, is not considering any significant development in that desertic area, both for the high costs involved and the nonexistence of potential uses.

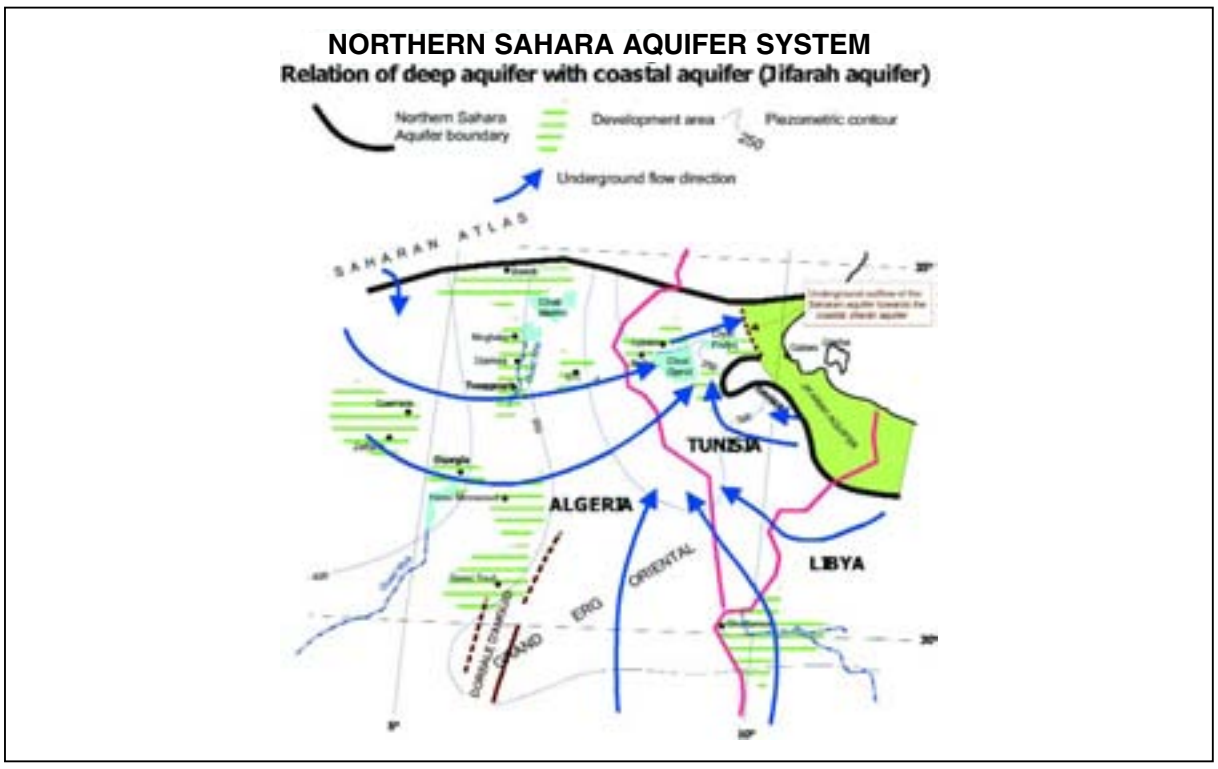
Groundwater hydraulics that may have international implications

Water abstraction from an aquifer transforms and re-organises the groundwater flow in proportion to the piezometric adjustments induced. This has a number of practical consequences:

1. Modification of the groundwater flow pattern

Groundwater flow through an international boundary cannot be measured directly. It results from calculation of the product of the length of the border by the transmissivity and by the hydraulic gradient. This calculation is usually performed through mathematical model run on computer. Water abstraction on one side of the border may alter the flow through the border, either reducing it if abstraction takes place upstream the border or increasing it if abstraction occurs downstream the border. In the case of the Northern Sahara Aquifer System (see opposite figure), the underground outflow of the deep aquifer (Continental Intercalaire) is a source of recharge for the coastal aquifer (Jifarah aquifer). According to the mathematical model run in 1982[1], an additional water development from the deep aquifer in Algeria only would reduce the outflow to the coastal aquifer by 5%. Obviously, the development scenario simulated on the model (CI6) was selected in such a way as to minimise the impact of Algerian development on the Tunisian coastal aquifer. A similar scenario, where additional abstraction was located in Tunisia only was simulated on the model and produced a much stronger effect on the outflow to the coastal aquifer due to the proximity of the development areas to the outlet, but that became an internal Tunisian problem.

1. UNDP/OPE. *Ressources en eau dans les pays de l'Afrique du Nord.* RAB/80/011. Tunis, 1983.



Groundwater flow reduction related to upstream withdrawal in a nearby country may have harmful effect on the water resources of the country: decrease of the recharge of an aquifer (case of the Tunisian coastal aquifer), decrease of spring outflow or even disappearance of springs, decrease of river flow.

2. Modification of the piezometric pattern

Groundwater abstraction from wells causes modifications in the piezometric head distribution of the aquifer, in order to increase the hydraulic gradients towards the abstraction zone and so to let the aquifer supply the amount of water pumped. The effect of pumping on the head distribution spreads in all directions and not only in the direction of the flow as it would be expected when comparing to surface water where withdrawal affects only the downstream section of the river.

There are many examples of cones of depression resulting from groundwater abstraction and spreading beyond an international border. As a broad conclusion of this section it may be stated that the propagation of the cone of depression cannot be avoided but it may have dramatic consequences when lowering the water level means:

- Increasing cost of pumping in the area affected by the water level decline,
- Decreasing springs' discharge or even drying out of springs,
- Withering natural vegetation when the latter draws its water from the shallow aquifer in connection with the transboundary aquifer.

3. Deterioration of the water quality

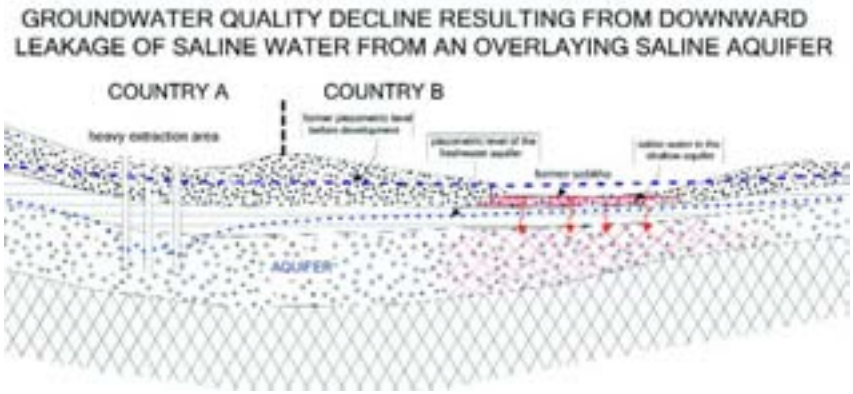
As extraction grows, head distribution and flow patterns change, drawing low quality water into fresh water. This general statement applies also to the transboundary aquifers when water abstraction in one country may determine directly or indirectly the migration of low quality water into the fresh aquifer. Vulnerability to groundwater quality decline as a response to groundwater extraction in a nearby country may be higher in the following contexts:

Proximity of coastal zone:

intrusion of seawater is a common response to local overexploitation of an aquifer. However in the case of confined aquifer, where influence can spread far away from the extraction zone, it may happen as suggested in the opposite figure that high pumping rate in country A can let seawater migrate into the aquifer in country B, even if water extraction in that country is limited or even nil. Vulnerability of aquifer is higher in case of groundwater flows through formations where large interconnected fractures or cavities are present and encourage rapid flow (case of the karstic aquifers).

Similar problems may occur in case of the presence of low quality water in adjacent rocks. An example is illustrated by the opposite figure showing the significant change of the flow pattern resulting from the additional extraction in Siwa (Egypt) and the new development in Jaghbub (Libya) simulated on a mathematical model[2]. The saline water contained in the aquifer now some 20–25 km north of Siwa would probably migrate towards the development areas, essentially towards Siwa.

2. IFAD funded Programme for the Development of a Regional Strategy for the Utilisation of the Nubian Sandstone Aquifer System.



Interbedded high and low quality water aquifer:
this situation occurs very often mainly in arid and semi-arid areas. Pumping from high quality water in a country A (see opposite figure) may cause or accelerate vertical migration of poor quality water from aquifers located above or below the exploited horizon in country B. This may happen in areas where topographic depressions favoured the evaporation of groundwater when its piezometric level was above ground. With the growing groundwater development in the area, particularly in country A of the example, the piezometric level fell down inducing the saline water to migrate downwards to the fresh aquifer.

4. Pollution

The significance of groundwater pollution is greatly increased by the long term time scale (decades or even centuries) at which mass transport processes affecting groundwater function. Water usually takes several years to move through the unsaturated zone above the aquifer. Once in the aquifer, water with the polluting agents may take many tens or hundred of years to flow from the source of pollution to the supply boreholes. Moreover, the filtration capability of porous rocks attenuate and often absorb pollutants. However, aquifers with fractures and fissures (typically karstic aquifers) allow water to flow rapidly and tend to be more vulnerable to pollution.

In the case of transboundary aquifers, the risk of pollution obviously exists for a country located downstream of a polluting country. But only in the case of karstic aquifers the risk for the pollutants to migrate rapidly (within a few weeks or months) from the polluting country to a downstream country can be considered.

Transboundary aquifer management issues

Two categories of aquifer may be considered for management purpose: renewable resources aquifer and non renewable resources aquifer.

1. Renewable resources transboundary aquifer

In the case of renewable resources aquifer, the global strategy consists in trying to let the sum of natural outflow to be preserved and of the water abstraction, not to exceed the average annual recharge of the aquifer. This result can only be achieved through joint management among the countries concerned. However, even if the aquifer is globally in equilibrium, local over-exploitation may occur and result in undesirable effects on natural outflows or on water quality (seawater intrusion in particular); this situation is usually a local question not related to international issues but additional groundwater extraction from the same aquifer beyond an international border may contribute and aggravate the phenomenon and should therefore be taken into account in a joint management of the groundwater system.

2. Non renewable resources transboundary aquifer

Non renewable resources can be expressed as a volume of water stored in the ground. The decision to utilize this depletable – even though in the long term - resource, and the amount of water to be extracted by each country should therefore be subject to international agreement in which location and annual rate of extraction, as well as predictable medium and long term respective effect of the water development on both sides of the countries are specified. The purpose of these agreements would be to let each country concerned to know and accept the effect – even if harmful – on its own resource, of groundwater development in the nearby countries.

Non renewable transboundary aquifers are known in arid and semi-arid areas – Africa and Middle East particularly – where the development of non renewable resources is often the main source of water supply for both domestic and agricultural uses. Among the countries competing for the use of shared groundwater resources, essentially non renewable, it is worth to mention:

- Algeria, Tunisia and Libya sharing the Northern Sahara Aquifer System mostly developed in Algeria and Tunisia,
- Libya, Egypt, Sudan and Chad sharing the Nubian Sandstone Aquifer System developed only in Libya and Egypt,
- Egypt and Israel sharing the Nubian Sandstone aquifer in Sinai and Neguev,
- Saudi Arabia and Jordan sharing the Saq aquifer.

In all these cases, no formal agreement exist so far but studies are in progress, sometimes

Proceedings of the International Workshop
Tripoli, Libya, 2–4 June 2002

sponsored by international organisations[3], to establish the basis of agreements regulating the groundwater extraction in each of the concerned countries.

Conclusions – Prerequisite to a joint management of a transboundary aquifer

A transboundary aquifer does not have any particular behaviour with regards to the effects of water abstraction. A transboundary aquifer differs from a national aquifer in the management issues resulting from the international character of the problems created by the resource partition and specifically from the economic, social and physical disparities between the countries concerned.

Although a joint management of transboundary aquifers through bi- or multi-lateral agreements is highly desirable in all circumstances, there are still a number of issues and principles to be discussed and agreed, on which to base high level technical and political dialogue:

- Availability of high quality information on the functioning of the groundwater systems, possibly on mathematical models able to simulate development scenarios and to predict their medium and long term effects in term of natural outflow, environmental impact, water level and water quality change;
- Setting up of an information exchange mechanism on groundwater development processes in each country and local (within the country) effect of such development;
- Establishment of partition rules to be specified and approved by all parties:
  - > Principle of unity of an aquifer system mainly for renewable resources aquifers: the location of major recharge areas in one country does not confer major water rights to this country;
  - > Principle of equivalence of effects: when possible, the physical and economic effects of a water extraction programme in a country A to the nearby country B should be equivalent to the effects of country B's programme to country A.

3. IFAD funded Programme for the Development of a Regional Strategy for the Utilisation of the Nubian Sandstone Aquifer System and IFAD funded Project on Northern Sahara Aquifer System

Scope of the International Workshop on Transboundary Aquifers in the African Region

Bo Appelgren

International consultant, UNESCO-FAO

Abstract

The transboundary aquifers in Africa are dominated by the sub-regional sedimentary systems of Sahara and Central and Southern Africa. The systems, from north to south, include the Saharan-Libyan, the Sahel Basin with the Taoudenni, the Iullemeden and the Chad and the Congo, the Kalahari and the Karoo in Southern Africa. In addition to the sub-regional aquifers there are also a multitude of local transboundary systems shared by two or more adjacent countries.

Exploration of aquifer systems carries risk and uncertainty and could have far-reaching transboundary impacts on pressures and piezometric level with consequent risk of inter-aquifer exchange and quality degradation, especially in confined and artesian aquifers. The sub-regional aquifer systems are predominantly located, and of highest importance, in arid and semi-arid dryland zones of the continent that are continuously threatened by accelerated land degradation, loss of productive land and ecosystems as man-induced desertification. The management issues and the transboundary implications consequently reach beyond water balance and control of the hydraulic systems and include land use and protection in recharge and humid and discharge areas.

To address this important and highly strategic area and to define and initiate appropriate and well concerted joint action in the Region, The General Water Authority of the Libyan Arab Jamahiriya organizes the present International Workshop on 'Managing Shared Aquifer Resources in Africa'. The main objectives of the conference are to evaluate how to:

- Set up an appropriate framework for studying and assessing groundwater resources in African countries with particular focus on Regional Aquifer Systems;
- Present and discuss case studies on African Regional Aquifer Systems;
- Provide support to the African countries for improving cooperation to study and assess groundwater resources;
- Prepare an inventory of the existing African Transboundary Aquifers;
- Launch an ISARM Africa Programme.

The paper provides guidance and suggestions to the workshop participants, to define the scope of the workshop in more detail, highligh tthe priority items to be addressed and elaborate on resources and other requirements for concerted joint action under a regional programme. In particular, one suggestion is to focus on active programming to initiate and identify resources for field activities under an ISARM Africa Programme and the importance to start concrete projects and activities and identify the necessary donor resources is emphasised. This will be require consistent programming and project formulation that will respond to and include the following items and project components: (a) identification of regional aquifer systems in Africa, (b) definition of transboundary aquifer system; (c) water and land linkages; (d) country perspectives and positions; (e) threats and objectives; (f) action, activities and outcomes; and (g) institutional arrangements and responsibilities.

■ Part I Introduction: Transboundary Aquifers in the African Region

A discussion of the background for a regional initiative, and identification of issues, approaches and requirements for joint management of shared

transboundary aquifer systems in Africa entails some basic reflections, where the workshop can be expected to review also the following aspects and items:

(a) The differences between aquifer systems and transboundary surface water systems, recalling that an aquifer is not only a flow between recharge and discharge areas in a basin but also a reservoir that is sensitive to man-induced or natural manipulations that impact on the hydrodynamic conditions and could have wide impacts in all parts of the system, especially in confined or artesian aquifers (Margat, 1992[1]). In this situation a basin concept will not be sufficient as the base to define the resources for ownership and responsibilities of the properties that reach beyond simple water balance, quantity and quality,

(b) The complexities of the aquifer systems and the consequent relatively high level of uncertainty dictates the need to adopt pragmatic risk-based management approaches rather than to aim for exact and integrated water resources planning frameworks,

(c) The non-renewable aquifer resources provide a secure and drought-proof supply. The workshop is therefore recommended to further elaborate on the utilization of non-renewable ground waters, based on the recommendations in the Tripoli Statement, 1999,

(d) The wide and still undefined scope of the task, versus the limitations in manpower, institutional and funding resources in the region necessitate a well focused and pragmatic program focused on effectiveness rather than on holistic scopes and scientific depth and that and is consistent with and responds to established policies, perspectives and institutional and socio-economic capacities at country and sub-regional level, and

(e) It will be important to adapt to and follow the mainstream directions to promote development and alleviate poverty in a region that, in its majority, remains poor, with low levels of development and investments and a general scarcity of capital resources. Any programme proposed by the workshop need to be well focused on poverty alleviation and environmental protection. In this case the programme also carries higher possibility to attract external funding support.

At the starting point of important regional initiatives it is would also be pertinent to recognize several socio-economic realities and priorities in the region where poverty alleviation and food security are standing out together with environmental conservation. The following observations and considerations, consistent with the initial reflections, need to be recalled and highlighted in the workshop:

- While water and land resources in Africa are at high socio-economic and hydrological risk and uncertainty international cooperation on shared aquifer resources represent a unique ultimate opportunity to reduce and share the risk. The social and environmental risk is common to the countries in the sub-regions and joint risk-based management and ultimately allocation of resources based on the common goal and solidarity for minimized risk can be expected to carry a high level of acceptability and facilitate the practices of voluntary negotiated agreements between sovereign states – which has often proven to be a slow process. The approaches are suggested to be risk-based, to minimize and share current and future risk and provide for a jointly defined preparedness and responsibilities to handle the uncertainty and the unexpected events that are becoming increasingly common in the region,
- While scientists should always thrust in the right directions of technical cooperation, information exchange and analysis care needs to be taken to impose appropriate, affordable and graspable concepts that can be sustained and for which the institutional and economic resources are locally available. To be sustained activities need be limited to what is implementable and justified and driven by development requirements in the context of national and sub-regional political economics.
- Due to, (1) the large number of large systems, many of which are not yet identified or defined ; (2) the high level of scientific complexity but the absence of a solid knowledge base; and (3) the large land area related and linked to the transboundary aquifers, the scope of the subject and of a regional programme is wide. The transboundary aquifer resources in Africa are dominated by large sub-regional systems with the sedimentary basins of Sahara-Sahel and the Central and Southern Africa. The systems include, from

1. Margat, J. *Problèmes spécifiques aux nappes souterraines transfrontière.* Sophia Antipolis, April 1992.

north to south the Sahara-Libyan and the Sahel Basin with the Taoudenni, the Iullemeden and the Chad and the Congo, the Kalahari and the Karoo in Southern Africa. The water resources contained as storage and in most cases also the annual recharge of these systems are significant and of high strategic importance especially in the arid and semiarid parts of Africa. The observations in Table 1 below give some indications, with rapid fall in water levels, of the threats and the current conditions of utilization under high uncertainty. The major basins are multi-aquifer systems, where the individual aquifers carry specific properties for recharge and discharge areas, hydrodynamics and piezometric levels and water quality. The large sedimentary basins, including their recharge and discharge areas, cover very large land areas (in the order of 10 million km^2, or close to one third of the surface area of the African continent) sensitive to land degradation and subject to current accelerated desertification (the annual loss of productive land in Niger is reportedly 250,000 ha). In addition to the sub-regional aquifers, as reported in the country papers, there are also a multitude of aquifer systems, or sub-systems shared by two or more adjacent countries that have only in few cases been well identified or managed under joint management frameworks.

- The recharge areas of the systems are of crucial importance and need to be identified, monitored and protected. As the result of land degradation the recharge of the free aquifers, for example in the Iullemeden aquifer system, has increased with as much as 5–10 times over only about fifty years with rising water levels and enhanced water resources but at the costs of loss in land resources from waterlogging and salinization. Other emerging risks relate to the discharge areas of the aquifer systems where humid and oasis zones represent important habitable and productive areas where vegetation covers and the eco-systems depend on shallow water levels and the fragile balance of aquifer seepage.
- With the perspective and an ultimate objective of congruous sharing and development of the aquifer resources between neighbouring countries, it will be important to recall and review also the legal basis, for example the principle formulated already in 1978 (by Caponera, Alheritiere 1978, see Margat, *ibid*) that the physical extension or the location of recharge areas in one country do not prejudice the sharing of common aquifer resource that represent and will be managed

Table 1. Sub-regional aquifers in arid and semi-arid Africa countries

Countries (Basin)	*Area (10^3km^2)*	*Storage (m^3)*	*Recharge (mm^3/yr)*	*Withdrawal (mm^3/yr)*	*Observations*
Nubian Sandstone	2,000	–	–	–	Egypt, Libya, Sudan, Chad
Senegal- Mauritania	200	–	–	–	Gambia, Guinea-Bissau, Mauritania, Senegal
Lake Chad	1,400	–	–	–	Cameroon, Niger, Nigeria, Central African Rep., Chad
Algeria, Tunisia, (Northern Sahara)	350 (Terminal complex) 600 (Continental...)	6 x 10^{13}	500 270	400 200	Max. fall in level: 29 m in 14 years
Libya (Kufrah)	1,800	6 x 10^{13}	Appr 1,000	160	15–20 m in 4 years
Mali, Niger, Nigeria (Iullemeden)	500	4–8 x 10^{10}	Not assessed	Not assessed	Max fall in level: 100 m
Mauritania, Senegal	200	1.5 x 10^{12}			Fall in level over two-thirds of the area

and shared as one sole system. It will be important to discuss whether under the conditions of high uncertainty and limited resources the precautionary principle and preventive action is even realistic or implementable. In view of the complexities and lack of visibility joint management of a shared aquifer systems requires however a common knowledge base of the structure and the dynamics of the system and need to be focused on sharing or joint collection and quality control of information required for management purposes (Margat, *ibid.*). A common, transparent and regularly updated knowledge base need to include information on piezometric level, salinity and water quality, recharge and discharge but also on abstractions and development for common assessment of joint and shared risk.

■ Part II
Scope of the International Workshop, components, organization and support of the African program

To define and initiate appropriate and well concerted joint action in the Region, The General Water Authority of the Libyan Arab Jamahiriya has organized the present International Workshop on 'Managing Shared Aquifer Resources in Africa'.

The main objectives of the conference are to evaluate how to:

- Set up an appropriate framework for studying and assessing groundwater resources in African countries with particular focus on Regional Aquifer Systems,
- Present and discuss case studies on African Regional Aquifer Systems,
- Provide support to the African countries for improving cooperation to study and assess groundwater resources,
- Prepare an inventory of the existing African Transboundary Aquifers, and
- Launch an ISARM Africa Programme.

The scope of the workshop need to be carefully elaborated in order to set priorities and address the most critical issues, in harmony with main institutional, and natural resources management initiatives in the region and in a way that will secure a long term sustainable national, regional and external financial support. To guide and frame the workshop discussions in this direction and focus the scope of the workshop towards practicable and implementable outputs, some priority items and steps of action to organize and identify the necessary resources for an active and well concerted regional programme are suggested here in.

It is suggested that the workshop would consider the following items in order to identify the starting point and set the scene for the discussions:

- water scarcity and lack of access to water in a growing number of African countries in the region form major constraint to socio-economic development,
- groundwater represents a safe water resource as current and potential strategic sources of freshwater to supplement surface water resources and provide for water security in the region increasingly affected by recurrent drought,
- the African region is endowed with large aquifer resources that in many parts have not yet been well defined and as a consequence remain under-utilised.
- the principal aquifer resources in Africa are to a large extent transboundary and shared between two or more countries.
- the shared transboundary aquifer systems are of strategic importance for socio-economic and agricultural development, improved welfare and public health, alleviation of poverty and food security for the present and current African populations,
- the growing pressure and environmental threats on sub-regional scale to aquifer and related land resources is resulting in loss of water resources, productive land and life-supporting eco-systems in the region,
- the scarcity of regional hydrogeological information and gaps in the understanding of the role of groundwater in supporting development, sustaining livelihood and welfare and protecting life-supporting ecosystems, and the current situation of uncertainty forms a threat to water security, a constraint to manage regional and local water risks and a potential cause for international pressures and water conflict,
- as reflected in recent ministerial declarations, intergovernmental and regional co-operation for improved joint management of the shared aquifer resources is enjoying the highest political support at regional, sub-regional and national level.

Based on the above considerations, the workshop consultations are expected to provide guidance

and identify appropriate arrangements and action in response to the five workshop objectives:

Objective 1

Options for a framework for studying and assessing groundwater resources in African countries with particular focus on Regional Aquifer Systems

- Regional co-operation on shared surface and groundwater resources was emphasized and endorsed in the recent Abuja Ministerial Declaration on Water, as one important component under the African Ministerial Conference on Water (AMCOW),
- Strengthening of the scientific and institutional capacities for regional co-operation on shared aquifer resources as emphasized and endorsed in the recent Abuja Ministerial Declaration on Water will form an important item on the agenda of AMCOW,
- One option for a suitable framework would therefore be built on AMCOW at the regional level and involve the sub-regional water sectors of SADC and ECOWAS.
- Effective joint management of Shared Aquifer systems will by and large be based on national manpower and institutional capacities, and require strengthening of the present national manpower and institutional capacities, coordinated under a regional network with sub-regional steering and national focal points.

Objective 2

Present and discuss case studies on African Regional Aquifer Systems

The country case studies presented in the workshop are suggested to be harmonized and the information at country level collated into a common regional assessment and a data base on the African Regional Aquifer Systems, based on the formats defined in the ISARM Framework Document and UN-WWAP approaches,

It is further suggested to consider the establishment of regional Guidelines for monitoring of the African Regional Aquifer Systems.

In these connections it is suggested that the workshop solicits the support of IGRAC for management of a Data Base on African Regional Aquifer System and of UN-ECE for monitoring of the African Regional Aquifer Systems.

Objective 3

Provide support to the African countries for improving co-operation to study and assess groundwater resources

The national manpower and human resources capacities for assessment and joint management of the shared transboundary aquifers are in a majority of the African countries limited and need strengthening. In response to this requirement the proposed Inter-African Program on Regional Aquifers Systems executed by UNESCO/IHP and coordinated under the UN-WWAP, with proposed participation from the Libyan Government focused on and in close cooperation with the Observatory of Sahara and Sahel – OSS and the Southern African Development Community – SADC and its 14 members and with the Saharan- Sahelian Group of African countries. The proposed Inter-African programme project offers a framework to strengthen the capacities and progress on enhanced regional scientific co-operation on the transboundary groundwater resources. It is suggested that the countries would come forward with their strengthening requirements to form the base for a regional manpower and institutional assessment.

Objective 4

Prepare an inventory of the existing African Transboundary Aquifers

In accordance with the ISARM approach progressing from global to regional to sub-regional and local it is suggested that a regional inventory based on active participation of the countries of the African Transboundary Aquifers forms a first requirement for further action.

The African countries are encouraged to co-operate and establish updated rapid group of country assessments on national in-country groundwater and shared aquifer resources.

African countries sharing transboundary aquifer resources are recommended to co-operate to exchange information, establish common knowledge bases and jointly harmonize the

assessment for shared aquifer resources, based on the ISARM Framework Document.

The regional assessment of the transboundary aquifer resources in Africa forms a global priority of importance for the implementation within the time-frame of UN-WWAP.

It is therefore suggested that the workshop entrusts UNESCO/IHP and ISARM to formulate a project for an Inventory of the African Transboundary Aquifers as part of a proposed global assessment under the GEF-IW window.

Objective 5

Launch an ISARM Africa Programme

It is suggested that the scope of an ISARM African programme would be defined in the Workshop and submitted for consideration in a next meeting of AMCOW. The recommended action will be incorporated under a Regional ISARM Africa Program to be launched and made part of a global ISARM framework

UNESCO/IHP and ISARM in contact with relevant funding partners could be requested to formulate and identify the required resources for concerted action on the Regional and sub-regional Aquifer Systems, initially focused on the SADC and the Saharan-Sahel Groups of countries. It is suggested that the ISARM partners be requested by the workshop to approach and identify external donor resources for the implementation of a comprehensive program.

The success of the programme will depend on actual field activities and the capacity to define, formulate and initiate a number of representative sub-regional field projects. There are several on-going and planned project initiatives on studies and development of management frameworks for specific shared aquifer systems in the region including the North African and the Saharan-Sahel sedimentary basins and the Karoo aquifer systems in the SADC sub-region.

The GEF/UNEP IW – OP#9 MSP project on 'Water And Land Management In Recharge Areas And Humid Zones Of The Shared Iullemeden Aquifer' that has been prepared by UNESCO/IHP and the ISARM members together with IAEA and other contributing partners and endorsed by the Governments of Mali, Niger and Nigeria is suggested as a first priority activity under the African ISARM program. It will therefore be important that the Iullemeden project is discussed and supported in the workshop and presented to AMCOW and the West Africa Water sector.

Another suggested priority is the Karoo-Kalahari project where project formulation has been initiated. It is suggested that the SADC Group of countries finalises the formulation including identification of donor resources for implementation.

To ensure the sub-regional balance it will be important to identify, formulate and put forward a priority programme on transboundary aquifer systems in the Central and Eastern African Groups of countries.

To secure the progress of an African ISARM program it will be important to actively engage the countries and the sub-regional water sectors together with the donor community, including the GEF implementing agencies to formulate projects on shared, transboundary aquifer systems. As mentioned in the introduction the management issues for transboundary aquifers are related to linkages between the aquifer resources and the overlying land and eco-systems. From this aspects and to support and progress the formulation of activities and attract external resources for implementation it is suggested that the workshop will identify, discuss and conclude on the priority topical issues including the following: (a) regional aquifer systems in Africa; (b) water and land linkages; (c) definition of transboundary aquifer system; (d) country perspectives and positions; (e) threats and objectives; (f) action, activities and outcomes; and (g) institutional arrangements and responsibilities. To this end it is suggested that the workshop would support the establishment of one or more topical working groups.



Country contributions and technical papers

Contribution des isotopes à l'étude des ressources en eau souterraines transfrontalières en Algérie

A.S. Moulla, A. Guendouz, M.E.H. Cherchali

Centre de Recherche Nucléaire d'Alger
Département des Applications en Hydrologie et Sédimentologie

Résumé

L'accroissement des besoins en eau dans le monde et en particulier dans les zones arides et semi-arides a fait que toutes les méthodes d'investigation des eaux souterraines possibles ont été mises à contribution. Ainsi et au cours de ces trente dernières années, il s'est développé une nouvelle méthodologie basée sur l'application des techniques isotopiques. Elle est ainsi devenue de nos jours l'un des principaux outils de recherche appliquée dans le domaine. La capacité de ces outils à obtenir des informations très difficiles voire impossibles à acquérir par les méthodes classiques n'est plus à démontrer tant ils ont apporté et contribué à une meilleure gestion des ressources en eau en général et souterraine en particulier.

Les réservoirs souterrains du Sahara constituent d'immenses réserves d'eau à composante essentiellement ancienne (fossile). Ces réserves posent aux gestionnaires de ces ressources d'énormes problèmes relatifs d'une part, à l'estimation précise des paramètres de leurs bilans hydriques (évaporation et infiltration) et d'autre part, à leur qualité chimique (potabilité).

Les études s'intéressant aux questions en suspens ne sont pas toujours faciles dans ces régions, car en plus des contraintes techniques et matérielles s'ajoutent des conditions climatiques extrêmes. C'est justement dans ces cas là que les méthodes mettant en jeu les isotopes du milieu apparaissent non seulement comme des techniques d'appoint mais indispensables sachant que chaque type d'eau possède sa propre empreinte ou signature isotopique.

Par ailleurs, les teneurs en isotopes stables (^{18}O, ^{2}H, ^{13}C), radioactifs (^{3}H, ^{14}C, ^{36}Cl) mais également en gaz rares (Xe, Ne, Ar, Kr, He) permettent de préciser l'origine des masses d'eau de ces aquifères, ainsi que la variabilité de leur recharge dans le temps et la reconstruction des climats anciens.

Nous nous attacherons dans le présent travail à présenter l'apport de ces méthodes à quelques aquifères sahariens en citant les principales conclusions auxquelles ont abouti les études menées dans différentes régions du pays. Il s'agit du bassin du Grand Erg Oriental dont les eaux sont partagées avec la Tunisie et la Libye, mais aussi du bassin du Tin-Séririne dans le Tassili Oua N'Ahaggar dont les réserves hydriques sont communes avec le Niger.

Méthodologie générale

Introduction

Les premières applications des isotopes en Algérie ont été initiées sous l'égide de l'UNESCO au début des années 1970 à l'occasion du projet ERESS (Etude des Ressources en Eau du Sahara Septentrional)[1]. L'application des techniques isotopiques dans les zones arides et semi-arides s'est montré dès lors d'un apport certain dans la résolution des problèmes liés aux ressources en eau.

Sur le plan méthodologique, les possibilités du traçage isotopique naturel ont été ainsi utilisées pour préciser des mécanismes (ayant lieu dans les cycles des solutions naturelles) difficiles

ou impossibles à déterminer par les méthodes classiques.

Le présent travail donnera un aperçu général des possibilités et de l'apport de l'outil isotopique à une meilleure gestion des ressources hydriques notamment en régions arides et semi-arides, ponctué par des exemples des résultats auxquels sont arrivés quelques unes des études menées jusqu'à présent.

Rappels d'hydrologie isotopique

Les isotopes les plus communément utilisés en Hydrologie Isotopique sont logiquement ceux qui font partie intégrante de la molécule d'eau à savoir : l'oxygène-18 (^{18}O), le Deutérium ou Hydrogène lourd (^{2}H ou D) et le Tritium ou Hydrogène radioactif (^{3}H ou T) qui sont dits traceurs intrinsèques. Les autres isotopes sont ceux de la forme dissoute : le Carbone-13 qui est stable (^{13}C) et le radiocarbone (^{14}C).

Considérant seulement les isotopes stables d'intérêt, les espèces isotopiques possibles qui peuvent être rencontrées pour l'eau sont : $H_2{}^{16}O$, $HD^{16}O$, $D_2{}^{16}O$, $H_2{}^{18}O$, $HD^{18}O$, $D_2{}^{18}O$. Dans la nature, deux mécanismes ayant lieu au sein du cycle de l'eau peuvent modifier la composition en isotopes « intrinsèques » d'une eau naturelle. Ce sont :

- le changement de phase (condensation, évaporation) ;
- les réactions d'échange.

qui peuvent être illustrées pour O-18 respectivement par les deux réactions suivantes :

$$H_2{}^{16}O_{liq} + H_2{}^{18}O_{vap} \rightleftarrows H_2{}^{18}O_{liq} + H_2{}^{16}O_{vap}$$

et

$$\tfrac{1}{2}C^{16}O_2 + H_2{}^{18}O \rightleftarrows \tfrac{1}{2}C^{18}O_2 + H_2{}^{16}O$$

Dans le cas d'un équilibre chimique et isotopique, et pour une température donnée, les rapports isotopiques des composés impliqués sont reliés par une constante appelée «facteur de fractionnement isotopique», notée •. Ainsi pour les deux réactions décrites auparavant, le facteur de fractionnement isotopique sera respectivement comme suit :

$$\alpha_{A-B} = \frac{R_A}{R_B} = \frac{\left(^{18}O/^{16}O\right)_L}{\left(^{18}O/^{16}O\right)_V} \quad \text{et}$$

$$\alpha_{A-B} = \frac{R_A}{R_B} = \frac{\left(^{18}O/^{16}O\right)_{CO_2}}{\left(^{18}O/^{16}O\right)_{H_2O}}$$

En géochimie isotopique, les résultats sont exprimés en différence de ces rapports isotopiques R entre deux substances. Cette différence appelée communément d de l'échantillon E par rapport à un standard donné S, s'exprime en pour mille (‰) et est définie comme suit :

$$\ddot{a}_E = \left[R_E/R_S - 1 \right] \cdot 10^3$$

Ainsi, si $\delta_E>0$, on dira que l'eau est enrichie en isotopes lourds (^{18}O, ^{2}H) et si $\delta_E<0$, on dira alors que l'eau en est appauvrie et déduisant par la même occasion les phénomènes auxquels l'eau a été soumise. Les standards ou étalons ont par définition une composition isotopique $\delta_s\bullet = 0$ ‰. Pour les eaux naturelles, le standard utilisé est le « SMOW » (Standard Mean Ocean Water).

A l'échelle du globe, les teneurs en Oxygène-18 et Deutérium des pluies d'origine océanique sont corrélées entre elles d'une façon linéaire. L'équation de cette droite météorique mondiale a été trouvée comme suit [2,3] :

$$\delta\,^{2}H = 8\,\delta^{18}O + 10$$

De même, il existe des droites météoriques locales comme celle du domaine méditerranéen ou encore celles des eaux souterraines fossiles comme illustré ci-dessous. Par ailleurs, il existe également une relation simple entre les teneurs en isotopes lourds des pluies et la température de condensation. Celle-ci se traduit notamment par des effets de latitude, d'altitude et de saison. Ainsi à l'échelle mondiale, Dansgaard[3] a proposé en 1964 une corrélation linéaire entre les teneurs moyennes annuelles en isotopes des précipitations et la température moyenne annuelle du sol :

$$\delta^{18}O = 0.69\,\overline{T} - 13.6$$

$$\delta\,^{2}H = 5.6\,\overline{T} - 100$$

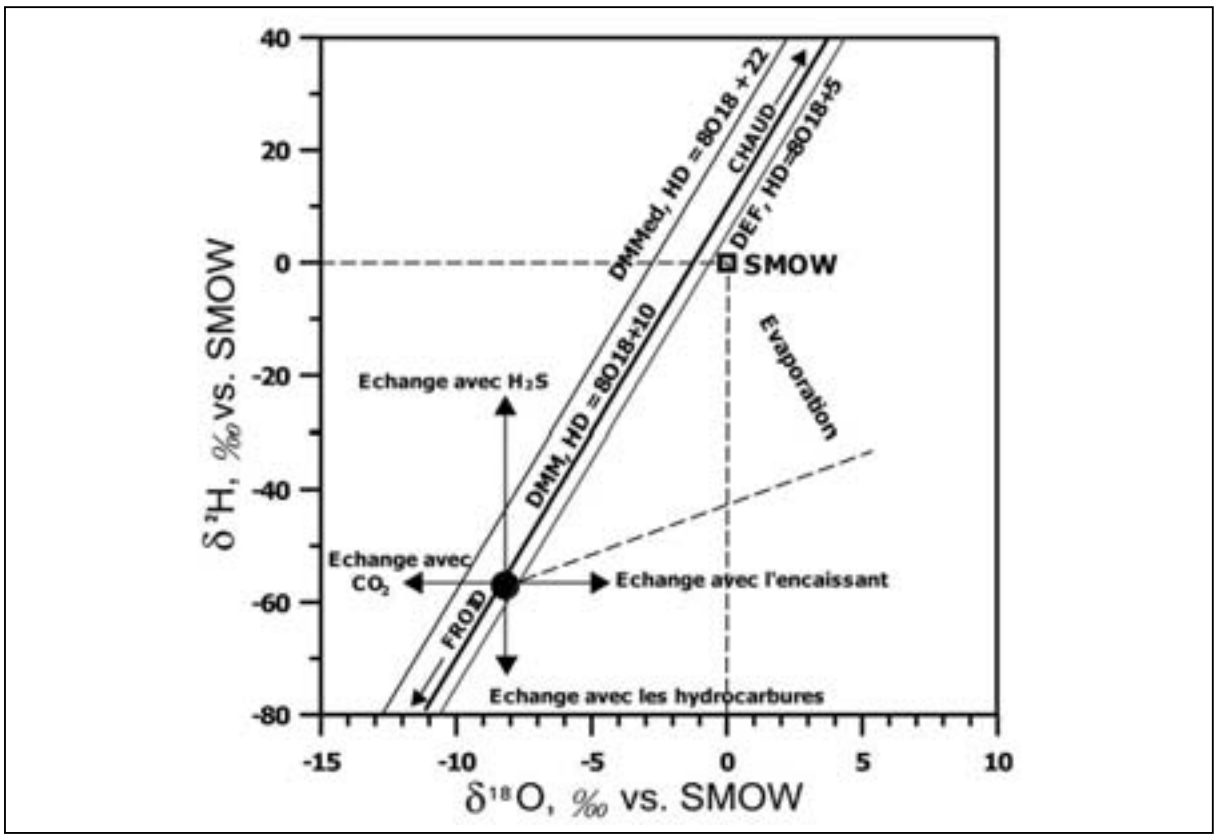


FIGURE 1. Domaine de répartition des eaux naturelles sur diagramme $\bullet^{18}O - \bullet^{2}H$ [2]

La connaissance des variations de la composition isotopique des eaux météoriques à travers les temps géologiques est nécessaire pour établir l'origine des eaux des formations aquifères profondes qui ont pu être mélangées ou rechargées depuis plusieurs millions d'années. Ces variations de teneurs en isotopes lourds des eaux météoriques peuvent résulter :

- de la variation du terme source, c'est-à-dire de la composition isotopique des océans ;
- du changement des conditions climatiques de l'aire de recharge.

Les isotopes radioactifs comme leur nom implique, sont instables et sont donc régis par la loi exponentielle de décroissance radioactive, chaque élément ayant sa constante de décroissance spécifique et par conséquent sa propre période de demi-vie. Cette dernière est le temps suffisant et nécessaire pour que le stock d'atomes initialement présent dans le système se réduise de moitié. Les radioéléments les plus couramment utilisés en hydrologie sont le tritium, le carbone-14 et le chlore-36. Ils sont d'origines diverses (cosmogénique, technogénique ou pédogénique).

L'intérêt du tritium dans les études hydrologiques et en science de l'eau en général réside dans le fait qu'il est partie intégrante de la molécule d'eau. En effet, c'est l'isotope radioactif de l'hydrogène, émetteur de particules béta (β^-) de faible énergie ($E_{max} = 18.6$ keV) et ayant une période de demi-vie relativement courte de 4500 jours ou 12.32 années).

Compte tenu de ses caractéristiques et surtout de sa période, il est ainsi utilisé pour tracer le déplacement des masses d'eau dans les cycles hydrologiques relativement courts qui ont lieu la plupart du temps à la surface des continents (eaux de précipitation, eaux superficielles : rivières, lacs, etc., retenues de barrage, eau interstitielle, …).

Les concentrations en tritium des eaux naturelles sont habituellement mesurées et exprimées en Unités de Tritium (UT) sachant qu'une UT correspond à la présence d'un atome de H-3 pour 10^{18} atomes d'hydrogène stable (^{1}H). Cette activité équivaut à 7.2 dpm ou encore 3.24 pCi par litre d'eau.

Contrairement au tritium, le radiocarbone possède une période de demi-vie bien plus longue (5730 ans) et décroît en émettant un rayonnement β^- d'énergie maximale équivalant 156 KeV. Ses caractéristiques lui permettent d'être utilisé comme radiochronomètre pour la matière carbonée et lui confèrent un spectre d'utilisation pouvant atteindre 40 000 ans.

Par des processus chimiques et biochimiques complexes liés au cycle naturel du carbone, le radiocarbone se retrouvera inévitablement dans l'eau, comme résumé par la réaction ci dessous, au travers de la forme carbonatée et bicarbonatée dissoute. C'est cette dernière qui pourra permettre à l'eau d'être datée. En conséquence et de façon générale, il est préférable d'exprimer les teneurs en Carbone-14 en pour cent de carbone moderne (pmC) qu'en âges car ces derniers ne seront qu'une estimation. Moins il y aura de Carbone-14 dans la forme carbonatée dissoute, plus l'eau sera évidemment ancienne.

$$MeCO_3 + CO_2 + H_2O \rightleftarrows Me(HCO_3)_2$$

Pour ce qui est du Chlore-36, il a une période de demi-vie (3.01×10^5 a) très longue qui lui confère le pouvoir de dater des eaux de plus de 50 000 ans. Les concentrations en cet élément sont exprimées de deux façons: soit en atomes de ^{36}Cl par atomes de chlore total ou encore en atomes par litre.

Caractéristiques des eaux souterraines profondes au Grand Erg Oriental (Algérie, Tunisie, Libye)

Contextes géographique et hydrogéologique

Le bassin sédimentaire du Sahara septentrional s'étend sur ~780.000 km^2 (dont ~700.000 en Algérie). Il est limité au Nord de la frontière marocaine au golfe de Gabès par l'Atlas saharien, à l'Ouest par la vallée de la Saoura, au Sud par la bordure des plateaux de terrains anciens du Sahara central (Hammadas du Tademaït et du Tinrhert); à l'Est par la Méditerranée (golfe de Gabès), par les reliefs du Djebel Dahar (Tunisie) et conventionnellement par la frontière algéro-libyenne (Fig. 2). Il comprend deux grandes nappes aquifères (Fig. 3).

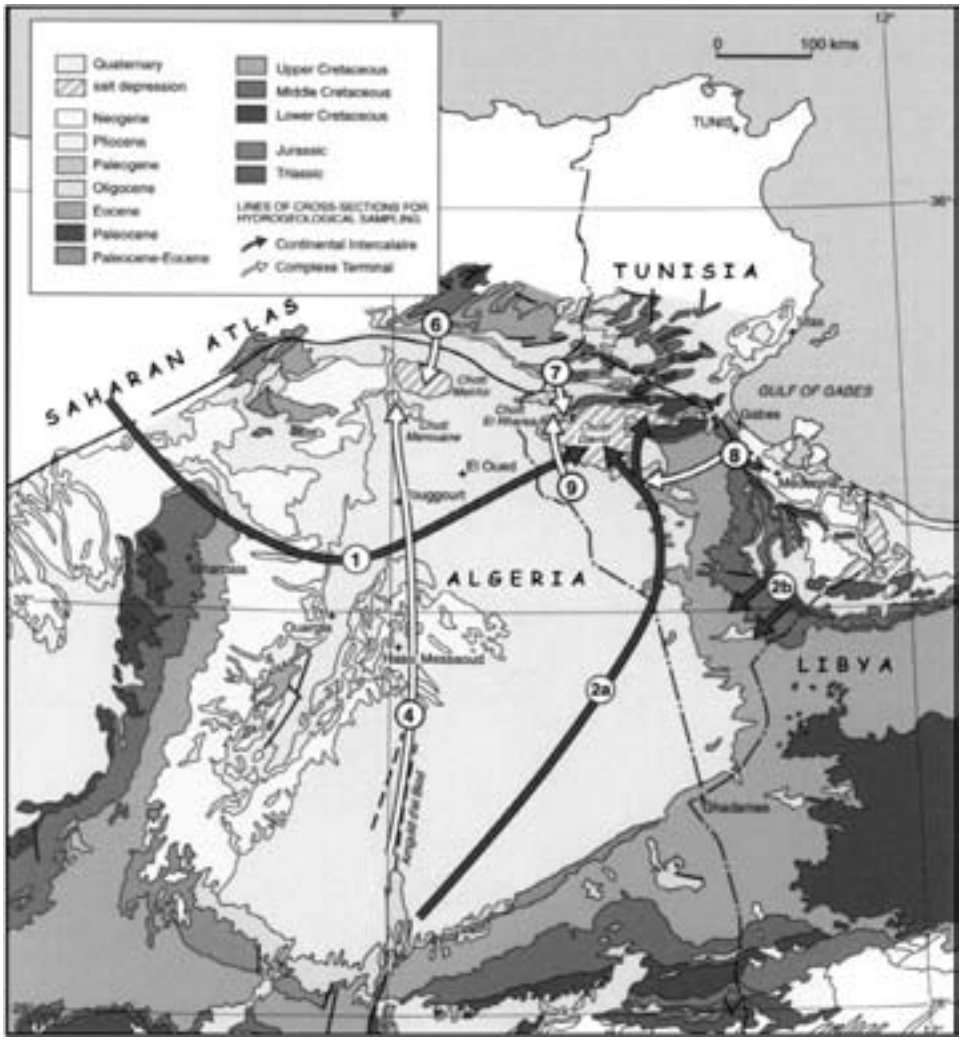


FIGURE 2. Carte hydrogéologique de la région [4]

Le réservoir du ***Continental Intercalaire*** s'étend sur ~600.000 km^2. Il est contenu dans les formations continentales des horizons sableux et argilo-gréseux du Crétacé inférieur[5].

La dorsale du M'zab, véritable pont structural entre l'Atlas saharien et le plateau du Tademaït, divise l'aire du réservoir en deux bassins : l'un occidental, l'autre oriental.

Au Nord-est de la dorsale du M'zab, le toit du système aquifère, constitué d'argiles et d'évaporites du Cénomanien, est continu sur tout le bassin. La profondeur du toit augmente du Sud au Nord (1 000 m au bas Sahara, 2 000 m sous les Chotts), provoquant ainsi une forte charge de la nappe sur tout le bassin.

Le substratum est constitué de formations argilo-sableuses et argileuses ou carbonatées d'âge de plus en plus récent en allant du Sud vers le Nord.

Le réservoir du ***Complexe Terminal*** groupe sous une même dénomination plusieurs aquifères situés dans des formations géologiques différentes[1]. Cette nappe peut circuler dans l'une ou les trois formations lithostratigraphiques suivantes :

- Sénonien et Éocène carbonatés;
- Miopliocène sableux (Continental Terminal);
- Quaternaire, sables dunaires, sables argileux et gypseux.

Isotopes stables : (O-18, HD)

La nappe du Continental Intercalaire est captive sur la plus grande partie du bassin oriental. Les teneurs en isotopes stables de ses eaux sont très homogènes et centrées autour des valeurs de $\delta^{18}O = -8.4 \pm 0.4$ ‰ et $\delta^{2}H = -61 \pm 3$ ‰ [6,7,8,9,10]. Ces valeurs propres à un aquifère protégé sont caractéristiques de la nappe du C.I. qui est exempte de toute contribution à partir d'autres nappes.

La comparaison avec d'autres aquifères de grandes dimensions de par le monde montre le même caractère homogène et appauvri en isotopes lourds. C'est notamment le cas en Égypte, en Libye, en Arabie Saoudite, au Soudan et en Australie[11]. Ceci est directement lié aux conditions sous lesquelles ces aquifères ont été rechargés.

En effet, le diagramme de la Figure 4 ci-après montre que ces eaux se situent sous la droite mondiale des eaux météoriques (DMM) tout en s'alignant parallèlement à celle-ci[10,11,12,13,14], L'excès en deutérium de +5 ‰ suggère une humidité atmosphérique supérieure à celle des conditions climatiques actuelles (droite des eaux fossiles).

Bien que sur toute cette zone la nappe du Complexe Terminal se trouve séparée des niveaux aquifères du C.I. par plusieurs centaines de mètres de formations argileuses et anhydritiques du Cénomanien, le problème d'une drainance verticale conforté par des arguments chimiques et isotopiques se trouve posé. En effet, sur le diagramme de la Figure 5 sont reportées les teneurs en chlorures en fonction des compositions isotopiques en O-18 des différentes nappes.

Les points représentatifs s'ordonnent selon un schéma triangulaire qui correspondrait à un mélange de trois types d'eau:

- une eau bien homogénéisée contenant près de 500 ppm de chlorures et une teneur en O-18 voisine de −8.3 ‰, qui correspondrait à la nappe du Continental Intercalaire;
- une eau à caractère évaporé contenant près de 1000 ppm de chlorures et une composition

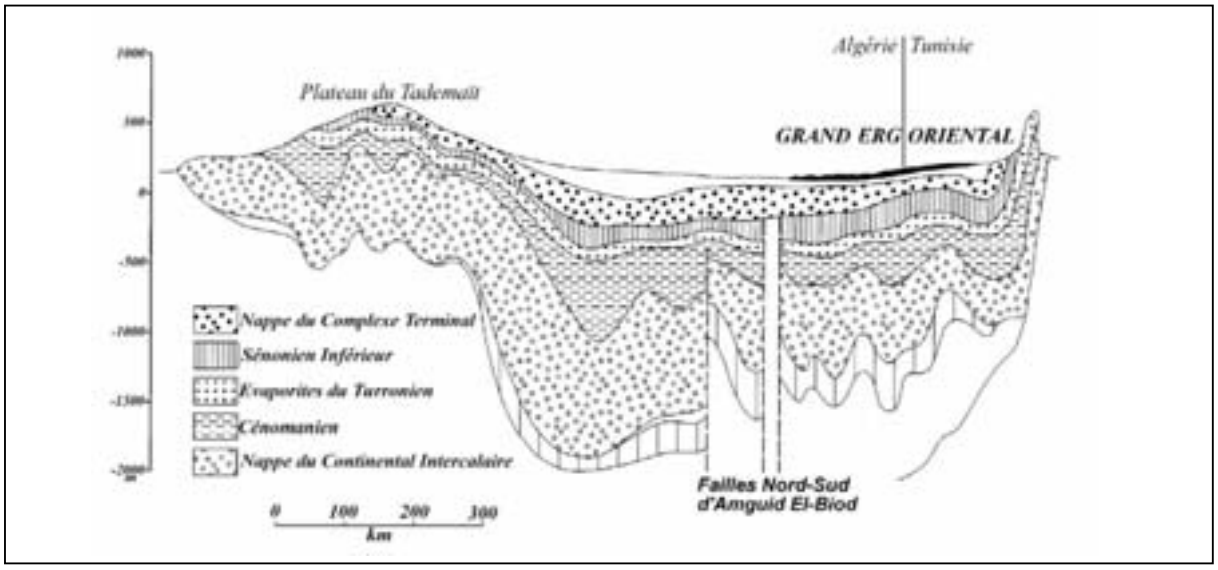


FIGURE 3. Coupe hydrogéologique SW-NE du sous bassin du Grand Erg Oriental

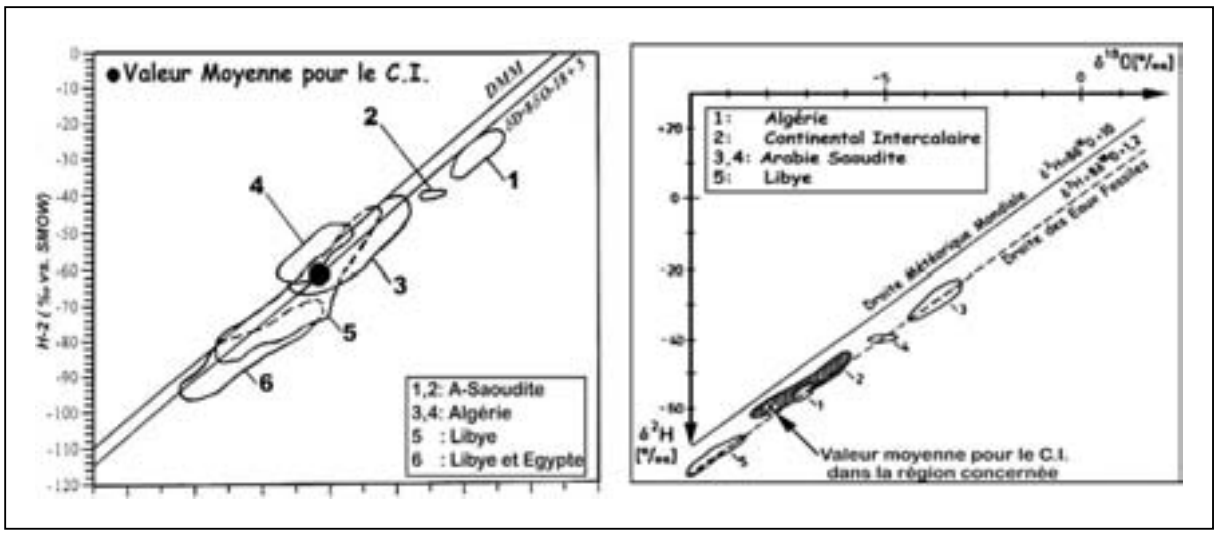


FIGURE 4. $\delta D - \delta^{18}O$ du C.I. au G.E.O., comparé à celui d'autres nappes d'eau fossile [10,11,12,13,14]

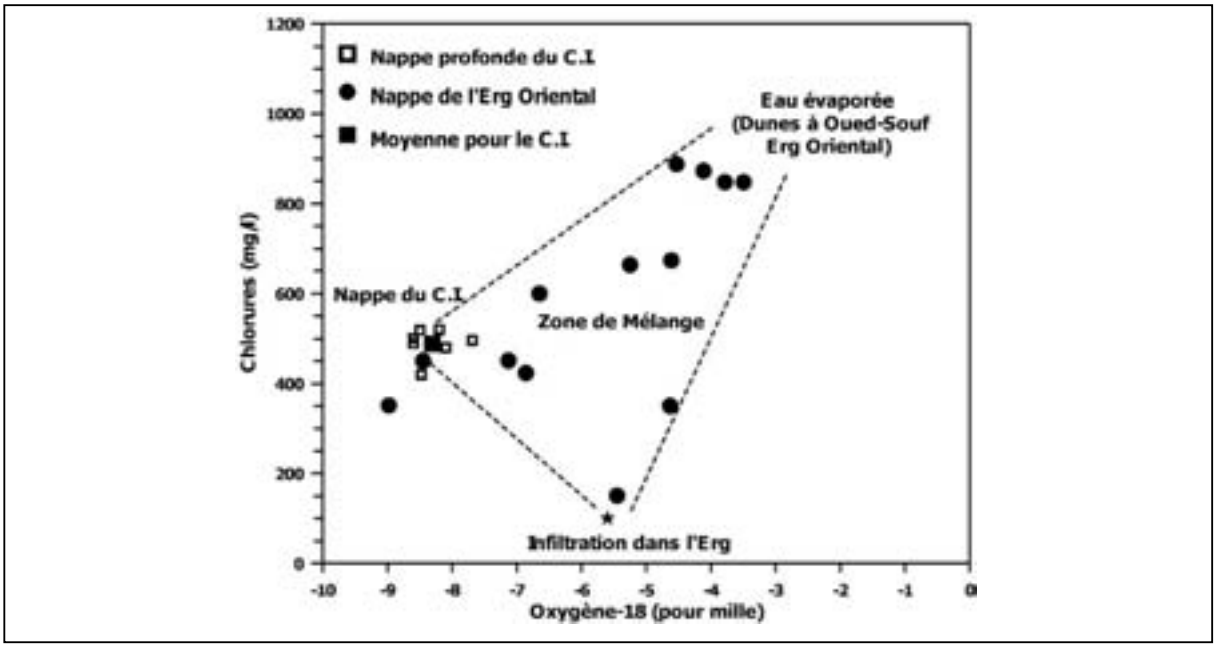


FIGURE 5. Relation Chlorures/O-18 des eaux du CI et de l'Erg Oriental (C.T.)

isotopique en O-18 voisine de 4 ‰. Elle correspondrait à la masse d'eau de la nappe du Complexe Terminal de l'Erg Oriental dans la région du Souf;

- et une eau ayant une concentration autour des 100 ppm en chlorures et une concentration en O-18 de 5.5 ‰. Elle représenterait des eaux assez récentes, comme en témoigneraient des teneurs assez élevées en C-14, qui se seraient infiltrées à travers les dunes de sable du Grand Erg Oriental.

Sur le plan structural, ces apports ascendants semblent être directement liés aux prolongements Nord-Est de la dorsale d'Amguid où des faibles à forts rejets verticaux (600 m à l'Ouest de Rhourde El Baguel et 350 m à El Borma) favorisent les communications entre les systèmes aquifères (Fig. 2).

Isotopes radioactifs : Tritium, Carbone-14 et Chlore-36

Toutes les eaux de la nappe du C.I. à l'échelle du bassin oriental ont été trouvées quasiment dépourvues de tritium. Les activités mesurées en carbone-14 sont très basses et varient entre 0 et 6 pmC (pour cent de Carbone Moderne)[4,6] sur toute la partie centrale du bassin et sont relativement élevées sur les zones de recharge (de 50 à 80 % au Nord-ouest de Laghouat et 50 % sur les monts du Dahar en Tunisie).

Les âges corrigés, déterminés à partir des activités en carbone-14, varient entre 20 et 40 ka. En termes paléoclimatiques, les eaux du C.I. sont liées à la phase humide majeure de recharge du Pléistocène inférieur, qui a été reconnue dans plusieurs ensembles aquifères du globe de même

que récemment dans le Tidikelt autour de In-Salah [15].

La limite théorique de datation par le radiocarbone (40 ka) étant atteinte pour les eaux du C.I., un autre radiochronomètre à savoir le Chlore-36. Vingt échantillons ont été analysés en ce radioélément sur les chlorures dissous dans les eaux de la nappe à travers tout le bassin du Grand Erg Oriental.

Les rapports atomiques $^{36}Cl/Cl$ exprimés en $at.at^{-1}$ et en $at.l^{-1}$ ont montré une diminution dans le sens de la direction principale d'écoulement des eaux, c'est-à-dire de l'Atlas saharien (Nord-ouest de Laghouat en Algérie) vers le Golfe de Gabès en Tunisie. Les valeurs ainsi mesurées varient entre 100×10^{-15} et 8×10^{-15} ($at.at^{-1}$) et 3.5×10^{8} et 0.9×108 ($at.l^{-1}$). Cette diminution est simplement attribuée à la décroissance radioactive. Ainsi entre la dorsale du M'zab et la vallée de l'Oued Rhir, le temps de résidence calculé le long de cette direction d'écoulement varie entre 50 et 600 ka [16].

L'étude a également concerné toute la région sise autour de la ville d'El-Oued du côté de la frontière Tunisienne et qui est confrontée depuis quelques années à un phénomène de remontée du niveau piézométrique des eaux de la nappe phréatique. En effet, ce phénomène a entraîné la disparition de milliers de palmiers-dattiers, principale richesse de la région et menace présentement à certains endroits de la ville, les fondations des habitations.

Sur le plan isotopique, les données en oxygène-18 ($\delta^{18}O$) de la nappe phréatique dans toute la région du Souf sont variables et se trouvent comprises entre –1.8 et –4.5 ‰. En comparaison avec les teneurs en cet isotope des précipitations ayant lieu dans la région (–7.4 ‰), on peut dire que ces eaux sont évaporées. De plus, il a été mesuré une valeur moyenne en tritium égale à 16.3 UT pour les pluies. [17,18,19,20,21,22,23,24]

D'autre part et pour les isotopes radioactifs du milieu (respectivement ^{3}H et ^{14}C), entre 0 et 25 UT et 20 et 120 pmC ont été mesurés pour la nappe phréatique. Cela veut dire que cette dernière est en fait constituée d'un mélange d'eau ancienne et d'eau récente.

Les eaux de la nappe du Complexe Terminal de leur côté, ont montré des valeurs homogènes dénotant également un caractère évaporé de par un $\delta^{18}O_{moy}$ de –4.1 ‰ (sur 44 forages). Cependant, les teneurs en tritium et celles en ^{14}C sont comprises respectivement entre 0 et 4.8 UT et 2 et 14 pmC. Ceci veut dire que ces eaux sont en fait anciennes, ce qui est conforme aux résultats d'autres études menées sur cette nappe qui prônent une recharge d'âge datant de l'Holocène.

La corrélation entre les teneurs en tritium et la minéralisation (Fig. 6), nous a permis de distinguer trois composantes différentes constituant les eaux de la nappe phréatique :

- Des eaux ayant autour de 25 UT et une minéralisation moyenne $\overline{M} \approx 3$g/l qui correspondraient à l'infiltration rapide et récente des eaux de précipitation.
- Des eaux de 10 à 15 UT ayant une minéralisation de 3 à 7 g/l, qui correspondraient à un mélange d'une composante récente (pluies) et d'une autre faiblement tritiée provenant de la nappe profonde qui est exploitée (C.T.).
- Enfin, des eaux contenant moins de 10 UT et une salinité moyenne $\overline{M} \approx$ 5g/l. Cette masse d'eau qui comprend la grande majorité des échantillons, correspondrait essentiellement à un apport à partir des forages de la nappe du Complexe Terminal utilisée principalement pour l'irrigation.

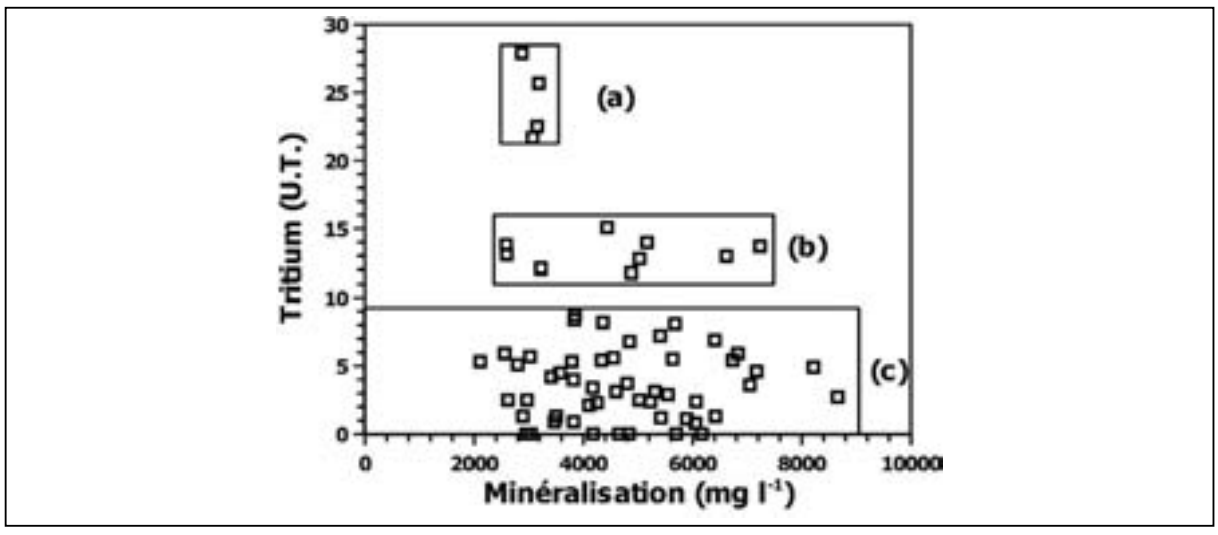


FIGURE 6. Corrélations expliquant les différentes contributions à la nappe phréatique

La nappe du Complexe Terminal étant profonde (200–250 m) et captive sur toute la région du Souf, ses zones d'alimentation se situent au Sud et au Sud-est sur tout le Grand Erg Oriental où la nappe devient moins profonde et libre (niveau statique : 30 à 40 m) (Fig. 7).

Le caractère homogène et évaporé des eaux du C.T. peut être expliqué par une alimentation ancienne à partir des eaux de pluies ayant subi des modifications de leur composition isotopique au cours de l'aridité du Sahara Nord-est septentrional. Il s'agit donc de réserves d'eau 'fossile' qui sont exploitées actuellement sur la région du Souf.

Gaz nobles

Dans les eaux naturelles, les gaz nobles (dits aussi rares, Ne, Ar, Kr, Xe, He) proviennent initialement de leur mise en solution à partir de l'air atmosphérique. La teneur des eaux en gaz rares dissous suit la loi de solubilité de **Henry** et dépend essentiellement de la température. Pour les eaux souterraines, cette concentration dépendra logiquement de la température qui prévalait lors de la recharge. Ainsi, la détermination des teneurs en gaz nobles d'une eau souterraine permettra de déduire des informations d'ordre paléoclimatique.

Les teneurs en gaz rares des eaux des nappes du C.I. et du C.T. ont été mesurées sur 17 échantillons. Pour le C.I., treize échantillons ont été analysés dont dix ont été choisis le long de la direction principale d'écoulement. Les températures de recharge calculées pour ces échantillons ont été trouvées variant entre 12°C et 24°C avec une moyenne de 15°C[25].

Les échantillons provenant de la nappe du C.T. quant à elles, exhibent des températures de recharge qui reflètent la valeur moyenne annuelle prévalant actuellement sur les zones d'études (~20°C). La différence de température entre les deux aquifères de ~5°C confirme que les eaux de la nappe du C.I. se sont infiltrées dans des conditions climatiques plus humides, reflétant ainsi une recharge qui a eu lieu durant le Pléistocène inférieur (20 à 40 ka) (Fig. 8).

Étude des eaux souterraines du Bassin du Tin Seririne dans le Tassili Ouan'Ahaggar et du Tidikelt

Introduction

Cette étude a englobé toute la région autour de la ville de Tamanrasset en proie à un problème accru d'alimentation en eau. Elle s'est intéressée donc aux nappes d'eau de l'inféro-flux au Hoggar Central et aux nappes d'eau profondes des ceintures paléozoïques des Tassili et mésozoïques du Tidikelt. Il était question de prouver l'existence ou non d'une recharge, d'estimer

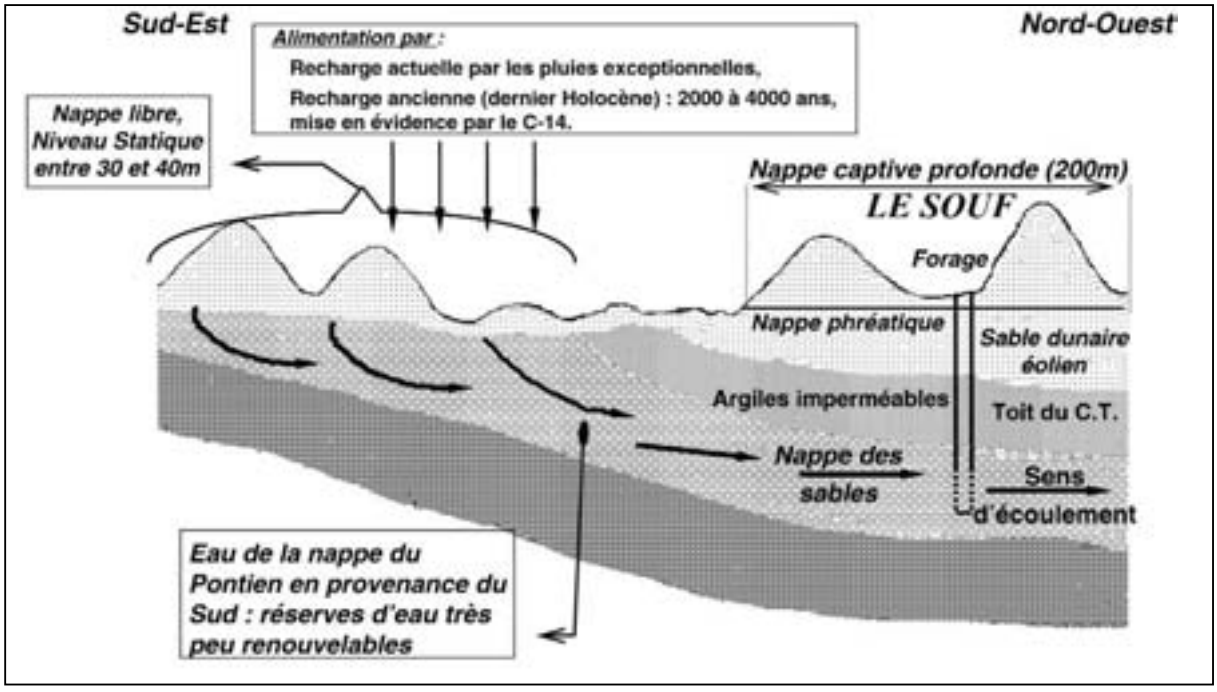


Figure 7. Schéma explicatif de l'origine des eaux de la nappe Complexe Terminal

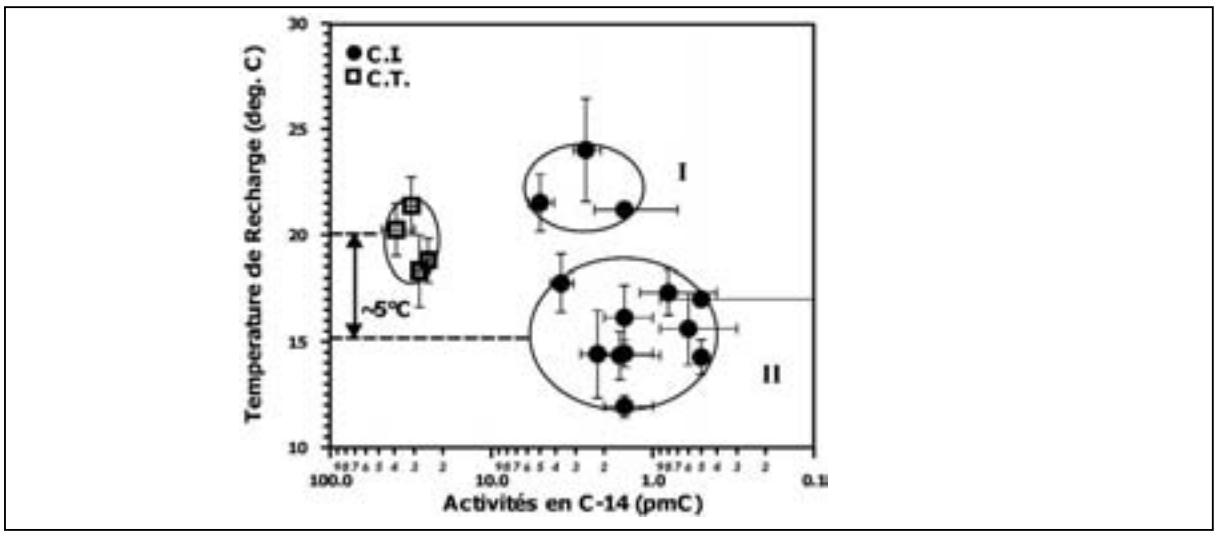


FIGURE 8. Relation entre la température de recharge et les teneurs en C-14[25]

l'âge et le temps de transit des eaux dans les nappes profondes et de répondre aux préoccupations des gestionnaires locaux des ressources en eau.

Le bassin de Tin-Séririne couvre une superficie de 45.000 km^2, et s'étend à la fois sur les territoires algérien et nigérien (Fig. 9). Le réservoir le plus important qui s'y trouve est celui des grès du Cambro-Ordovicien qui couvrent une superficie de 21 000 km^2. Leur profondeur varie des flancs, jusqu'à atteindre une profondeur de 400 m dans l'axe du bassin. Les eaux du Cambro-Ordovicien s'écoulent selon une direction NNE-SSW, la nappe est libre sur les bordures ainsi qu'à l'extrémité Nord du bassin. Ailleurs, elle devient captive et même artésienne au Niger.

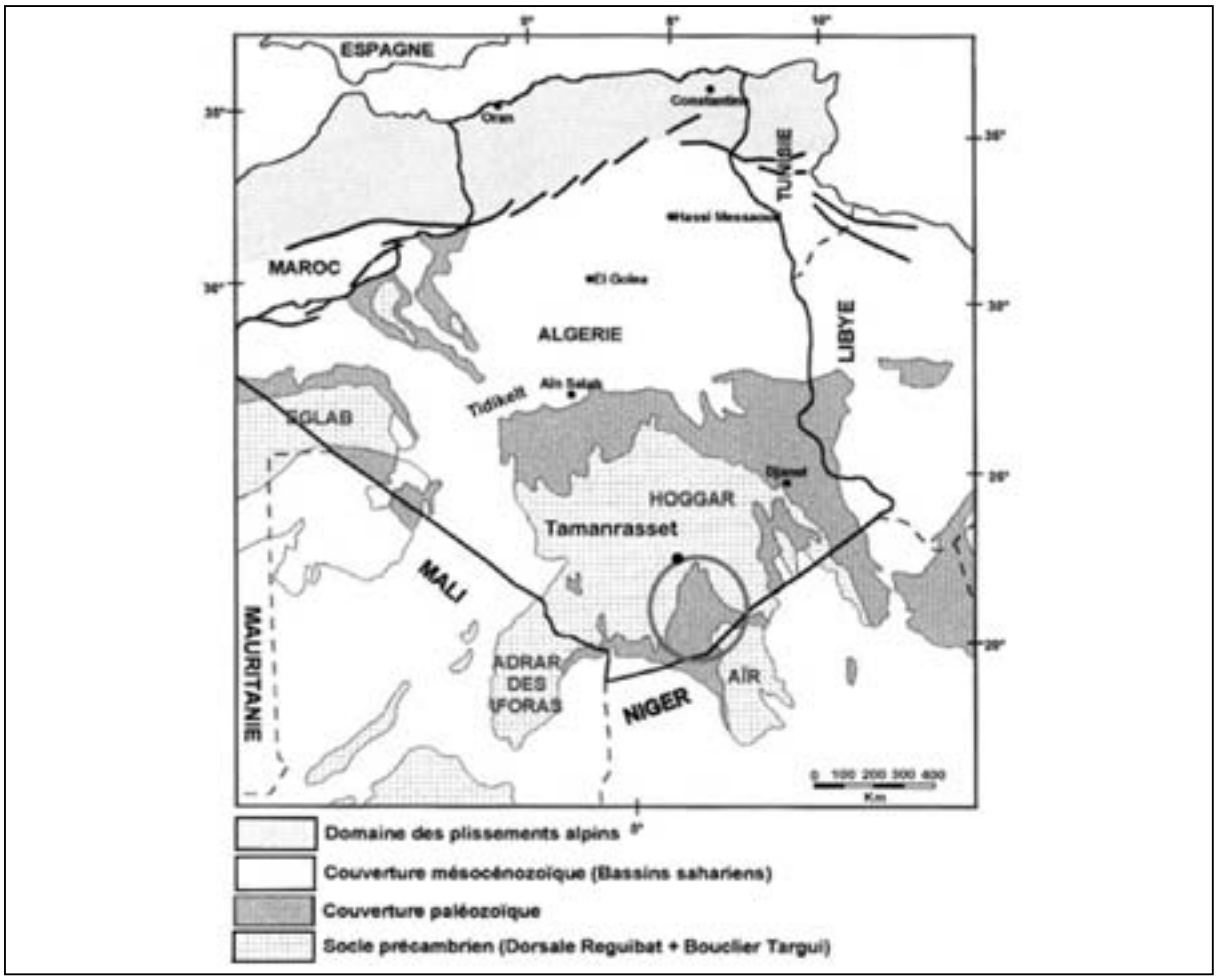


FIGURE 9. Carte géologique montrant la situation du bassin du Tin Séririne

Les isotopes stables, ^{18}O et HD

Les échantillons du C.I. du Tidikelt ont été trouvés appauvris en ^{18}O et ^{2}H, exhibant ainsi le même cachet que ceux de la même nappe dans le Grand Erg Oriental. La signature isotopique est parfaite et témoigne d'une homogénéité de l'aquifère. Les points représentatifs s'alignent sur la droite des eaux fossiles ce qui signifie qu'elles se sont infiltrées sous un climat plus froid et plus humide que l'actuel.

On retiendra pour le Tassili Oua-N'Ahaggar (Tin-Sériríne), que les eaux sont homogènes et appauvries en isotopes lourds (Fig. 10). Les points sont groupés autour des valeurs moyennes $\delta^{18}O$ = 8.8 ‰ et $\delta^{2}H$ = 66.9 ‰ sur la droite des eaux fossiles. Ceci nous permet de dire que ces eaux proviennent d'une recharge paléoclimatique issue d'un pluvial ancien, dont les caractéristiques climatiques étaient différentes de l'actuel.

Le tritium et le carbone-14

Les eaux de précipitation de la région, ont une teneur moyenne de 11 U.T. Elle est plus élevée que celle des eaux souterraines du Tassili et du Tidikelt. Les eaux souterraines des deux régions exhibent des teneurs inférieures à 5 U.T., nous permettant ainsi d'affirmer qu'il n'y a pas de renouvellement régulier mais plutôt des épisodes de recharge sporadiques très irréguliers[15].

Le premier constat qui découle des données du radiocarbone est que l'eau de l'aquifère du C.I. est beaucoup plus ancienne et homogène que celle du Cambro-Ordovicien. A cela une raison, pour le Tassili, l'impluvium des grès est important, impliquant des possibilités de recharge plus grandes que pour celles du Tidikelt.

Les âges calculés varient pour le Tidikelt, de 19 ka à plus de 40 ka, alors que pour le Tassili les âges s'orientent autour de 12 000 ans (Fig. 11). On constate que pour deux points, les âges augmentent en fonction du sens de l'écoulement, alors que pour un autre situé plus au Sud (In-Guezzam) l'âge obtenu est plus récent. Ceci peut-être expliqué par la présence d'accidents structuraux en plus du fait que cette région est plus sujette aux perturbations de la mousson soudano-saharienne.

Conclusion

Les techniques isotopiques ont été appliquées en Algérie surtout durant la dernière décennie dans plusieurs études concernant les ressources en eau en milieu fissuré ou poreux sous climat aride ou semi-aride. Leur contribution réside principalement dans la différenciation de plusieurs types

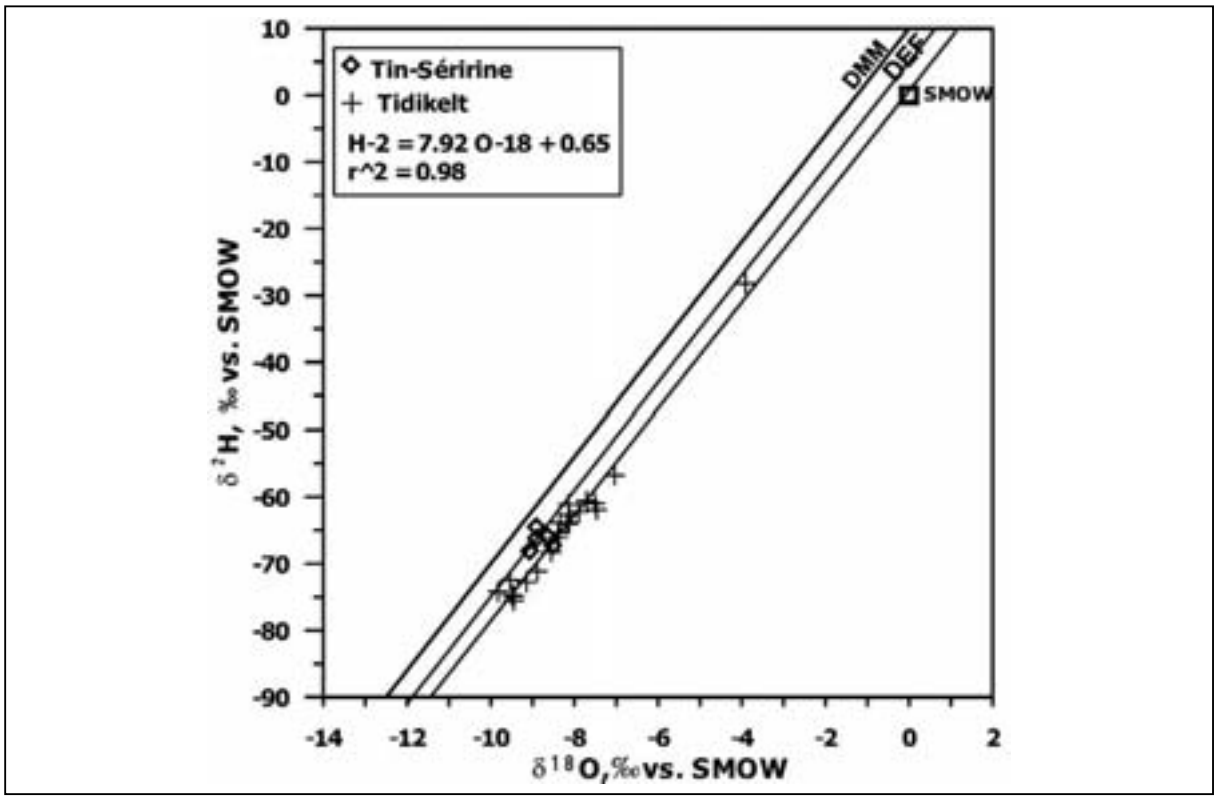


FIGURE 10. Diagramme $^{18}O-^{2}H$ pour les eaux du Tin-Sériríne et du Tidikelt

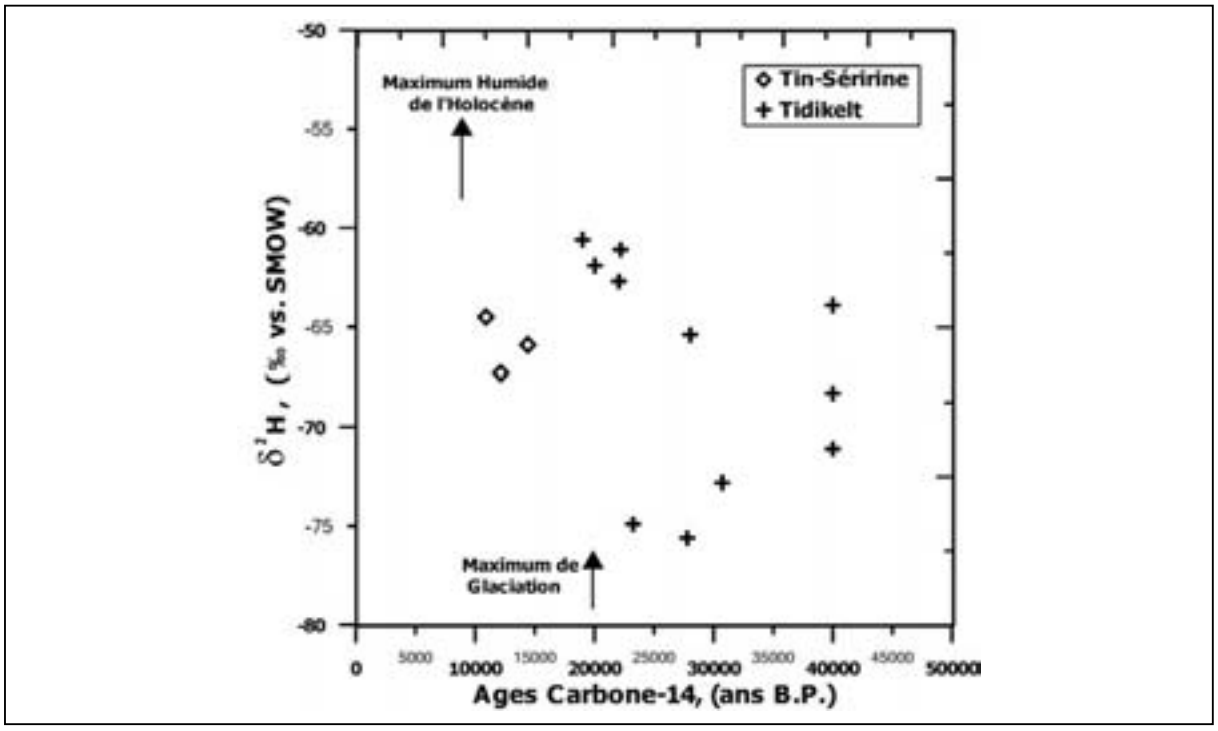


FIGURE 11. Relation ages carbone-14 - Deutérium des eaux profondes

d'eaux en présence dans un système aquifère. De plus, ces outils peuvent démontrer l'existence ou non de recharge contemporaine, quantifier des termes du bilan hydrique,…

Au niveau du bassin du Grand Erg Oriental, un des plus grands système aquifère au monde, ces outils ont permis en outre de mettre en évidence globalement et localement les informations suivantes :

- Les eaux du C.I. qui sont homogènes et fossiles, ont été rechargées lors des périodes humides et plus froides du Pléistocène inférieur. Cette assertion est également confirmée au niveau du Tidikelt dans le bassin occidental.
- Les eaux du Complexe Terminal sont également anciennes et se seraient par contre infiltrées durant l'Holocène.
- L'existence d'une drainance ascendante à partir du C.I. au centre du bassin par la biais de forages détériorés et des prolongements des failles d'Amguid El-Biod.

Dans la région du Tassili Oua-N'Ahaggar et du Tidikelt, les principaux résultats ont été que les eaux souterraines des grès du Cambro-Ordovicien du Tin-Séririne et du C.I. au Tidikelt proviennent d'un pluvial ancien dont les caractéristiques étaient différentes de l'actuel. A l'échelle temporelle humaine, elles sont donc sont très peu ou pas rechargées du tout.

Les implications immédiates sont que pour tout projet de développement des régions concernées, c'est bien à une révision du programme de gestion des eaux qu'il faudra procéder. L'avenir de ces territoires est donc directement lié aux décisions, peut être lourdes de conséquences pour les générations futures, qui sont ou seront prises, s'il n'était pas tenu compte des données actuelles. On ne pourra prétendre vouloir développer l'une ou l'autre région sans considérer un fait fondamental, que rien ne peut occulter, à savoir que c'est bien une gestion de type minière qu'il faudra instaurer. La concertation entre les pays est d'autant plus nécessaire que les ressources sont partagées et que le problème de l'eau en Afrique, les changement climatique aidant, devient de plus en plus délicat et requiert plus d'attention et de responsabilité.

Références bibliographiques

[1] UNESCO (1972) : Projet « ERESS », Etude des Ressources en Eau du Sahara Septentrional. Rapport final, 7 plaquettes, Paris.

[2] CRAIG, H. (1961) : Isotopic variations in meteoric waters, Science, 133, p. 1702-1703.

[3] DANSGAARD, W. (1964) : Stable isotopes in precipitation. Tellus, XVI, p. 436-468.

[4] EDMUNDS, W.M., SHAND, P., GUENDOUZ, A.H., MOULLA A.S., MAMOU, A., ZOUARI, K. (1997) : Recharge characteristics and groundwater quality of the Grand Erg Oriental Basin,

Final report. EC (Avicenne) Contract CT93AVI0015, BGS Technical report WD/97/46R, Hydrogeology Series.

[5] CORNET, A. ; (1964) : Introduction à l'hydrogéologie saharienne. Rev. Géogr. Phys. & Géol. Dyn., Vol. VI, Fasc. 1, pp. 5-72 .

[6] GUENDOUZ, A. ; (1985) : Contribution à l'étude hydrochimique et isotopique des nappes profondes du Sahara Nord-est Septentrional, Algérie. Thèse Doct. 3ème cycle, Univ. Paris XI, 243 pages.

[7] GUENDOUZ, A., MOULLA, A.S.; (1996) : Drainance de la nappe profonde du Continental Intercalaire vers les aquifères superficiels à Ouargla: Arguments isotopiques. Séminaire International sur l'Application des Techniques Isotopiques dans le Domaine des Ressources en Eau et en Sol. Mahdia, Tunisie (14–18 Juin).

[8] MOULLA, A.S.,GUENDOUZ, A., REGHIS, Z.; (1994) : Etude hydrochimique et isotopique des eaux souterraines de la cuvette de Ouargla (Algérie) : 2ème rapport sur l'interprétation des données hydrochimiques de la 2ème campagne et isotopiques de 1ère et 2ème campagnes d'échantillonnages. Rapport Interne, CDTN, Alger, 30 pages.

[9] GUENDOUZ, A., MOULLA, A.S.; (1995) : Application des techniques nucléaires aux problèmes des ressources en eaux souterraines profondes du Sahara Nord-Est septentrional Algérien. 2ème Colloque National Climat–Environnement. L'eau, une réalité, une urgence, un défi. Oran (du 24 au 25 /12/1995).

[10] GONFIANTINI, R., CONRAD, G., FONTES, J.Ch., SAUZY, G., PAYNE, B.R., (1974) : Etude isotopique de la nappe du Continental Intercalaire et de ses relations avec les autres nappes du Sahara Septentrional. In Isotope Techniques in Groundwater Hydrology. Proc. Symp., IAEA, Vol. I, Vienna, pp. 227-234.

[11] SONNTAG, C., KLITSCH, E., LOHNERT, E.P. MUNICH, K.O., JUNGHANS, C., THORWEIHE, U., WEISTROFFER, K. SWAILEM, F.M., (1978) : Palaeoclimatic information from ^{2}H and ^{18}O, in ^{14}C dated north-Saharan groundwater. Groundwater formation in the past. in Isotope Hydrology, Vienna: IAEA, pp. 569-581.

[12] EDMUNDS, W.M. WRIGHT, E.P., (1979): Groundwater recharge and paleoclimate in the Sirte and Kufra basins. Libya. J. of Hydrology, 40, pp. 215-241.

[13] MOSER, H., PAK, E., RAUERT, W., STICHLER, W., ZÖTL, J.G., (1978): Isotopic composition of waters of Al Qatif and Al Hasa areas. In: S.S. Al-Sayari and J.G. Zötl (Eds.) Quaternary Period in Saudi Arabia 1: Sedimentological, Hydrogeological Hydrochemical, Geomorphological and Climatological Investigations in Central and Eastern Saudi Arabia, Springer Verlag, Vienna: 153-163.

[14] DRAY, M. GONFIANTINI, R., ZUPPI, G.M.,(1983) : Isotopic composition of groundwater in the southern Sahara. In: Palaeoclimates and Palaeowaters: A collection of Environmental Isotope Studies, Proceedings of an Advisory Group Meeting, November 1980, Vienna: 187-199.

[15] CHERCHALI, M.E.H. ; (2000) : Etude hydrochimique et isotopique des eaux souterraines du Hoggar central, des Tassilli N'Ajjer et Oua N'Ahaggar et du Tidikelt. Projet Modèle AIEA, RAF/8/022. Rapport final, Nov. 2000, 119 pages.

[16] GUENDOUZ, A. MICHELOT, J.L., ALLAN, G. : Chlorine-36 in deep groundwaters from north-eastern Sahara (Algeria). (En préparation).

[17] GUENDOUZ, A., MOULLA, A.S., REGHIS, Z.; (1993) : Etude de la remontée des eaux de la nappe phréatique de la région de Oued Souf (Erg Oriental, Sahara Nord-est Septentrional) par les méthodes isotopiques et hydrochimiques. Deuxièmes Journées de Géologie Appliquée. Actes du Séminaire, Sfax, Tunisie (17 19 Mai 1993), pp. 289–299.

[18] MOULLA, A.S., GUENDOUZ, A.; REGHIS, Z.; (1992) : Etude isotopique et hydrochimique de la remontée des eaux de la nappe phréatique de la région de Oued-Souf. 1er rapport sur l'interprétation des données hydrochimiques et isotopiques de la campagne d'échantillonnage effectuée en mai 1991. Rapport Interne, CDTN, Alger, 72 pages.

[19] MOULLA, A.S., GUENDOUZ, A.; REGHIS, Z.; (1993) : Etude isotopique et hydrochimique de la remontée des eaux de la nappe phréatique de la région de Oued-Souf. Rapport préliminaire sur l'interprétation des données hydrochimiques et isotopiques de la campagne d'échantillonnage effectuée en Février 1992. Rapport Interne, CDTN, Alger, 21 pages.

[20] MOULLA, A.S., GUENDOUZ, A., REGHIS, Z.; (1994) : Etude isotopique et hydrochimique de la remontée des eaux

de la nappe phréatique de la région de Oued-Souf. 3ème rapport sur la qualité chimique et bactériologique des eaux de la nappe phréatique de la région de Oued-Souf. Rapport Interne, CDTN, Alger, 9 pages.

[21] GUENDOUZ, A.; MOULLA, A.S.; (1995) : Application des techniques nucléaires aux problèmes des ressources en eaux souterraines profondes du Sahara Nord-est septentrional Algérien. 2ème Colloque National Climat–Environnement. L'eau, une réalité, une urgence, un défi. Oran (du 24 au 25 /12/1995).

[22] MOULLA, A.S., GUENDOUZ, A., REGHIS, Z.; (1995) : Qualité chimique et bactériologique des eaux de la nappe phréatique de la région de Oued-Souf. (Sahara Nord Est Septentrional, Algérie). 2ème Colloque National Climat Environnement. L'eau un réalité, une urgence, un défi. Oran (24–25/12/1995).

[23] MOULLA, A.S., GUENDOUZ, A., REGHIS, Z.; (1997) : Etude de la remontée des eaux de la nappe phréatique de la région de Oued Souf. Rapport Final de Synthèse. CDTN, Alger, 19 pages.

[24] MOULLA, A.S., GUENDOUZ, A., REGHIS, Z.; (1997) : Hydrochemical and isotopic investigation of rising piezometric levels of Saharan phreatic aquifers in the Oued Souf region (Grand Erg Oriental basin, Algeria). International Conference on Water in the Mediterranean. Collaborative Euro Mediterranean Research : State of the Art, Results and Future Priorities. Istanbul, Turkey (25–29 Nov. 1997).

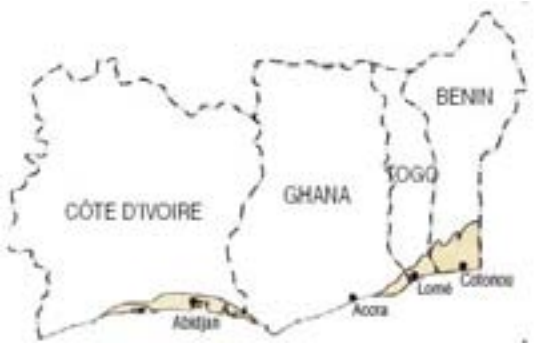
[25] GUENDOUZ, A., MOULLA, A.S., EDMUNDS, W.M., SHAND, P., POOLE, J., ZOUARI, K., MAMOU, A., (1997) : Palaeoclimatic information contained in groundwaters of the Grand Erg Oriental, North Africa. International Symposium on Isotope Techniques in the study of past and current Environmental Changes in the Hydrosphere and the Atmosphere. Vienna, IAEA (14–18 April, 1997). IAEA-SM-349/43. pp. 555-571.

Utilisation des aquifères du bassin sédimentaire côtier entre le Bénin et le Togo dans un contexte de variabilité climatique ; problèmes émergeants

Félix Azonsi

Chef du Département des Ressources en Eau
Direction de l'Hydraulique (Bénin)

Introduction



L'Eau est une ressource vitale tant pour le développement socio-économique que pour les écosystèmes. Résultant de la croissance ininterrompue de la demande, du gaspillage et de la progression de la pollution dans le monde entier, les contraintes qui pèsent sur les ressources en eau douce de la planète s'aggravent et engendrent de graves préoccupations.

OMM, 1997

Les ressources en eau qui ne connaissent pas les limites administratives, se trouvent bien souvent partagées entre plusieurs régions voire plusieurs pays, c'est ainsi que Bénin et le Togo deux pays du golfe de Guinée situés entre le Nigeria et le Ghana se partagent avec leurs voisins, des ressources en eau souterraine accumulées dans le bassin sédimentaire côtier qui occupe la partie méridionale des deux pays On y distingue quatre principaux aquifères identifiés et attribués au quaternaire et au récent, au Continental Terminal, à l'Eo-paléocène et au Crétacé supérieur (Maestrichtien).

Au fil des années, la surexploitation dictée par l'augmentation de la demande, a généré des impacts qui pèsent sur les ressources en eau. Cette situation a si bien fragilisé la ressource qu'il est devenu impérieux de bâtir un partenariat autour d'elle afin de garantir l'équité et la rationalisation dans ses multiples utilisation et usage.

Le présent document traite particulièrement du cas des aquifères du Continental Terminal qui pour des raisons économiques sont les plus exploités.

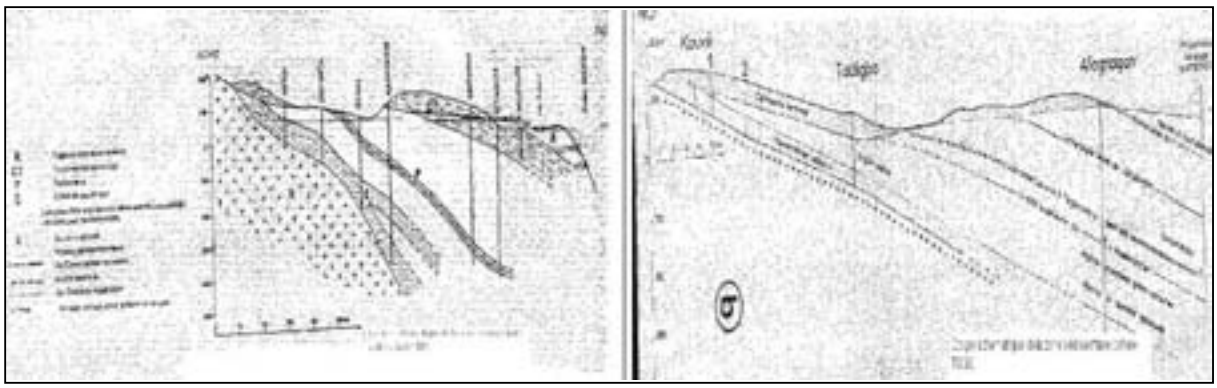
Des contraintes résultant de la croissance démographique, de l'augmentation de la demande, de la progression de la pollution, du gaspillage et autres ont commencé par entamer sérieusement les potentialités de cet important aquifère. Dans un contexte de changement climatique caractérisé par une variabilité et une diminution sensible des pluies, il devient impérieux pour les deux pays voire ceux de tout le bassin de rechercher les formules concertées d'exploitation afin de prévenir ou de minimiser les éventuels problèmes qui pourraient résulter d'une gestion trop sectorielle de cette ressource commune.

Point des connaissances sur les aquifères

Les principaux aquifères sont constitués par: les sables du crétacé, les calcaires et les sables de l'éocène, les calcaires du paléocène, les sables du mio-pliocène ou Continental Terminal et les sables littoraux ou alluviaux du quaternaire. Ils peuvent être regroupés en quatre aquifères répartis comme suit (Figures 1 et 2).

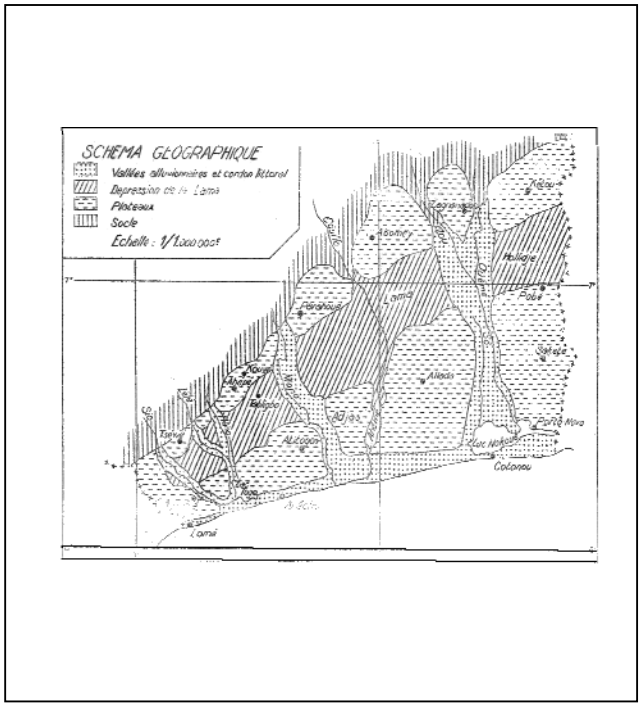
Le quaternaire

Il est représenté par les sables qui forment la plaine littorale. C'est une série d'aquifères souvent exploitée par les populations installées sur

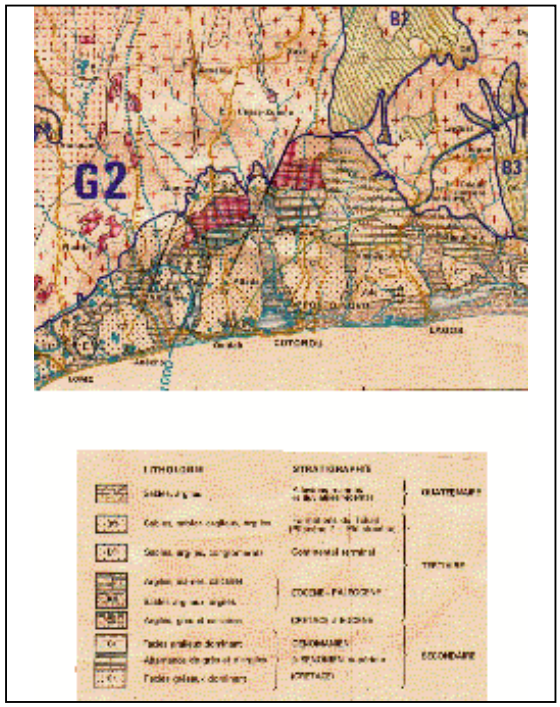


(*Source :* d'après M. Bourgeois, 1979)

FIGURE 1. Coupe géologique de la zone sédimentaire côtière Bénin-Togo



(*Source :* M. Slansky, 1953)



(*Source :* Carte hydrogéologique de l'AO CIEH et BRGM 1/2.000.000)

FIGURE 2. Formations géologiques et aquifères des zones côtières du Bénin et du Togo

le littoral à l'aide de puits peu profonds. La production avoisine 1 et 15 m^3/h et le niveau statique environ de 1 à 2 mètres.

Le mio-pliocène ou Continental Terminal (CT)

Constitué de sables colorés, de sables argileux, de galets de quartz, d'argiles bariolées, le Continental Terminal (CT) est l'un des plus importants aquifères exploités dans le bassin sédimentaire côtier. Il a une puissance variable (45 à 150 mètres) mais peut fournir des débits de 150–200 m^3/h. Ce sont des aquifères libres et semi- captifs avec des niveaux statiques de 10 à 20 mètres avec des manifestations d'artésianisme par endroits. La profondeur des ouvrages varie de 25 à 150 mètres. Les coefficients d'emmagasinement varient de 1,8 $x10^{-6}$ à 1,1 x 10^{-1}. Les transmissivités sont de l'ordre de 8 $x10^{-4}$ et 3 $x10^{-2}$.

L'éo-paléocène

Il est représenté par une succession de calcaires et de sables dont la puissance varie entre 2 à 30 mètres. Ils s'enfoncent en gradins vers le Sud et vers l'Est par le jeu de quelques failles mineures. Ils contiennent par endroits des phosphates qui confèrent aux eaux une odeur fétide.

Le crétacé

Les aquifères du Crétacé constituent une très grande réserve en eau pour les pays de la région côtière. Ils sont plus profonds avec une puissance pouvant atteindre 200 et 800 m environ. Ils peuvent fournir des débits exploitables de l'ordre de 200 m^3/h avec un artésianisme jaillissant.

Croissance démographique et augmentation des besoins et de la demande en eau

La sous-région Ouest-Africaine compte 16 pays et 230 millions d'habitants (FUNAP 1995). Le taux de croissance y était de 5 % en 1997 et les projections prévoient que cette population atteigne 500 millions en 2025. La zone d'étude s'inscrit dans cette réalité car avec un taux d'accroissement de 4,3 % et un indice synthétique de fécondité (ISF) de l'ordre de 6 enfants par femme, la population totale du Bénin est estimée en 2000 à 6,3 millions d'habitants. Les projections pour les années 2025 et 2050 varient respectivement entre 13 et 15 millions et 18 et 30 millions (Fig. 3) Dans les mêmes conditions, la population du Togo est de 4,5 millions et les projections aux horizons 2025 et 2050 donnent selon les sources, 9 à 11 millions et 13 millions (OCDE/BAD/CILLS 1995, WRI/UNEP/UNDP/WB 1998, INSAE 1999; DH 1999) (Fig. 4). La zone côtière connaît les plus fortes densités comprises entre 156 et 280 hab./km^2. Après l'évaluation de la première DIEPA, beaucoup de pays surtout africains se sont fixés des objectifs ambitieux d'AEP dans le cadre de la réduction de la pauvreté. C'est ainsi que dans la zone étudiée, les ratios sont sensés passer de 10 l/j/hab. à 50 l/j/hab. en milieu rural et de 20 l/j/hab. à 110 l/j/hab. en milieu urbain pour 2025. Ces estimations ne prennent pas en compte le développement industriel et agricole et la satisfaction des besoins bien que pressante se heurte à des difficultés liées à l'inégalité de la répartition de la ressource qui se trouve souvent inversement proportionnelle à l'étendue du territoire concerné. Il a été observé de par le monde que les multiples utilisations et usages de l'eau se sont accrus à un rythme qui correspond au double du taux d'augmentation de la population.

Pour ce qui concerne les pays africains et ceux de l'Afrique de l'Ouest en particulier, qui connaissent une poussée démographique aggravée par l'exode rural interne et la migration de l'hinterland (Sahel) et qui amorcent un développement industriel, les besoins en eau sont de plus en plus importants et risquent à terme de créer des conflits entre les nombreux utilisateurs dont les signes précurseurs sont les accrochages entre éleveurs et agriculteurs en période de transhumance.

Parallèlement à la croissance de la population, l'exode rural vers les grandes mégalopoles régionales et côtières induit par la sécheresse

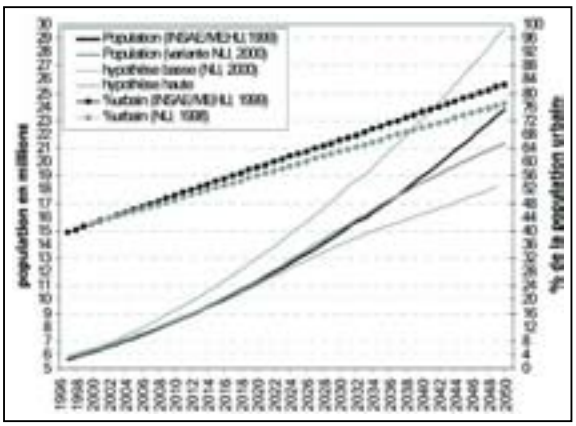


FIGURE 3. Projection démographique en 2050 au Bénin

persistante pourrait s'aggraver. Il atteindrait dans ce cas un taux 4,5 %/an qui se répercutera sur la croissance de la population urbaine. Ce phénomène verrait le décuplement de la population de certaines grandes villes qui se traduirait entre autre par l'apparition d'une conurbation entre Accra (Ghana) et Ibadan (Nigeria) et incluant les villes de Lomé (Togo), Cotonou (Bénin) et Lagos (Nigeria). Cet ensemble urbain étalé sur environ 400 km de long pourrait atteindre 100 millions d'âmes au lieu de 18,5 millions actuellement. Ces hypothèses et tendances impliqueraient une augmentation et une polarisation rapides des besoins en eau. En admettant une consommation domestique sur la base d'un ratio minimum de 100 l/j/hab., l'étendue couverte par la conurbation Accra-Ibadan nécessiterait 6.750 Mm^3 par an pour la seule consommation des ménages dont environ 520 Mm^3 pour l'ensemble urbain formé par Porto-Novo, Cotonou et Lomé soit environ 8%. Sur les dernières quinze années, l'exploitation des aquifères du CT pour la partie béninoise connaît une augmentation de l'ordre de 7 millions de mètres cubes par an (cf. Fig. 4).

Diminution de la pluviométrie

L'analyse des données pluviométriques permet de constater que le sud du Bénin et du Togo connaissent une tendance avérée à la diminution (Fig. 5).

En effet, l'Afrique de l'Ouest en général se caractérise par une forte fluctuation des pluies annuelles tout au long du XX^e siècle et plus particulièrement au cours de sa seconde moitié (Nicholson, 1998) (Fig. 6). Sur la base des observations de la période 1920–2000, l'évolution des

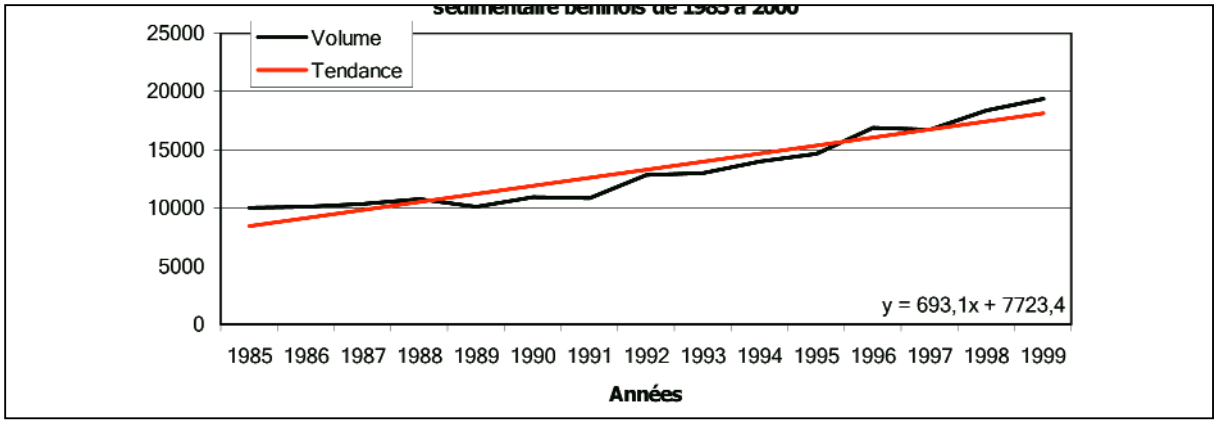


FIGURE 4. Évolution de la production d'eau en milliers de mètres cubes dans le bassin sédimentaire béninois de 1985 à 2000

pluies annuelles paraît affectée par plusieurs phénomènes :

- Une diminution tendancielle de l'ordre de 0,5 à 5 mm/an et exceptionnellement 13 mm/an (Fig. 5) ;
- Une variabilité « inter décennale » se traduisant par une alternance de séquences d'années sèches ou humides. Ces séquences ont une durée comprise entre 10 et 20 ans et une amplitude de l'ordre de 150 à 200 mm. La dernière séquence sèche s'est produite entre 1970 et 1990 avec un déficit moyen sur l'ensemble de l'Afrique de l'Ouest de 200 mm. Au Bénin, cette séquence sèche a été perceptible de 1970 à 1988 avec un déficit de 195 mm.
- Une variabilité inter annuelle dont l'amplitude est supérieure à celle de la variabilité inter décennale. Il peut donc y avoir des années humides au cours de période pluri-décennale sèche et inversement.

Rappelons que la séquence d'années déficitaires 1970-1990 a eu des conséquences drastiques sur les cultures pluviales en zone sahélienne et sur les ressources en eau superficielle de l'ensemble de l'Afrique de l'Ouest.

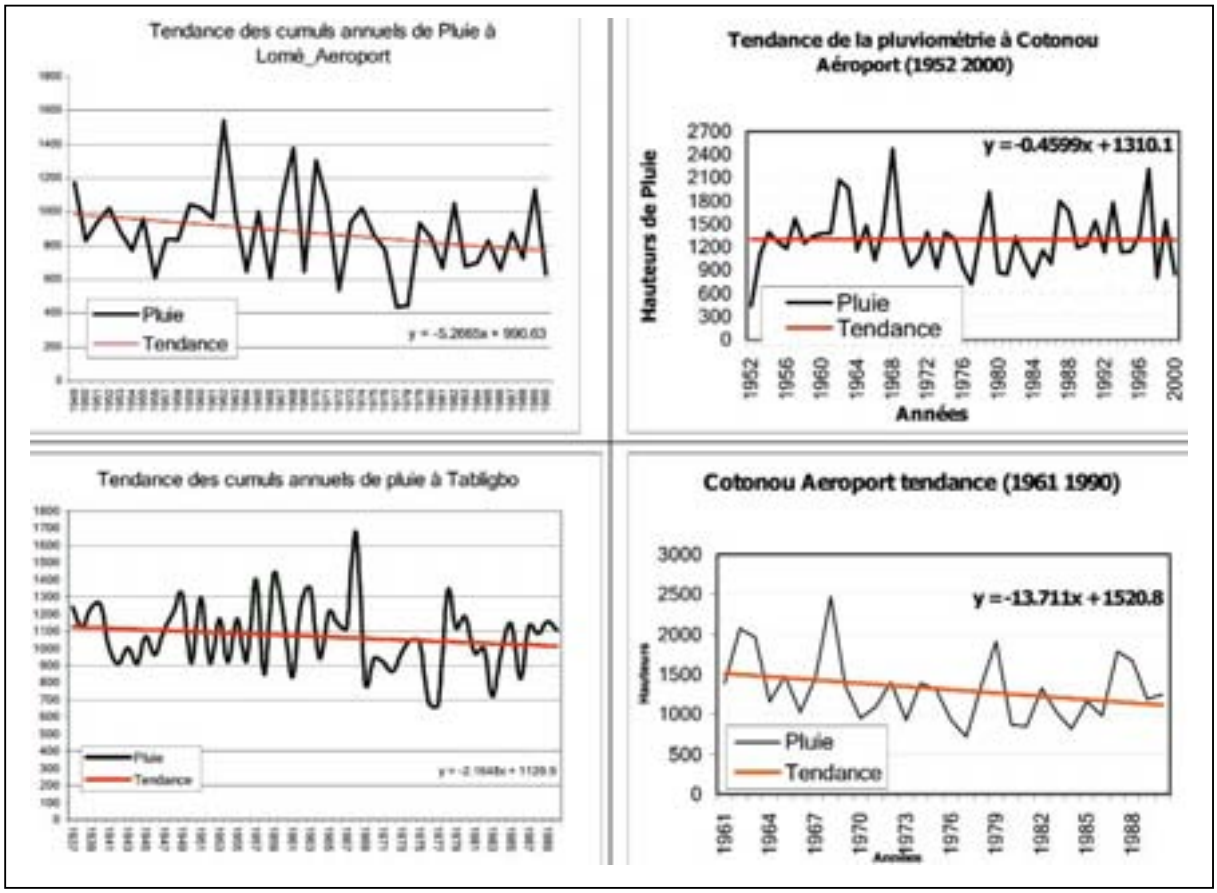


FIGURE 5. Évolution tendancielle de la pluviométrie sur la zone côtière du bassin sédimentaire (Bénin, Togo)

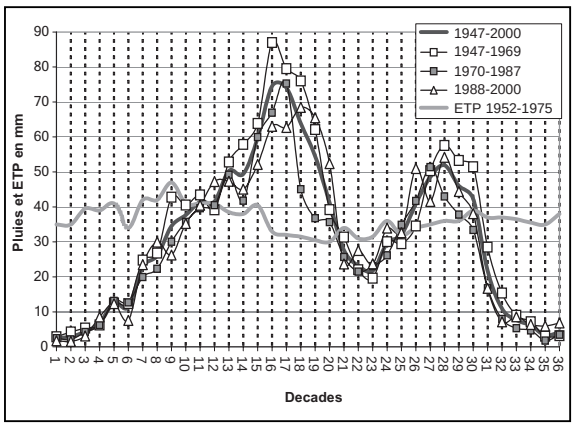


FIGURE 6. Évolution Pluie et ETP 1952 - 1975

Impacts des facteurs anthropiques sur les aquifères

Les grands centres urbains que constituent Cotonou, Lomé, Aného, Porto-Novo, Ouidah, Aklakou, Tabligbo et autres connaissent une extension très rapide. L'accroissement de leurs populations et de leurs besoins induisent une série de situations dont les effets se lisent à travers l'occupation du sol et d'autres paramètres qui sont :

- **L'intensification de l'intrusion saline**

  Situés à proximité de l'océan et de plans d'eau où la conductivité dépasse parfois 4 000 µs/cm, les aquifères côtiers en général soumis à une sur exploitation sont envahis par le front salin. Les champs de captage de Godomey à Cotonou et de Agouévè à Lomé ont vu l'exploitation de certains de leurs ouvrages s'arrêter pour freiner la progression de phénomène. A Lomé, le problème se pose avec beaucoup d'acuité à telle enseigne que l'eau est tirée depuis Tsévié pour compléter l'exploitation d'Agoévé.

  En dépit de la suspension du pompage au niveau des forages contaminés, la propagation du sel se poursuit et se fait remarquer surtout à la suite d'années à pluviométrie déficitaire. Les solutions précaires apportées jusqu'à ce jour ont, au lieu de passer par des méthodes scientifiques consisté à déplacer la concentration de l'exploitation. Il est évident que ces palliatifs soient très limités pour résoudre un problème aussi complexe que celui en question.

- **La réduction de la recharge des aquifères**

  Les aménagements qui découleraient de l'urbanisation (conurbation) pourraient influencer négativement le fonctionnement des zones humides dont les relations avec les aquifères se passent de commentaire. Pour la zone étudiée, la perméabilité de la couche superficielle a été évaluée pour la partie argileuse à 7,5 $x10^{-6}$ m/s (Willaine 1983), les coefficients de ruissellement sont inférieurs à 2,5 % et la perméabilité moyenne K = 2,5 $x10^{-6}$ m/s. D'après SGI (1981) et SOGREAH/SCET-Tunisie (1997) l'infiltration moyenne représente environ 12 % du volume des pluies sur la période considérée.

  Dans ces conditions, il n'est pas exclu que l'occupation du sol réduirait substantiellement par compactage le taux de rechange des aquifères.

- **L'augmentation de la pollution des eaux**

  En plus de la pollution chimique apportée par les plans d'eau salés et/ou l'océan. Il faut prévoir une pollution biologique. En effet, les champs concernés sont habités parfois de façon anarchique avec des constructions sous conçues sans norme. Mieux l'installation de petits ateliers de mécanique où les hydrocarbures sont manipulés sans précautions pourrait introduire à terme des métaux lourds dans les aquifères. La situation pourrait s'aggraver si les installations industrielles ne sont pas contrôlées avec suffisamment de rigueur.

Conclusions et recommandations

Bien que des incertitudes persistent au regard de l'avenir des ressources en eau et que beaucoup de pays africains continuent de compter sur la « générosité » du ciel, il est tout de même évident que les exigences en demandes et en consommation iront grandissant. Les pays de la sous-région Ouest-Africaine surtout ceux de la zone côtière ne semblent pas percevoir l'imminence d'une crise de l'eau. En tenant compte des hypothèses de Engelman et Leroy (1993) qui définissent le « *water stress* » entre les seuils de 1 000 m^3/hab./an et 1700 m^3/hab./an, il est évident qu'à partir de 2025, le sud du Bénin et du Togo serait en situation d' alerte à pénurie d'eau puisque le ratio sera de 1570 m^3/hab./an. La situation pourrait s'aggraver pour atteindre celle de pénurie chronique d'eau en 2050 avec un ratio de 760 m^3/hab./an (Azonsi et Depraeter).

Cette situation très préoccupante pourrait se gérer dans le cadre d'une prospective à long terme en utilisant le concept de la gestion inté-

grée des ressources en eau (GIRE). Cette démarche qui consiste à concilier les approches sectorielles est pour le moment la seule qui permettra à la sous-région de devancer les cas de graves pénuries en établissant des stratégies cohérentes. L'idée établie par le SISCOA/GIRE/AO à travers le plan d'action régional –GIRE devrait être encouragée et financée dans optique prospective dans la zone CEDEAO. Dans cette logique mais à une plus grande échelle, les conclusions des initiatives telles que la conférence ministérielle africaine devraient être mises à contribution afin de créer un forum régional sur la vision africaine de l'eau. Ceci permettra entre autre, de suivre l'évolution de l'eau en Afrique à travers un environnement propice à la coopération internationale.

Shared knowledge, a key to equitable utilisation of transboundary aquifers

Chakalisa J. Chilume

Department of Water Affairs,
Gaborone, Botswana

Sedimentary basins hosting some important aquifers extend beyond Botswana's national borders into the neighboring countries of Namibia, South Africa and Zimbabwe. This poses a challenge to the authorities charged with managing groundwater resources in these countries, as studies carried out in such situations/environments are often not conclusive enough because of a lack of data on either side of the boundary. Although it would be desirable to have such knowledge from across the border, this may not always be possible because of several factors including absence or scarcity of such data, government bureaucracy, etc. This often frustrates the efforts of groundwater professionals who wish to study the aquifer system as a whole without the interference of man-made boundaries. This paper discusses issues that relate to transboundary aquifers from four sedimentary basins in Botswana, three of which belong to the Karoo Supergroup.

The Nata sub-basin of the Karoo Supergroup is located in northeastern Botswana on the border with Zimbabwe. Extensive groundwater investigations targeting the Mea Arkose Formation and Ntane Sandstone were carried out between 1997 and 2000. Groundwater flow-lines from this study indicate that the aquifers are being recharged from the northeast, possibly in Zimbabwe. Unfortunately no hydrogeological data was available from Zimbabwe to establish this although certain media reports have indicated an intention to exploit the resource there. The Tuli sub-basin in eastern Botswana is also part of the Karoo and extends into Zimbabwe and South Africa. Little information exists in Botswana regarding aquifers in this basin but localized studies for village water supplies have identified a highly productive sandstone aquifer within the Lebung Group comprising of sandstones, siltstone and mudstones. There are plans to carry out more extensive studies of aquifers in this basin. It is known that there are major irrigation schemes on the South African side but there is no information as to whether they use surface water from the Limpopo River or groundwater. The Southwestern Karoo basin in western Botswana extends into Namibia and South Africa contains aquifers that are primarily recharged in Namibia. Recent studies of this basin have identified vast fresh water aquifers (in an area where salinity is a problem) that are to be developed to supply some demand centers in that part of the country. There have been reports though of elevated nitrate values in some boreholes although the source of this has not been established. The fourth trans-boundary basin, the Ramotswa Dolomite basin, is found in southeastern Botswana and extends into South Africa. A major village overlies the main aquifer found in this basin, which has resulted in the pollution of the groundwater by pit latrines and septic tanks. A wellfield established in this aquifer has since been shut down because of this pollution.

Groundwater resources of Ghana with focus on international shared aquifer boundaries

William A. Agyekum

CSIR Water Research Institute
Accra, Ghana

Abstract

Over 90% of the geology of Ghana is made up of a variety of hard rocks of Pre-Cambrian and Paleozoic ages, while the rest consists of Tertiary to Recent unconsolidated sediments, and Eocene/ Cretaceous limestone beds. The wide range of geological formations has given rise to variations in groundwater resources potential, with regards to the occurrence, distribution, recharge, yield and other hydrogeological characteristics. Groundwater occurrence in hard rocks is either confined or semi-confined, and is largely controlled by the presence of secondary porosities, developed as a result of weathering and fracturing. The hard rock aquifers are largely varied and limited in areal extent, and their yields are variable, ranging between 0.4–30 m^3/hr. Borehole depths in the hard rock areas are lower than 80 m.

In the Eocene and Cretaceous limestone beds, borehole depths range between 80–300 m, while in the Tertiary to Recent unconsolidated sediments borehole depths are shallower (8–35 m). The aquifers in the two formations are either semi-confined or unconfined and are extensive, extending to the Republic of Togo where the recharge area is partly located. Borehole yields in the two formations are generally high (4–1,000 m^3/hr), and the potential still exist for larger groundwater abstraction with detailed hydrogeological investigations. Groundwater from these two aquifers has been exploited since 1950s for urban water supplies in both countries. However, the groundwater abstraction rates and their management outside Ghana is unknown. The total groundwater abstraction in Ghana is estimated to be 140 million m^3/yr, and it represents only about 25% of the total water supply of the country. However, groundwater still remains the most reliable source of water supply to most scattered rural and sub-urban communities in the country.

Introduction

The Republic of Ghana is located along the west-coast of Africa. It lies within latitudes 4° 30′–11° 05′ N and longitudes 3° 15′ W – 1° 10′ E. It is bounded to the north by Burkina-Faso, the east by the Republic of Togo, the west by Côte d'Ivoire and to the south by the Gulf of Guinea (Figure 1). It has a total area of 238,000 km^2, with estimated population of 18.84 million of which 56% live in rural communities (Ghana Statistical Service, 2000). Even though surface water abounds in the country, groundwater remains the major and reliable source of water supply for the rural communities and some urban and sub-urban towns. This is partly due to the huge financial outlay required to develop the surface water resources to supply the numerous scattered rural communities; and partly due to the seasonal flow of most of the rivers in the country. Furthermore, surface waters are often polluted and are the source of water-related diseases. Most rural communities hitherto, depended mainly on hand-dug wells constructed through the overburden to a mean depth of 6 m by the inhabitants themselves using locally manufactured tools. However, due to poor management practices, polluted surface water seeped into them and they became contaminated. Considering the effect of the contaminated water on the health of the rural dwellers and the economic loss to the nation, the government of Ghana commissioned 'the water resources sector studies' between 1969 and 1970. This was aimed at formulating a framework of supplying portable water to as many rural communities as possible.

Consequently, it became a national policy that rural communities with population less than 500 be provided with hand-dug wells. Supplies to Communities with population between 500–2,000 were to be served by means of hand-pumped boreholes, while those with population higher than 2000 were to be served with pipe-borne water supply. Since 1990, the efforts of the government in this direction have been supplemented by many non-governmental and foreign-donor agencies with grants to support the water sector. This has led to the accelerated provision of boreholes fitted with hand-pumps to many rural and some sub-urban towns in the country. Since the boreholes were meant to supply rural communities, boreholes yielding at least 13.5 l/min were considered as successful. However, in a relatively difficult geological environment, boreholes with yields as low as 6.0 l/min were developed.

Currently, available data on wells in the country indicate that there are over 60,000 groundwater abstraction systems, comprising approximately 15,000 boreholes and 45,000 hand-dug wells and dug-outs in different geological formations throughout Ghana. Using the available borehole records, the Water Research Institute (WRI) of the Council for Scientific and Industrial Research (CSIR) has carried out a comprehensive assessment of the groundwater resources potential of the country, including the development of hydrogeological maps for optimal groundwater utilization and management purposes. These reports and hydrogeological maps have become useful and reference documents for all stakeholders in groundwater development in the country.

Geological setting

The geology of Ghana may be grouped into three broad hydrogeologic units. These are:

- Precambrian Crystalline Basement Complex rocks,
- Paleozoic consolidated sedimentary rocks, and
- Tertiary to Recent unconsolidated sediments and Cretaceous limestone beds.

Apart from these major geological units, minor geological provinces consisting of Cenozoic/



FIGURE 1. Location map of Ghana

Mesozoic sedimentary strata and Quaternary alluvia occur at the coast and along narrow belts of major rivers.

Pre-Cambrian crystalline basement complex rocks

The Pre-Cambrian crystalline basement rocks underlie about 54% of the country. This geological unit shares common boundaries with the southern part of Burkina-Faso, as well as the whole eastern block of Côte d'Ivoire. On the basis of lithological differences, geology and groundwater conditions, the crystalline basement complex rocks are sub-divided into five different geohydrologic units (Gills, 1969). These sub-divisions are the Birimian System and the associated granitic intrusives, Dahomeyan System, Tarkwaian system, Togo Series and the Buem formation. The distribution of these rock units is shown in Figure 2.

The Birimian system consists of a great thickness of isoclinally folded, metamorphosed sediments intercalated with metamorphosed tuff and lava. The rocks are generally strongly-foliated and fractured, and are also intruded by batholitic masses of granites. They are not inherently permeable, but secondary permeability and porosity

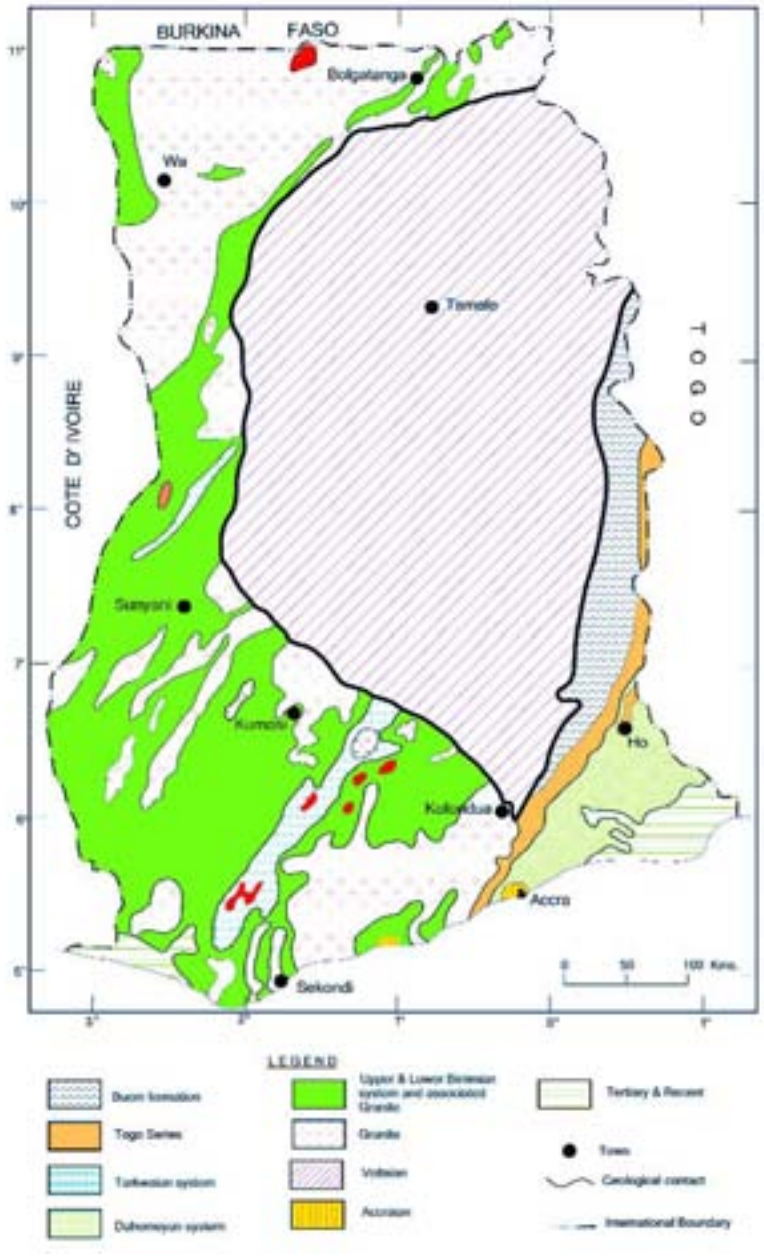


FIGURE 2. Geological map of Ghana (after Geological Survey of Ghana)

have been developed as a result of weathering and fracturing. The rocks consist mainly of schists, phyllites, gneisses, quartzites, migmatites and granitic-gneiss.

The Dahomeyan formation consists mainly of crystalline gneiss and migmatite, with minor quartz and biotite schists. The gneiss is generally massive and has few fractures. The two main varieties are the silicic and mafic gneisses, which weather respectively to slightly permeable and impermeable calcareous clays.

Even though the rocks of the Tarkwaian System, Togo Series and Buem formation are different in ages, they have similar lithologic sequence. Tarkwaian rocks consist of slightly metamorphosed, shallow-water sedimentary strata, comprising mainly sandstone, quartzite, shale and conglomerate. The Togo Series consists of metamorphosed and folded arenaceous and argillaceous sedimentary strata, comprising rocks such as indurated sandstone, quartzite, schist, phyllite and shale. The Buem formation consists of a thick sequence of shale, sandstone, and some minor volcanic rocks with subordinate limestone, conglomerate and grit. Lithologically, rocks of the three formations are largely impervious but contain openings along joints, bedding and cleavage planes.

Paleozoic consolidated sedimentary rocks

These rocks form the Voltaian formation and underlie about 42% of the country. The Voltaian is made up of well-consolidated and gently-folded rocks consisting predominantly of sandstone, shale, arkose, mudstone, sandy and pebbly-beds and limestone. On the basis of lithology and field relationships, Junner and Hirst (1946) subdivided the Voltaian formation into three groups comprising:

- Upper Sandstone, consisting of massive sandstones and thin-bedded sandstones,
- Middle Voltaian or Obosum/Oti beds, comprising arkose, mudstone, shale, sandstone, limestone and conglomerate, and
- Lower or basal sandstones consisting mainly of quartz-sandstones and pebbly-grit beds.

Recent to Tertiary unconsolidated sediments and Cretaceous limestone beds

These formations constitute the two separate coastal aquifers of great international importance since they are located at the southwestern and southeastern borders of Ghana.

The Cretaceous to Lower Tertiary sedimentary rocks are located at the southwestern corner of Ghana and share a common boundary with Côte d'Ivoire. This area is locally referred to as the Tano Basin. The geology of the basin consists of thick sections of alternating sand and clay with occasional thin beds of gravel and fossiliferous limestone. The limestone is known to have oil and gas potential (Gyau-Boakye and Dapaah-Siakwan, 2000).

The Tertiary to Eocene and Cretaceous unconsolidated alluvial sediments, which consist of alternating limonitic sand, sandy-clay, gravel, marine shales and limestones are located to the southeastern corner of the country. This area shares a common boundary with the Republic of Togo, and is locally referred to as the Keta Basin. The geology is exposed, being covered extensively by lagoons, marshes and thick under-growths. The surficial sediments of this formation are very permeable due to their sandy and unconsolidated nature, and the high water percolation rate. Rainwater thus finds its way down to the gravel bed where large quantity of water is stored. The geology of the Keta Basin is shown in Figure 3.

Groundwater conditions and occurrence

The crystalline rocks have very little intergranular pore space and are thus characterised by negligible primary porosity and permeability. Where the rocks occur near the surface, they are usually fractured and weathered and acquire some significant secondary porosity. The main sources of groundwater supply to the rocks are thus the weathered layer or rigolith developed on the crystalline basement rocks and fractures within the bedrock. The areal extent, thickness and physical characteristics of the weathered layer vary from one area to the other, depending on a number of factors. These factors include regional climatic conditions (temperature, the amount, intensity and distribution of rainfall), topography, lithology and the degree of fracturing, as well as vegetation cover. Due to the variations of the geological formations and their corresponding structural characteristics, groundwater condition is generally related to the three basic geological units of the country.

Pre-Cambrian crystalline basement complex rocks

As a result of weathering, fracturing, jointing and faulting in Pre-Cambrian Crystalline Complex

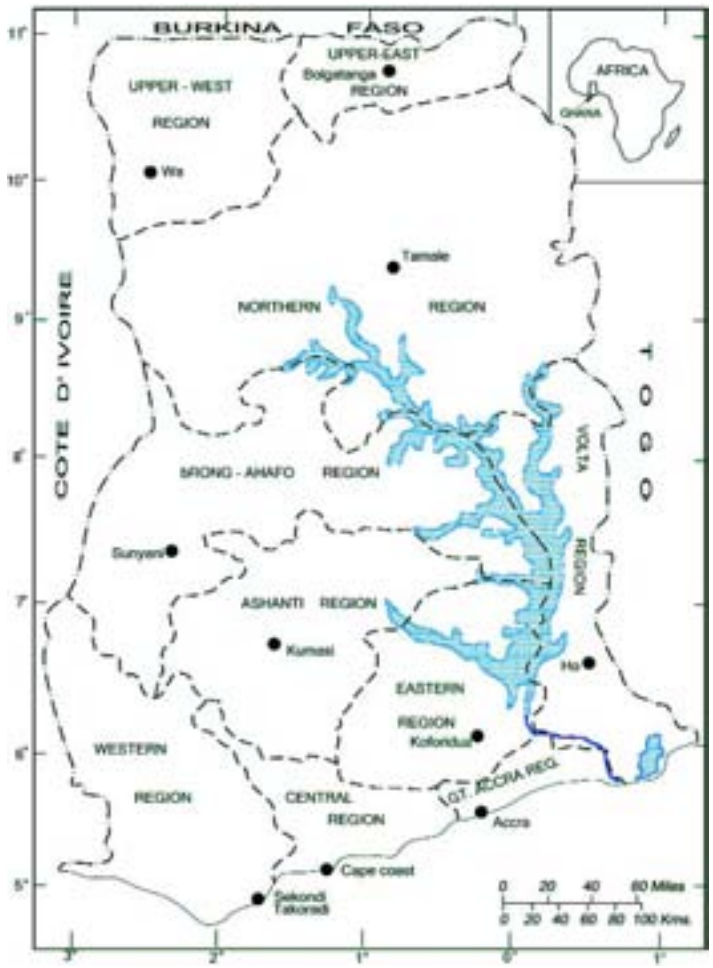


FIGURE 3. Geological map of the Keta Basin (after Akiti, 1977)

rocks, groundwater may accumulate in the weathered layer, fracture zones and at the contact zones between the bedrock and the overburden.

- ***The Birimian System***

  The Birimian system is considered important in the water economy of Ghana due to the fact that it underlies extensive and densely-populated areas of the country. It stretches from the north through the mid-west to the south-western parts of the country. When the Birimian rocks are intruded by quartz-veins, pegmatites and/or are highly fractured, they yield substantial quantities of groundwater to wells. Major fault zones constitute one of the major aquifer zones. Boreholes tapping the Birimian rocks have yielding capacity ranging between 0.4–30 m^3/hr, with a mean of 12.7 m^3/hr. Borehole depths range between 35–62 m with a mean of 42 m. Static water levels in boreholes are generally low, ranging from 5.9–25.8 m below ground level.

- ***Granites***

  Granitic rock areas have variable overburden thickness of clay and shale. Areas with higher rainfall intensity have relatively thicker overburden material ranging between 100 and 140 m (Kesse, 1985). On the other hand, where the rainfall is low, granite occurs as massive, poorly-jointed inselbergs rising above the surrounding lowlands as typified in the Bongo district of the Upper-East region of the country. Weathered granite can produce permeable groundwater reservoir, and when the rocks are fractured, they also yield substantial volume of groundwater to wells. Records of about 7,000 boreholes drilled in the granitic rock formations throughout the country indicate a mean borehole depth of 50 m. The mean depth to aquifer horizons is about 34.0 m. Borehole yields are very variable, ranging between 0.5–21.0 m^3/hr, with a mean of 4.8 m^3/hr, and static water levels averages 8.4 m. The variation in well yields is

largely attributed to the degree of weathering, extent of structural deformation of the underlying bedrock and the degree of fracture interconnections. The computed transmissivities of boreholes in this formation ranges between 0.3–114 m^2/d, with a mean of 6.6 m^2/d.

- ***Dahomeyan formation***

  The generally impervious nature of the weathered zone and the massive crystalline structure of the Dahomeyan rocks limit their groundwater yielding capacity. Analyses of data from over 300 boreholes drilled in this formation indicate that borehole yields range between 1–3 m^3/hr, and borehole depths are in the range of 45–70 m, with a mean of 55 m. The Dahomeyan rocks have the least mean transmissivity of 4.5 m^2/d (Darko, 2001).

- ***Togo Series, Tarkwaian and Buem formations***

  When fracture openings in the Togo Series, Tarkwaian and Buem rock formations are extensive and are not filled with impervious material, substantial amount of groundwater can be obtained from boreholes. The average yield from these rocks is about 9.5 m^3/hr, and ranges from 0.7–24 m^3/hr. Borehole depths range between 33–55 m. The hydrogeological characteristics of boreholes in the various geological formations are shown in Table 1.

Paleozoic sedimentary formation

The Voltaian rocks are the least explored in terms of groundwater development due to the fact that they underlie sparsely populated areas in the country. Borehole depths range between 45–75 m, with a mean of 55 m. Aquifers are generally encountered between the depth range of 23–30 m, with a mean of 26.0 m. Borehole yield ranges between 0.40 m^3/hr – 9.0 m^3/hr with a mean of 4.1 m^3/hr. The success rate of drilling boreholes in this formation is about 48%, and it is among the lowest in the country. Transmissivity values of boreholes in this rock ranges between 0.3–267 m^2/d with a mean of 11.9 m^2/d. The relatively low borehole success rates in the Voltaian rocks and the wide range of borehole yields could be attributed to the large variations in the transmissivity (0.3–267 m^2/d) and the very heterogenous nature of the aquifers.

Recent to Tertiary unconsolidated sediments and Cretaceous limestone beds

Records of about 500 boreholes drilled in this

TABLE 1. Summary of borehole characteristics in various geological formations

Hydrogeological unit	*Number of boreholes*	*Borehole success rate * (%)*	*Range of borehole depths (m)*	*Range of borehole yields (m^3/hr)*
Basement Complex				
Birimian	5,200	68 – 85	35 – 62	0.4 – 30
Granite	7,000	59 – 76	35 – 55	0.5 – 21
Dahomeyan	300	28 – 40	45 – 70	1 – 3
Tarkwaian	350	80 – 86	34 – 60	1 – 23
Togo	350	85 – 90	33 – 55	0.7 – 24
Buem	300	85 – 90	30 – 45	0.7 – 24
Paleozoic consolidated rock formation	512	22 – 53	45 – 75	0.4 – 9
Cretaceous recent sand and clays				
Keta Basin	350	75 – 90	3 – 12	1 – 15
Tano Basin	30	70 – 85	70 – 100	10 – 32
Cretaceous Tertiary limestone beds (Keta basin)	100	60 – 75	100 – 609	6.4 – 1,000

* A successful borehole has a minimum yield of 13.5 litres per minute (0.81 m^3/hr).

Source: WRI, 2001.

geological formation have indicated the presence of three separate aquifer systems. These are:

(1) Shallow, rain-fed and phreatic sandstone aquifer occurring in the Recent sand, and lying very close to the coast. This aquifer lies at a mean depth of 6 m and contains fresh meteoric water. The mean depths of hand-dug wells and boreholes in this aquifer are extremely low, about 3 m and 12 m respectively. Inventory of hand-dug wells indicates that the shallow, rain-fed aquifer constitutes the most prolific aquifer system in the Keta Basin (WRI, 1995). About 60% of hand-dug wells in the country are located within this formation where large volume of water is abstracted for domestic purposes and vegetable farming. Aquifers in this rock formation have the highest transmissivity values, ranging between 0.7–1,624 m^2/d, with a mean of 22.2 m^2/d.

(2) Intermediate aquifer, which is either semi-confined or confined and occurs mainly in the Red Continental deposits of sandy-clay and gravel. The depth of this aquifer varies from 18–25 m, and contains mostly saline water.

(3) The third is the deep limestone aquifer, which contains large quantities of fresh water at depths exceeding 85 m in inland areas, and up to 600 m towards the sea. This aquifer extends to the Republic of Togo. Boreholes drilled into this aquifer have shown that they are either semi-confined or confined with artesian wells at some places. Static water levels vary from flowing wells to depths of over 20 m (Akiti, 1977). Yields ranging between 18–1,000 m^3/hr have been recorded. The combined potential yield from only four boreholes located at Agbosume, Klikor, Nagopo and Hatsukope in the Keta Basin is estimated to be over 4,000 m^3/hr (Bannerman, 1994). This yield is far in excess of water demand in the whole of the south-eastern part of the country.

Even though the limestone aquifer does not outcrop in Ghana, studies have identified two possible recharge areas in the country. One is centered at Avenukope/Agbodrafo on the west of the basin, while the other occurs near Dzodze and Ehie on the eastern part. A third most likely recharge area has been traced to the Mono river in the Republic of Togo where the limestone outcrops (Figure 4). The Mono river flows south-eastwards along the limestone outcrop (Akiti, 1977) for a distance of about 112 km northeast of Keta area. Aquifers developed in the Cretaceous to Recent Sand and Clays in the Keta Basin have the highest mean transmissivity value of 57.2 m^2/d (Darko, 2001)

Groundwater supplies from boreholes in the Cretaceous to Lower tertiary sediments between Esiama and Half-Assini in south-western Ghana (Tano Basin) are obtained largely from the upper 91.4 m of the sediments. The average yield of the few boreholes drilled into this aquifer is about 12.6 m^3/hr. The transmissivity variations of the various rocks and their hydraulic characteristics are shown in Table 2.

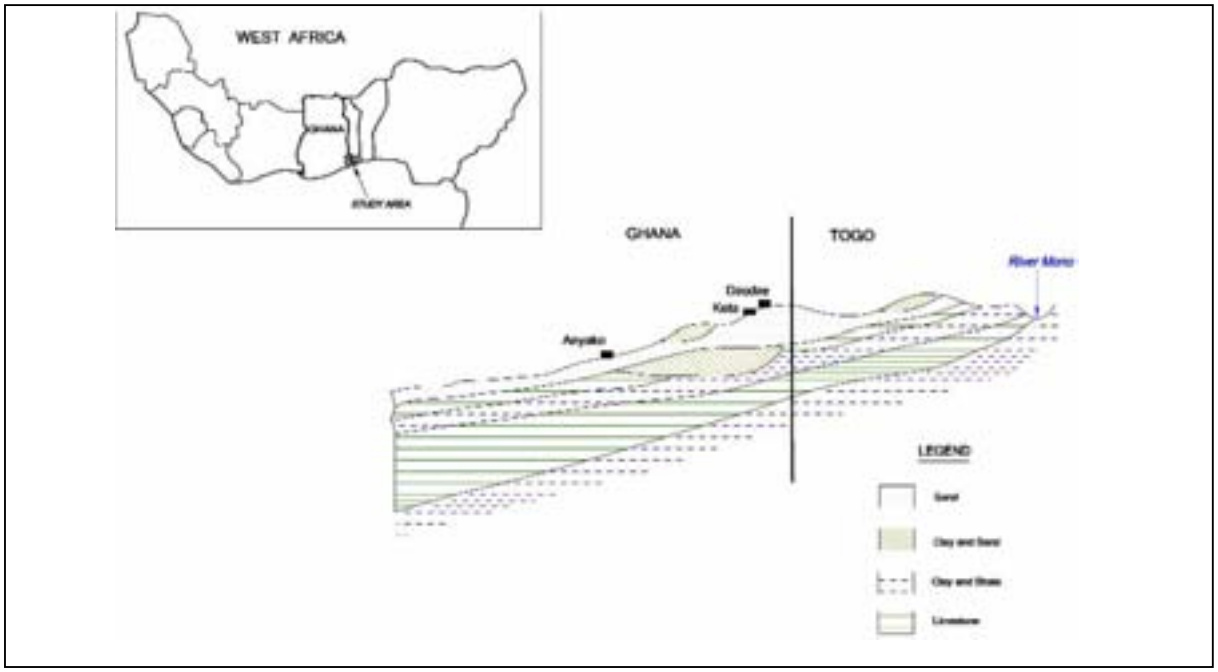


FIGURE 4. Schematic cross-section of the Limestone Aquifer, showing possible recharge area (modified after Akiti, 1977)

TABLE 1. Summary of borehole characteristics in various geological formations

Hydrogeological unit	*Number of wells analysed*	*Transmissivity (m^2/d)*		*Regional hydraulic characteristics*
		Mean	*Range*	
Basement Complex				
Birimian and Tarkwaian	152	7.4	0.2 – 119	Low to intermediate transmissivity with moderate variations Hydrogeological environment is fairly heterogenous
Granite	467	6.6	0.3 – 114	Low to intermediate transmissivity of moderate variations in fairly heterogenous environment
Dahomeyan	69	4.5	0.3 – 42	Medium to low and moderate transmissivity variation in a fairly heterogenous environment.
Togo and Buem	53	8.0	0.9 – 43	Low to intermediate transmissivity with small to moderate variation in a fairly heterogenous environment
Paleozoic Consolidated rocks	332	11.9	0.3 – 267	Intermediate to low transmissivity with large variations. Hydrogeological environment is considerably heterogenous
Cretaceous Recent sand and clays	31	22.2	0.7 – 1,624	Large variation in transmissivity that ranges from high to low in magnitude in a very heterogenous environment
Cretaceous Tertiary limestone beds	22	57.1	12 – 490	Intermediate to high transmissivity in fairly heterogenous environment.

Source: Darko, 2001.

Groundwater management practices and constraints

- Population growth and the increasing demand for portable water in the various sectors of the economy have led to the construction of a large number of boreholes and hand-dug wells, and infact more are expected to be drilled. These boreholes have been drilled without carrying out any comprehensive studies into the amount of groundwater held in storage, recharge characteristics and sustainability of the aquifers and environmental aspects. The impact of these developments on land and water resources calls for a holistic view of water resources management practices in Ghana.

- The two coastal province aquifers comprising the Tano and the Keta Basins are described as internationally-shared aquifers. They stretch to Côte d'Ivoire and the Republic of Togo respectively, as shown in Figure 3. There is however, no information on the extent of groundwater exploitation from these aquifers in the two neighboring countries. More importantly, the extent of the recharge areas and their environmental conditions are unknown. In order to ensure sustainable development of these internationally-shared aquifers, many authors including Bannerman (1994) have suggested the need for mutual collaboration and scientific cooperation between Ghana, Côte d'Ivoire and Togo on effective management of these important aquifers.

- The total groundwater abstraction in the country is estimated to be 1.4×10^8 m^3/yr. Considering the large groundwater abstraction rate in the country, there is the urgent need to carry out comprehensive water balance

studies to determine the amount of water that replenishes the aquifers and the capability of the aquifers to sustain both current and anticipated increased abstractions in future.

Conclusion and recommendation

Groundwater occurrence in the Pre-Cambrian Crystalline Basement Complex rocks and the Paleozoic consolidated sedimentary formation is structurally controlled with variable yields, ranging from as low as 0.4m^3/hr to as high as 30 m^3/hr. The discrete nature of aquifers in such hard rocks gives rise to localized flows, thus making regional aquifer evaluations rather difficult.
The southwest and southeast coastal aquifers constitute important internationally-shared aquifers. Considering the large amount of groundwater being abstracted from these aquifers within and outside Ghana, there is the need to carry out comprehensive recharge studies to determine the amount of water that recharges the aquifers. Modeling of these aquifers will help to determine the safe yield of the aquifers as well as monitoring pollution levels.

Groundwater level and quality monitoring networks must be established within the basins of the internationally-shared aquifers to study the groundwater level fluctuations and their quality trends.

The enactment and enforcement of laws to protect the recharge areas of the aquifers are necessary for their sustainable development.

Since these shared aquifers lie close to the sea, groundwater abstraction rates should be monitored and controlled to prevent or minimize seawater intrusion into them.

References

AGYEKUM, W. A and Kortatsi, B. K (1998): *Environmental Impact Assessment of Large Scale Shallow Groundwater Abstraction in the Keta Strip of Ghana.* WRI technical Report, Accra.

AKITI, T. T (1977): *Groundwater from the Keta-Anlo Artesian Basin.* Proceedings of 10th Biennial Conference of Ghana Science Association, Accra.

BANNERMAN, R. R (1994): Appraisal of the Limestone Aquifer of the Keta Basin, Ghana. Proceedings of International Conference Helsinki, Finland

DAPAAH-SIAKWAN and P. GYAU-BOAKYE (2000): *Hydrogeological Framework and Borehole Yields in Ghana.* Hydrogeology Journal, Vol. 6, No. 4; pp. 405-416.

DARKO, P. K (2001): *Quantitative Aspects of Hard Rock Aquifers: Regional Evaluation of Groundwater Resources in Ghana.* Ph.D Thesis, Charles University, Prague, Czech Republic.

GHANA STATISTICAL SERVICE (2000): *Population Census Report of Ghana,* unpublished.

GILLS, H.E (1969): *A Groundwater Reconnaissance of the Republic of Ghana with a description of Geohydrologic Provinces.* USGS, Water Supply Paper.

JUNNER, N. R and HIRST, T. (1946): *The Geology and Hydrogeology of the Voltaian Basin: Gold coast Geological Survey,* Mem. 8, 51pp.

KESSE, G. O. (1985): *The Mineral and Rock Resources of Ghana.* A. A Balkema, Rotterdam.

KORTATSI, B. K. (1994): *Groundwater Utilization in Ghana.* Proceedings of International Conference Helsinki, Finland.

MINISTRY OF WORKS AND HOUSING (1998): *Water Resources Management Study Report of Ghana.* Part II, Vol. II, Accra.

WRI (2001): *Groundwater Resources Assessment of Ghana.* Technical Report, Water Research Institute (CSIR), Accra.

WRI (1995): *Inventory of Hand-dug wells and Springs in south-eastern Ghana.* Technical Report, Water Research Institute (CSIR), Accra.

Les ressources en eau souterraine de la Côte d'Ivoire et le cas des aquifères transfrontaliers entre la Côte d'Ivoire et le Ghana

Jean Patrice Roger Jourda

Laboratoire des Sciences et Techniques de l'Eau et de l'Environnement
Université de Cocody

Introduction

Les ressources en eau souterraine constituent les principales sources d'approvisionnement en eau potable des grandes agglomérations. Si la croissance des métropoles est un phénomène mondial, elle est cependant plus marquée dans les pays en développement avec une poussée démographique exponentielle. Les eaux souterraines seront donc très sollicitées Aussi, ces ressources méritent-elles d'être connues dans le but de leur gestion durable. Cette communication se propose, à partir de données de synthèse, de faire l'état des connaissances de ces ressources en Côte d'Ivoire et de faire des projection dans l'avenir au niveau des perspectives en vue de leur gestion intégrée .

Cadre géographique

La Côte d'Ivoire est située dans l'Ouest de l'Afrique entre les latitudes 4°30′ N et 10°30′ N et les longitudes 2°30′ W et 8°30′ W. Elle est bordée à l'Est par le Ghana, à l'Ouest par le Libéria et la Guinée, au Nord par le Mali et le Burkina Faso et au Sud par l'Océan Atlantique (Figure 1).

Le relief de la Côte d'Ivoire peut être divisé en deux parties :

- la partie ouest du pays est fort accidentée marquée des altitudes atteignant parfois les 1 000 m et même plus ;
- les autres parties du pays ont un relief assez monotone et très peu contrasté.

La végétation du pays peut être subdivisée en trois zones :

- la zone forestière au Sud ;
- la zone de savane arborée au centre ;
- la zone de savane au Nord.

La Côte d'Ivoire a un climat équatorial humide au Sud et un climat tropical dans les régions du centre et du nord.

Le pays est drainé par quatre grands fleuves : le Cavaly, le Sassandra, le Bandama et la Comoé. Ils ont tous une direction d'écoulement sensiblement nord-sud et se jettent dans l'océan Atlantique.

Cadre géologique

La géologie de la Côte d'Ivoire (Figure 1) se subdivise en deux grands ensembles :

- l'ensemble de socle cristallin et métamorphique ;
- l'ensemble du bassin sédimentaire côtier.

L'ensemble du socle cristallin et métamorphique

L'ensemble cristallin et métamorphique couvre 97,5 % de la superficie du territoire, et est subdivisé en deux grands domaines :

- le domaine Libérien ou Kenema-Man d'âge Archéen, affectée par l'orogenèse Libérienne et dont la lithologie est constituée de migmatites et de gneiss granulitiques, des charnockites sous forme d'intrusion dans le socle granito gneissique, ou sous forme de mobilisat anatectique (Kouamelan, 1996) ;
- le domaine Eburnéen ou Baoulé-Mossi est situé à l'Est de l'autre domaine et séparé par la faille de Sassandra. Ce sont des formations birimiennes d'âge protérozoïque inférieur (paleoprotérozoïque).

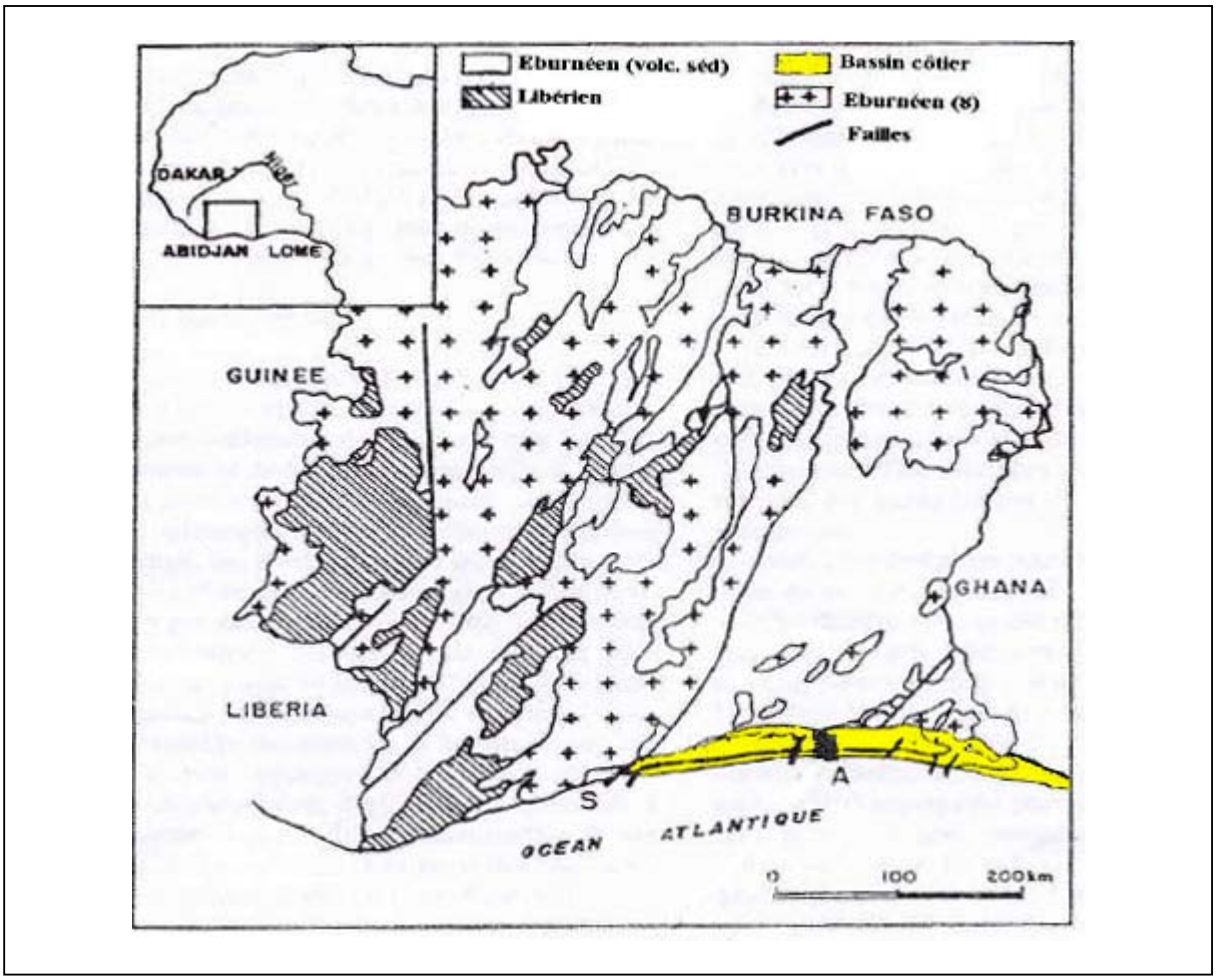


FIGURE 1. Carte géologique de la Côte d'Ivoire (aquifère transfrontalier en jaune)

L'ensemble du bassin sédimentaire côtier

La couverture sédimentaire de la Côte d'Ivoire est formée d'un étroit bassin sédimentaire recouvrant 2,5 % de la superficie du territoire ivoirien et disposé le long de la côte atlantique au sud. Il est d'âge Crétacé-Quaternaire avec une histoire assez simple. Le bassin a connu trois phases de transgression allant du Crétacé au Quaternaire : Aptien-Albien (étage supérieur du Crétacé inférieur), Maastrichtien-Eocène inférieur et Miocène inférieur On note également deux lacunes de sédimentation : lacune fin Précambrien-Crétacé et celle de l'Oligocène.

Les ressources en eau souterraine

En Côte d'Ivoire, les ressources en eau souterraine se rencontrent respectivement dans les formations du bassin sédimentaire côtier, les horizons d'altérites au toit du socle, les séries volcano-sédimentaires et les granitomigmatites. Ces réservoirs étant évidemment liés à la géologie, il va sans dire que les plus grandes ressources en eau souterraine du pays sont contenues dans le socle cristallo-métamorphique.

Ressources en eau souterraine du bassin sédimentaire côtier (Fig. 2)

■ La nappe du Continental Terminal

La nappe est contenue dans la série sédimentaire tertiaire dite du Continental Terminal dont les couches sont formées de sables fins, sables grossiers, et parfois de sables moyens. Les niveaux 3 et 4 constituent l'essentiel de l'aquifère (Figure 5). Au toit du niveau 3, des bancs argileux lenticulaires rendent localement la nappe captive. Les niveaux 3 et 4 forment une seule nappe en l'absence de ces bancs. Cette nappe est la plus importante réserve d'eau souterraine de la région d'Abidjan et est exploitée pour l'alimentation en eau potable de la ville d'Abidjan (Fig. 3). Son épaisseur est variable et peut atteindre 200 m avec un débit important pouvant atteindre parfois

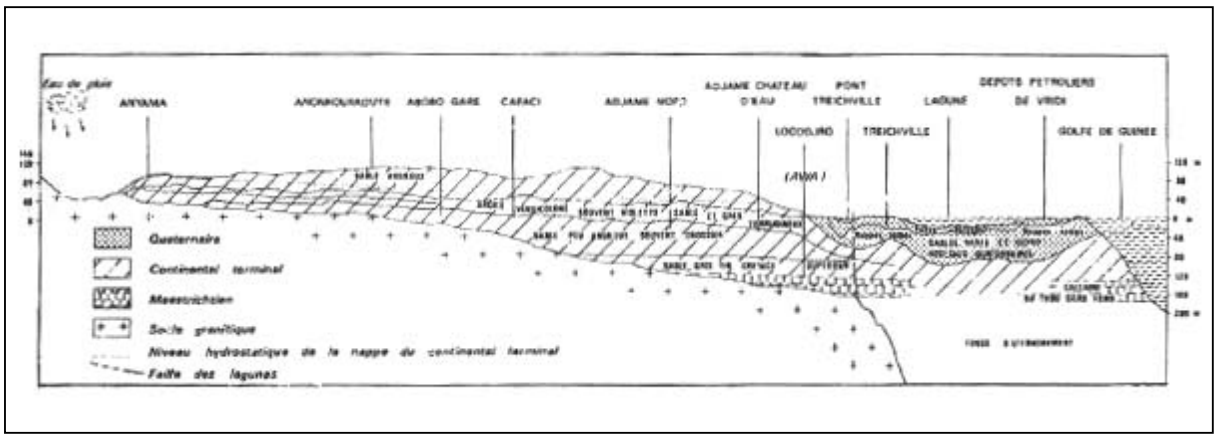


FIGURE 2. Coupe Nord-Sud du bassin sédimentaire côtier de la Côte d'Ivoire

près 300 m^3/h. Sur le plan hydraulique, elle présente les caractéristiques suivantes : la transmissivité est comprise entre 0,14 et 20 m^2/s avec un coefficient d'emmagasinement de 0,05 à 0,2. La perméabilité est de l'ordre de 10^{-3} m/s dans les sables fins à grossiers et pouvant baisser localement jusqu'à 10^{-5} ou 10^{-6} m/s par suite de variation de faciès.

La nappe du Continental Terminal est aussi exploitée dans la région de Bonoua plus à l'Est en allant vers le Ghana pour alimenter la ville de Bonoua et celle de Grand-Bassam, la première capitale de la Côte d'Ivoire. Cette dernière connaît depuis un certain temps des problèmes dans l'alimentation en eau potable de sa population. La décision a été prise d'aller prendre l'eau un plus à l'Est et de la transporter par canalisation

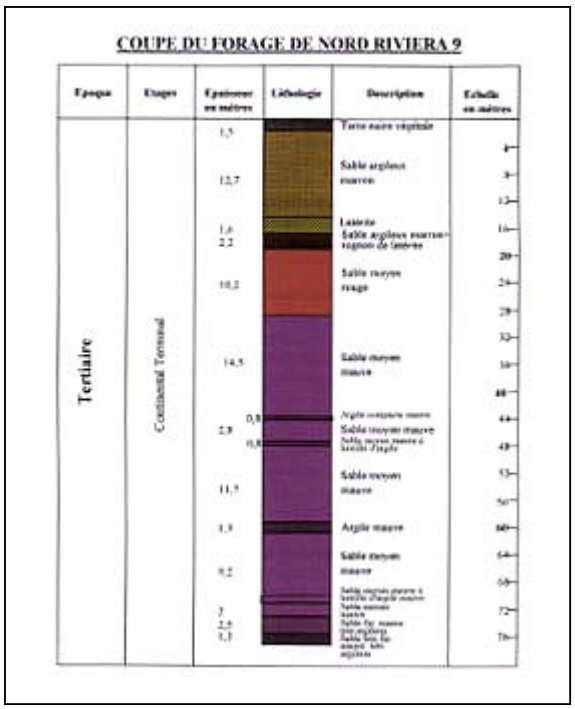


FIGURE 3. Coupe géologique dans l'aquifère du Continental Terminal aux environs d'Abidjan

sur près de 20 km. Cette nappe sera également exploitée comme une eau minérale (eau minérale AKWABA). Le niveau exploitée est située entre 170 et 200 m de profondeur avec un débit de près 20 m^3/h .

Sur le plan chimique, les eaux du Continental Terminal sont très faiblement minéralisées. La conductivité électrique varie de 19 à 55 µS/cm mais on note des exception dans les forages d'Adjamé (350 µS/cm), Plateau (222 µS/cm) et du puits de Pass (138 µS/cm). Elles ont un pH acide compris entre 3,5 et 5,36. On distingue 4 faciès hydrochimiques : le faciès le plus fréquent est le faciès chloruré sodi-potassique avec une variante chloruré calcique ; le faciès sulfaté sodi-potassique ; le faciès bicarbonaté sodi-potassique et le faciès peu fréquent est le faciès sulfaté sodique et légèrement chloruré magnésien.

■ Les aquifères du quaternaire

Deux niveaux aquifères existent dans les sédiments du quaternaire : les sables marins grossiers (nappe du Nouakchotien) et les sables fins à grossiers (nappe de l'Oogolien). Ces nappes libres sont très vulnérables à la pollution à cause de leurs surfaces piézométriques très proches de la surface du sol (entre 0 et 1 m sous le sol). La perméabilité varie de 10^{-3} à 10^{-4} m/s avec un débit variant de 2 m^3/h à 100 m^3/h. Sur le plan chimique, la minéralisation totale varie entre 85 et 142,2 mg/l et les pH varient de 3,78 à 6,58. La conductivité électrique varie de 150 à 255 µS/cm, valeur relativement élevées par rapport à celle de la nappe du Continental Terminal. Les ions chlorures et sodium sont les ions dominants dans ces eaux où on distingue le type chloruré sodi-potassique et le type bicarbonaté sodi-potassique. Ce sont des eaux très exposées aux influences du biseau salé.

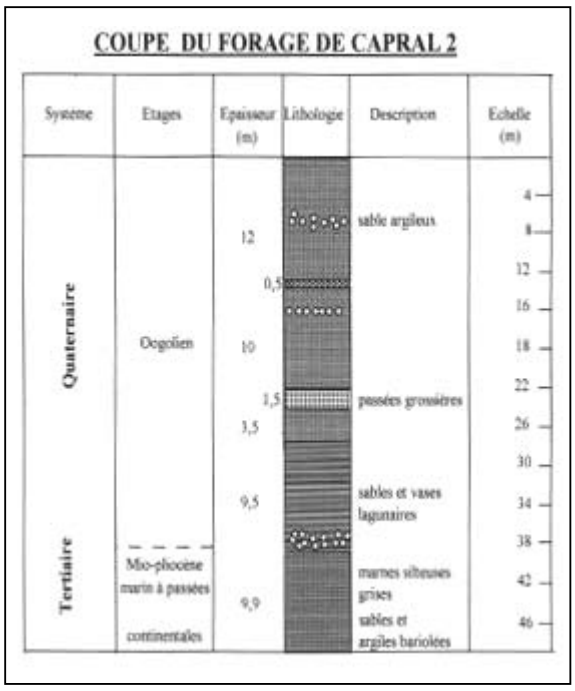


FIGURE 4. Coupe du forage Capral 2 dans le quaternaire

■ Les aquifères du crétacé supérieur

La nappe du crétacé supérieur (Maestrichien) est contenue dans le réservoir de bancs de calcaires peu fissurés gréseux à gros grains de quartz roulés. Elle est située à 200 m de profondeur. Cette nappe est captée par un seul forage et est exploitée pour la production d'une eau minérale naturelle, l'eau AWA.

L'ensemble des aquifères est résumé dans le log hydrogéologique ci-dessous.

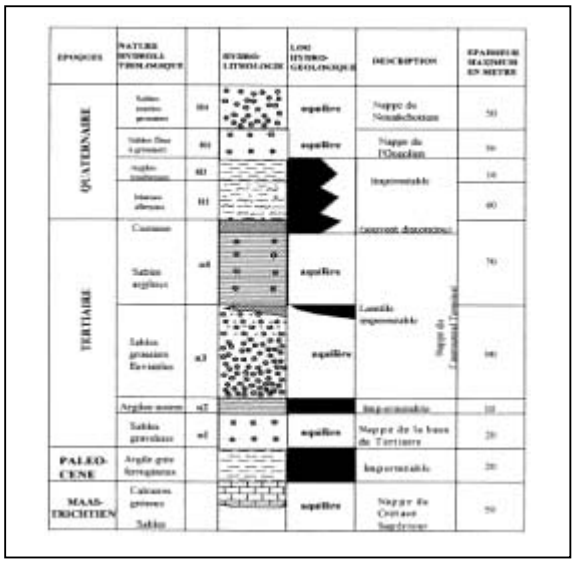


FIGURE 5. Log hydrogéologique du bassin sédimentaire côtier de la Côte d'Ivoire avec tous les aquifères (Aghui et Bièmi, 1984 in Oga, 1998)

Ressources en eau du socle

Les ressources en eau du socle se situent dans trois types d'aquifère qui sont les aquifères des altérites, des séries volcano-sédimentaires et des granito-migmatites.

■ Les aquifères des altérites

Ils sont les mieux connus en Afrique de l'ouest, tant des milieux paysans que des sociétés de forage. En effet, pendant longtemps, ils ont été considérés comme étant les seuls à pouvoir contenir des ressources en eau exploitables sur le socle cristallin et cristallophyllien (Figure 1). Sur les granitoïdes, ce réservoir est composé, de haut en bas, de cuirasse latéritique, sables argileux et arènes grenues dont l'épaisseur atteint parfois 50 m. Les arènes grenues constituant les niveaux les plus productifs et donc les plus recherchés. Les réservoirs d'altérites des séries volcano-sédimentaires sont en général les plus épais : 15 à 20 m en moyenne et atteignant les 100 m en Côte d'Ivoire dans la Boucle du cacao. Ces aquifères sont caractérisés par une très faible perméabilité et une forte porosité utile 2 à 5 %. Cependant, l'exploitation des réservoirs d'altérites est en nette régression, du fait des profondeurs souvent assez grandes des niveaux d'eau (20–25 m), de l'épaisseur fréquemment faible des altérites saturées (5 m), et surtout des profondeurs des puits modernes qui ne dépassent pas 35 m. Ces réserves d'eau sont sujettes aux variations climatiques de telle sorte qu'elles tarissent pendant la saison sèche.

■ Aquifères ou réservoirs des séries volcano-sédimentaires

Les séries volcano-sédimentaires sont des complexes schisto-gréseux très hétérogènes à nombreux plis isoclinaux, dont les flancs sont généralement redressés. Ces roches se caractérisent par d'importantes schistosités pouvant augmenter la porosité des réservoirs. Elles peuvent également acquérir des potentialités en eau énormes, quand elles sont affectées par des phénomènes de fracturation. Leur perméabilité est généralement faible et donc les ressources qu'elles renferment sont limitées. Cependant, dans les cas où la roche présente une intercalation détritique ou volcano-détritique jouant le rôle de drain, les réservoirs peuvent acquérir une importance fonction capacitive en profondeur.

■ **Aquifères ou réservoirs des granito- migmatites**

Ce sont des aquifères de fissures dont la présence se déduit du nombre impressionnant des arrivées d'eau dans les forages profonds réalisés directement dans le socle (Figure 1). En effet, à des profondeurs parfois assez élevées sous les horizons altéritiques (120 m au Mali ; 124 m en Côte d'Ivoire ; 400 m dans les mines de Tarkwa au Ghana), ont été enregistrées de nombreux venues d'eau qui témoignent de la richesse en eau des formations cristallines, non nécessairement altérées. L'eau circule dans les roches cristallines à travers les réseaux de fractures à fonction drainante, généralement bien alimentés et capables de fournir des débits assez importants quand ils sont bien captés par les forages. A l'heure actuelle, les forages captant les fractures sont les plus sûrs et les moins influençables par les fluctuations saisonnières ; contrairement aux puits réalisés dans les altérites et qui sont placés sous l'influence directe du rythme des saisons. Ces ressources sont sollicitées dans le cadre de l'hydraulique villageoise. Les débits varient de 2 à 10 m^3/h.

Aquifères transfrontaliers

Le long de la côte de l'océan Atlantique s'étend un bassin sédimentaire qui part de la ville de Fresco à l'Ouest (Côte d'Ivoire) jusqu'à la ville d'Axim (Ghana) à l'Est. Ce bassin contient des ? ressources en eau importante. Si la croissance des métropoles est un phénomène mondial, elle est cependant plus marquée dans les pays en développement. En Afrique particulièrement, les régions côtières connaissent une affluence démographique particulière avec une concentration de populations importantes nécessitant une sollicitation de plus en plus importante des ressources en eau souterraine. La ville d'Abidjan est un exemple (Antoine et Henry, 1983 in Kouadio, 1998). La ville coloniale passe de 1 400 habitants en 1912 à 65 000 en 1950 et s'étend alors sur 600 ha.

Elle devient portuaire en 1950 et jusqu'en 1970 avec 550 000 habitants et couvrant 12 000 ha. L'agglomération moderne atteint le million d'habitants en 1976 et en 1978 elle est divisée en 10 communes. La barre des 2 millions est franchie en 1989, celle des 2,5 millions en 1995 sur un territoire de plus 60 000 ha. Aujourd'hui, Abidjan dépasse les 3 millions de personnes. Avec une telle population, les besoins en eau sont énormes et qu'il faudrait satisfaire.

Prélèvements en eau

Cette croissance démographique accompagnée de l'extension de la ville va aller de pair avec les prélèvements en eau qui sont en constante augmentation (Tableau 1) pour satisfaire les besoins en eau.

Les pompages AEP atteignent actuellement un débit moyen de 2,2 m^3/s, soit environ 70 millions de m^3/an. Les volumes prélevés par les industries ne sont pas connus avec précision mais

Année	*Population (x 10^3 hab.)*	*Production (x 10^3 m^3/an)*	*Consommation (x 10^3 m^3/an)*	*L/ hab. j*	*Nombre de forages*
1912	2				
1937	17	500			3
1950	65				
1955	125				
1959		6 000			4
1960	190	8 906	4 958	71	11
1962	235	11 700	10 493	122	13
1965	325	16 953	14 312	120	
1966	355	17 830	15 116	116	16
1969	485	23 668	20 118	113	20
1970	550	25 000	212 215	105	
1972	732	31 126	27 338	102	28
1975	952	40 662	34 439	99	
1979	1 350	59 323	46 390	94	36
1980	1 450	65 048	50 699	95	
1982					59
1984	1 646				
1988	1 934	70 275			
1992	2 272		59 708	72	66
1995	2 570	75 555	64 313	66	60
2000	(3 180)	(95 000)	81 250	70	
2005	(3 980)	(115 000)	(100 400)	70	
2010	(4 890)	(145 000)	(125 000)	70	

TABLEAU 1. Alimentation en eau potable de la population abidjanaise

Proceedings of the International Workshop Tripoli, Libya, 2–4 June 2002

les chiffres de la période 1989-1994 donnent un volume moyen annuel de 1,5 millions de m^3/an. Les volumes prélevés par les ouvrages d'hydraulique villageoise ou ouvrages privés s'élèvent à environ 1,2 millions de m^3/an. Selon des simulations, les prélèvements doivent doubler d'ici dix ans. A côté des prélèvements de l'agglomération d'Abidjan, il faut ajouter les autres grandes villes situées sur ce bassin dont l'alimentation en eau potable provient de cet aquifère transfrontalier.

État de connaissance de cette nappe

En Côte d'Ivoire, cette nappe est bien connue (voir le paragraphe ci-dessus sur les ressources en eau du bassin) mais il n'existe pas une concertation pour une gestion intégrée de celle-ci entre la Côte d'Ivoire et le Ghana.

Perspectives

Au niveau des perspectives, une concertation aussi bien nationales que régionales est plus que nécessaire pour une gestion intégrée de cette ressource. La Côte d'Ivoire et le Ghana doivent mener des actions concertées et des échanges de données dans le but d'une exploitation durable de cette ressource.

Conclusions

La Côte d'Ivoire dispose de ressources en eau importantes contenues dans quatre types d'aquifères qui sont les aquifères des altérites exposées aux variations saisonnières, les aquifères des séries volcano-sédimentaires, les aquifères des formations granito-gneissiques et les aquifères du bassin sédimentaire côtier. C'est dans ce bassin sédimentaire qu' existent des aquifères, à cheval entre la Côte d'Ivoire et le Ghana, dont l'état de connaissance est encore parcellaire. Une gestion intégrée de ces nappes est souhaitée entre les deux pays.

Bibliographie

ANONYME. 1996. Etude de la gestion et de la protection de la nappe assurant l'alimentation en eau potable d'Abidjan : étude sur modèle mathématique, Rapport de phase 3, version provisoire, SOGREAH .

BIEMI, J. 1992. Contribution à l'étude géologique, hydrogélogique et par télédétection des bassins versants Subsaheliens du socle précambrien d'Afrique de l'Ouest : hydrostructurale, hydrodynamique, hydrochimie, isotopie des aquifères discontinus de sillons et aire granitique de la haute Marahoué (Côte d'Ivoire). Thèse de Doctorat d'État, Université d'Abidjan, 480 p.

JOURDA, J.P. 1987. Contribution à l'étude géologique et hydrogéologique de la région du grand Abidjan (Côte d'Ivoire). Thèse de Doctorat de 3ème cycle, Université de Grénoble I, Institut Dolomieux, 299 p.

KOUADIO, L.P.; ABDOULAYE, S.; JOURDA, P.; LOBA, M.; RAMBAUD, A. 1998. Conséquences de la pollution urbaine sur la distribution d'eau d'alimentation publique à Abidjan, Cahier de l'Association Scientifique Européenne pour l'Eau et la Santé, Volume 3, N°1.

KOUAMELAN, A. N. 1996. Géochronologie et géochimie des formations archéennes et Proterozoiques de la dorsale de Man en Côte d'Ivoire. Implications pour la transition archéen-proterozoique. Thèse de Doctorat de l'Université de Rennes 1, 277 p.

LASME, T. 2000. Hydrogéologie des réservoirs fracturés de socle : Analyse statistique et géostatistique de la fracturation et des propriétés hydrauliques. Application à la région des montagnes de Côte d'Ivoire (Domaine Archéen). Thèse de Doctorat d'État. Univ Poitiers. 232 p.

OGA, M.S. 1998. Ressources en eaux souterraines dans la région du Grand Abidjan (Côte d'Ivoire). Approches hydrochimiques et isotopiques. Thèse d'État. Univ. Paris-Sud. 211 p.

TASTET, J.P. 1979. Environnements sédimentaires et structuraux Quaternaires du littoral du golfe de Guinée, Côte d'Ivoire, Togo, Bénin. Thèse d'État. Univ. Bordeaux I, N° 621, 2t, 181 p, 127 fig,

Groundwater resources in Kenya

Fred K. Mwango, B.C. Muhangú, C.O. Juma, I. T. Githae

Laboratoire des Sciences et Techniques de l'Eau et de l'Environnement
Université de Cocody

Abstract

The hydrogeological zones of Kenya can be regarded as simplified geological areas, which are characterized by:

- Volcanic rocks,
- Pre-Cambrian Metamorphic Basement rocks,
- Sedimentary rocks.

The Volcanic rocks cover about 26% of the country and are more common in the Western and Central Kenya. The lithology is widely variable and includes Phonolites, Trachytes, Tuffs and Basalts. Groundwater in this geological setting is stored in the old weathered surfaces between the Lava flows and the older formations, as well as between successive flows.

The Pre-Cambrian rocks are widely distributed in the Central, Western and North-Western parts of Kenya and covers about 17% of the country. The lithology is dominated by granites, gneisses, schists and sediments. The aquifers in these geological formations are found within fractures and weathered surfaces of the formation.

The Sedimentary rocks cover about 55% of Kenya, predominantly in the Eastern, North-Western parts, L. Victoria regions and the coastal areas. These rocks are mainly composed of sands, clays, sandstones, shales and limestone. Aquifers are mainly found within the coarse grained sediments and solution cavities.

Surface water bodies cover 2% of the land surface.

The groundwater in Kenya is extremely variable in chemical composition, and the variation occurs both spatially and seasonally. Its quality is influenced by the geological formation in which the aquifer occurs. In Central and Western Kenya, the quality is generally soft with moderate alkalinity. In the Coast, Eastern and Northeastern regions the water is saline and of poor quality. The water quality is one of the major limiting factors in groundwater utilization in Kenya

One of the main shared groundwater resource is the Merti aquifer in the North Eastern part of the country and which occurs in semi-consolidated Merti Beds of Pliocene age. The Merti Beds include gravel, grit, sand, silt and clay and are of variable thickness, extent and lithologic character, suggesting rapid deposition of detrital materials derived from the erosion of adjacent areas of older rocks. This aquifer extends from North East of Habaswein through the Kenya/Somalia border at Liboi and beyond into Somalia.

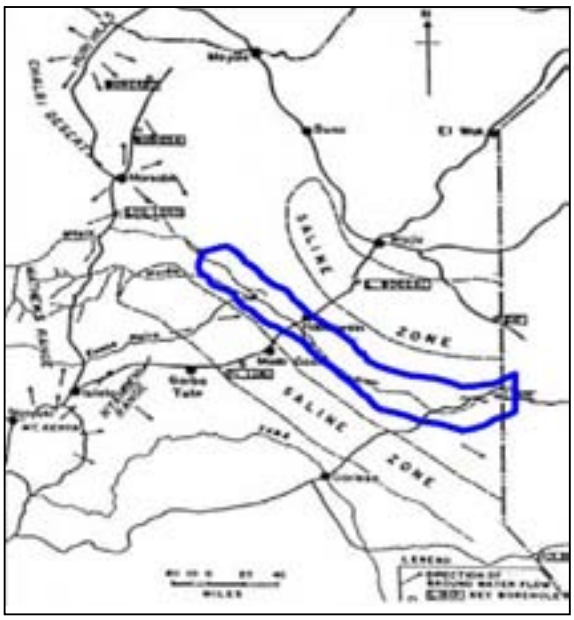


FIGURE 1. Groundwater resource in the eastern and central parts of Kenya (The Merti Aquifer)

Groundwater flow at Liboi area has been estimated (Swarzenki and Mundorft, 1977) to be about 7,200 m^3/day. This is the amount of groundwater that leaves Kenya daily and enters Somalia.

Overview of groundwater resources

Location and physiography

The Republic of Kenya covers an area of about 592,000 square kilometres and is bound by latitudes 5°20′ N and 4°40′ S and longitudes 33°50′ E and 41°45′ E. The location of Kenya along the equator and the greatly varied surface configuration ranging from sea level to heights of over 5,500 m above sea level combine to create a physical environment varying from almost equatorial characteristics to polarial ones on highlands. The country's topography can be divided into two distinct physical regions, which are the lowland and upland. The entire terrain is dominated by wellpreserved plateaus whose height is used as a rational basis for dividing the country into eight physiographic units. These are the Coastal Belt and plains, the Duruma-Wajir Low Belt, the Low Foreland Plateau, the Kenya Highlands (Western and Eastern), the Kenya Rift Valley, the Nyanza Low Plateau, the Nyanza Lowlands, the Northern Plain land. The present drainage pattern is either radial from the Central Highlands or up from the south foothills of the Ethiopian Highlands.

Geology

The Rift Valley system is represented by volcanics as well as igneous and Pre-Cambrian metamorphic complexes divided into four major systems. The Palaeozoic is well-developed and mostly important in terms of surface coverage and is represented by Quaternary sedimentary and Tertiary volcanic rocks. These igneous, metamorphic and sedimentary rocks occupy 26%, 17% and 55% of the land surface, respectively. Water availability and water quality depend on all the four major geologic areas that are represented in the complex geology of Kenya.

The structural geology is dominated by a gentle domeshaped asymmetrical shield. The earliest fault probably appeared in late Miocene, and another phase of major faulting is known to have occurred in Pliocene and Quarternary times.

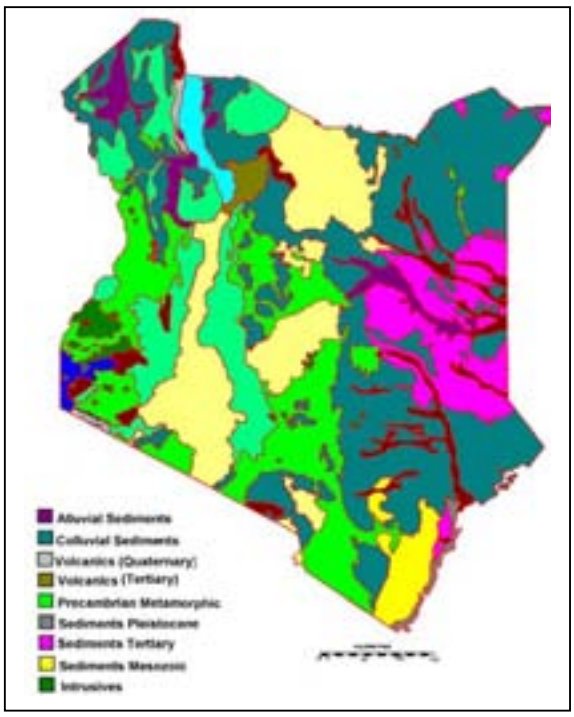


FIGURE 2. Simplified geological map of Kenya

Groundwater resources

Groundwater is extremely variable in chemical composition and this variation occurs both spatially and seasonally. The major uses of boreholes are public water supply, agricultural, domestic, industrial, and livestock. Rock type remarkably affects aquifer characteristics. Groundwater abstraction has seldom been investigated in Kenya. The total present groundwater abstraction rate in Kenya is estimated at 57.21 million m^3/year. Total safe abstraction rate in Kenya is estimated to be 193 million m^3/year.

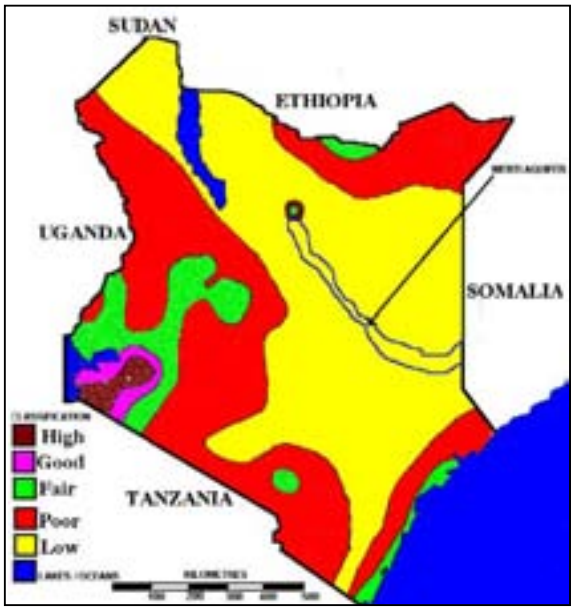


FIGURE 3. Hydrogeological map: groundwater potential in Kenya

Case study of the Merti Aquifer

There are several aquifers shared between Kenya and her neighbours. One of these is the Merti Aquifer that stretches from Yamicha through Habaswein to Liboi at the Kenya/Somali border.

This paper is based on the hypothesis that the Merti Aquifer is limited both spatially and vertically and that the increase in human and livestock development both within the project area and catchment zones accelerates groundwater abstractions and hence over exploitation. The primary aim of this paper is to analyse and qualify the existing information on the aquifer characteristics and propose the way forward. The information on aquifer characteristics, which is either lacking or inadequate at present, is essential for sound planning, water resources development and management.

Previous studies

There have been a number of studies covering eastern Isiolo, Wajir and Garissa Districts. Ministry of Works (1963), carried out a hydrogeological assessment. The report stated *'… It is believed that, with the exception of areas near Mado Gashi and north-east of Habaswein, groundwater of good quality can be obtained by drilling anywhere.'* Subsequent studies have improved upon this assessment and shown up differences. Swarzenki et al. (1977) described the hydrogeological components of an extensive range of development project that covered the whole of North Eastern Province and Eastern Isiolo District. Part of the project's activities was the drilling of exploratory boreholes across much of the Merti Formation, thus allowing a clearer indication of the presence of portable water within it. In respect of the Modogashe area, the report indicated that saline water would be encountered in the Modogashe-Sericho-Merti area, and to the east of Habaswein: however, the Habaswein area itself was reported to be underlain by a fresh water aquifer. Lester (1985), evaluated the results of borehole drilling undertaken in the area and recommended that a comprehensive geophysics programme to delineate the freshwater Merti Aquifer, that boreholes in the fresh water aquifer drilled not less than 110 metres below ground level Shallow boreholes adjacent to the Ewaso Nyiro to exploit alluvial aquifers and that '*No boreholes, either shallow or deep, should be drilled along the Galana Gof east of Benane. Fresh water supplies can be developed from clay fill subsurface dams in the sandy river bed'*. Ministry of Water Development (1991) defined all the Merti Formation in the southern part of the Isiolo District as *'…very poor…'*, stating that *'the southern part of this area offers no good chances for groundwater development as the groundwater is highly mineralised'*. Lane (1995), in his thesis, attempted a synthesis of all data available on the Merti Aquifer, and broadly confirmed the findings of earlier studies. Geologists from the Water Development Department have also been carrying out hydrogeological surveys and studies at various locations within the Merti Aquifer. These surveys have been conducted on demand basis or as need arises. The resulting data for the entire study area has not been analysed in details.

Description of the study area

Presently, the several Rural Towns which lie within the study area with a human and livestock population of 235,500 and 511,700 respectively have a mean daily demand of 11,675 m^3 and 25,585 m^3 respectively. Groundwater abstraction for domestic and livestock purposes averages 4,800 m^3 per day. During and immediately after the rains, the project area relies on a number of public and privately-owned pans and water holes situated on the banks of the Lagh Dera, the seasonal watercourse traversing the various Centres and markets. Water Supply in the study area is acutely sensitive to drought and a number of water holes are usually dry three months after the end of the rains.

The topography of the project area is generally flat, with elevation differences of the order of few metres and range from 360 metres in Urura area of Isiolo, 300 metres within Habaswein and 90 metres within Liboi on Kenya/Somali border. Mean annual rainfall at Habaswein town, which is typical of the study area is 261.1 mm. However, year-on-year rainfall variability is high. Rainfall distribution is bimodal, with two wet seasons in April and November. The annual evaporation is about 2,330 millimetres per year, thus the study area lies in a very arid zone .

There are no perennial streams in the area. The nearest perennial water body is the Tana River located over 100 km to the south. The ephemeral Ewaso Nyiro rises west of Isiolo and traverses Merti, Sericho and eventually reaches the alignment of the Lagh Dera at the vicinity of Habaswein and towards Liboi. The Galana Gof flows only after heavy rains and disappears underground before reaching the Lagh Dera.

Proceedings of the International Workshop
Tripoli, Libya, 2–4 June 2002

Geology

The soils of the area are generally sandy, with some clay patches. Sub-soils comprise fine sand, silt and clay, which are the erosion products of the mudstones and shales. These soils are poorly permeable, thus limiting the ease with which rainfall can infiltrate.

There are beds of alluvial sands and sandy clays laid down adjacent to the watercourse during flooding by the Lagh Dera, Ewaso Nyiro and Galana Gof. However, outcrops are presently obscured by latter deposition as well as thicker riverine vegetation.

The recent deposits are underlain by the Merti Formation, which is a marine to peri-marine sedimentary formation of Miocene to Pliocene age. The formation is of unknown thickness in this area, though in the Garissa area it is believed to be at least 270 metres thick (Nyagah, 1995). The Merti Formation is underlain by a succession of Jurassic and Cretaceous rocks, which are in turn underlain by metamorphic rocks of the Mozambique Belt, more commonly known as Basement.

Tertiary/Jurassic marine clays, sands and conglomerates, the so-called Merti Beds cover the whole eastern area, extends also to Somali. Sands and conglomerates form extensive aquifers.

Rivers have incised the Merti Formation to create sand rivers which are filled to varying depths with sands and clays in varying proportion.

Hydrogeology and aquifer characteristics

Methodology

The hydrogeological and geohydrological aspects of the Merti aquifer are described in this section. These aspects have been determined by using various methods.

■ **Geological maps and sections**

The Geological Map of the area was used to delineate the hydrogeological zones that outline the fresh water aquifer.

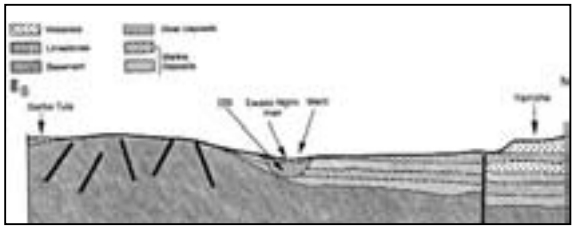


FIGURE 4. Hydrogeological section at the Upper part of Merti Aquifer

■ **Resistivity method**

The purpose of the resistivity surveys was to determine the lateral extent and the geometry of the fresh zone of the Merti Aquifer. The resistivity surveys have been carried out between the Yamicha-Boji-Habaswein area. The soundings were conducted across the Choichuff Lineament. The aim of this survey was to find out whether there exists a buried Paleo-Channel that runs from Yamicha to Habaswein and along the Choichuff Lineament and that recharge the Merti Aquifer.

Other surveys have been carried out around Habaswein, Daadab and at Liboi among other small rural centres within the Merti Aquifer.

The soundings were carried out with a current electrode spacing of between 500 metres and 800 metres using the Schlumberger configuration. The type of apparent resistivity curves obtained during the geophysical site investigations is a function of the resistivities, thickness of the layers and electrode configuration. This anomaly of homogeneity continuity as marked by the resistivity values were used to estimate the dimensions and geometry of the aquifer system with reasonable degree of accuracy.

The plotted resistivity curves indicate low resistivity values on the flanks with moderate values of 20–50 ohms metres within the Paleo-Channel. This is an indication of the Paleo-Channel flanks being inclined at an angle towards the middle section. The width and the thickness of the aquifer is estimated to 6 kilometres and 15 metres, respectively, with the discharge boundary occurring at Liboi on the Kenya-Somali border, a distance of 340 kilometres. Thus the method provides a tentative aquifer dimension.

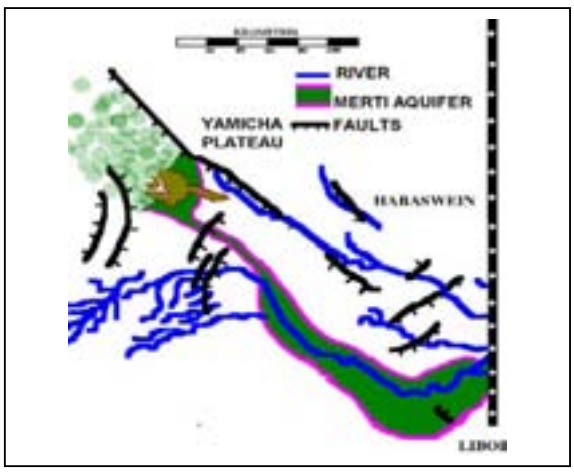


FIGURE 5. Paleo-Channel obtained from resistivity data

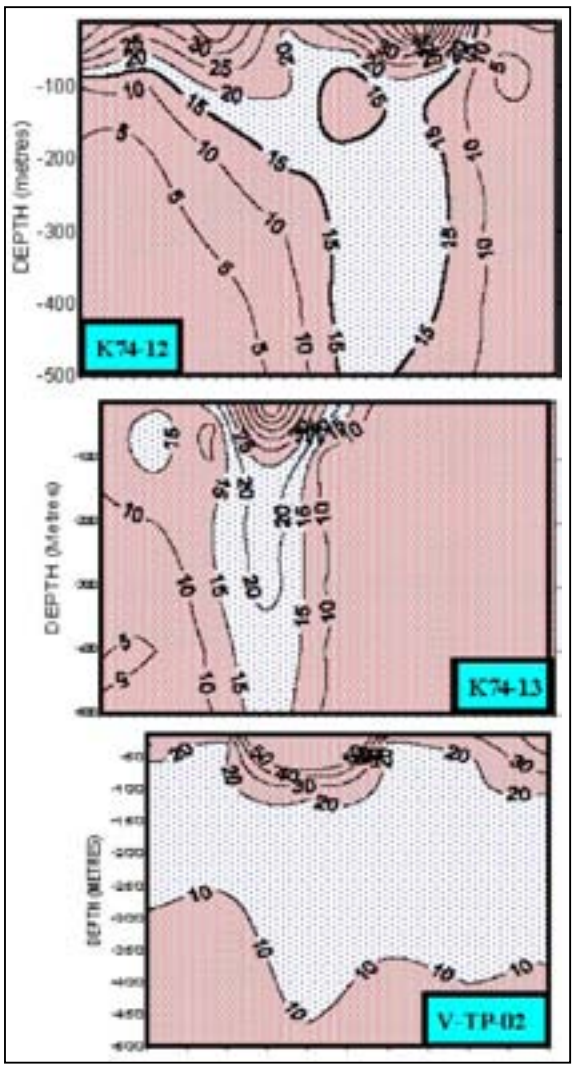


FIGURE 6. Apparent resistivity sections indicating width of fresh water Paleo-channel

■ Borehole data

There are several boreholes that have been drilled within and along the fresh zone of the Merti Aquifer. The Static water levels, water rest levels and borehole lithological logs have been recorded for all boreholes drilled within the Merti aquifer. Some of the boreholes have the Test Pumping data.

These data have been analysed to determine the approximate depth to the Aquifer, thickness a piezometric levels of the Aquifer, and the Aquifer and material. The test-pumping data during the borehole pumping and recovery phases of several boreholes has been analysed in order to deduce information on discharge, transmissivity and storage capacity.

Table 1 shows data of selected representative boreholes evenly distributed over the entire Aquifer length.

The boreholes between the Yamicha to the North of the Habaswein have yields ranging between 4–18 m^3/hr, while those between Habaswein and Daadab have yields averaging 8–15 m^3/hr. Boreholes between Daadab and Liboi, have yields ranging between 10–19 m^3/hr. The water struck levels range between 110–180 metres, while water rest level ranges between 110 and 140 metres below ground level. The hydraulic gradient between Habaswein and Liboi is 1.66 x 10^{-3}.

Borehole Number	*Locality*	*Depth (m)*	*Struck level (m bgl)*	*Rest level (m bgl)*	*Yield (m^3/hr)*	*Quality (MS/cm)*
C-3830	Sericho	129.5	118; 129	107	10.9	2.55
C-3893	Hadado	213	195	190	2.3	5.5
C-10094	Daadab	153.5	104-120	110	4.5	
C-3877	Sebule	131.97	96.9	94.7	8.2	
C-4176	Arba Jahan	109	104 -106	–	12.5	
C-4586	Yamicha	150	116; 130	128	3	
C-4587	Yamicha	164	120	123	2	
C-5795	Habaswei	156	124; 110	123	8.4	1.92
C-4699	Yamicha	170	33; 94	30.34	6	0.62
C-9758	Habaswei	130.5	86; 93.8	91.41	11	
C-9009	Liboi	123	93	88.12	9	
C-9384	Diri	170	112	108	3.5	1.2
C-9758	IFO	130.5	913	914	11.7	1.1
C-3684	Kulan	119.2	108.3	102.8	9.6	
C-9749	Ifo	141	110	108.8	6.9	
C-3684		119.2	108.2	102.7	6.9	

TABLE 1. Selected representative borehole data

Aquifer type

The Merti Aquifer is unconfined in some areas and semi-confined in other areas. The aquitards are comprised of clays and sandy clays, which are lacking in the areas where the Aquifer is unconfined. The Aquifer material comprises of sands and clayey sands.

Recharge

One of the catchment for the Merti Aquifer is the Yamicha-Marsabit area, whose average annual rainfall is 290 mm.

Groundwater movement from recharge area is controlled by on the available recharge, the aquifer characteristics and the mode of discharge. These conditions are not uniform in the project area mainly due to variations in precipitation in different recharge areas of the same system and geological conditions underground. Structural features such as the faults and lineaments contribute to the flow direction.

The groundwater flow is in two directions. In the northern part of the System, groundwater flow is in a south-eastern direction, while in the south it flows eastward.

The other main catchment is the Ewaso Nyiro whose source is the Aberdare Ranges and mount Kenya to the west. Intensive human activities and settlement on these catchments has reduced the flow in recent times.

From the above data, the recharge has been estimated to be 23,633 per hour assuming the flow is concentrated within the Ewaso Nyiro graben that extends through Habaswein.

The faulted basement boundary acts as one of the draining channels of the Ewaso Nyiro river towards the north and north-west but the flow along this fault zone is interrupted by other fracture systems trending in the north-west-south-east direction and moving beyond Sericho. These fracture systems drain the water back to the Ewaso Nyiro rift like graben and thus recharging the Merti Aquifer.

Tabulated below (Table 2) is miscellaneous flow measurements taken at various station in 1991, by MENR.

The open channel evaporation is insignificant compared to infiltration and seepage, which accounts for 99.8% of the flow. The latter amount percolates as groundwater and into the Merti Aquifer.

The Lagh Choichuff Lineament forming an almost a straight line, indicates partial but permanent recharge from a large catchment of Yamicha and Mt Marsabit to the north.

Station	*Evaporation m^3/day*	*Discharge cumecs*	*Discharge cumecs*
Archers Post		5.558	+2.421
Malka Daka	622.88	7.979	-3.203
Mertil	1551	4.776	-3.656
Sericho		1.12	

TABLE 2. Selected representative River gauging data

Assuming that only 4% of the total annual rainfall infiltrates into the ground and the recharge area is approximately 340 x 100 km^2. For each square kilometre of land therefore, 228.67 x 10^6 m^3 of water is recharged into the ground aquifer annually.

The assumed recharge may be underestimated considering information gap between Habaswein and Liboi and that the actual aquifer dimension is irregular both laterally and vertically. The figure serves as an ideal estimate for planning on abstraction and formulation of an abstraction future policy and as water demand increases.

Available groundwater

Based on an average thickness of 15 metres, a length of 340 kilometres and a width of 5 to 50 kilometres and that the aquifer material is not well sorted but is mainly composed of fine sands with a mean specific yield of 0.33 then the volume of water stored estimated is:

= 15 x 340,000 x 50,000 x 0.33 m^3 of aquifer volume

= 8.4 x 1,010 m^3 of the aquifer volume.

Underground flow

The underflow beneath the Liboi area can be computed from Darcy's Equation:

$Q = T.W.I$,

where

Q = Quantity; T= Transmisivity: W=Width: I= Hydraulic Gradient. I = 1.66 x 10^{-3}; W = 50 Kilometres; T = 80 m^2/day.

Thus the underflow at Liboi is

= 80 x 50,000 x 1.66 x 10^{-3}

=6,640 m^2/day.

Swarzenski and Mundroft (1977) established the flow to be 7,200 cubic metres per day.

Water quality

There are very few monitoring boreholes that are observed along the length of the aquifer. The

actively monitored boreholes are at refugee camps in Ifo, Hargadera, Dagahaley and Liboi near Kenya/Somali border.

Although the monitoring boreholes are few, they are ideal since they are located towards the end of the aquifer as it enters Somali.

The data obtained from these boreholes reportedly indicate no adverse fluctuations in terms of quality and quantity. This implies that the aquifer has not undergone any kind of strains.

More monitoring boreholes have been proposed to be drilled at 20 kilometres intervals between Yamicha all the way to Liboi.

For a typical Habaswein groundwater, electrical conductivity ranges from 1,000 to 1,900 µS/cm and Urura groundwater 1,400 µS/cm. The waters from both C-3830 and C-3893 are clearly not potable. The electrical conductivity decreases with increasing proximity to the Lagh Dera.

Most of the groundwater in the marine sedimentary rocks is fossil and saline, but part of it has been replaced by fresh water infiltrating into the aquifer.

Conclusion/Recommendations

The primary aim of analysing information was achieved in this study. An integrated approach was useful in delineating the fresh/saline water zones and hence estimates on the aquifer dimension and potential. Consequently, it was possible to confirm the hypothesis that the fresh water zone within the Merti Aquifer is limited both laterally and vertically.

It is further observed that a future development needs an integrated approach and use of mutually agreed guidelines for water quantity quality and seasonal variations.

This paper concludes that whereas Yamicha-Habaswein area has been fairly established in terms of information on Aquifer characteristics the rest of the Aquifer from Habaswein to Liboi on the Kenya-Somali border has not been well established. Where applied, the integrated groundwater survey method has been found to be more reliable in accurately mapping the Aquifer geometry and potential areas for development.

- Monitoring systems should be put in place to facilitate data collection;
- Further integrated surveys on Merti Aquifer from Habaswein towards Liboi on Kenya-Somali border should be carried out;
- Increase co-ordination between water development authorities between Kenya and Somali;
- Facilitate co-ordination between the water Department and other stakeholders in development;
- Facilitate co-ordination among various stakeholders to ensure that catchment area management is treated as part of the water project management;
- Train and empower communities to start income generating projects using the water resources available.

References

KENYA BUREAU OF STANDARDS (KBS). 1996. Kenya *Standard: Specification for Drinking Water: KS 05459, Part 1, 1996. (ICS 13.060.20).* KBS, Nairobi.

KENYA METEOROLOGICAL DEPARTMENT 1990. *Pluviometric Catalogue 6th Edition.* KMD, Nairobi.

LANE, I.M. 1995. A Preliminary Assessment of the Hydrogeology and Hydrochemistry of the Merti Aquifer, North Eastern Province, Kenya, and Lower Juba, Somalia. Unpublished thesis, University College London.

LESTER, B. 1985. Hydrogeology of Eastern Isiolo District. EMI Programme Office, Embu, Eastern Province.

MWANGO, F. K. 2000. *Kenya National Report on Capacity Building in Integrated Water Resources Programme in IGAD Sub-Region.*

MINISTRY OF WATER DEVELOPMENT (WRAS). 1991. Water Resources Assessment Study: ISIOLO. (Main Report Only). Water Resources Assessment Section/ TNO-Institute of Applied Geoscience. Delft, Nairobi.

MINISTRY OF WORKS, HYDRAULICS BRANCH, 1963. *An investigation into the Water Resources of the Ewaso Ng'iro Basin, Kenya.* Nairobi, Report No. 5, 50 p.

NYAGAH, K. 1995. Stratigraphy, depositional history and environments of deposition of Cretaceous through Tertiary strata in the Lamu Basin, southeast Kenya and implications for reservoirs for hydrocarbon exploration. *Sedimentary Geology,* 96, pp. 43-71.

SOMBROEK, W.G.; BRAUN H.M.H. and VAN DER POUW B.J.A. 1982. Exploratory Soil Map and Agroclimatic Zone Map of Kenya, 1980, scale 1:1,000,000. Kenya Soil Survey, Nairobi.

SWARZENSKI, W.V. and MUNDORFF, M.J. 1977. Geohydrology of North Eastern Province, Kenya. USGS Water Supply Paper 1757-N.

WRIGHT, E.P. 1989. Loose Data on Boreholes in Northern Kenya. Unpublished.

WOODHEAD, T. 1968. *Studies of Potential Evaporation in Kenya*. Water Development Department, Ministry of Natural Resources, Kenya.

Groundwater resources of Malawi

Peter P. Mkandawire

Ministry of Water Development,
Mzuzu, Malawi

Abstract

In Malawi groundwater plays a vital role as a source of water supply to the rural and urban population. Although groundwater appear abundant, economically exploitable resources are limited. There are no extensive aquifers but disjointed with relatively low yields, and in most areas, these aquifers are highly localized.

Groundwater resources in Malawi occur mainly in three aquifers namely basement complex, fractured and fault zones, and alluvial formations. In most areas these aquifers are shared by adjacent states. The quality of groundwater is generally good although isolated and sporadic occurrences of saline groundwater exist. This paper will attempt to assess the characteristics of these shared aquifers and examine how they are managed in the country.

Introduction

Groundwater resources have played a crucial role in water supply for both rural and urban areas in Malawi, a country of 12 million inhabitants. Boreholes equipped with hand pumps are the primary sources of water for human consumption in rural areas while the urban centers require high capacity motorized boreholes.

A comprehensive groundwater resource assessment has not been examined for Malawi a country, which relies on groundwater. Understanding of the extent of the resource is imperative with demand rapidly outstripping the capacity of government institutions to provide clean drinking water. This has resulted from population growth and regular impacts of severe droughts. To address this problem the Government of Malawi through the Ministry of Water Development has embarked on capacity building, and advocate effective and efficient management and utilization of water resources by ensuring that a comprehensive assessment and evaluation of the resource is done.

Geology

The greater part of Malawi is underlain by Crystalline metamorphic and Igneous rocks of Precambrian to Lower Palaeozoic age referred to as Basement Complex. These are composed of different rock types such as gneisses of amphibolite and granulite facies, biotite and hornblende gneisses. The other rock types commonly found are quartz-feldspathic gneiss and calc-silicate gneisses, schists, quartzites and marbles. These rocks are believed to be of sedimentary origin. They are rich in graphite and frequently contain sulphide mineralisation. They are at times intruded by pegmatite veins and dolerite dykes. The Basement Complex has been subjected to several phases of deformation and metamorphism. The Mozambican orogeny affected a vast area with high grade metamorphism in the south of Malawi.

Along the Lake shore plain and large parts of the shire valley the basement complex is covered by unconsolidated quaternary alluvium. These are described as highly variable , interdigiting sequences of clays, silts, sands and occasional gravels. There are considerable differences in the occurrence of sand and clay over short distances because of the complex nature of alluvial deposition in outwash fans, river channels and flood plains. The mineralogy of rock fragments in the alluvium show that they are derived from weathering of the escarpment area.

Topography

Malawi has a wide range of relief, which strongly influences climate, hydrology, occurrence of groundwater and population distribution. Hence the country is divided into Water Resource units largely on the basis of topography. The main topographic zones are: plateau areas, upland areas, rift valley escarpment and rift valley plains.

Plateau areas

These are peneplained, gently undulating surfaces with broad valleys and large level areas on the interfluves. These areas are on both sides of the rift valley and are generally 900–1,300 m above mean sea level. The plateau areas are largely covered by a thick weathered material which forms an extensive and important aquifer.

Upland or mountainous areas

There are several mountain areas and smaller uplands rising abruptly from the plateau where the underlying strata are more resistant to erosion. These have an elevation of 2,000–3,000 m above mean sea level.

Rift Valley escarpment areas

These areas fall steeply from the plateau areas and slopes are commonly very dissected. There is considerable faulting in association with the development of the Malawi Rift Valley system which is the southern end of one limb of the East African rift valley system. In these areas there is little potential for groundwater development except perhaps very locally.The aquifers are poor and discontinuous because the weathering products are often stripped away by erosion.

Rift valley plain

The alluvial plain of the Rift valley floor are gently sloping and of very low relief. The elevation is below 600 m above mean sea level. These areas have considerable potential for groundwater wherever suitable sedimentary sequences are found.

Climate

Malawi has markedly seasonal climate, and rain is largely associated with the migration of the Inter-Tropical Convergence Zone (ITCZ) and the associated Equatorial Troughs which bring the region alternately under the influence of the SE trade winds and the monsoons from the North. However climatic conditions are complex due to the wide topographic variation and the influence of Lake Malawi. For instance rainfall is much higher in the highlands than the low lands (Figure 4). Temperatures are also closely related to altitude, and the effect of latitude is much less significant. Mean annual temperature is 22–23 °C. Pan evaporation is closely related to topography. The annual pan evaporation is 1,500–2,000 mm on the plateau areas and 2,000–2,200 mm along the lakeshore and in the shire valley plain.

Groundwater occurrence

Groundwater occurrence in Malawi is controlled by the extreme topography and lithological and structural variation in rock types. It occurs in three main aquifers namely weathered basement, fractured and fault zones, and alluvial aquifers.

Weathered basement aquifer formation

Prolonged in situ weathering of crystalline basement has produced more or less a continuous and persistent layer of unconsolidated material termed as Saprolite. The granular horizons within the zones of the saprolite form the important aquifers and are generally the sources of good yields through boreholes. The thickness of the saprolite ranges from 5 to 25 metres. Borehole yields vary depending upon the composition of the saprolite. If the saprolite consists of clay, nearly a dry borehole is the result of drilling. However, yields as high as 7 to 10 m^3/h are obtained from the boreholes penetrating the granular horizons in saprolite. At places alluvial deposits consisting of clay, sand and gravel overlie the saprolite. At such places the yield could be much higher and could exceed 10 m^3/h.

Aquifer characteristics

Transmissivity of the aquifers are generally in the range of 5 to 35 m^2/d. The estimated hydraulic conductivities of the weathered basement aquifers range from 0.01 to 1 m/d. The storage coefficient for the weathered basement has not been determined as there were no observation

wells for all the pumping tests carried out. However because of the semi-confining nature of the clay matrix overlying the aquifer it is assumed that the storage coefficient ranges from 0.01 to 0.001. The aquifer characteristics of the neighboring states may have been fully determined but such information is not shared to jointly manage these aquifers.

Groundwater is commonly first struck near the base of the clays and usually rises (sometimes by several metres) above the base of the clay. This suggests that the groundwater is under unconfined to confined conditions. The piezometric level generally follows the topography and is closer to the surface in the valley parts and deeper away from the valley.

Groundwater resources development

Malawi has renewable fresh water resources of about 3,000 cubic metres per capita per year but its distribution is very variable seasonally and across the country. Apart from the Lake Malawi and the Shire river plus other smaller rivers which are perennial, the rest of the surface network of flowing water bodies dry out or collect into pools for nearly six months during the dry period of the year. Therefore groundwater provides the only alternative and reliable source of water supply for, especially, the rural areas and some urban centers.

The existing development, utilization and management of groundwater lack sustainable strategies, despite its extensive use for rural water supply. The monitoring and assessment of groundwater is almost non-existent. Donors, non governmental organisations and Government departments construct boreholes without agreed and consistent control, coordination and regulation policies and legislation for the implementation of boreholes development and construction programmes. The boreholes construction industries are equally uncontrolled and unregulated to check compliance with standards and protect the water resources from degradation and the public from malpractice. In fact very little groundwater research programmes are being done to improve the development and management technologies. Most areas in Malawi cannot have boreholes with adequate supply for irrigation or urban water supply due to limitations in the understanding of groundwater hydraulics and appropriate technologies.

However the developed water supply systems are vulnerable to the effects of drought and unreliable dry season flows. Following the failure of 1991–1992 monsoons, Malawi suffered the worst drought in over 40 years and this affected a number of states in the region. Many rivers feeding piped water systems to towns dried up for extended periods. In the rural areas most shallow wells dried out placing increased pressure on working boreholes. Increasing use was made of unsafe surface sources such as Lake Malawi. Large number of boreholes failed but how many failed due to falling groundwater levels and how many failed due to maintenance problems (exacerbated by increased use) is unclear.

In order to protect the present and future investments and usage there is need for a comprehensive monitoring network for establishing early warning systems. Numerous systems have been set up to give early warning of food shortages, particularly in relation to drought. Similar systems are needed to detect the early symptoms of water stress.

Drought is a normal, recurring event in this part of Africa and should be treated as such. Institutional planning is very limited but vital to the successful mitigation of groundwater drought. In Malawi efforts were concentrated on emergency borehole drilling programs. These are hastily planned and of limited benefit during the drought and in the long-term.

Groundwater resources in Malawi are often developed based on single user and single purpose. It is purely developed for domestic purpose. There is little regard to multi-purpose nature of groundwater resources exploitation. At present 16,000 boreholes have been drilled and these serve 40% of the rural population. Of the total 12 million, 5.5 million people would be dependent on groundwater as a source of safe water and about 25,000 boreholes equipped with handpumps will be required.

Groundwater monitoring

A few recorders were installed in 1980 in some observation wells. These consist of manual and automated measurements of the fluctuations of piezometric levels. Unfortunately these boreholes with recorders are not spread in all aquifer systems to have monitoring coverage of the response due to the onset of drought and increased pumping.

According to Smith Carrington et al. (1983), available water level data suggested that groundwater levels in the alluvial basins fluctuate by about 1–3 m on a seasonal basis. Groundwater levels were monitored from 1981–1983

and meanwhile the equipment is either vandalized or spare parts are not procured to have them repaired.

Generally, groundwater levels are measured at the time of borehole construction and subsequently only when the handpump is removed for repairs. The reliability of these later readings is suspect.

Groundwater recharge

The amount of recharge received by these aquifers is important in determining the safe yield which can be abstracted from that aquifer in conjunction with a knowledge of storage. It also allows the effects of 'mining' or over-abstraction to be quantified and economically evaluated if requirements exceed the safe yield. In Malawi estimates of recharge have been done in the alluvial aquifer using a variety of methods such as analysis of river hydrographs, groundwater level fluctuations, flow nets and catchment water balances. Results obtained were variable. Estimated recharge in the alluvial aquifers in Malawi is 1 to 7 % of rainfall. It was therefore concluded that recharge is directly related to rainfall and rainfed recharge vary spatially with the permeability of surface deposits. Also recharge by seepage from more permeable river beds is likely to be concentrated to the escarpments. This is an area that requires more work to be done to evaluate the potential of the existing aquifers on the basis of replenishment.

Groundwater resource availability

The Government of Malawi has embarked on borehole drilling programmes to supply water to the rural inhabitants. It is always thought that there must be enough recharge to support the present and medium-term future domestic water requirements. Meaningful quantification of groundwater resources in Malawi has not been done.

Groundwater quality

The quality of groundwater in the weathered basement complex aquifer is generally acceptable although localized groundwater quality problems do occur due to high concentration of salts. In the alluvial aquifer groundwater is more mineralized. The main agents affecting groundwater quality are iron, fluoride, sulphate, nitrate, chloride and total dissolved solids (TDS). Where TDS are low this suggests that groundwater is derived from relatively recent recharge.

Conclusion

The existing hydrogeological data in Malawi suggest the existence of an extensive weathered rock aquifer system in the plateau area which would provide adequate amount of water to the rural inhabitants. Equally important are those areas with substantial alluvial deposits where high yields could be obtained for irrigation use. A comprehensive National groundwater resource assessment and evaluation need to be initiated. A joint management of these international aquifers should be encouraged to ensure protection, equitable sharing, and rational use of the aquifers through the establishment of regional and sub-regional frameworks.

État de la connaissance des eaux souterraines au Mali

Malick Alhousseini

Direction nationale de l'hydraulique
Bamako, Mali

Le Mali est un pays enclavé de l'Afrique de l'Ouest qui couvre une superficie de 1.204.000 km^2. il s'étend entre les latitudes 10°30′ S et 25°00′ N et les longitudes 12°00′ O et 4°00′ E. Le Mali est limitée au Nord par l'Algérie, à l'Est par le Niger, au sud par la Guinée, la Côte d'Ivoire, au sud Est par le Burkina Faso, à l'Ouest par le Sénégal et au Nord Ouest par la Mauritanie.

La population du Mali est d'environ 10 millions d'habitants dont 80 % sont des ruraux répartis dans 11.700 villages. Le taux de croissance de la population tourne autour de 3 % an.

Les principales activités sont l'agriculture et l'élevage.

Les caractéristiques critiques climatiques du Mali sont liées à sa continentalité et à l'absence de reliefs marqués pouvant perturber de déplacement du front intertropical qui conditionne le régime des précipitations et l'alternance des saisons. Le climat au Mali est tropical avec une saison sèche de 6 à 9 mois et une saison pluvieuse. La hauteur des pluies varie de 1000 mm au Sud à 200 mm au Nord.

Le pays connaît depuis une trentaine d'années une grave sécheresse qui a entraîné la baisse des précipitations, des nappes souterraines et ralentit le développement socio-économique du Mali.

Au Mali les cours d'eau permanents sont localisés dans le sud du pays et les principaux sont :

- le Sénégal : 1700 km dont 850 km au Mali,
- le Niger : 4200 km dont 1700 km au Mali.

Ces deux fleuves et leurs affluents constituent une importante source d'eau dont le potentiel est estimé à 70 milliards m^3 en année moyenne et 30 milliards en année sèche.

La majeure partie de la population du Mali est localisée le long de ces cours d'eau qui fournissent aussi l'essentiel de besoins énergétiques.

La concentration humaine animale industrielle et agricole de long des deux fleuves a rendu leurs eaux polluées et doivent faire l'objet de traitement avant consommation.

Les formations géologiques représentées au Mali couvrent les principaux ensemble stratigraphiques définis pour la géologie de l'Afrique ; avec de la périphérie vers l'intérieur du pays des séries de plus en plus récentes. Le Mali occupe la majeure partie du bassin sédimentaire de Taoudenni.

Les ressources en eaux souterraines du Mali

Les réserves en eaux souterraines du Mali sont estimées à 2 700 milliards de m^3 avec une capacité de renouvellement annuel à partir des eaux de pluies et cours d'eau égale 66 milliards de m^3 d'eau.

Elles sont contenues dans 9 systèmes aquifères profonds classés en deux catégories.

I. Aquifères généralisés

Ces aquifères sont caractérisés par une perméabilité de type intergranulaire et par des nappes continues couvrant la majeure partie des régions sahéliennes et désertiques de l'Est et du Nord pour une superficie de plus de 630 000 km^2 (51 %) de la superficie du Mali. Ils sont constitués par des formations essentiellement détritiques et d'origine continentale qui se sont accumulées depuis le Secondaire dans trois vastes bassins sédimentaires.

- le bassin de Taoudenni,
- le détroit Soudanais,
- le bassin du Niger.

L'épaisseur de ces formations essentiellement sablo-argileux varie en fonction des mouvements

orageniques qui se sont produits dans leur aire de sédimentation durant la fin du Secondaire et du début du Tertiaire.

Les aquifères généralisés du Mali ont des extensions vers le Niger, l'Algérie, la Mauritanie et le Burkina Faso. Les principaux sont :

a) L'aquifère du Continental intercalaire

Le bassin du continental intercalaire au Mali est l'extension géologique du bassin des Inllemimeden ou proprement dit Bassin Mali-Niger. Il est d'une grande importance pour notre pays à cause de son prolongement vers le Niger et l'Algérie.

L'épaisseur des formations du continental intercalaire (grès, sables, conglomérats) est de l'ordre de 1500 m. Dans la partie de l'Est de l'Adrar des Iforas, l'alimentation principale provient de l'Aïr et peut atteindre 116 millions m^3/an. Par manque de données, il est difficile d'estimer l'importance de l'alimentation dans la zone au Sud et à l'Ouest de l'Adrar des Iforas.

Le coefficient de perméabilité varie entre 0,01 et 0,1 m/h. L'eau est toujours douce et les résidus secs ne dépassent pas 100 mg/l. Les zones favorables à l'exploitation sont dans la vallée de l'Azaoud avec des débits spécifiques de 4 à 6 m^3/h.

b) L'aquifère du crétacé

L'aquifère du bassin du crétacé est la continuation du bassin d'Iullemeden (Mali/Niger). L'épaisseur des formations du crétacé dans l'ensemble est de l'ordre de 300 à 400 m dans la partie Est de l'Adrar des Iforas et 100 m dans la partie Ouest. Les alimentations proviennent des pluies tombant sur les affleurements.

L'importance de l'alimentation totale est de 65 millions de m^3/an. Le coefficient de perméabilité est de l'ordre 1,2 au sud et 0,6 m/h au Nord. Les résidus secs varient de 400 à 5 000 mg/l.

La zone favorable à l'exploitation se trouve au sud de l'Adrar des Iforas et les débits spécifiques sont de l'ordre de 1 à 3 m^3/h/m.

c) L'aquifère du continental terminal

Il couvre un grand territoire et l'épaisseur des formations varie entre 10 et 200 m. l'alimentation principale provient des eaux de pluies tombant sur le bassin versant de la vallée de l'Azar et sur les affleurements des ses formations.

L'importance de l'alimentation est de l'ordre de 0,8 millions de m^3/an. Le coefficient de perméabilité varie 0,4 à 0,01 m^2/h. Les eaux sont douces et ne contiennent pas plus de 700 mg/l de résidus secs.

Les données disponibles sur ces 3 aquifères ne permettent pas aujourd'hui de déterminer toutes leurs caractéristiques. Des études supplémentaires sont indispensables et cela en collaboration avec les pays voisins.

II. Aquifères fissurés

Ils sont semi-continu ou discontinus. Ils sont caractérisés par leurs faibles perméabilités intrensèques. Les ressources en eau proviennent de la fissuration dans la partie profonde de la formation ou de l'altération de leur partie supérieure.

Ces aquifères s'étendent au Centre et au Sud et à l'Est du pays et se retrouvent dans des formations cristallins et sédimentaires du Précambrien et du Primaire à savoir :

- le primaire de Taoudenni (calcaires, grés),
- le cambrien (schiste, Sholes, calcaires, grès),
- l'infracambrien tabulaire (grès, grès schisteux et schistes),
- l'infracambrien plissé métamorphique (schistes, calcaires),
- le socle granitique (granites, grauweckes, mécaschistes).

L'essentiel des forages réalisés au Mali ont été exécutés dans les aquifères fissurés. La profondeur dans ces formations varient à 35 à 90 m. Les débits moyens varient entre 3 à 6 m^3/h. les niveaux statiques sont autour 20 à 35 m. Le taux de succès est de l'ordre 40 à 70 %.

III. Aquifères du recouvrement ou aquifères superficiels

Des formations récentes, en général meubles ou peu consolidées, d'âge et d'origine variée couvrent la majeure partie du Mali. Elles constituent le premier réservoir interceptant les eaux d'infiltration issues des précipitations et du ruissellement. Elles ne forment cependant des aquifères exploitables que lorsqu'elles bénéficient d'un rechange périodique suffisante pour compenser les pertes occasionnées par l'évaporation.

Les nappes peuvent être semi-continues (quand la pluviométrie dépasse 400 mm / an) ou locales (par infiltration directe des eaux de ruissement dans les zones Nord sahéliennes et désertiques).

Les aquifères fissurés et de recouvrement du

Mali dépassent les frontières du Mali et se retrouvent en Côte d'Ivoire–Sénégal, Guinée–Burkina-Faso.

Les 30 années de sécheresse ont poussé les autorités maliennes à faire de l'approvisionnent en eau des populations une priorité. Aussi, grâce à l'aide des partenaires aux développements et des populations, le Gouvernement a initié et exécuté plusieurs projets. Ces actions ont permis d'atteindre les résultats suivants :

- 8 244 puits modernes,
- 21 013 forages dont 14 726 positifs et 11 876 équipés de pompes,
- 156 centres urbains et ruraux équipés d'adduction sommaire,
- 27 centres urbains équipés d'adductions d'eau dont 16 gérés par l'EDM.

Aujourd'hui le taux de satisfaction des besoins en eau potable en milieu rural est de 52 % et en milieu urbain et semi-urbain il est de 47 %.

Ces résultats montrent que beaucoup d'efforts restent à faire car 5 600 localités du Mali ne bénéficient encore d'aucun point d'eau moderne et à cela il faudra ajouter les besoins industriels et agricoles qui ne cessent d'accroître. Pour mener à terme la politique de la gestion de l'eau le Gouvernement a adopté les dispositions suivantes :

- La loi 90-17/AN-RM du 27 Févier 1990 fixant le régime des Eaux au Mali ;
- Le projet de loi portant Code de l'Eau au Mali ;
- L'ordonnance du 15 Mars 2000 portant organisation du service public de l'eau potable ;
- La stratégie Nationale d'alimentation en milieu rural et semi-urbain ;
- Le 95-034 portant code des Collectivités Territoriales qui accord au conseil municipal la responsabilité de la politique de création et de gestion des équipements hydrauliques et d'assainissement.

Le Mali pour forfaire sa politique en eau de gestion des ressources en eaux souterraines, a besoin de connaître la réelle dimension de la ressource. Pour cela beaucoup d'études supplémentaires s'avèrent indispensables notamment dans le Nord et l'Est du pays. Dans ces zones où la densité de la population est faible, très peu de forages d'eau ont été réalisés et cela ne permet pas de connaître les différents paramètres des aquifères et surtout celles que l'on partage avec les pays voisins.

Il est indispensable de lancer des études régionale en collaboration avec la Mauritanie, l'Algérie, le Niger, le Burkina Faso pour mieux connaître le régime hydrogéologique des différents bassins que nous partagerons. Le Mali a aussi besoin aujourd'hui d'un véritable appui institutionnel pour structurer le secteur de l'eau et l'adapter au contexte de la décentralisation administrative et de l'intégration des économies africaines.

Des besoins énormes en formation, équipements scientifiques et financiers sont indispensables pour connaître et maîtriser les ressources en eaux souterraines du pays.

La mise en place d'un arsenal juridique avec les pays voisins est indispensable pour une gestion rationnelle et paisible des aquifères partagés.

État des connaissances des aquifères Grands bassins sédimentaires au sud du Sahara : approche stratégique

Bassirou Diagana

Hydrogéologue
Expert en ressources en eau et en environnement
(Mauritania)

Résumé

L'espace couvert par les aquifères des grands bassins sédimentaires au sud du Sahara correspond aux pays sahélo sahariens limitrophes du Sahara. Cet espace couvre à lui seul plus de 5 millions de km^2 qui se répartissent d'ouest en est sur le Sénégal, la Mauritanie, le Mali, le Niger et le Tchad. La Guinée Bissau et la Gambie, bien qu'étant situés plus au sud et ayant un climat guinéen, constituent une zone privilégiée et favorable à la réalimentation sénégalo-mauritanienne du bassin aquifère.

Les bassins aquifères du Sénégalo-mauritanien

Il doit être désormais une priorité pour les États. Contrairement aux pays du nord du Sahara, les aquifères au sud sont relativement peu exploités.

Actuellement, l'état des connaissances est basé sur les synthèses de nombreux programmes d'hydraulique villageoise réalisés dans le cadre de la DIEPA. Ces programmes, bien que mis en œuvre pour l'AEP des villages ayant subi les effets néfastes de la sécheresse, constituent une source importante de renseignements pour entreprendre une étude approfondie des aquifères. Des études spécifiques de recherche étant coûteuses et ne constituant pas une priorité des États par rapport à l'équipement des villages en points d'eau, elles sont peu développées.

Malgré tout, les caractères généraux des aquifères des grands bassins sédimentaires sont déjà connus. En 1976, l'aire soudano-sahélienne, qui correspond du point de vue géographie et climatologie à l'espace du sud Sahara, a fait l'objet d'études de la part du Comité interafricain d'études hydrauliques (CIEH). Depuis lors, suivant l'importance accordée à l'exploitation de ces ressources, certains pays ont mené des études ponctuelles, mais indispensables pour la régionalisation de la connaissance des bassins.

La stratégie mise en œuvre pour une meilleure connaissance de ces aquifères est déjà amorcée par l'OSS. La tenue d'ateliers régionaux, initiés depuis près d'une décennie, des pays concernés et des partenaires scientifiques constitue un cadre efficace de cette coopération de la conception OSS sur la « Conscience bassin ».

La présente communication est relative à l'étude sur l'état des connaissances des ressources en eau souterraines dans les pays au sud du Sahara. Cette étude a été réalisée pour le compte de l'Observatoire du Sahara et du Sahel (OSS) en 1997. Le programme d'étude des aquifères profonds au sud du Sahara a été initié en 1992 par l'OSS en partenariat avec le CIEH, qui a réalisé le premier bilan-analyse des connaissances et a fait l'objet d'une publication en 1994. Elle est déjà présentée à l'atelier sur une meilleure connaissance des aquifères des grands bassins sédimentaires qui s'est tenu à Niamey en 1996.

L'objectif final recherché par cette étude est, autour de ce que l'on a appelé « Conscience de bassin », de créer un cadre de concertation pour un partage des ressources communes et la nécessité d'agir ensemble pour leur exploitation. Cette « Conscience de bassin », doit, pour chaque bassin, s'organiser par un échange d'informations et de données.

Cadre géographique

Identification des aquifères profonds au sud du Sahara

Les aquifères des bassins sédimentaires au sud du Sahara concernent, d'ouest en est : la Mauritanie,

le Sénégal, le Mali, le Niger et le Tchad. Leur extension couvre d'autres pays, peu influencés par les effets néfastes des grandes sécheresses que le Sahel a connu au cours des années 70, tel que la Guinée Bissau. Tous transfrontaliers, les aquifères de ces bassins s'identifient plutôt aux pays dont ils ont emprunté le nom.

Extension des bassins

Tous les bassins aquifères concernés par cette entité au sud du Sahara sont transfrontaliers (voir Tableau 1). Ce caractère impose un effort conjugué des uns et des autres en vue d'entreprendre des actions communes pour leur meilleure connaissance.

État des connaissances des ressources en eau

Eaux de surface

Malgré la situation géographique et le caractère du climat, les grands cours d'eau de l'Afrique de l'Ouest qui prennent leur source presque entièrement dans les monts du Fouta-djalon en Guinée, jouent un rôle capital dans le cycle hydraulique des pays concernés.

Les bassins versants hydrologiques pouvant avoir un apport avec les aquifères des grands bassins sédimentaires du sud du Sahara sont présentés sans le Tableau 2.

Au regard de leur régime et des zones traversées, les cours d'eau de ces bassins constituent les sources essentielles de recharge des régions qu'ils arrosent.

Eaux souterraines

Bien qu'elles ne constituent pas encore un enjeu entre les États partageant un même bassin aquifère, les eaux souterraines constituent les ressources essentielles de toute la partie septentrionale des pays concernés. Seules sources alternatives de cette zone, elles ont été sollicitées à grande échelle à partir des années 70 dans le cadre de la Décennie internationale de l'eau potable et l'assainissement (DIEPA). Depuis lors, de nombreux programmes de captage, tant au niveau de l'État qu'au niveau des particuliers, sont mis en œuvre, dans le seul but de l'approvisionnement en eau des populations et du cheptel.

En l'état des connaissances actuelles, les caractéristiques des aquifères des différents bassins sédimentaires sont résumées dans les tableaux suivants.

Exploitation

L'exploitation actuelle des eaux souterraines au sud du Sahara est presque exclusivement destinée aux besoins humains. Les autres besoins

TABLEAU 1

Nom du bassin	*Pays concernés*	*Superficie du bassin (km²)*
Sénégalo-mauritanien	Mauritanie, Sénégal, Gambie, Guinée Bissau	240 000
Toudéni	Mauritanie, Mali, Algérie	500 000
Iullemeden	Mali, Niger, Algérie, Nigeria	200 000
Tchad	Tchad, Niger, Nigeria, Cameroun	350 000
Total		1 290 000

TABLEAU 2

Bassin versant	*Pays concernés*	*Superficie du bassin versant (km²)*
Sénégal	Guinée, Mali, Sénégal, Mauritanie	34 000
Gambie	Guinée, Sénégal, Mauritanie	80 000
Niger	Guinée, Sénégal, Gambie, Guinée Bissau	200 000
Tchad	Cameroun, Niger, Nigeria, RCA, Tchad	2 500 000

industriels et agricoles sont encore relativement peu importants et leur part dans les volumes totaux peut paraître peu significative malgré la multiplication des industries (voir Tableau 3).

État de la recherche scientifique

La recherche scientifique dans le domaine des eaux souterraines n'est pas encore une priorité au niveau des gouvernements, qui s'attèlent beaucoup plus à l'équipement des villages en points d'eau.

Toutefois, malgré leur budget limité, mais en association avec d'autres institutions de recherche du nord, les universités mènent des activités encourageantes pour une meilleure connaissance des aquifères. C'est dans ce sens que des travaux géophysiques (parfois liés à la recherche pétrolière), de piézométrie et de modélisation de certains aquifères sont menés notamment dans le bassin sénégalais.

Les piézomètres permettraient d'évaluer et/ou d'estimer l'apport du fleuve dans la réalimentation des aquifères du bassin sénégalo-mauritanien. Malheureusement, depuis près de sept ans, le réseau Mauritanien n'a fait l'objet d'aucun suivi.

Les modèles les plus significatifs et constituant un apport essentiel vers une meilleure connaissance des aquifères sont ceux établis sur les champs captant de IDINI et de BOULANOUAR alimentant respectivement Nouakchott et Nouadhibou d'une part et les models réalisés au Sénégal d'autre part.

Contraintes d'exploitation

La priorité des gouvernements étant d'abord la desserte des populations en eau par rapport à une meilleure connaissance des systèmes d'eaux souterraines constitue déjà un handicap à la régulation des exploitations, qui demeurent une composante de l'étude des aquifères.

Par ailleurs, l'adéquation entre les besoins à satisfaire et le volume d'eau exploitable est très souvent occultée dans les programmes de développement. Aussi la gestion des ressources qui en dépend connaît-elle toujours de fortes contraintes liées à l'insuffisance des dispositions réglementaires (décrets d'application devant d'une part, délimiter le domaine de chacun des intervenants du secteur de l'eau, et d'autre part, favoriser une meilleure police de l'eau).

L'eau étant la base de tout développement socio-économique durable, cet élément doit être pris en compte par tous les programmes des autres secteurs (développement du cheptel à travers les zones de transhumance…). Au-delà de cet aspect législatif, l'une des contraintes majeures se situe d'une part, au niveau de la coordination entre les différents intervenants, et d'autre part, au niveau du manque de communication des données et des informations et leur harmonisation.

Les paramètres essentiels à collecter à travers la mise en place d'un réseau de surveillance sont :

- niveau stratégie - flux entrants,
- niveau dynamique - plus sortant,
- débits - qualité.

Or, il n'existe pas encore, même au niveau national et encore moins au niveau régional, une

TABLEAU 3

		Mauritanie	*Sénégal*	*Mali*	*Niger*	*Tchad*
Besoin	AEP		1 103 106 m^3/j		7.10^7–1.10^8 m^3/j	
	AEI		62 430 m^3/j		2 10^7 m^3/j	
	Agriculture		5 331 106 m^3/j		108 m^3/j	
Utilisation	AEP		463 220 m^3/j		25 l/h/j	
	AEI		52 020 m^3/j		2 106 m^3/j	
	Agriculture		130 109 m^3/j		5 108 m^3/j	
Taux de satisfaction	AEP		51 %		59 %	
	AEI		40 %		couvert	
	Agriculture		42 %		couvert	

méthodologie commune de collecte de ces données pour pouvoir suivre un aquifère dans son ensemble.

Approche pour une meilleure connaissance des aquifères

L'approche déjà menée par l'OSS constitue la seule alternative dans un cadre sous-régional pour tendre vers une meilleure connaissance des aquifères.

L'espace OSS est constitué de deux zones : les pays situés au nord du Sahara et ceux situés au sud. Les pays du sud du Sahara comprennent quatre grands bassins hydrogéologiques. Après un atelier de mise en œuvre du projet, un document a synthétisé l'état des connaissances actuelles. Des ateliers spécifiques sont initiés pour chaque bassin aquifère. C'est dans ce cadre que s'est tenu, en juillet 1999, le premier atelier sur le bassin des Iullemeden, suivi, en juillet dernier, par une session de formation sur la modélisation mathématique.

L'organisation de cette dynamique doit se poursuivre et bénéficier aux autres bassins, à savoir :

- Le bassin sénégalo-mauritanien,
- Le bassin en Taoudenni,
- Le bassin du Tchad.

Conclusion et recommandations

Les ressources en eau douce en Afrique ne présentent pas le même niveau de connaissances suivant que l'on se trouve dans sa partie septentrionale ou dans les pays du sud du Sahara, tant au niveau des aquifères généralisé que pour les nappes à comportement discontinue. L'enjeu n'est également pas le même dans les deux entités. En tout état de cause, des mesures doivent être menées en vue d'une meilleure connaissance de nos ressources en eau douce qui constituent déjà un facteur limitant et militant de toutes les actions de développement durable. C'est dans cette perspective que l'OSS à entrepris, depuis près d'une dizaine d'années, l'approche de la « Conscience de bassin », basée essentiellement sur les capacités propres des États par la concertation et l'échange de données et d'informations, mais également par l'organisation de sessions de formations, d'ateliers et de séminaires.

Groundwater management in Mauritius

Rajeshwar Pokhun

Vice-Chair of the SADC sub-committee for hydrogeology

Introduction

Mauritius is of volcanic origin. The geology consists of a relatively impermeable stratum made up of the ancient lavas (8 to 5 million years) underlying flows from the Intermediate series (3.5 to 1.5 million years) and Recent series (1.5 million years to 25,000 years).

There are five main aquifers in Mauritius located in the Recent and Intermediate series and which accounts for most of the groundwater water of Mauritius.

The groundwater potential has been estimated at 390 Mm^3.

Groundwater has been used in Mauritius as from the eighteen century through large diameter ,hand-dug wells. The first scientific exploration and exploitation of groundwater was undertaken in the mid-nineteen sixties under the FAO sponsored study. Since the nineteen seventies, intensive hydrogeological investigations have been carried out all over the island. To date more than 1,500 boreholes (150–300 mm diam.) and coreholes (50–100 mm diam.) have been drilled.

Groundwater utilisation in Mauritius

Presently there are 350 boreholes in use in Mauritius. These are classified as follows:

Number of boreholes in use	: 350
Potable	: 110
Industrial (private)	: 112
Agriculture (private)	: 128

The contribution of groundwater to potable water supply is about 57%.

The overall contribution of groundwater is 15%.

Groundwater legislation

- The Groundwater Development and Management is governed through the Ground Water Act of 1970.
- The protection of groundwater quality is controlled through the Environmental Protection Act of 1991.

Groundwater licensing

- A written authorisation is required from the authority (WRU/CWA) for any person who wish to drill a borehole.
- A groundwater licence is mandatory for any abstraction of groundwater.
- Groundwater licences are renewed annually for industrial boreholes and on a three year basis for agricultural boreholes.
- Authorisation for drilling of private boreholes and issue of groundwater licences are approved in a groundwater licence committee meeting after taking into consideration various technical aspects.

Groundwater information system

- There are a total of about 1,510 boreholes and coreholes in the WRU data base. Of these, about 450 are cored-drilled holes for exploration and geological/hydrogeological purposes.
- Hydrogeological data such as piezometric levels, pumping tests data, borehole and core-

hole logs, electrical resistivity, water quality and any other information/data pertaining to boreholes have been computerised and can be used in GIS.

Groundwater monitoring in Mauritius

- Mauritius has developed an excellent groundwater monitoring network over years. There are about 350 observation wells spread over the island to monitor groundwater level fluctuations on a monthly basis. Besides, our groundwater pumping stations for domestic use (110 boreholes) are also monitored on a 2-weeks basis and data such as pumping rate, dynamic water level etc… are collected.

- Twenty automatic data acquisition system (data loggers) have been recently installed in Mauritius and parameters such as water level, conductivity and temperature are being monitored continuously.

- One of these data loggers is also fitted with a GSM system and can be interrogated from our office.

- Freshwater-sea water interface are being controlled in coastal aquifers using specially designed observation wells. Water quality of boreholes in sensitive zones are also being monitored.

- Groundwater monitoring committee meetings are held regularly to assess, review and manage the groundwater situations.

- Boreholes used for domestic water supply are monitored on a 2-weeks basis. Dynamic water level and pumping rate are adjusted to maintain a stabilised dynamic water level, especially in dry seasons.

- Strict control is also exercised on private boreholes. Both Industrial groundwater and agricultural users submit groundwater abstraction on a monthly basis.

- Groundwater developments in heavily exploited zones are controlled closely.

- All pumping tests are carried under the supervision of the WRU & Well interferences are avoided.

- Production boreholes, observation wells, etc. in the vicinity are monitored during the pumping tests to assess well interferences.

Groundwater quality monitoring

- The chemical water quality of boreholes used for domestic water supply (110 boreholes) are monitored on a two-months interval (complete chemical analysis)

- Strict control is also exercised on private boreholes. Industrial groundwater users submit borehole water physico-chemical analysis and effluent analysis on a monthly basis.

- Major agricultural users submit results of chemical analysis of borehole water as and when required (twice a year), particularly in the sensitive zones.

- Environmental Impact Assessment Certificate is made compulsory for any activity that may represent risks for pollution to our environment.

- Standards for effluents to be discharged on lands.

- Standards for water to be used for irrigation purposes.

Coastal aquifer management

- Groundwater abstraction and quality are monitored closely in the coastal zones.

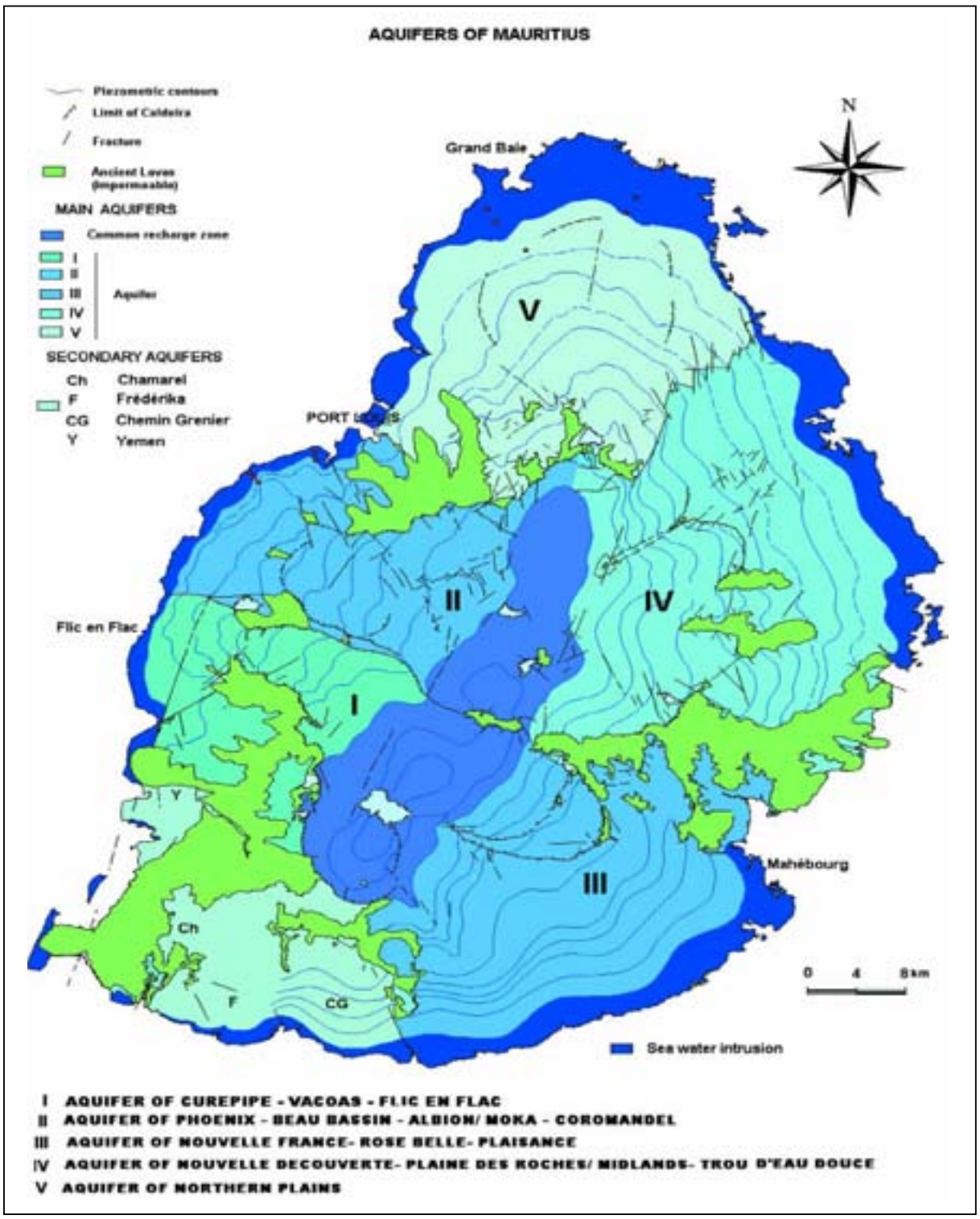
- Domestic water supply boreholes are monitored on a 2-weeks basis.

- Industrial and irrigation boreholes users keep a record of daily groundwater abstractions and submit same on a monthly basis.

- Authorisation for drilling of boreholes/issue of groundwater license are approved in a groundwater license Committee after taking into consideration various technical aspects.

- Dynamic water levels are kept high as possible.

- Sensitive zones have been frozen and no further groundwater development are being allowed.
- Monthly samples are collected in domestic water supply boreholes and major parameters are analysed.
- Industrial boreholes users submit monthly chemical analysis of borehole water.
- Irrigation boreholes users situated in the coastal aquifers submit chemical analysis of borehole water at least twice a year.
- Movement of freshwater-seawater interface are controlled by interface control piezometers.
- Spot checks are carried out regularly on specific boreholes to monitor the water quality.
- Data loggers have been installed at specific locations which records water level, conductivity and temperature continuosly.



International shared aquifers in Namibia

Swama Ndengu

Ministry of Agriculture, Water and Rural Development
Department of Water Affairs, Division of Geohydrology
Republic of Namibia

Introduction

Namibia is the driest country in southern Africa and depends largely on groundwater. However, groundwater resources, being closely associated with underground rock types that vary with the geological situation, are unevenly distributed across the country. There are only a few favourable places where high volumes of groundwater can be sustainable abstracted. Namibia's understanding of transboundary aquifers and their international experience in shared aquifer management are limited.

The management of the country water resources on a regional scale is the responsibility of the Department of Water Affairs. The management and approach to international aquifer is limited since the understanding and the quantification of regional groundwater system is also limited. In this document potential shared aquifers are identified and combined with all available information on these aquifers.

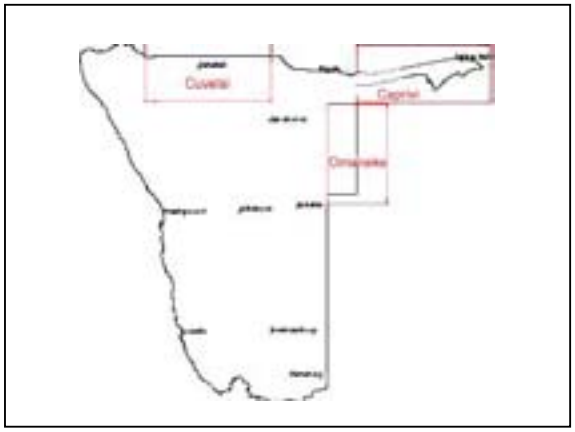


FIGURE 1. Map showing possible transboundary aquifers

Internationally shared aquifers in Namibia

There is minimal available literature on transboundary aquifers. Identification and investigation of other shared aquifers in Namibia hasn't been highlighted except the South-eastern Kalahari/Karoo Aquifer. The aim of this paper is to identify potential shared aquifers. Figure 1 shows possible areas that were identified except the Stampriet Artesian Basin that is part of the Kalahari/Karoo aquifers.

Caprivi Strip aquifer

Background of the shared aquifer system

The Caprivi Strip aquifer is shared by neighbouring Namibia, Botswana and Angola Recharge occurs in Angola and thus flowing down to Namibia and Botswana. The area is flat and is characterised by rather uniform geological conditions at the surface, dense vegetation and the highest rainfall and lowest evaporation rates in the country. Sediments of the Kalahari Sequence and more recent deposits overlie the entire area. Outcrops of underlying rocks are scarce and the geology is known to form a few exploration boreholes. Subsurface geology on the western edge is dominated by Damara Sequence consisting of a quartzitic sandstone and dolomite, partly covered by volcanic rocks in the central and western parts. The east subsurface is characterised by volcanic rocks that underlie the Kalahari sediments although sandstone of Etjo Formation are present in some parts.

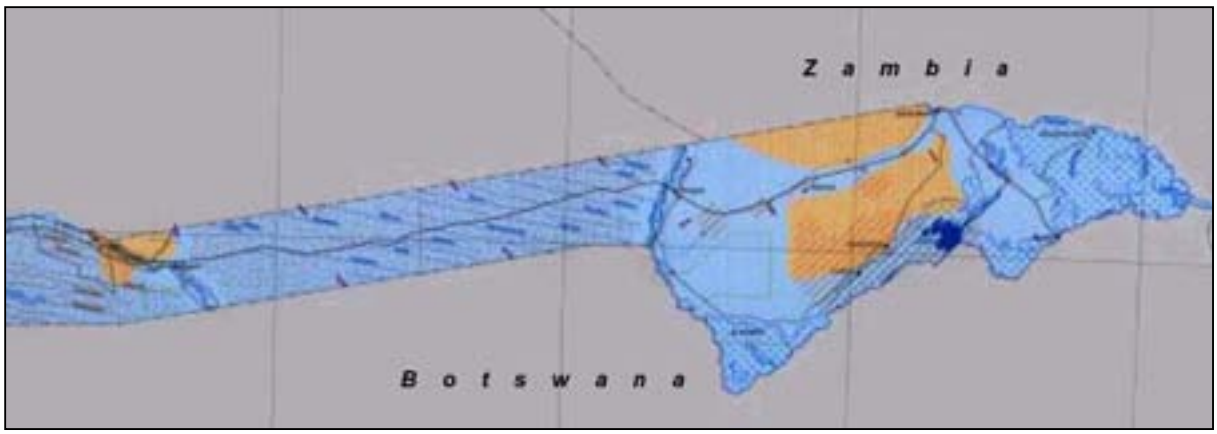


FIGURE 2. Caprivi Strip aquifer

Referring to Figure 2, the blue colour indicates high potential to medium potential porous aquifers while the brown indicates rock bodies with minimum or no potential of groundwater. The purple arrows indicate the groundwater flow direction. The groundwater flow is clearly form a North to South direction.

Beneficial uses of the water resources in the shared aquifers

The aquifer crosses in Angola, Namibia and Botswana. Information about the aquifer in Botswana and Angolan is limited. The water usage varies along the Namibian border. The main use of the water is usually for domestic and stock watering. There are however areas although not on the border itself that uses the water for irrigation, i.e. sugar plantation. Irrigation might have a long-term effect on the water-balance. The demand for water usage has already increased on the Namibian side.

The biggest constraint to the beneficial development of the resources is the lack of knowledge about the aquifer. A very few exploration boreholes where drilled in the area since it's quite expensive to drill borehole in the Kalahari sand due to the large volume of sand and the fact that boreholes not properly cemented collapse. The aquifer system is quite complicated, saline water is distributed all over the strip and the rate of successful boreholes drilled is low. The are no information available regarding the direct influence between countries due to non-existence of monitoring data, quantification of water usage, the actual recharge and flow regime of the aquifer systems. Recharge or aquifer replenishment cannot be quantified but it's known that the aquifer is replenished from floods in Angola.

There is no technical co-operation between the countries that share this aquifer. The resource management and approach to the aquifer by the various countries together is lacking.

Okavango–Epukiro basin

Background of shared aquifer

The Okavango-Epukiro basin is located at the north-eastern border between Botswana and Namibia. The aquifer system consists of several isolated interconnected aquifer system. The area has several parts, which are desolated, but where it is inhabitant water is mainly use for communities and stock watering.

The geohydrology division knowledge about the geology and geohydrology is limited. It is known that the area is covered by Kalahari sand and that the bedrock that underlies this huge sand-filled basin consists of various rock types. Outcrops of carbonate and quartzite of the Damara Sequence are present in several parts of the area. Dolerite dyke and sills occur in the area, but outcrops are scarce and it's only detected by geophysical methods. Recent geophysical surveys done in the area indicated the presence of dolomitic material especially in the Aha Hills. The aquifer has never been quantified and recharge mechanism has never been studied. The aquifer in Namibia altitude is higher downsloping to Botswana. Recharge thus occurs in Namibia and the groundwater flow direction indicates it. The population on the Namibian side of the aquifer hasn't been quantified but it's a very sparsely populated area and farmers living in the area always have water shortage problems.

The direct influence of abstraction on countries is not known since water use figure, recharge and flow regimes of the aquifer are not known. A monitoring program was recently erected in the area to have better understanding of the area.

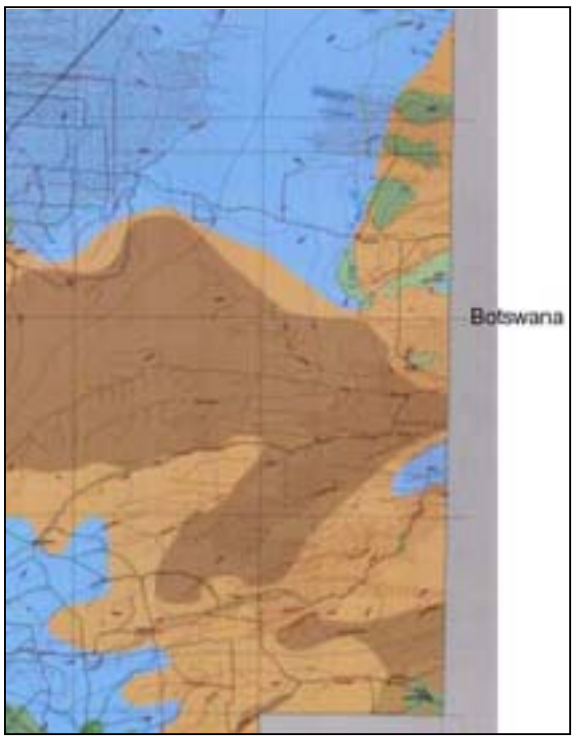


FIGURE 3. Okavango-Epukiro basin

In Figure 3 the green colour indicates the several-isolated fractured or karstified aquifer. These aquifers usually have a very high to medium potential of groundwater. The flow direction nearby the national border is visibly to Botswana. The brown colours indicates rock bodies with minimal or no groundwater potential.

Beneficial uses of the water resources in the shared aquifer

The current use of water is mainly for domestic and stock watering purposes. Occasional small-scale irrigation practices are found in the dolimitic areas where high yielding boreholes exists. The demand for water supply in Namibia, in on the increase. There is no information available about the water usage in Botswana. The water quality differs from good quality in the carbonatic areas to acceptable quality in the Kalahari sand aquifers.

Significant issues concerning the shared aquifer

The dolomitic areas are easily prone to groundwater contamination. Very little knowledge about the aquifer and its sustainability is known. The major issue at this stage is for all three countries to obtain a proper understanding of the aquifer for joint management of the resource. The countries can then work out a legal framework as to a common abstraction policy. The major issue at this stage is for involved countries to obtain a proper understanding of the aquifer for joint management of the resource.

Anticipated focus of the case study

The key focus of this case study will contribute to the improved understanding of the following:

- A proper understanding of the resource,
- The emplacement of institutional interaction between the countries,
- The outlining of a legal framework for joint management of the resource,
- The development of a 'groundwater treaty/ agreement'.

Cuvelai basin

Background of shared aquifer

The Cuvelai basin, including Etosha Pan, is part of the much larger Kalahari Basin covering parts of Angola, Namibia, Zambia, Botswana and South Africa. It contains a very thick series of rock of various ages. The basin floor consists of gneissic and granitic basement. The hydrogeological Cuvelai basin comprises the Omusati, Oshana, Ohangwena and Oshikoto regions and parts of the Kunene Region. Most of the land surface of the basin is very flat dipping from some 1,150 m above sea level (asl) in the north-east to 1,080 m asl in the Etosha Pan, which is the largest pan in Namibia. All drainage is thus in the direction of the Etosha Pan.

All the groundwater within the basin flows towards the Etosha Pan. This is due to the structure of the basin and the pan is the deepest point in the basin. The aquifer is recharged once a year from floodwaters from Angola, that flow via the oshanas into the Lake Opono and can even reach Etosha Pan in years of high flow.

In Figure 4 the green indicates fractured or karstified aquifers of high to moderate potential for groundwater. The blue indicates porous aquifer of high to moderate potential for groundwater. The brown indicates rock bodies with minimal or no groundwater potential. It's visible that groundwater flow is from Angola to Namibia. The horizontal stripes indicate that the water is saline.

Beneficial uses of the water resources in the shared aquifer

The Cuvelai Basin is the mostly densely populated area of Namibia and most of the inhabitants

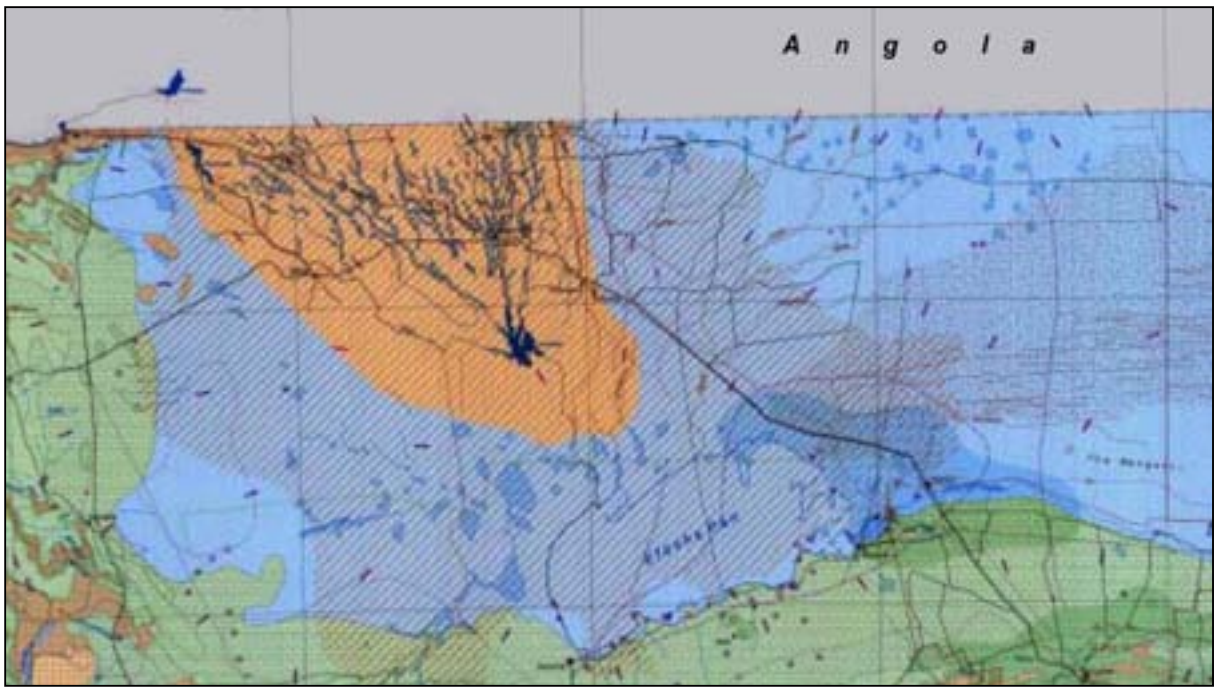


FIGURE 4. Cuvelai Aquifer basin

live in rural communities dependent on agriculture. The relative high and reliable rainfall (300 m/a to 600 m/a) allows dry land crop farming in addition to cattle and small stock farming. Light industries and businesses have been established in town like Oshakati. The groundwater usage is limited due to bad water quality. Many handdug well are found in the area but the groundwater is saline and only suitable for livestock watering.

Due to low rainfall this year this area is hit by severe drought. Studies are currently under way to understand the groundwater flow system and to investigate if fresh water is found below the saline water.

Constraints concerning the shared aquifer

The water quality of the basin varies from brackish to saline with local freshwater lenses on top of the saline water. The lenses form after flood events, mainly underneath the 'oshana' channels and the water quality deteriotes during the dry season. In general, the deeper aquifers, underlying the southern and eastern part of the basin are under artesian pressure. With this deep artesian aquifers an upper freshwater layer and a lower very brackish horizon (TDS = 6,700 mg/L) is found.

Drilling optimal production boreholes in the Kalahari Region is difficult and rather costly. Drilling deep boreholes in the Kalahari sand (>150) cost U$9,000 to U$15,000 (N$90,000 to N$150,000) and there is always the threat of the borehole collapsing if proper casing is not install directly after the boreholes has been drilled.

Anticipated focus of the case study

There is currently a German-Namibian project pending to study and investigating this aquifer. The study mainly focuses on finding fresh water lenses above and under the saline water. This will help to manage the aquifer advantageously and to drill successful wells.

The key focus of this case study will contribute to the improved understanding of the following:

- A proper understanding of the resource,
- The emplacement of institutional interaction between the countries.
- The outlining of a legal framework for joint management of the resource.
- The development of a 'groundwater treaty/ agreement'.

The major issue at this stage is for both countries to obtain a proper understanding of the aquifer for joint management of the resource. The countries can then work out a legal framework as to a common abstraction policy.

Kalahari/Karoo aquifer

Background of shared aquifer



FIGURE 5. Map showing boundaries of aquifer in Namibia and generalised flow directions

The aquifer is shared by Namibia, Botswana and South Africa although it is predominantly used in Namibia where most recharge probably occurs.

There is a comparatively good understanding of the geology and hydrogeology of the aquifer in Namibia (Fig. 6). Water occurs in the Auob and Nossob sandstones of the Ecca Group (lower Karoo Sequence), as well as in the overlying Kalahari. The dip of the formations is slightly (about 3 degrees) towards the southeast and in general the water quality deteriorates also in that direction. The current study is in the process of constructing a numerical model of the system where after it is anticipated that a management plan will be in place.

Population on the Namibian side is generally sparse with a greater emphasis being placed on irrigation and stock farming. Although the system is large, because of the uncertainty of recharge at this stage it is uncertain that the resource can sustain large irrigation schemes, so a conflict between irrigation and sustainability is currently envisaged.

Beneficial uses of the water resources in the shared aquifer

The Southeast Kalahari Artesian aquifer borders against the SW part of Botswana and the South African Kalahari National Game Park and then against the Gordonia District. In Gordonia the water quality of the Karoo aquifers appear to be very poor, like in the so-called Salt block in the southeastern part of the Artesian basin in Namibia.

At present water is used in Namibia for stock watering and increasingly for irrigation purposes. The system also supplies five smaller towns with water. By far the largest portion of the aquifer falls within Namibia, which is expected to have the largest demand from the system and where need, is expected to rise in the future.

Significant issues concerning the shared aquifer

The major issue at this stage is for all three countries to obtain a proper understanding of the aquifer for joint management of the resource. The countries can then work out a legal framework as to a common abstraction policy.

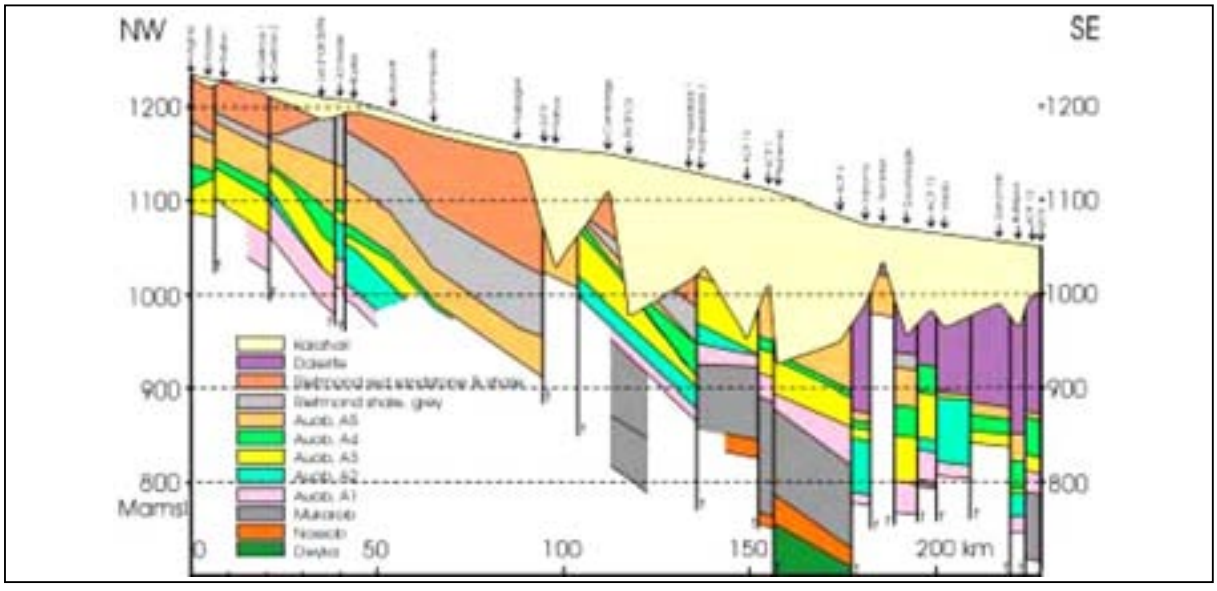


FIGURE 6. Cross-section from NW to SE of the area within Namibia

Anticipated focus of the case study

The key focus of this case study will contribute to the improved understanding of the following:

- A proper understanding of the resource,
- The emplacement of institutional interaction between the countries,
- The outlining of a legal framework for joint management of the resource,
- The development of a 'groundwater treaty/ agreement'.

Essential data in tabulated form (for Namibia)

Surface area: *65,000 km^2*
Pop. in the area: *Approx. 35,000*
Resources in storage: *In the process of being determined*
Current Ann. Prod.: *Approx. 5,000,000 m^3/ annum*
Potential development resource: *In the process of being established*
Mitigation of negative impacts: *Non at this stage*.

Conclusion

Groundwater plays a very important in a semi-arid country like Namibia. In rural communities groundwater is the only source of available fresh water. It is estimated that 80% of rural population rely solely on groundwater for their needs.

The regional importance of groundwater resources as a source of water supply is well known. However the beneficial use of these precious resources in an international framework is constraint. Namibia has three aquifers that are shared by neighbouring countries such as Botswana and Angola. The Stampriet Artesian Basin, which is part of the Kalahari/Karoo, is the only internationally shared aquifer in Namibia that is well studied and properly investigated. The ISARM (Internationally Shared Aquifer Resources Management) is using the Stampriet Artesian Basin as a case study. This aquifer is recharge in Namibia and flow thorough to Botswana. The water resources in Namibia are use for domestic purposes, stock watering and supply at least towns with groundwater. This resource is increasingly used for irrigation and the demand on the Namibian site is increasing annually.

The Cuvelai Basin aquifer is shared by Namibia and Angola. The aquifer is recharge from the fast floods in Angola and flows down in Namibia through the oshanas. The aquifer carry a considerable volume of water but the water quality varies from brackish to saline. The water quality is so poor that the water is only suitable for stock watering. In some parts it's not even suitable for the stock watering. It has been discovered from studies done recently that lenses of fresh water is overlying and underlain by saline water. Namibia is currently working on optimal method to abstract the fresh water without contamination from saline water. The Cuvelai Basin aquifer is one of the most densely populated areas and water demand is on the increase.

The Okavango-Epukiro and Caprivi basins are not well studied and define. The population in these areas are low. These two basins should be considered for future studies as possible international aquifers. The demand for water has also increased in these areas. This can create water shortage in some parts of the aquifer system if it's not fully understood.

There is a critical need to assess and understand the coupled regional ground and surface water systems in order to manage the resources optimally. Anticipate, mitigate impacts of droughts and reduce the risk of over exploiting the limited resources. There is a need to enhance capabilities and scientific strength on these shared aquifers. The major issue at this stage is for all countries to obtain a proper understanding of these aquifers for joint management of the resource. The countries can work out a legal framework to obtain a common abstraction policy.

Bibliography

CHRISTELIS, G. and STRUCKMEIER, W. 2001. Groundwater in Namibia – An explanation to the Hydrogeological Map of Namibia'. Windhoek, 2001.

ISARM: Info for Framework document – Kalahari/ Karoo Aquifer Case Study.

Caractérisation des systèmes aquifères transfrontaliers du Niger

Abdelkader Dodo

Hydrogéologue, Enseignant Chercheur
Directeur des Ressources en Eau
(Ministère de l'Hydraulique, de l'Environnement et de la Lutte Contre la Désertification, Niamey, Niger)

Introduction générale

Le Niger partage plusieurs bassins avec ses pays frontaliers (Fig. 1). Il s'agit du :

- grand bassin sédimentaire du Niger (Algérie, Mali, Niger, Nigéria),
- bassin du lac Tchad (Cameroun, Niger, Nigéria, Tchad),
- bassin du Djado- Bilma (Niger, Libye, Tchad),
- bassin du Tafassasset (Algérie, Niger).

A ces bassins sédimentaires s'ajoutent les *aquifères discontinus* du socle cristallin :

- de l'Aïr appartenant au Bouclier Touareg (zone *mobile* panafricaine) regroupant les massifs du Hoggar (Algérie) et de l'Adrar des Iforas (Mali),
- du Liptako-Gourma, partie du craton *stable* ouest africain (bouclier du Man), partagé par le Niger et le Burkina Faso.

La présente note se focalise essentiellement sur

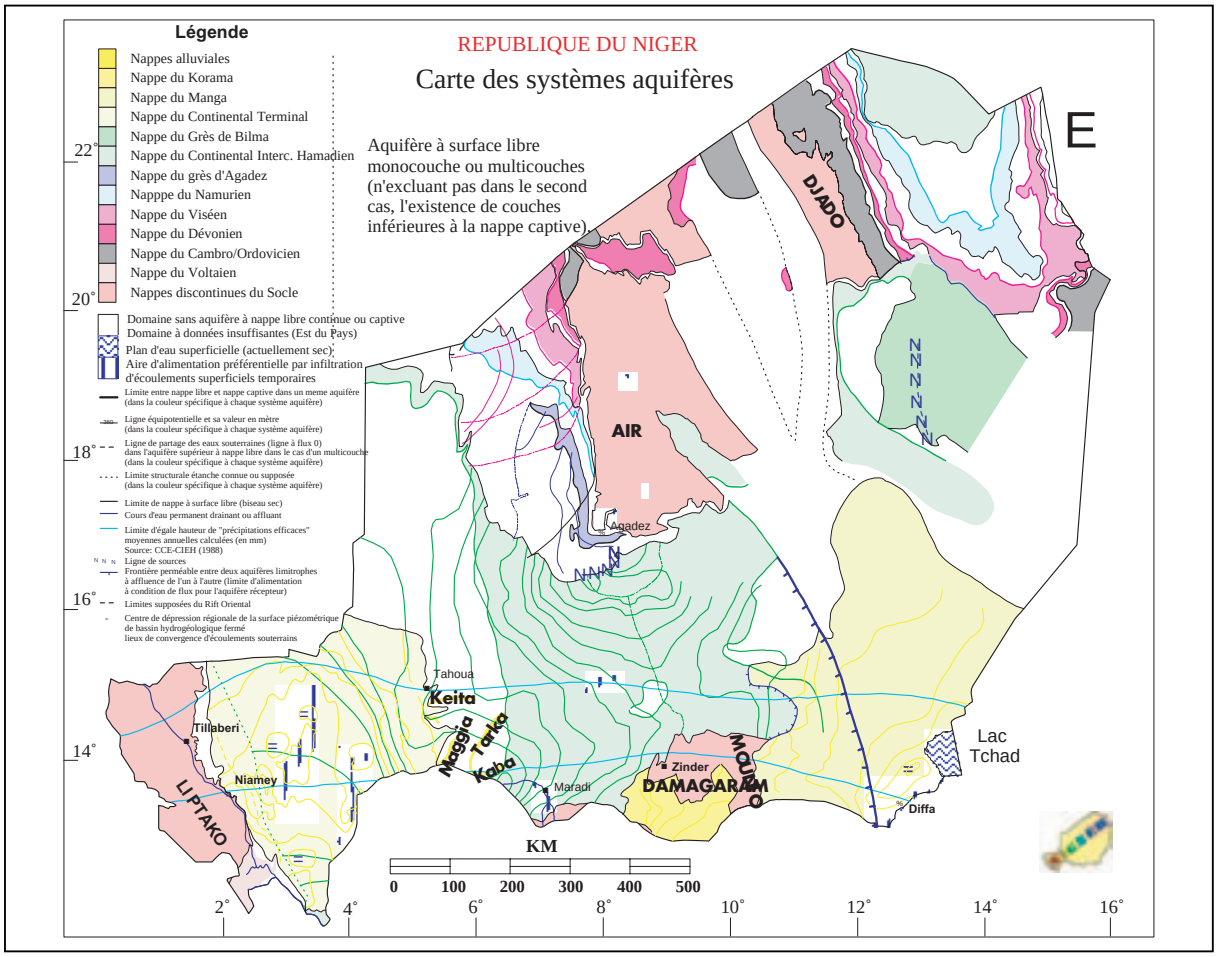


FIGURE 1. Carte des systèmes aquifères dans les bassins d'Iullemeden et du lac Tchad

les *aquifères continus* des bassins du Niger et du Lac Tchad, compte tenu du degré de connaissance sur les ressources en eau et du souci constant de la recherche d'une adéquation entre les ressources en eau disponible et de la demande sans cesse croissante exprimée par les consommateurs potentiels. En effet, pratiquement 99% de la population nigérienne (environ 10 millions d'habitants) vit dans ces deux bassins.

L'objectif est de présenter les principales caractéristiques des systèmes aquifères partagés par les pays frontaliers, et les relations pouvant exister entre eux.

Le grand bassin sédimentaire du Niger

Il est composé des sous-bassins de Tin Sériri ne-Irhazer et d'Iullemeden ; le premier est partagé par l'Algérie et le Niger, le second par le Mali, le Niger principalement, le Nigeria et le Bénin dans une moindre mesure.

Ce bassin est comblé sur plus de 3 000 mètres épaisseur, par plusieurs aquifères, gréseux pour la plupart, et échelonnés du Cambrien au Quaternaire. Ceux-ci sont intercalés entre eux par des formations argilo-gréseuses et argileuses peu perméables. La série sédimentaire est affectée par des accidents tectoniques la plupart hérités du socle.

Le sous-bassin du Tin Sériri ne-Irhazer

Il occupe une disposition de graben-synclinal limité par le Hoggar au nord, l'Aïr à l'est et la dorsale d'In Guezzam à l'ouest (Fig. 1). Il est composé des aquifères allant du Cambrien au Crétacé inférieur, sur une épaisseur de plus de 1 000 mètres. Seulement le Cambro-Ordovicien (CO) et le Dévonien inférieur sont partagés par le Niger et l'Algérie. Le CO, de part ses caractéristiques ci-après (Tableau 1), représente le réservoir principal de la région.

Les écoulements dans ses aquifères s'effectuent du Nord vers le Sud avec un gradient hydraulique moyen de l'ordre de 5×10^{-4} (Fig. 1). Des phénomènes de drainance du Cambro-Ordovicien au Dévonien inférieur existent entre eux ; un débit de percolation verticale a été estimé à 0,03 l/s/km^2.

Les **modèles conceptuels d'écoulement souterrain** selon le plan vertical, synthétiques et cohérents avec les observations réelles, permettent de hiérarchiser une nappe en **systèmes d'écoulements souterrains** juxtaposés ou superposés pour mieux représenter son comportement dans ses conditions naturelles et sous l'effet perturbateur de l'intervention humaine. Ils offrent un cadre idéal pour apprécier le degré d'interaction entre les aquifères et comprendre le fonctionnement des circulations profondes dans les bassins et sous-bassins. Ainsi, les réservoirs paléozoïques du Tin Sériri ne alimentent par drainance ceux de l'Irhazer (Fig. 2).

Paramètres	*Cambro-Ordovicien*	*Dévonien inférieur*
Profondeur des ouvrages [mètre]	600 à 800	500 à 600
Profondeur du niveau piézométrique [mètre]	0 à 20 mètres. Localement artésien	19 mètres. Localement artésien (+60 m) au sud
Perméabilité [m/s]	5×10^{-6} à $1{,}3 \times 10^{-2}$	2×10^{-5} à 2×10^{-4}
Transmissivité [m^2/s]	4×10^{-4} à 2×10^{-2}	7×10^{-3} à 3×10^{-2}
Cœfficient d'emmagasinement	5% en nappe libre 2×10^{-4} en nappe captive	8 à 10%
Débit spécifique [m^3/h/m]	0,04 à 8	0,05 à 0.5
Salinité [g/l]	0,1 au nord 0,6 au sud	0,1 au nord 21,5 au sud
Température [°C]	Jusqu'à 61	56 à 58

TABLEAU 1. Caractéristiques des aquifères du Cambro-Ordovicien et du Dévonien inférieur

Proceedings of the International Workshop
Tripoli, Libya, 2–4 June 2002

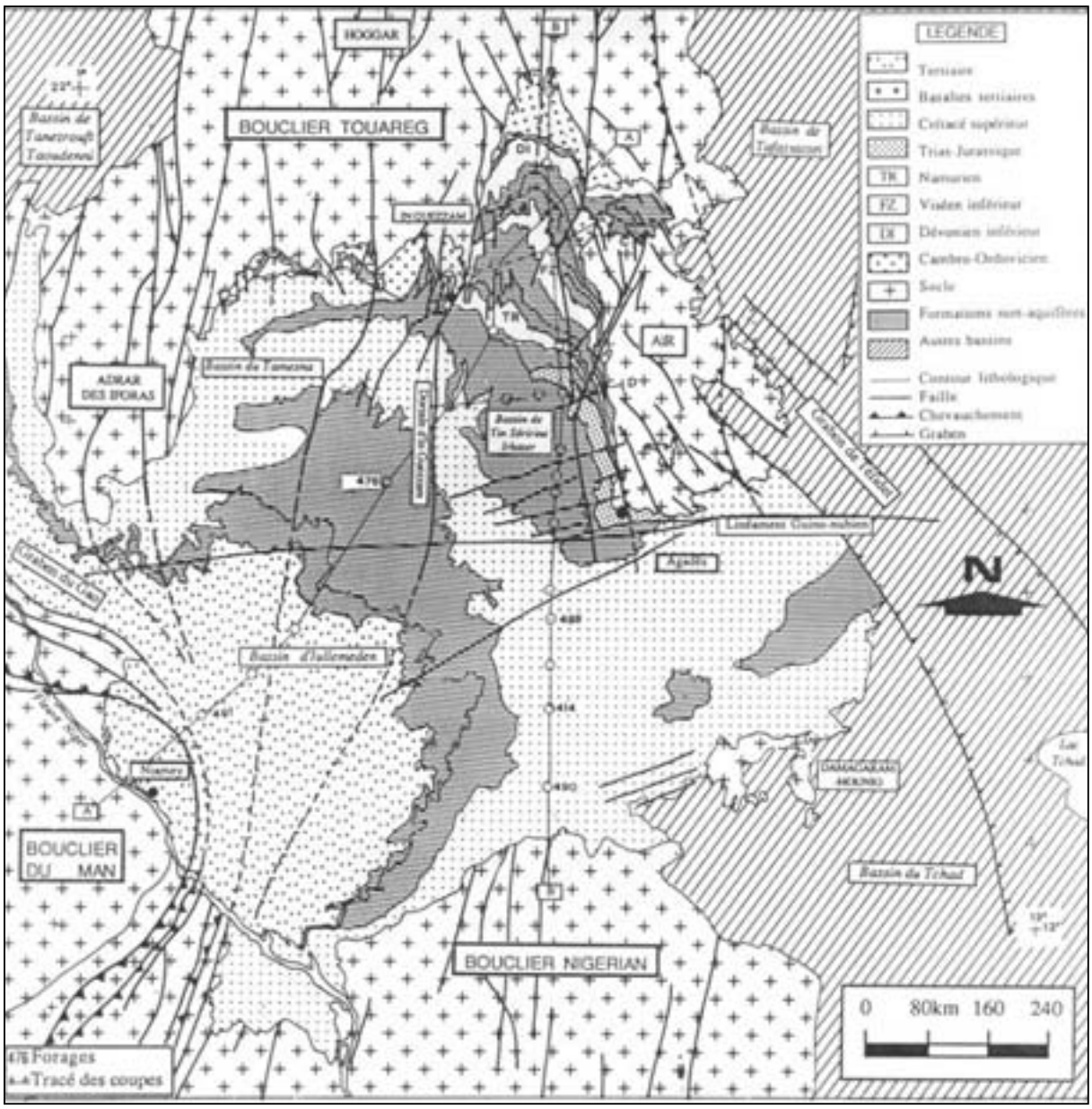


FIGURE 2. Hydrogéologie du bassin du Niger
(Dodo et Bouzelboudjen, BRGM, No. 1, 1992)

Le sous-bassin d'Iullemeden

Il est composé de deux grands systèmes aquifères : le Continental intercalaire (CI) et le Continental Terminal (CT). Ce dernier est subdivisé, au Niger, en trois horizons aquifères avec, de bas en haut, le CT_1, le CT_2 et le CT_3. Au Nigeria, dans le bassin de Sokoto, le CT est représenté par deux horizons aquifères. Ces deux grands systèmes se retrouvent dans le bassin du lac Tchad. Leurs caractéristiques sont les suivantes (Tableau 2).

Les écoulements dans l'aquifère du Continental intercalaire vont du Nord vers le sud et convergent vers le fleuve Niger au sud-ouest, et vers le lac Tchad au sud-est. La ligne de partage des eaux est matérialisée par la dorsale Aïr–Damagaram. Dans les aquifères du CT, les écoulements convergent tous vers le sud avec certaines particularités : dôme et dépression piézométriques.

Le modèle conceptuel décrit des écoulements locaux situés, pour la plupart, dans les réservoirs du CT_2 et du CT_3 ; les aires d'alimentation sont dans les dallols (Fig. 3). Les exutoires sont le fleuve Niger, et, entre les dallols. Un système d'écoulement intermédiaire englobe les aquifères du CT et en partie le CI ; l'exutoire est situé dans le CT_2 qui draine à son tour les eaux vers le sud. Un système d'écoulement régional issu du CI, alimente les réservoirs du CT.

Les aquifères du bassin du lac Tchad

En règle générale, le bassin du Lac Tchad est

	CT	*CT1*	*CT2*	*CT3*
Profondeur des ouvrages [mètres]	100 à 1000	100 à 300	70 à 170	10 à 80
Profondeur du niveau piézométrique [mètre]	0 à 50 artésien au sud	0 à 40 artésien au sud	20 à 80	10 à 70
Réserve par mètre de rabattement [m^3/km^2]	15000	8	52	5000
Transmissivité [m^2/s]	1×10^{-5} à 10^{-3} au Niger 5 à 9×10^{-5} au Nigéria	1×10^{-4} à 10^{-2}	10^{-3} à 10^{-2}	1×10^{-3} à 10^{-2}
Coefficient d'emmagasinement	• 5% à 10% en nappe libre au Niger • 0.3 à 5×10^{-3} en nappe captive au Niger • 2 à 5×10^{-4} au Nigeria • 5% à 8% au Mali	–	–	–
Débit spécifique [$m^3/h/m$]	13 au Niger	1 à 4	4 à 12	4 à 15
Salinité [g/l]	0,1 à 1 du nord au sud, au Niger	0,5 au nord à 1,4 au sud	0,4 à 1,2 du nord au sud	0,4 jusqu'à 1 au sud

TABLEAU 2. Caractéristiques des aquifères du Continental intercalaire et ceux du Continental Terminal

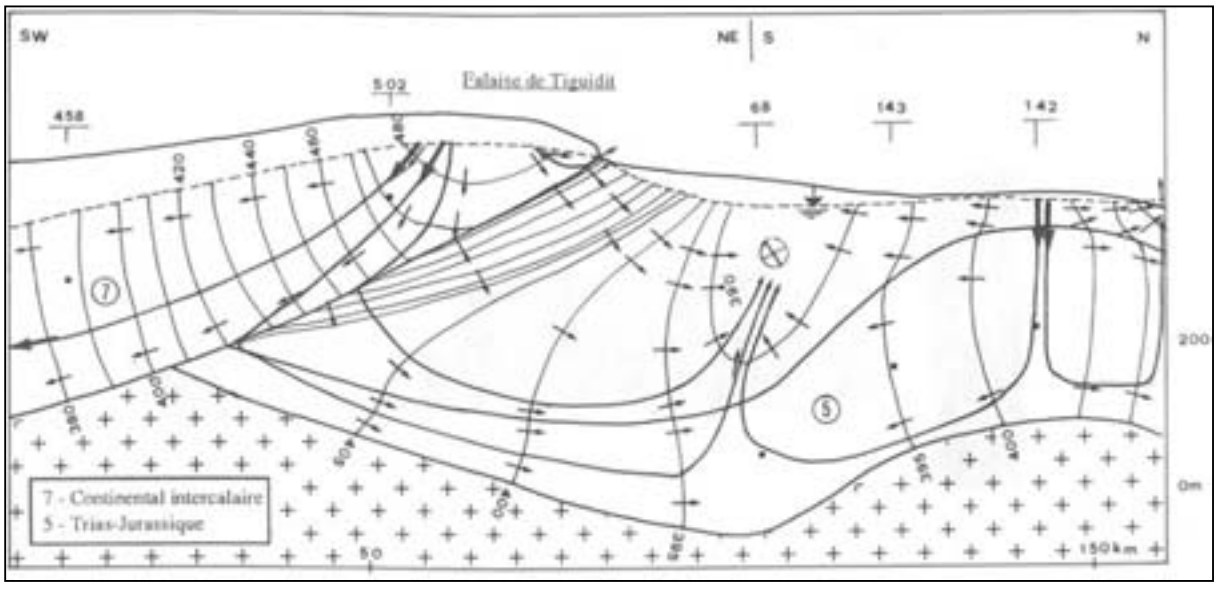


FIGURE 3. Schémas conceptuels d'écoulement en coupe NS-NE-SW : relations entre les bassins d'Irhazer et d'Iullemmeden

composé des aquifères suivants : le Continental intercalaire/Continental Hamadien, le Continental Terminal, le Pliocène inférieur,et le Quaternaire. Cependant, la terminologie adoptée pour ces formations varie d'un pays à un autre, d'une région à l'autre. Par exemple, si les termes « Formations du Tchad » et « Continental Terminal » sont reconnus de part et d'autre des frontières, en revanche, les formations géologiques qui leur sont attribuées ne sont pas les mêmes (Tableau 3).

Dans la région de Maiduguri (Nigéria)

Nigeria	*Niger*
Chad formation **Upper** (Pleistocene)	Nappe phréatique du Quaternaire (**Upper** aquifer des formations du Tchad)
Chad formation **Middle**	Nappe captive du Pliocène inférieur (**Lower** aquifer des formations du Tchad)
- Chad formation **Lower** (Pliocene ?) - Kerri Kerri formation (Palaeocene)	Continental terminal (Oligo-Miocène)
- Gombe Sandstone ? (Maestrischian) - Fika shale (Senonian) - Gongila formation: sandstone and shales series (Turonian)	Crétacé supérieur
Bima sandstone (Albian)	Continental Hamadien/Continental intercalaire

Tableau 3. Corrélation hydrogéologique entre les formations aquifères et aquicludes de part et d'autre de la frontière Niger/Nigéria

notamment, la formation supérieure du Tchad (Upper zone) est subdivisée en trois zones A, B, C. Ailleurs, ces zones se confondent et forment un ensemble hydraulique multi-lenticulaire.

Au Niger, Les aquifères du Pliocène et du Quaternaire sont les plus sollicités et suivis, donc mieux connus. Leurs caractéristiques sont regroupées dans le tableau ci-après (Tableau 4).

Gestion intégrée et concertée des ressources en eau

Au Niger, en vue de répondre à la demande en eau, les aquifères ont été regroupés en *Ressource renouvelable* liée aux écoulements annuels des cours d'eau temporaires (koris) et qui est identique à un flux, et en *Ressource non renouvelable* liée aux réserves et qui est identique à un stock.

Or, si l'on excepte les aquifères du CT_3, le CI dans sa partie à nappe libre, et le Quaternaire du bassin du lac Tchad, la plupart des aquifères partagés sont à nappe peu renouvelable. Les teneurs en ^{14}C sont de l'ordre de 1 à 3 pmc ; celles de $\delta^{18}O$ de −6 à −8 ‰ SMOW. L'exploitation de telles ressources nécessite une concertation entre les pays concernés en vue d'élaborer des Protocoles d'accord, analogues à ceux des eaux de surface partagées comme :

Caractéristiques	***Pliocène inférieur***	***Quaternaire***
Profondeur des ouvrages [mètre]	300 à 350	0 à 50
Profondeur du niveau piézométrique [mètre]	Artésien	0 à 45
Débit d'exploitation [m^3/h]	Plus de 50	
Débit spécifique [$m^3/h/m$]	–	2.5
Débit d'artésianisme [m^3/h]	0 à 80	–
Salinité [g/l]	0.4 à 1.7	0.1 à 0.3 7.5 en bordure du lac
Réserve par mètre de rabattement [m^3/km^2]	10	15 000

Tableau 4. Caractéristiques des principaux aquifères du bassin du lac Tchad

- le fleuve Niger avec l'Autorité du Bassin du Niger (ABN),
- le lac Tchad avec la Commission du Bassin du lac Tchad (CBLT),
- la maggia, le goulbi N'Kaba, le goulbi de Maradi, la Komadougou, avec un protocole d'accord signé entre le Niger et le Nigéria.

Ainsi, pour une gestion rationnelle de ces ressources peu renouvelables, des modèles mathématiques de connaissance ont été réalisés pour les aquifères du Cambro-Ordovicien en Algérie, du Continental intercalaire et du Continental Terminal au Niger, des aquifères du Quaternaire et du Pliocène inférieur intéressant le Niger, le Nigéria, le Cameroun et le Tchad.

Conclusion

La gestion des ressources en eau souterraine partagées nécessite une concertation entre les acteurs concernés en vue d'améliorer la connaissance des systèmes aquifères, et de simuler plusieurs scénarios d'exploitation afin d'éviter de compromettre irrémédiablement, l'avenir des générations futures.

Recommendations

- Une volonté politique : élaborer des **protocoles d'accord** entre les pays ayant les eaux en partage, **base juridique** pour une gestion concertée de la ressource globale,
- Renforcement des capacités dans l'évaluation des ressources,
- Identifier et combler les lacunes de connaissances sur les systèmes aquifères par des programmes d'intervention sur le terrain et en laboratoire par des équipes composées des représentants des pays concernés,
- Établir une adéquation entre les ressources disponibles et la demande exprimée par chaque pays concerné,
- Élaborer des modèles de gestion intégrée qui sont consultés à chaque nouvelle intervention humaine significative,
- Mener des études d'impact sur la ressource notamment par l'évaluation des risques de surexploitation entraînant la salinisation des nappes de bonne qualité chimique, et l'accélération de la désertification par le dessèchement des racines des plantes (couvert végétal),
- Créer d'un Centre Africain de Recherches sur la Gestion des Eaux Souterraines Partagées CARGESP.

Documents consultés

ANONYME, 1990. Schéma directeur de mise en valeur et de gestion des ressources en eau du Niger. Ministère de l'Hydraulique et de l'Environnement, PNUD/DAES.

ARMAND, C. 1987. Actualisation de l'atlas des eaux souterraines du Niger. Rapport BRGM / FAC / Ministère de l'Hydraulique et de l'Environnement.

DADDY, G. A. 1993. Étude des nappes aquifères du Continental terminal entre les dallols Bosso et Maouri, département de Dosso, République du Niger. Thèse de Doctorat, Univ. Liège (Belgique), 258 p.

——. 1995. Exploitation de la nappe alluviale du dallol Maouri pour des cultures irriguées au Niger. Sécheresse 1995, 6, p. 257-263.

DODO A., 1992. Etude des circulations profondes dans le grand bassin sédimentaire du Niger : identification des aquifères et compréhension de leurs fonctionnements. Thèse de Doctorat ès Sc., Univ. Neuchâtel (Suisse), 101 p.

DODO, A. et ZUPPI, G.M. 1997. Etude des écoulements souterrains dans le bassin de Bilma-Djado à l'aide des isotopes de l'environnement. C.R. Acad. Sci. Paris, Sciences de la terre et des planètes, 325, p. 845-852.

——. 1999. Variabilité climatique durant le Quaternaire dans la nappe du Tarat (Arlit, Niger). C.R. Acad. Sci. Paris, Sciences de la terre et des planètes, 328, p. 371-379.

EBERSCHWEILER Ch., 1993. Suivi et Gestion des ressources en eaux souterraines dans le bassin du lac Tchad. Cartographie des aquifères, gestion des ressources en eau. BRGM, R 35 985, Commission du Bassin du Lac Tchad.

GREIGERT J., 1978. Atlas des eaux souterraines du Niger : état des connaissances. Rapport BRGM 79AGE001, Tomes 1 et 2.

La gestion et l'exploitation des eaux souterraines au Niger

B. Ousmane

Professeur, Université Abdou Moumouni, Niamey

Introduction

Le Niger, vaste de 1 267 000 km se caractérise par un climat de type sahélo-saharien (0 à 200 mm) de pluie sur les 2/3 de sa superficie au Nord, et un climat de type sahélo-soudanien (200 à 750 mm de pluie) dans sa partie sud. L'insuffisance voire l'absence des précipitations au Nord, les graves déficits pluviométriques récurrents depuis trois décennies en zones sahélo-soudanienne, et enfin la faible mobilisation des eaux de surface pour l'irrigation, sont autant de facteurs qui sont entre autres les causes des graves déséquilibres alimentaires aux conséquences socio-économiques dramatiques pour le Niger.

Cependant le Niger est partagé entre plusieurs bassins sédimentaires (bassins des Iullemeden, du Tamesna, du Tchad, du Djado, du Bilma) qui renferment dans leurs sous-sols d'importantes ressources d'eau souterraine. Aussi conscient de l'importance de ce potentiel hydrique pour un développement agro-pastoral peu dépendant des aléas climatiques, le gouvernement du Niger a adopté des orientations politiques et stratégiques dans le secteur de l'eau, afin d'affiner la connaissance des eaux souterraines en vue de leur gestion et leur exploitation pour un développement socio-économique durable du pays.

Aussi, notre exposé va porter sur les points suivants :

- rappel succinct des principaux aquifères et de l'état de leur connaissance ;
- approche pour une gestion et une exploitation intégrée des eaux souterraines au Niger ;
- conclusions et recommandations.

Rappel succinct des principaux aquifères et de l'état de leur connaissance

La carte hydrogéologique simplifiée du Niger (Fig. 1) montre que les principaux systèmes aquifères du Niger sont :

- les aquifères du paléozoïque ;
- les aquifères du continental intercalaire/ Hamadien ;
- les aquifères du continental terminal et du pliocène ;
- les aquifères du quaternaire.

Les aquifères du paléozoïque

Les formations sédimentaires anciennes attribuées au primaire dans les bassins du Tamesna (Ouest de l'Aïr) et du Djado (Nord-Est du pays) renferment d'importants réservoirs d'eau souterraine dans les niveaux gréseux du cambro-ordvicien, du dévonien inférieur et supérieur (grès de d'Idekel et de Touaret, et d'Amesgneur dans le bassin de Tamesna), du Viséen inférieur et du Namurien (grès de Farazaket, du Guezouma et du Tarat dans le Tamesna) et enfin dans les grès du Westphalien (grès de Madama dans le Djado). Ces différents aquifères malgré leur importante potentialité hydrique estimée il est vrai à partir des travaux pétroliers uniquement, se situent en zone désertique quasi inhabitée par conséquent ils ne sont presque pas sollicités. Par ailleurs les quelques données hydrochimiques des variations considérables de la salinité au sein d'une même

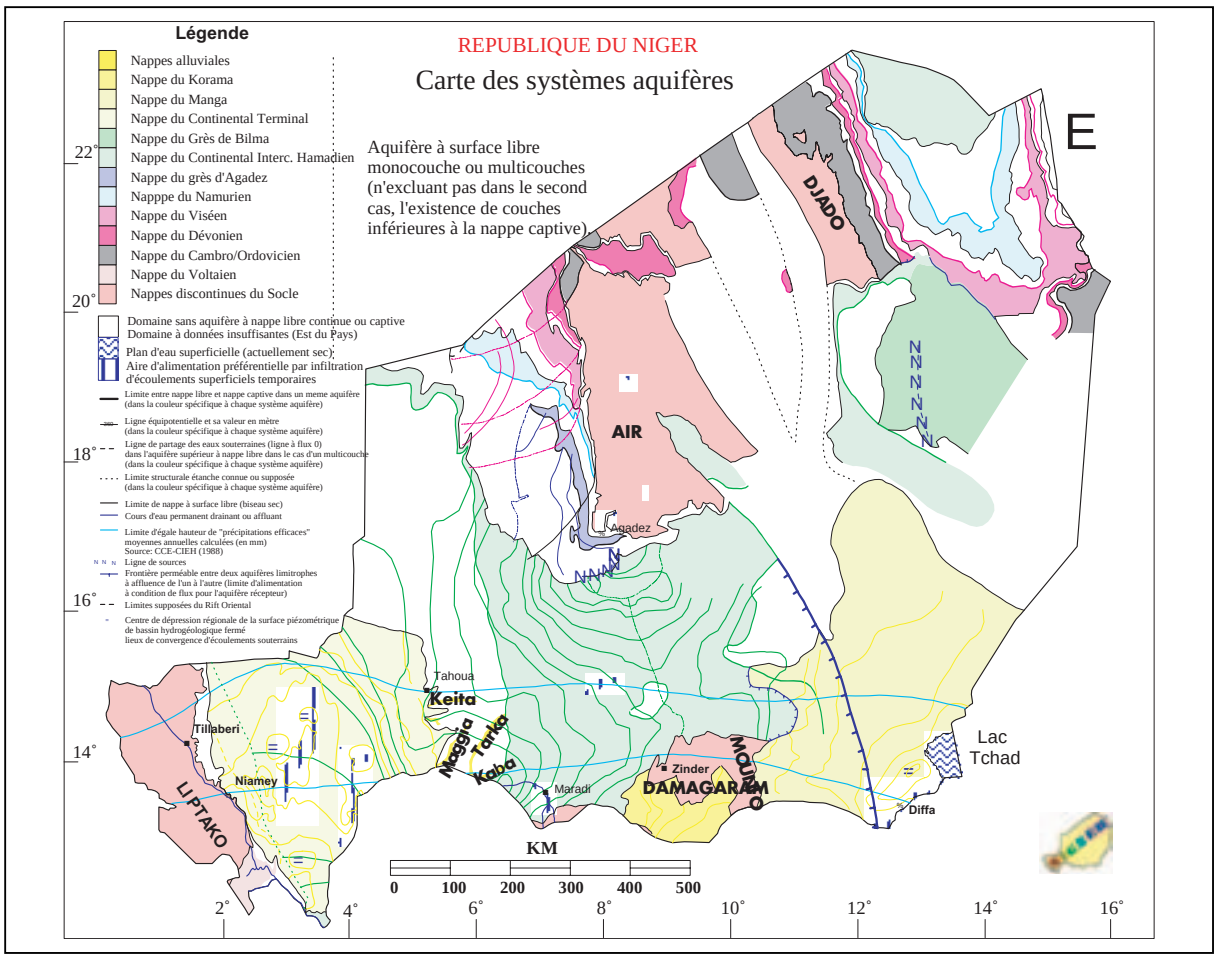


FIGURE 1. Carte des systèmes aquifères dans les bassins d'Iullemeden et du lac Tchad

nappe et d'une nappe à l'autre. Certaines eaux ont une concentration en sels dissous dépassant les 28 g/l. Enfin les résultats isotopiques ont montré qu'il s'agit d'eaux fossiles avec les teneurs en oxygène-18 variant de –7 à –11‰ vs Smow et des activités très faibles voire nulles en ^{14}C.

Les aquifères du Continental Intercalaire/Hamadien

Le Continental Intercalaire (CI) regroupe les formations géologiques continentales déposées du Permien au crétacé inférieur dans les bassins des Iullemeden et de Bilma. Le Continental Hamadien (C.H) correspond aux faciès continentaux du crétacé supérieur déposés en bordure occidentale et méridionale du bassin des Iullemeden occupé sur le reste de sa superficie par des mers dès le cénomanien.

Les formations du Continental Intercalaire/Hamadien renferment dans les bassins des Iullemeden et de Bilma les principaux aquifères suivants :

- l'aquifère d'Izeguandane (Permien)
  Bien connu dans l'ouest de l'Aïr, il est intensément exploité par les sociétés minières.
- le système aquifère multicouche des grés d'Agadès (Trias-jurassique supérieur)
  Mise en charge par les argiles de l'Irhazer ces aquifères sont relativement bien étudiés et sont exploités par la SONICHAR principalement. Plusieurs forages ont coulé pendant des années dans l'Irhazer avant d'être fermés ce qui n'est certainement pas sans conséquence sur ces aquifères. Des études complémentaires seraient nécessaires pour affiner leur connaissance, car ils actuellement visés pour des exploitations de grande envergure dans la perspective de mise en valeur des plaines de l'Irhazer.
- Les systèmes aquifères du Continental intercalaire/Hamadien
  Il s'agit en fait des aquifères suivants :
  - bassin des Iullemeden : aquifères des grès du Tegama (crétacé inférieur), des grès argileux du Farak (Cenomanien inférieur) et des grès de l'Hamadien (crétacé supérieur). Le Tegama étant en continuité avec

l'Hamadien sur la bordure occidentale et méridionale du bassin.
- bassin de Bilma ; aquifères des grès d'Achegour (CI), des grès de Kaffa (Senonien-base du crétacé supérieur) et des grès de Bilma (Campanien-Maestrichien).

Ces différents aquifères parfois multicouches renferment d'énormes réserves en eau souterraine aussi bien dans le bassin des Iullemeden que dans celui du Bilma.

Ainsi dans le bassin des Iullemeden la nappe du Tegama, étendue sur une superficie de près de 400 000 km^2 pourrait libérer un volume d'eau de 13 à 15 milliards de m^3 d'eau pour un rabattement de 1 mètre sur l'ensemble de l'aquifère. De même le forage F2 de Bilma captant la nappe de CI a donné un débit 300 m^3/h avec une pression de 1,9 kg/cm^2. La charge saline des eaux de ces nappes varie généralement de faible à moyenne (150 mg/l à 1 g/l). Toutefois des teneurs assez fortes en Na, Cl, en fluor et des fortes températures, s'observent dans certains secteurs des nappes, les rendant ainsi inaptes à l'irrigation et à la consommation humaine (fluorose osseuse à Tibiri).

Les eaux sont généralement fossiles, issues des périodes climatiques différentes de l'actuelle, les teneurs en $S^{18}0$ varient de –7 ‰ à –11 ‰ vs SMOW, quant aux activités en ^{14}C, elles varient de 0 à 1.8 %, affichant des âges supérieurs à 40 000 ans.

Cependant dans le bassin de Bilma, contrairement aux teneurs en $S^{18}0$ proches de celles des eaux du bassin des Iullemeden, les activités en ^{14}C sont relativement élevées variant de 21 % à 91,5 % (comme dans le bassin du Djado), s'agit-il de rajeunissement lié à des pollutions des sources de prélèvement, et/ou à la présence de composante importante d'eau rechargée au cours des périodes humides tardives du quaternaire (4 500 ans B.P) ?

Les aquifères du Continental Terminal (CT) et du pliocène

Du centre à l'extrémité Sud-est du bassin des Iullemeden, les formations sableuses, sablo-argileuses et silteuses, et, oolithiques d'âge mio-pliocène, appelées continental terminal (CT) d'origine fluvio-lacustre, renferment un puissant système hydraulique. On y distingue deux aquifères à nappes captive et semi-captive (CT1 et CT2) et un aquifère à nappe libre (CT3). Les ressources en eau des différents réservoirs exploités essentiellement, du moins au Niger, pour la satisfaction des besoins en eau de boisson des populations et de leurs animaux, pourront jouer un rôle important dans le développement de la production agro-pastorale, de part leurs potentialités hydriques surtout renouvelables pour l'aquifère phréatique. Cependant les études menées surtout celles en cours montrent que ce système hydraulique du CT est relativement complexe avec des transferts de flux et de masses au sein du système d'une part et entre celui-ci et les nappes sous-adjacentes et sub-adjacentes.

Enfin dans le bassin du Tchad, un aquifère à nappe captive et même artésienne sur une grande partie de sa superficie existe dans les formations sablo-argileuses d'âge pliocène. Cette nappe qui s'étend sur le Niger, le Nigeria et surtout le Tchad où elle est relativement bien connue dispose des réserves en eau importantes malheureusement de qualité chimique moyenne à médiocre limitant ainsi l'utilisation de cette nappe au Niger.

Les aquifères quaternaires

Les sédiments quaternaires du manga (bassin du Tchad) et des koromas, ainsi que les alluvions récentes et anciennes des vallées, koris et fonds de mares, renferment des nappes phréatiques très sollicitées pour l'alimentation en eau en milieu rural et pour la petite irrigation (cultures de contre saison). Cependant ces nappes malgré leur intérêt certain sont encore peu étudiées à quelques exceptions près (nappes des koromas, de la vallée de la Tarka), enfin les ressources en eau de ces nappes restent très dépendantes des fluctuations pluviométriques annuelles et pluriannuelles.

Conclusion

Ce bref rappel fait apparaître les énormes potentialités en eau souterraine estimées à plus de 2 000 milliards de m^3, dont dispose le Niger. Cependant à peine 20 % de ces ressources sont exploitées pour les besoins en eau de boisson des populations (taux de couverture de ces besoins moins de 70 %), de leurs animaux et pour quelques industries minières (uranium, charbon, etc.). Le rôle social mais également économique de ces eaux souterraines pour un développement durable du Niger, n'a pas échappé aux responsables politiques et administratifs du pays, aussi depuis près d'une décennie des orientations politiques et stratégiques dans le secteur eau ont été définies et adoptées par le gouvernement. Aussi nous tentons d'exposer assez brièvement ces orientations et stratégies dans la suite.

Approches pour une gestion et une exploitation intégrées des eaux souterraines du Niger

Le Niger a entièrement souscrit aux principes définis par la conférence sur l'eau et l'environnement tenue à Dublin (Irlande) en janvier 1992. Aussi le gouvernement du Niger a élaboré et adopté des orientations politiques et stratégiques dans le secteur de l'eau et de l'assainissement.

Pour les orientations politiques on peut retenir les quelques points suivants :

- la connaissance et la maîtrise des ressources en eau ;
- la valorisation des ressources en eau à travers une meilleure organisation des filières de production ;
- la protection des ressources en eau, de la qualité de l'eau et des écosystèmes, etc.

Pour les stratégies de mise en œuvre des orientations politiques on peut relever entre autres les options suivantes :

- création d'une commission nationale de l'eau et de l'assainissement dotée d'un secrétariat technique, elle est chargée en plus des missions de coordination des activités, de planification, de mise en valeur et de gestion des ressources en eau, de représenter l'état auprès des structures sous-régionales de coopération en matière d'eau ;
- approche globale et intégrée dans le cadre des systèmes hydrauliques (Bassin versant hydrologique et/ou hydrogéologique) pour l'affinement de la connaissance, la mise en valeur et la gestion des ressources en eau,
- augmentation de l'exploitation des ressources en eau par le développement de l'irrigation ;
- définition des mécanismes de financement du secteur eau (subventions, aide bilatérales et multilatérales, prêts, redevances, etc.) ;
- mise en place des cadres de concertation, des actions de formation, d'information et de recherche-développement ;
- mise en place des outils pour le suivi et évaluation des actions et résultats acquis.

Afin de traduire en actions concrètes les orientations politiques et les stratégies, le gouvernement s'est doté d'un programme d'hydraulique national (« Eau et Développement Durable » : « PHN-EDD ») .

Le PHN-EDD est bâti autour de quatre axes prioritaires qui sont :

- l'amélioration de la connaissance des ressources en eau en vue de leur meilleure gestion, leur protection et la sauvegarde du milieu ;
- la satisfaction des besoins en eau des populations, l'amélioration de la situation sanitaire et la prévention des nuisances liées à l'eau ;
- l'appui aux secteurs de production (agriculture, élevage, industrie-mines) ;
- le renforcement des capacités et du cadre institutionnel et juridique.

Le PHN porte sur le court terme (1999/2003) et le moyen terme (horizon 2010). Pour le court terme il a été défini un plan d'Actions Quinquennal (PAQ) dont les coûts de financement des opérations ont été estimés à un peu plus d'un milliard d'Euro.

Pour finaliser la mobilisation de ces fonds nécessaires à l'exécution du PAQ, le Ministère chargé du secteur eau a organisé courant 2001 une table ronde sectorielle sur l'eau à Niamey et les résultats atteints semblent très promoteurs pour réaliser les objectifs visés.

Conclusions et recommendations

Le rappel des principaux systèmes aquifères montre les énormes potentialités en ressources en eau souterraine dont dispose le Niger. Malheureusement pour des raisons socio-économiques ces eaux souterraines sont encore insuffisamment connues et très peu exploitées également.

Compte tenu du rôle déterminant de ce potentiel hydrique pour la promotion de la production (agriculture, élevage, industrie-mines), la satisfaction des besoins en eau des populations, la protection et la préservation de l'environnement, en d'autres termes pour le développement socio-économique durable du Niger, il a été défini des orientations politiques et stratégiques et des actions de programme pour les court et moyen termes.

Aussi il nous plait d'affirmer que cet atelier se situe dans les options du Niger en matière de gestion intégrée des ressources en eau, et en particulier de celles partagées. Nous souhaitons que nos travaux puissent aboutir à des résultats concrets.

Aussi nous proposons les quelques recommandations suivantes :

- création d'un comité ad-hoc pour élaborer très rapidement le cadre juridique et institutionnel de coopération relative à la gestion intégrée des aquifères transfrontaliers, et les

programmes d'étude de mise en valeur des ressources eau de ces aquifères. Le comité sera chargé également de faire le point sur des données existantes (documents, base de données, etc.) et des ressources humaines (ingénieurs de haut niveau, universitaires) dans les pays concernés ;

- Proposition de mécanismes permettant de mobiliser des fonds nécessaires à la réalisation des activités retenues dans un délai de huit mois au maximum ;

- large diffusion des résultats de l'atelier à l'endroit des Etats, des organisations sous-régionales, régionales et internationales par le comité ;

- définition des lieux et du planning des prochaines rencontres ;

- désignation de l'UNESCO comme organisme chargé de coordonner la mobilisation des fonds et de superviser l'exécution du mandat confié au comité ;

- motions de remerciement à l'endroit du gouvernement libyen et aux organisations sous-régionales et internationales tout en leur demander de persévérer dans leurs actions respectives.

Case studies on transboundary aquifers in Nigeria

Chris M. Maduabuchi

Federal Ministry of Water Resources
Department of Hydrology and Hydrogeology, Abuja, Nigeria

Abstract

Competing demands for water supply in Nigeria range from domestic through irrigation to industrial uses and there is increasing reliance on groundwater to meet these water needs. Consequently, some of the aquifer systems, particularly in the semi-arid sahelian states of northern Nigeria are subjected to tremendous stress. This is against the backdrop of inadequate information on the recharge of the aquifers, groundwater flow patterns and contaminant transport mechanism.

The paper presents the climatological and hydrogeological setting in Nigeria and discusses the three major sedimentary aquifer systems that extend beyond her boundary. They include the Chad Basin in the Northeast, which extends to the Republics of Tchad, Niger, Cameroun, Central African Republic, Sudan and northwards into Libya and Algeria. The Sokoto Basin, which is part of the greater Iullemeden Basin in the northwest, extends through Niger Republic to Mali and the Dahomeyan Basin in the southwest extends into the Republics of Benin and Togo. However, emphasis is placed on the first two because of their greater regional significance and location within critical ecosystem of semi-arid environment.

The structural trends, lithological dispositions and stratigraphical successions in these vast sedimentary aquifer systems are outlined including their hydraulic characteristics. The status of exploitation of the aquifers are then discussed. Available records show that the Iullemeden aquifer system which serves as a veritable source of water supplies is being subjected to extensive use with the sinking of about 4,000 deep boreholes in the Sokoto basin in Nigeria. In the Chad Basin area, a myriad of boreholes sunk at random tap the various aquifers particularly the Early Pliocene(Middle) Aquifer which has been extensively developed over the years. Though these multi-layered aquifer systems are generally under sustainable exploitation within most parts of the country, however, isolated cases of progressive decline in phreatic and piezometric surfaces are already manifest.

Suggestions are therefore proffered on national/regional activities that would facilitate formulation of effective management plan for sustainable development of these regionally shared aquifer systems in Africa.

Background

Water is one natural resource that rarely has a substitute. The steady growth in world population coupled with the extension of irrigated agriculture and accelerated industrial development and other economic activities have put tremendous stress on the quality and quantity aspects of groundwater resources the world over. Many groundwater basins or aquifers underlie two or more countries and are, thus, international or transboundary. Withdrawals from one country can drain life-giving water from a neighboring country and could be a potential source of severe and protracted conflict. There is therefore need for regional co-operation between contiguous nations in the case of shared groundwater resources in order to promote peace, understanding and equity in the development and management of the resources particularly in the semi-arid and arid environments where rate of groundwater recharge often leaves much to be desired.

Location of Nigeria, climate and geological setting

Nigeria is situated within longitudes 2°– 5° East of the meridian and latitudes 4° –14° North of the Equator. It is bound to the north by the Republic of Niger, while to the west and east, it is bound by the Republics of Benin and Cameroun respectively. The Bight of Guinea bounds it at the southern coast along a shoreline of 800 km. It occupies an area of 923,800 km^2. Nigeria is entirely within the tropics with semi-arid climate in northern part to humid tropical climate in the south. Rainfall varies from as low as 250 mm per annum in the extreme north to about 4,000 mm per annum in some parts of the Niger Delta along the coast. The rainfall is highly seasonal with the wet season coming in June–September in the northern part while it is between April and November in the southern part.

The population of Nigeria is more than 120 million with over 70% residing in the rural areas and engaging in agricultural activities.

The geology of Nigeria can be divided into two broad units – the Basement complex and the Sedimentary basins. The basement complex rocks are located in the north central, western and eastern flank of the country. The sedimentary formations are found in the north-west (Sokoto Basin), north-east (Chad Basin) and the coastal plains (Dahomeyan basin) where the aquifers extend beyond the boundary of the country. The hydrogeological properties of these basins are discussed in greater details in the paper.

Sokoto Basin

The Sokoto basin in Nigeria is part of the larger Iullemeden basin which extends through Niger Republic to Mali. There are about 60,000 km^2 (10%) of this basin within the Nigerian territory and it shares roughly 570 km boundary with the Republic of Niger. The states within the basin include Kebbi, Sokoto, Zamfara and parts of katsina state.

The Rima River Basin is the main drainage basin in the Nigerian sector of the Iullemeden basin. It has a complementary sister basin, the Sokoto River Basin in close proximity. The latter joins River Rima at the Dundaye area, some 5 km north of Sokoto town, and flows on as Sokoto River, draining into River Niger which empties into the Atlantic Ocean, ultimately. There are three intermediate rivers – Garon Gulbi, Zamfara and Gulbin-Ka including a number of minor rivers being tributaries of the above.

Principal aquifers of the Iullemeden basin in Nigeria

The Sokoto Basin is underlain by a sequence of inter-bedded semi-consolidated gravels, sands, clays and some limestone and ironstone of Cretaceous to Quartenary age resting on pre-Cambrain Basement Complex rocks which outcrop extensively to the East and South of Zamfara State as well as to the South of Kebbi State. There are four distinct sedimentary sequence consisting, from west to east, of the Tertiary Gwandu formation and Sokoto Group (Kalambaina and Dange formations); the Cretaceous Rima Group (Wurno, Dukamaje and Taloka formations) and the Gundumi-Ilo formations. See Table I. Thick sediments of both marine and continental origins constitute the series of aquifers in the basin with the oldest being the Gundumi formation that uncomformably overlies the basement complex. Sediment thickness increases westwards to a maximum of 390 m near the frontier between Nigeria and Niger but reaches more than 2,000 m in the depositional centre in Mali Republic (Kogbe, 1970).

The basement complex is composed of granite gneisses, migmatites and sediments of Precambrian origin. Where these rocks are deeply weathered and fractured, they serve as sources of groundwater to several localities with yields from boreholes rarely exceeding 100 litres per minute.

Gundumi-Illo Formations

The Gundumi formation uncomformably overlies the basement complex to the east while the Ilo formation does the same in the south. The outcrop area forms a narrow NE–SW strip that expands northwards. The two formations represent the oldest sedimentary rocks in the basin. They are also connected, hydrogeologically (Oteze, 1974) and are thus treated together. The aquifer is usually medium to coarse sand and is encountered at varying depths for instance at 76–91 m in Bakura, 81–87 m at Kuruwa Birni, 120–127 m at Sabon Birni, 400 m at Kaloye and over 900 m at Kurdula to the NW. The increase in depth follows the general dip of the basin (Umar, 2000). This aquifer is continuous throughout the basin.

In the outcrop areas it is subartesian but where it occurs at depth more than 250 m, boreholes tapping it could even be free-flowing, for instance at Balle and in Sokoto near water works. Around Isa the average yield of some boreholes was less than 13,638 litres/hour while in Bagudo area the average yield was 15,456.4 litres/hour. The prolific nature of this aquifer, notwithstanding, boreholes often terminate above it due to the presence of other shallower aquifers like the Rima Group and Gwandu formation.

Rima Group

The Rima Group is a sequence of marine deposits consisting of fine grianed sand, loosely cemented sandstone, mudstone and shale. These sediments are transitional from the terrestrial deposits of the Cretaceous Gundumi formation to the overlying marine calcareous deposits of the Tertairy Sokoto Group. The Rima Group could be subdivided into three formations in the area north of Sokoto River where the Dukamaje shale unit separates two aquiferous units- the underlying Taloka formation from the overlying Wurno formation. South of Sokoto River, the Dukamaje formation has wedged out and it is not possible to separate the Taloka and Wurno formations by surface mapping as they come into contact and have similar lithologies.

The Taloka formation with maximum thickness of 180m consists of fine to coarse sand, silty sands, shales and sandstones with many layers of clay/shale within the latter. The thickness of the Taloka formations from drilling activities are 90 m at Aliero, 65 m at Kajiji and 40 m at Yabo. The Taloka aquifer consists essentially of fine sand at Gwadabawa, Kuadawa and particularly around Illela and Gada. Screens with appropriate slots have to used for borehole construction in these areas to avoid sand pumping problem.

The Dukamaje consists of shale with gypsum and assemblage of invertebrate fossils at the base. It forms an aquitard where-ever it is present.

The Wurno formation is similar to Taloka except that it is a continuous layer with no clay intercalations. In the vicinity of Sokoto, the Wurno aquifer is encountered between 80–120 m and consists of medium to coarse sand with borehole yields between 13,638–18,184 litres/hour. A decline in water table has been noticed around Sokoto metropolis owing to heavy pumping from the numerous boreholes extracting water from the aquifer. The general flow direction is NE–SW and this appears to be the case for the other sedimentary aquifers. The Rima group is estimated to be 220 m thick at Sokoto. Towards Gudu areas, it was encountered at 300 m depth in an artesian borehole with free flowing height of 9 m. The main recharging area for the Rima Group aquifers is the outcrop area which is the strip from Goronyo to the east of Jega. It covers an area of about 13,600 km^2 (Oteze, 1989).

The Sokoto Group

The Sokoto Group, like the Rima group, consists of marine deposits with the shaley Dange formation at the bottom and limestones of the Kalambaina aquifer at the top. The Dange formation is an aquiclude while the Kalambaina formation is aquiferous especially in the outcrop areas. Many boreholes are tapping the Kalambaina aquifer but yield varies a lot from place to place. Where the aquifer is overlain by the Gwandu formation to the West or where the clay content is high, very little water can be extracted from it. The permeability of the limestone depends on joints and bedding planes enlarged by solution. Fluctuations in water level is very high often 5 m from place to place and also in any one borehole over time. Yields from boreholes also show great variations usually in the range 27–55 m^3/hr. Between 1994–1998, eleven boreholes in Sokoto recorded average water table decline of 4.2 m (Umar, 2000). Abstractions from this aquifer need to be controlled as cases of interference of wells are already evident. The aquifer is prone to pollution especially in the outcrop areas.

The Gwandu formation

The Gwandu formation outcrops from the Northwest to the South west of the basin and it consists of an alteration of clay and sand continental deposits of Tertairy age. Four aquifers have been identified in this formation alone (Oteze, 1974). These are mostly sand layers in between clay layers. The four layers are designated as Upper Zone I, Upper Zone II, Middle Zone and the Lower Zone. According to JICA 1990 the average specific capacity of the formation ranges from 50–100 m^3/d/m though in some areas (around Kalgo, west of B/Kebbi) values as high as 150 m^3/d/m were obtained. Generally speaking this formation has the most reliable aquifers in the Sokoto Basin. There are many free-flowing wells e.g. Balle, Karfen Sarki, Ganjalwa tapping this formation. Cases of high iron content have been recorded e.g. 6.8 mg/l at Tangaza and 5.2 mg/l at Balle. Decrease in groundwater level over the past five years ranging from 70–150 m has been observed in the northern fringe of

Nigeria and Niger which has mainly been attributed to preponderance of wells resulting in overpumping.

Chad Basin

The Chad Basin in Nigeria is located in the north-eastern part of the country, with an areal extent of about 152,000 km^2 representing only about 6.5 percent of the entire hydrographic basin which extends to Chad, Niger, Algeria, Libya, Sudan, Central African Republic and Cameroun. The basin covers Borno, Yobe and Jigawa states and parts of Kano and Bauchi states. An inland lake, within the Chad Basin, the Lake Chad (281 m.a.s.l) is surrounded by Nigeria, Niger, Chad and Cameroun and constitutes the main body of surface water in the basin. There are three main drainage systems into the lake – the Chari-Logone river with headwaters in the Central African Republic and the Cameroun respectively.The other two originate from Nigeria and include the Komadugu-Yobe river which descends from the Bauchi plateau and river Yedseram from the Biu plateau. The Nigerian rivers are essentially ephemeral and account for about 10% of the total surface water input into Lake Chad.

Principal aquifers of the Chad Basin in Nigeria

Notable sedimentary formations of the Chad Basin in Nigeria in descending order of depositional sequence include Quaternary, Early Pliocene, Continental Terminal, Gombe sandstone, Fika shale, Gongila, Yolde and Bima sandstone formations. The Bima sandstone has been geologically correlated to the regional Nubian Sandstone Aquifer System. The latter is one of the biggest transboundary basins covering about 2 million km^2 and extending through Egypt, Libya, Sudan and Chad. The Bima sandstone is the oldest member of the aquifer series in the Nigerian sector of the basin and rests uncomformably on the basement. Oil drilling activities in the Chad basin has encountered thick horizons of the Bima sandstone ranging from 300 m to 2,000 m at depths of about 2,700 m to 4,600 m.

The quaternary Chad formation (Upper and Lower Aquifers) and the tertiary Continental terminal consist of variable sequence of clays, silts, sands and alluvium (fluvio-lacustrine and aeolian sediments) deposited under alternating humid and arid conditions. These aquiferous units are separated by thick horizons of clays, silts or clay-sand intercalations resulting in artesian and sub-artesian conditions in places. These three aquifers are the ones actually exploited because of depth and water quality problems associated with the deeper aquifers.

Quaternary (Upper) Aquifer

The Upper aquifer consists of quaternary alluvial deposits with thickness varying from 15–100 m and up to 180 m in some localities. It is made up of a series of interbedded sand, clay, silt and discontinuous sandy clay lenses. The thickness of the sands increases considerably north of the lake because of subsidence movements. The aquifer has been highly developed for domestic water supply, vegetable gardening and livestock watering through handdug wells and shallow boreholes. Over the years, groundwater levels in this aquifer have been lowered, resulting in the deepening of wells. The aquifer is recharged largely through rainfall and occasional runoff. Transmissivity is in the range 0.6–8.3 m^2/d with discharge of about 10^5 m^3/d from the aquifer. Water quality is generally good with the exception of some zones affected by evaporates (polders from the lake) and few others of localized anthropogenic impact.

Early Pliocene (Middle) Aquifer

The Middle aquifer is the most extensively encountered aquifer in the Nigerian sector of the basin. It is separated from the Upper aquifer by a thick sequence of grey to bluish-grey clay (60–200 m). The aquifer is encountered at depths of about 240–380 m from the surface in several places and consists of sand beds with interrelated clays and diatomites. The sandy members are coarse, angular, quartz grains with felspar and mica contents. The thickness of the water bearing layer varies between 10–40 m with an average transmissivity of 360 m^2/d.

The aquifer has been extensively developed over the years with the result that the piezometric head of this confined aquifer has progressively declined and several wells in the aquifer have lost their free-flowing potentials. However, in 70% of the wells, groundwater is still under artesian condition with piezometric heads increasing from Maiduguri towards the Lake Chad. The slope in piezometric heads is about

0.015% in the NE direction. Abstraction from this aquifer is upwards of 10^5 m^3/d while free flowing yield (uncontrolled discharge) is between 0.12 and 90 m^3/hr. The quality of the water is not as good as in the Upper as it is often more mineralised.

Continental Terminal (Lower) Aquifer

The Lower Aquifer referred to as Continental Terminal in Chad and Niger Republics, consists of alternations of sand and clay and lies at depths of 450–650 m with an average thickness of about 90 m in Maiduguri. Transmissivity varies from 33 to 105 m^2/d. The piezometric surface slopes 0.115% in the N and NE direction. Free flows vary from 7 to 17 m^3/hr while groundwater abstraction from the aquifer is about 0.41 x 10^5 m^3/d. The aquifer presently serves as the major source of water supply to Maiduguri metropolis, capital of Borno state. The piezometric head of this aquifer, usually between 3–6 metres above ground level has also declined due to excessive development.

The Lower aquifer is encountered mainly in Maiduguri, capital of Borno State and to the East and Northeast of the city. At the latter locations, there is no upper aquifer between Mafa and Ngala due to clay-matrix (cotton-clay soil) in the formation which hinders direct infiltration (Oteze et al., 1989). West and Northwest of Maiduguri, only the Upper aquifer exists, while the Middle is perched or discontinuous and the Lower non-existent. Incidentally, in the Kanem region in Niger, the quaternary sands lie directly on those of the Lower aquifer forming a single aquifer with thickness often greater than 275 m (C. Eberschweiler, 1993). From current drilling experiences in the basin, the first and second aquifers thicken and thin out in places and in some cases disappear completely and thus not uniform in the basin. On the other hand, the Lower aquifer is normally encountered at a consistent depth range of 450–650 metres in the basin and is fairly extensive and uniform, though of restricted spatial occurrence.

Proposed joint action plan for development and management of transboundary aquifers in Africa

A Technical Working Group (TWG) of water experts from the respective countries needs to be set up and charged with the creation and maintenance of a comprehensive and unified data base pertaining to the regionally shared aquifers. Their terms of reference should include among others the following:

- **i) Determination of geometry of the aquifers**

  The areal extents of the multi-layered sedimentary aquifers of both the Chad and Iullemeden Basins in all the countries traversed by these geological formations should be determined. Their respective target depths from the ground surface or height above mean sea level including their individual thicknesses, lithologies and water bearing potentials should also be established through drilling of test wells at strategic geological locations.

- **ii) Determination of hydraulic parameters and aquifer response to exploitation (pumping)**

  From boreholes drilled as per i) above, litho-stratigraphical successions should be correlated and extrapolated within and among contiguous countries. Hydraulic parameters of the various aquifers – yield, transmissivity, storage coefficient, specific capacity, etc., should be evaluated through analyses of data from standard pumping tests, including drawdown and recovery response characteristics. Tests to be performed in separate boreholes penetrating exclusively the different aquifers. Quantification of groundwater reserve would then be carried out.

- **iii) Determination of flow direction and recharge characteristics of groundwater in the various aquifers**

  Contour plot of static water levels (water tables) when aquifer is not subjected to pumping for each aquifer system to obtain groundwater flow nets. Flow direction is usually opposite direction of increasing hydraulic gradient. Contour maps of groundwater level will show clearly for each aquifer the flow trend from one contiguous country to another which is a vital information for management of the shared water resources. Isotope techniques will be applied to determine origin of groundwater, recharge, resident time (age), mixing proportion of component flows, interconnectivity of the aquifers and surface water-groundwater interactions.

- **iv) Prevention of pollution of shared groundwater resources through identification and protection of recharge zones, proper drilling practices and sanitation measures**

Degradation in groundwater quality is a serious issue in contemporary water resources management owing to the world's ever-growing population, particularly in Africa and the tremendous pressure exerted on groundwater to assuage the competing demands of water for domestic, irrigation and industrial requirements. Literature review or studies will reveal the outcrop or catchment areas of the respective aquifers and the vulnerability of these aquifers to contamination (pollution). Study of physical, chemical and bacteriological constituents of water samples from selected surface and ground sources will give a clear picture of hydrochemical facies.

Considering that there is usually a paucity of aquifer wide data on most of transboundary aquifers, from both quality and quantity perspectives, the Technical Working Group may need to carry out complementary studies directly or through consultancy to among others:

a. identify inadequacies in available data and to propose remedial action to fill in perceived data gaps;
b. examine present and potential future uses of the respective groundwaters, taking into account demographic projections and socio-economic development plans;
c. assess the impact of present and potential development on transboundary groundwaters and related resources; and
d. examine the potential for, and the consequences of, drought, floods, and contamination in the border region.

Monitoring network of boreholes for groundwater quality and quantity measurements would have to be put in place particularly in zones considered to be critical because withdrawals are exceeding recharge or contamination is threatening groundwater quality. It is also necessary to establish hydro-meteorological stations for the comprehensive understanding of the total input into the basin, the surface runoff, losses and groundwater reservoir. Existing functional boreholes and hydrological stations could be integrated into the networks. These stations should be fitted with state-of-the-art equipment. Data collection should be regular and systematic and should be processed using appropriate computer softwares. Rainfall samples should also be collected from established stations and analyzed for environmental isotopes composition.

Proper costing of all proposed works should be carried out to obtain an idea of budgetary requirements. Possible sources of funding need to be considered and explored. There should be detailed Activity Time Chart for all works.

Details of Legal and institutional frameworks should also be worked out.

On the basis of results obtained, water conservation areas may have to be delineated with comprehensive and mutually agreeable groundwater management plan worked out regarding pumping limitations, well field management, etc.

Finally, in addition to regular meetings of the proposed Technical Working Group, there should be periodic Stakeholders Workshop to appraise local officials, technical people and the public of findings and plans and measures under consideration.

Conclusion

The status of exploitation of the transboundary aquifer systems in Africa particularly the Iullemeden and the Chad Basin aquifers in the respective countries spanned by these aquifers informs the need for mutually agreeable groundwater management plan to be put in place. This would be preceded by a review of existing hydrological, hydrogeological ,hydrochemical, hydrometeorological and isotope data followed by complementary actions by a Technical Working Group of water resources professionals from the respective countries with a view to determining areas of possible groundwater depletion and or degradation in water quality.

References

UMAR, I.U. 2000. An Outline of the Hydrogeology of the Sokoto-Rima Basin in Nigeria. Paper presented at the First National Workshop on Applications of Isotope Techniques in Water Resources Development and Management held in Sokoto, Nigeria.

OTEZE and FAYOSE. 1988. Regional Developments in the Hydrogeology of the Chad Basin. Paper published in the *Water Resources Journal of Nigerian Association of Hydrogeologists,* Vol. 1, No. 1.

OTEZE, G.E. 1989. Recharge Characteristics of the

Rima Aquifers, Sokoto Basin. *Water Resources Journal of Nigerian Association of Hydrogeologists,* Vol. 1 No. 2, Oct. 1989.

OTEZE, G.E., HANIDU, J.A. and MADUABUCHI, C.M. 1989. Geohydrology of Drought-prone areas in Africa – The Chad Basin in Nigeria (A Preliminary Report to the Commonwealth Science Council, London).

ISIORHO, S.A. 1992. Global Warming and the Water Resources of Sahel (Lake Chad Region). Paper published in *A Global Warming Forum – Scientific, Economic, and Legal Overview.* Edited by R.A. Geyer.

EBERSCHWEILER. 1993. *Monitoring and Management of Groundwater Resources in the Lake Chad Basin.* Report published by Lake Chad Basin Commission.

EDMUNDS, W.M. et al. 1997. *Groundwater, Palaeoclimate and Palaeo-recharge in the Southwest Chad Basin, Borno State, Nigeria.* Proceedings of an International Symposium on Isotope Techniques in the Study of Past and Current Environmental Changes in the Hydrosphere and the Atmosphere, organized by the International Atomic Energy Aency held in Vienna, 14–18 April, 1997.

JAPAN INTERNATIONAL CO-OPERATION AGENCY (JICA). 1990. *The Study for Groundwater Development in Sokoto State*, Vol. 2, Main Report.

JAPAN INTERNATIONAL CO-OPERATION AGENCY (JICA). 1995. *The Study of the National Water Resources Master Plan (NWRMP).* Final Report submitted to the Federal Ministry of Water Resources and Rural Development.

MOLT MAC DONALD INTERNATIONAL (Cambridge, U.K). in association with BCEOM (Montferrier-sur-lez, France). 1992. *Sub Saharan Africa Hydrological Assessment West African Countries. Country Report: Nigeria.*

KOGBE, C.A. 1970. *Preliminary Study of the Geology of the Nigerian Section of the Iullemeden Basin: African Geology Ibadan.* Edited by T.F. Dessavagie and A.J. Whiteman.

Sustainable management of shared aquifers

Almoutaz Abdalla Mohammed

Groundwater specialist
UNESCO Chair in Water Resources
Sudan

Introduction

One of the main water resources in Sudan is groundwater resources. In most parts of Sudan groundwater resources are playing a great role of essential activities for human beings and animal grazing. As well in many parts, groundwater is used for agricultural activities at present time. So it is one of the great component of the environment in Sudan that helps people and animal natural grazing specially in the east west and north of Sudan. In the coming decade Sudan will be under water poverty line indicating that, the surface shared water will no longer be enough according to population growth and condensation in the north due to the war. Therefore a wise look for groundwater resources should be, established by achieving sustainable groundwater resources management, especially in one of the main groundwater resources in Sudan, the shared Nubian sandstone aquifer that is located in the most suitable area for grain's growing belt in Sudan, which is the main food resource at present and future for northern people of Sudan.

This paper discusses the importance of groundwater in Sudan as well as the importance of sustainable management and the main principles in order to achieve sustainability. The paper also discusses some advanced methodology utilized for sustainable management such as groundwater modeling, environmental isotope, remote sensing and GIS. Finally, some examples on the use of these advanced techniques in Sudan are presented.

Importance of sustainable management

Groundwater has always been considered a readily available source of water for domestic agriculture and industrial use. With the increased demand, this resource is being over exploited resulting in a paramount deletion and associated environmental consequences. The world is being more concerned with sustainable, environmentally sound development and management. There is a need highlight key principles of sustainable management. The good sustainable groundwater resources management is to develop and manage them in such a way that the resources base is maintained over the long term. groundwater development begin typically with a few pumping wells, then more and more wells are scattered over the basin. In many cases, this expansion is rather unplanned and consequently issues such as over exploitation of water quality become apparent in many part of the basin. Thus the emphasis of groundwater management in shared basins has to be changed that the available is utilized in an efficient, sustainable and equitable manner contributing to the economic and social well beings of all sharing the basin.

Principles of sustainable management in Sudan

The following key principles reflect different concepts of concern in order to attain sustainability.

Long term conservation of groundwater resources

Groundwater development must be sustainable on a long-term basis, which implies that the role of extraction should equal to the role of recharge. In non-renewable aquifers in cases where the pumping exceeds recharge, a continual lowering of the water level is expected and this situation has to be carefully considered for some specific cases. A continual lowering of the water levels will steadily increase pumping cost and reduce

the benefit value at certain level. An assessment of the natural recharge is thus a basic prerequisite for an efficient and sustainable management.

As for the shared Nubian sandstone aquifer, recharge is still not accurately assessed and there is a need for extensive studies to answer questions such as:

- Is the Nubian Sandstone Aquifer a completely non-renewable resource or does it receive some recharge e.g. Nile recharge?
- If yes, what is the amount of recharge from the Nile and for how long distance the Nile influence extends?
- When the recharge is assessed then the management policy should be evaluated over a long period to consider the implications for future generations.

Protection of quality

The qualitative aspect is of basic concern for sustainable management. However, the quantity aspect is also critical importance and closely linked with the quality aspect.

The problem of the groundwater contamination and quality determination has been approached by different investigations from different points of view and the resulting achievements are very extensive.

Environmental impacts of groundwater development

The essential requirement in the evaluation of sustainable development is the recognition of environmental sustainability.

By making changes to groundwater system, changes in the broader context may result. This is particularly evident when the groundwater system is in hydraulic connection with the surface water system such as rivers. For environmental sustainability the management of groundwater resources should be considered as part of the integrated water resources management to achieve two main objectives namely, provision of water for beneficial use at minimum cost and avoidance of adverse effects on the environment.

Towards achieving sustainable management

Many groundwater professionals and decision makers, are normally concerned with the resources development to meet users needs by applying unsustainable abstraction of groundwater.

Consequently many countries have been faced with declining groundwater levels as well as deteriorating groundwater quality. If sustainable development is to be achieved some important strategies have to be implemented such as:

- Understanding of the groundwater system and its vulnerability should be enhanced.
- Resource managers and decision makers should recognize the groundwater system as an important component of the total water resources and the environment.

Strategy (1) can be outlined as follows:

- Understanding, of the occurrence and behavior of the groundwater system and quality.
- Consideration of aquifer capabilities, water needs and water quality requirements.
- Pollution sources identification
- Control on the location of wells and the pumping rates

In shared aquifers, the water authorities concerned with groundwater management in country should have the capabilities and expertise to institute the necessary data collection programs and elevation schemes. A very essential factor for sustainable development is close cooperation and coordination between the water authorities in different countries sharing the resource.

Strategy (2) implies an effective control of groundwater quality degradation.

For these effects to be successful there is a need for coordination and collaboration of different agencies within the countries sharing the same resource.

In summary, to achieve sustainable management of shared groundwater resources the following are important factors.

- Networking between countries sharing the same resource.
- Institutional collaboration and joint decision making regarding development policies.
- Joint studies and research programs for better understanding of the aquifer mechanism.
- Data exchange programs.
- Applying advanced technology for data collection.
- Implementation of advanced methodologies such as modeling, isotopes, remote sensing and GIS.

Advanced methodologies for sustainable management

Use of groundwater modeling

Groundwater modeling has played and is playing a great role in groundwater resources assessment

and management. By applying large-scale and small-scale models we can achieve sustainable Management in Shared Aquifers. The following are the main steps for developing a groundwater model:

- Model conceptualization;
- Boundary condition;
- Stresses inflows – out flows;
- Aquifer parameters: permeability, transitivity, riverbed conductance, storage coefficients etc.;
- Model running in a steady state condition;
- Model calibration;
- Model running in an unsteady state condition for along periods;
- Optimization for sustainable development;
- Model updating by applying a modern monetring network system.
- As well applying groundwater modeling from contaminant transport assessment and remediation.

In this paper some cases of model application in Sudan are presented.

Use of environmental isotopes

Environmental isotope techniques in hydrological investigations have been increasing, applied in the overall domain of water resources development and management. In areas where water resources are limited to groundwater the technique offers a powerful tool in solving many problems that are most critical for groundwater management. Results of isotope studies have substantially contributed to (IAEA, 1994):

- Improved understanding of the sources and origin of water, mapping of pales water and delineation and understanding of the hydraulic interconnection between different aquifer units;
- Estimation of groundwater recharge;
- Study of the sources and processes of water salination in coastal equations and identification of the sources of pollutants and their transport dynamics.

A case study of the application of environmental isotopes in Sudan is given later.

Use of GIS

Groundwater modeling is often hindered by lack of adequate information about the groundwater system. Such a lack of information usually necessitate the use of a tedious iterative methodology. Hence there is a need for an efficient system for data preparation manipulation and analysis. GIS a suitable system that has been found to be very effective in reducing the modeling effort. It can facilitate groundwater model develop as well display model parameters and results. GIS coupled with groundwater model can be used as a decision support system for aquifer operation and management. The use of GIS is appealing because of its ability to:

- Make the information in the data base available in the same screen during data preparation.
- Save and analyze spatial data and results as any GIS layers.
- Provide a graphical error check in continuous bases.
- Integrate data layers and performs spatial operations on data in a flexible manner.

Use of remote sensing

Remote sensing in one of the powerful advanced methodologies, these days. It helps to cover such big aquifers like Nubian aquifer for assessing its properties and makes clear understanding of its geology. Radar satellite images can show many geological formations that covered by sand and make clear vision to under stand the ancient hydrological processes that happen in this area.

Some examples from different countries that share the Nubian aquifer will be shown.

Some examples on the use of the advanced techniques in Sudan

1. The use of groundwater modeling

A - Case One
Assessment of groundwater pollution from domestic waste water in Khartoum area

Groundwater provides about 80% of the total water supply for the three main towns in Khartoum State, namely Khartoum, Khartoum North, and Omdurman as well as their suburbs. Treatment plants taking water from the Nile provide the remaining 20%.

The sewerage system in the three cities consists of three main systems: treatment plants in certain areas (centers), pit laterals which is the oldest system and commonly used in the surrounding areas of the three cites and septic tank – disposal well system which started at the last

three decades and growing fast in the three main cities.

Recently signs of serious groundwater contamination have appeared in a number of supply wells in the state, with the result that some of these wells had to be closed. Examples of areas where bacteriological contamination have occurred are Al Riyadh and Al Taef areas. Results of bacteriological examination for one well in Al Riyadh have shown total coliforrn counts as high as 80 per 100 ml of sample. In an unpublished study conducted by Dr. Izaddeen Yousif for UNDP, he found that out of 120 samples from various parts of Khartoum state, about 40 samples had shown serious background contamination. This is supported by complaints from consumers of water quality degradation as well as outbreaks of diarriah in some areas. Therefore, the belief that the upper and lower aquifers in Khartoum are completely separated and that groundwater is safe from contamination is incorrect. The obvious reason for such a serious contamination is the high concentration of septic systems (septic tank and deep injection well) used for waste disposal. In addition, indications of chemical contamination have appeared in the industrial area of Khartoum North where they use deep injection wells for industrial waste disposal, and in Omdurman where there are a number of solid waste dumpsites. High concentrations of total dissolved solids and heavy metals such as lead are found in these areas.

All these indicate the vulnerability of the aquifer of Khartoum due to pollution.

Objectives of the study

This study can be considered as a preliminary study for planning field investigation and determining the different parameters of the Khartoum aquifer, specially the transport parameters like dispersion and diffusion of different pollutants in the aquifer, as well as studying the system dynamics and understanding the physical processes such as flow directions and aquifer geometric system (layers), to give accurate results in the further studies of detecting and predicting contaminant transport and vulnerability in particular areas in Khartoum.

■ Geology

Khartoum sub basin is situated at the northern periphery of the Blue Nile rift basin. This sedimentary sub-basin is elongated on the northwest and southwest, and forms its bottom at depth that reaches more than 500 m (Konke et al. 1993).

Sedimentary chronological order:

- Cretaceous sandstone: Oumdurman formation lies below Upper Gazira formation depth up to 500 meter;
- Tertiary Gazira formation:
  - Upper Gazira formation: alluvial deposits, sand, gravel, sand stone and clay, thickness about 100 meter in Khartoum.
  - Lower Gazira formation: clay stone lies below upper Gazira formation and above Oumdurman formation at the northwestern part of the study area.
- The Nubian sandstone below 300 meter of Khartoum.

■ Hydrogeology

Aquifer system

Aquifers are unconfined to confined. From the geologic formations and cross section (Fig. 1) we

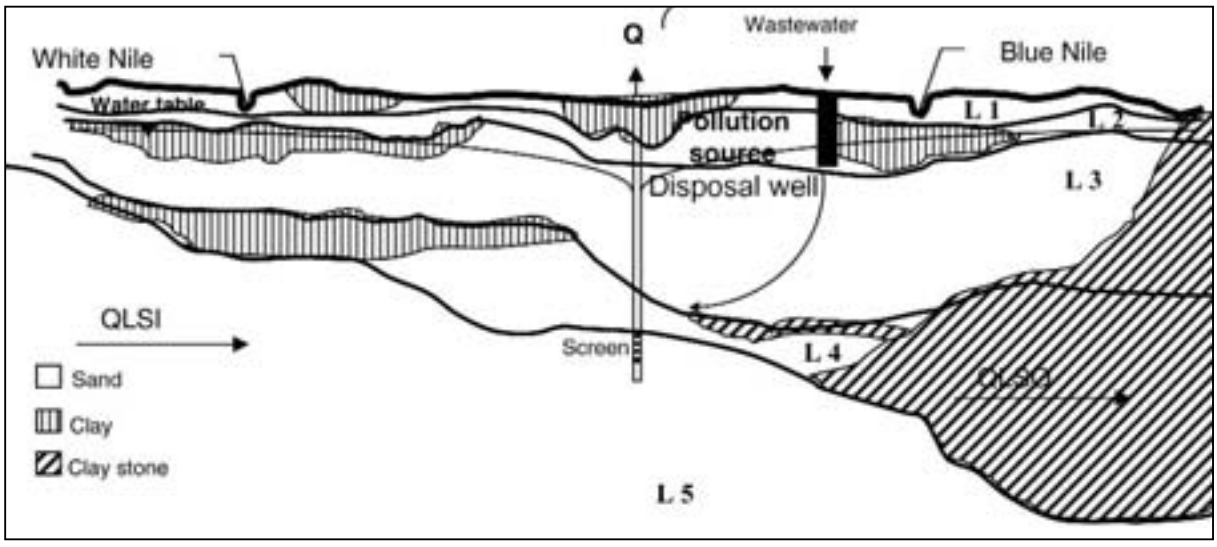


FIGURE 1. Model conceptualization.

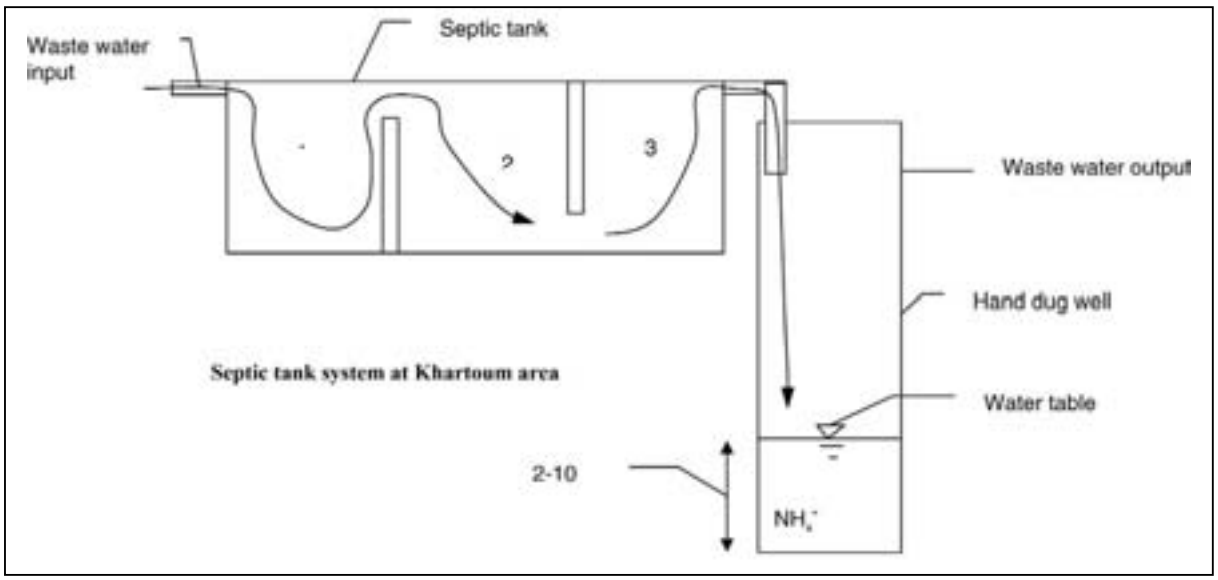


FIGURE 2. Ammonium existence and behavior in pollution source of Khartoum area

can find that the aquifer can be divided into many layers. Some of them are partly confining layers, which are represented in the pockets of clay and claystone.

The upper part of the aquifer is mainly clay and sand with some pockets of gravel and recent alluvial deposition and this mainly lies above the water level.

The lower and most thicker layer is a sand stone with some formations of sand and its thickness varies from 100 to 400 m covered by some pockets of clay (thickness 5–15 meters in the southern part) and a thick layer of claystone at Oumdurman area.

■ Hydrogeological stresses

Input stresses

Lateral inflow

The recharge components of the Khartoum aquifer is mainly the input lateral flow that comes from the southern part of Khartoum aquifer, which it is an extension of Umrawaba aquifer.

River recharge

Rivers Blue Nile, White Nile and the main Nile play an important role of recharging the groundwater, but in the study area the three rivers' contributions of recharge is very little because of the thick clay layer that bedded the rivers in the study area.

Out put stresses

Pumping

Several abstraction well are located in the area mainly for domestic and industrial use and represented about 60% of water supply in the area.

Lateral out flow

The lateral out flow mainly directed to the north direction, flowing according to the river Nile direction in a very few amount out of the area.

Determination of pollutant sources, behavior and development

The main sewerage system in the area is septic tank. The system is composed of three rooms for aeration and wastewater treatment is to be poured into a hand dug well as a disposal well, which is duged deep into the groundwater level and below, from 2–10 meters; see system (Fig. 2).

The initial concentration in the disposal well (Fig. 3) of ammonium is 60 mg/l this concentration can be considered as a constant concentration because:

- different samples has been taken from differ-

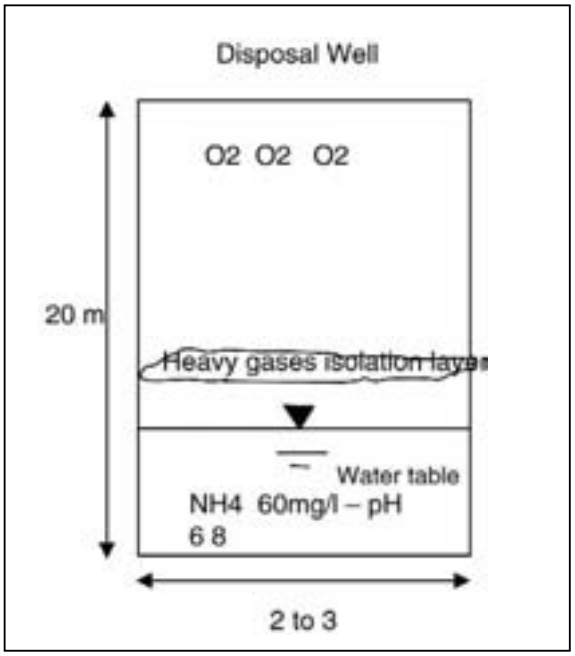


FIGURE 3. Chemical reactions in the disposal well

ent places and different times and it was constant in the range of 60 mg/l;

- pH value is equal to 6.8 therefore the ammonium percent in the water is about 95% (Behanke, J.).
- The physical and chemical conditions of the ammonium existence in the disposal well, where the ammonium is in saturated and anaerobic condition. As well there is an isolation of the wastewater in the disposal well from the atmospheric oxygen, because of heavy layers of gases like nitrogen and others which are resulted as chemical reactions output from waste water contact with atmospheric oxygen in the well trough its falling down to the saturated zone.

Therefore and with in the depth of 20 meters, the de-ammonification processes in the saturated zone can hardly happen due to lacks of oxygen. And it can be considered as a constant concentration of 60 mg/l.

Results and discussion

The shape of ammonium transport indicates that the main dominant transport mechanism after advection is diffusion with a low effect of dispersion and very high effect adsorption at clayey confining layers especially at Azharai and Reyadh area according to the following:

d- Spatial distributions of concentration increasing after 5, 10 and 30 years (min concentration is 0.078 mg/l – light blue) in layer 4 ≈ 200 in depth.

Conclusion

The aquifer is very vulnerable due to the septic tank sewerage system, and the rate of recharge is very low to wash up the contamination.

The water in very deep aquifer Nubian sandstone to the north west is a fossil water which contact to Khartoum state local aquifer is also vulnerable due to contamination even from other contaminants.

In a view of groundwater resources of Khartoum sustainability, there is a very high expectation of other contaminants, especially heavy metals and toxicants that they may damage this resource according to the recent domestic sewage practicing as well as industrial one.

Recommendations

- Since it is very hard – at least now – to alternate the septic tank sewerage system to a sewerage system with a treatment plant, the septic tank system should be improved till a big plant of the sewerage system is built up to be applied at the surrounding areas of Khartoum (flow direction towards the center).
- Developing a plan for replacing this system in stages.
- More data must be collected for accurate evaluation by doing more investigations, model calibration and apply modeling in small scales in the mentioned above zones.
- A system must be planed for remediation and cleaning the aquifer from the recent contaminant transport.
- Reducing the constant concentration in the disposal well and septic tanks can make an effective protection to the aquifer from pollution, by adding more oxygen for de-ammonification. As well denitrification processes must be applied to decrease the nitrate out put (60 mg/l of NH4+ needs 216 mg/l of oxygen to be deformed to nitrate).
- Transport mechanism parameters such as dis-

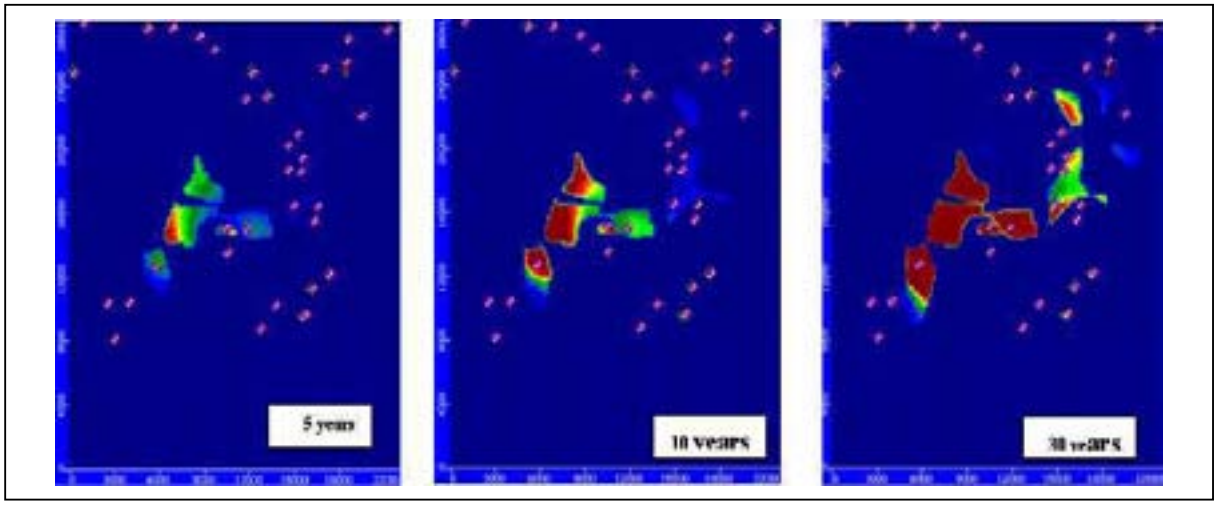


FIGURE 4

persion diffusion and adsorption for typical geological formation and expected contaminants of Khartoum area, as model uncertainties they must be detected and tested by lab experiments and field investigations.
- The conductivity of sandstone is very high (70 m/day according to the previous studies) this value can exaggerate the plume shape down to the aquifer as other parameters of uncertainties it must be re-evaluated.
- A reduction of pumping rate at Reyadh area must be applied at this area that has cone of depression.

B - Case Two
Applying groundwater modeling for optimal usage results for groundwater irrigation west Dongula north Sudan (in the Nubian aquifer) by considering the recharge from the Nile (in brief)

This case study is a quite small example that may represent the joint researches between two of the countries within the shared Nubian aquifer, Sudan (Ministry of Agriculture) and Libya (National consulting Bureau).

Objectives of the study

- Assessing the optimal usage results of groundwater irrigation.
- Assessing the Nile recharge into the aquifer.

■ Geology

The geological set-up of the area comprises (Fig. 5):
- the basement complex;
- the Nubian formation;
- the volcanic rocks;
- the alluvial deposits.

■ Hydrogeology

Aquifer system

The aquifer system in the area consist of three layers:
- First layer, the on top alluvial layer that has mean thickness of 80 meters.
- Second layer, the second layer of Nubian sandstone layer this layer mainly considered as unconfined to confined layer depending on alluvial deposits properties.
- Third, layer the impermeable basement complex layer.

■ Hydrogeological stresses

Inflows
- Recharge from the Nile (very limit).

Outflows
- Wells' abstraction;
- Discharge to the;
- Evaporation from Qaab depression.

■ Results

As shown in figures by applying full pumping capacity, half and quarter for 70 years the determination of draw down will be as shown in Figure 6.

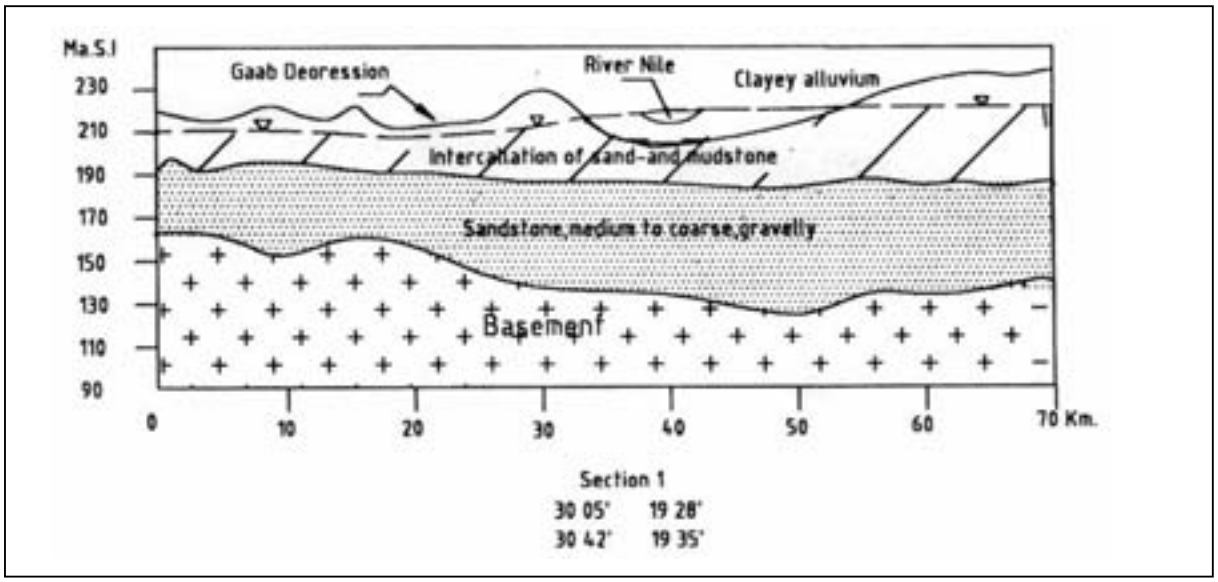


FIGURE 5

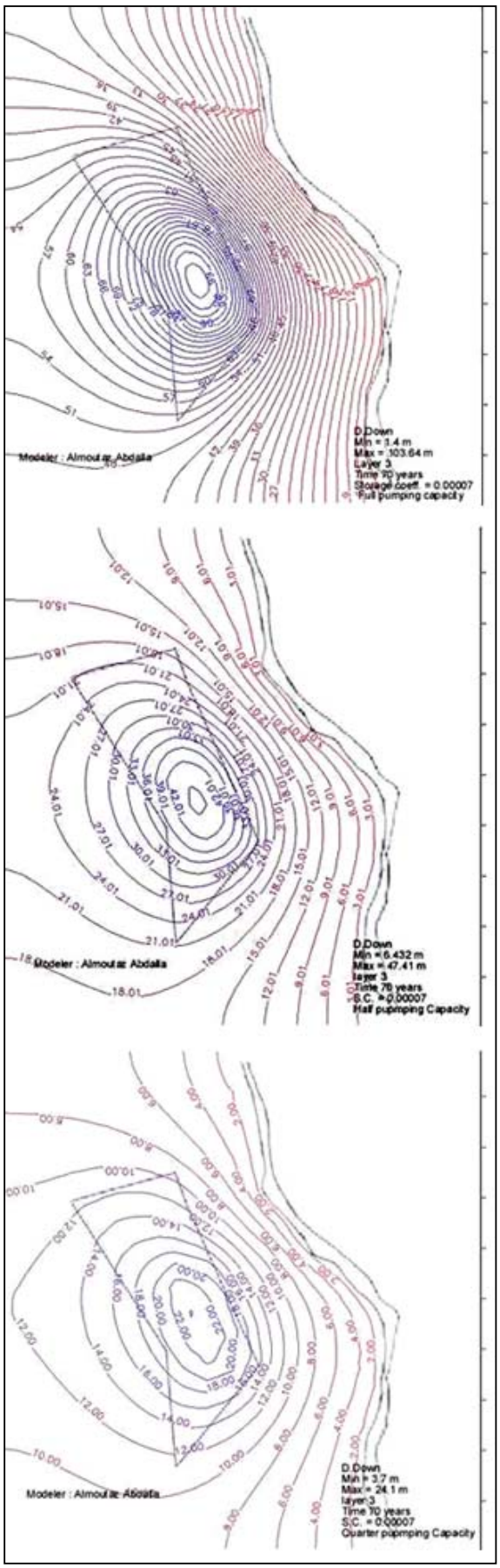


FIGURE 6

2. The use of environmental isotopes for groundwater resources evaluation in Northern State Sudan

The study area lies in Northern Sudan within the desert and semi desert climatic region with variable summer rainfall ranging from 0 to 100 mm/year. The potential evaporation is in the order of 3000 mm/year. Although the Nile river runs through the study area groundwater provides the major source of water for the population, estimated to be about one million. About 100 thousands people live away from the Nile were severely affected by the recent drought which has lead to a massive scale destruction of agricultural land and animal wealth. The efforts are now aimed at enhancing food production and attaining self sufficiency using groundwater resources.

The main objective of this study is to evaluate the groundwater resources in the area. Specifically the aim is to use hydrochemical and environmental isotope techniques to have a better understanding of interaction between aquifer systems in the area, the recharge mechanisms and rates, dynamics of flow and mixing proportions of different waters. Some other localized problems such as excessive drawdown and salinity increase were also investigated during the study. Moreover the ultimate goal is to suggest proper groundwater management policies in the area and to enhance the technical capabilities of the national staff in the use of isotope technique for solving other related groundwater problems in the country. The geological set-up of the area comprises (Fig. 5):

- the basement complex
- the Nubian formation,
- the volcanic rocks, and
- the alluvial deposits.

The major water bearing formations are the Nubian sandstone and the Nile alluvium. Very intensive small scale farmer managed agriculture is conducted using groundwater from the alluvium aquifer. Abstraction is estimated to be about 800 x 10^6 cubic meters per year. Another 40 x10^6 cubic meters per year is abstracted from the Nubian sandstone aquifer mainly for domestic use.

For the purpose of this study four sampling campaigns were made during which 200 samples were collected from 72 boreholes, driven wells, dug wells and the Nile. Well head measurements, chemical analysis and isotopic analysis were carried out. Chemical analysis was carried

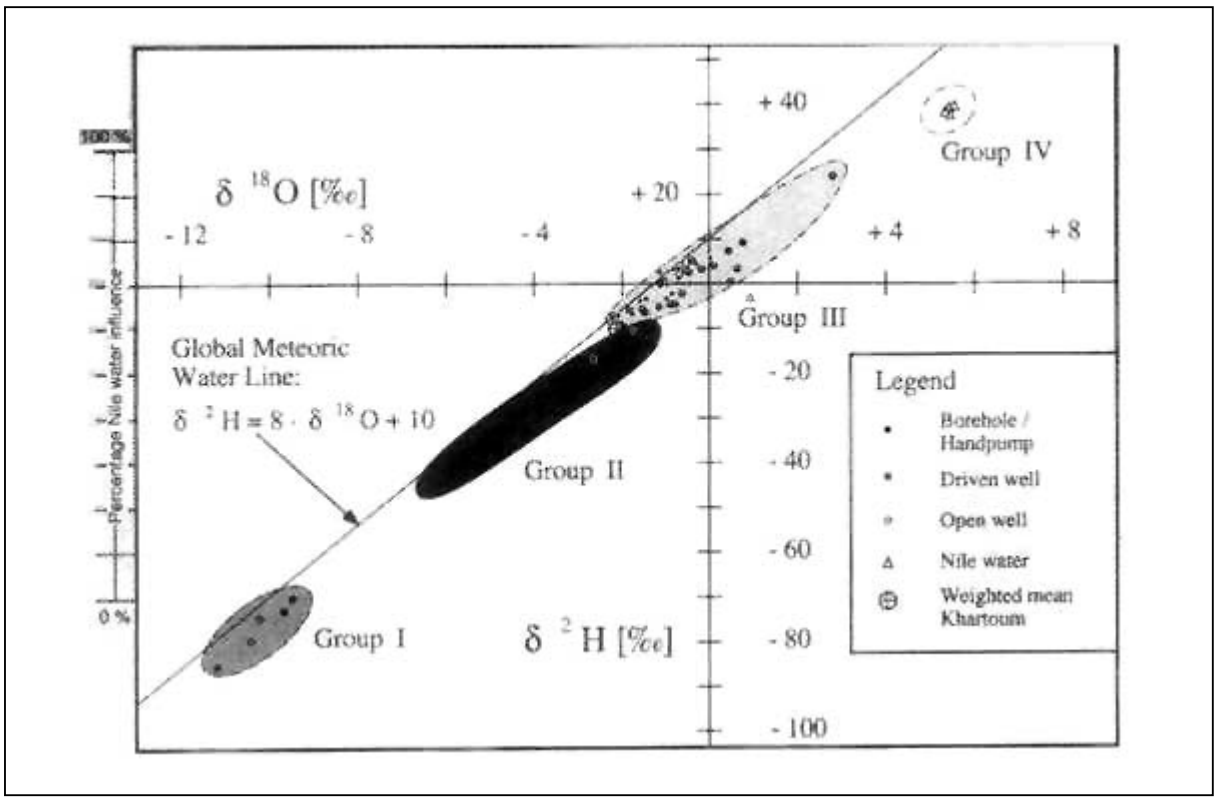


FIGURE 7

out locally while isotopic analysis was carried out in GSF, Germany.

The results of the chemical analysis reflects three water groups, sodium bicarbonate water in the Nile and the adjacent aquifer, mixed water with increase in Ca+Mg/Na and water with dominance of $S0_4$ and Cl and further increase in Ca+Mg/Na away from the Nile. The EC values suggest that the water is generally suitable for irrigation although in some locations problems of high salinity were detected. This is due to the excessive evaporation and irrigation return. Based on the results of stable isotopes distinguished (Fig. 7) four groups of water were:

(i) Paleo water remote from the Nile,
(ii) Paleo water influenced by the Nile,
(iii) Recent water which is originally Nile water,
(iv) Pure Nile water.

The Nile influence was found to extend up to 40 km by side. Beyond that groundwater is paleo and does not receive any recharge. Therefore groundwater development requires careful management.

Tritium results showed variation in concentration at water points with the same distance from the Nile indicating non uniform influence. The Nile river maintains the natural level of Tritium that was known before the nuclear bomb test (4.6 to 6 TU).

Only seven samples of C-14 were analyzed with values ranging between 2.08 pmc for locations remote from the Nile and 81.2 pmc in areas near the Nile. However some locations close to the Nile showed low C-14 (14.5 pmc) indicating contribution of paleo water to the wells near the Nile and possibly to the Nile base flow. This is confirmed by the directions of regional groundwater flow in the area.

3. Examples of the use of remote sensing

Here are some examples of radar satellite images that explain the shape of sub sand layers, ancient water shed, and as well the geological formations of various area in the Nubian shared aquifer countries.

- **Image 1. Nile River, Sudan**
  The white band in the top right of the radar image is an ancient channel of the Nile that is now buried under layers of sand. This channel cannot be seen in the photograph and its existence was not known before this radar image was processed. The area to the left in both images shows how the Nile is forced to flow through a chaotic set of fractures that causes the river to break up into smaller channels, suggesting that the Nile has only recently established this course.

Image 1. Nile River, Sudan



Image 2. Safsaf Oasis in southern Egypt

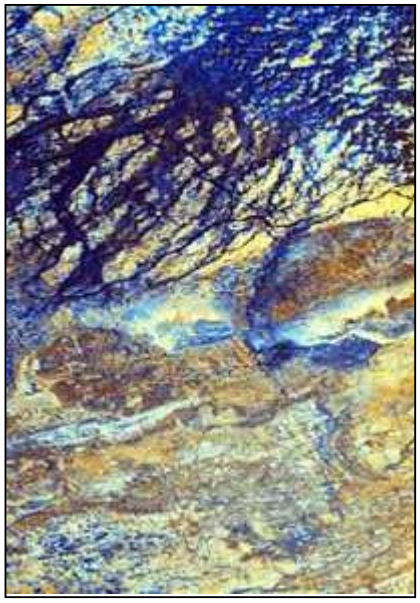


Image 3. Wadi Kufra, Libya



Image 4. Possible string of impact craters, Chad



- **Image 2. Safsaf Oasis in southern Egypt**
  It shows detailed structures of bedrock; the dark blue sinuous lines are braided channels that occupy part of an old broad river valley. On the ground and in optical photographs, this big valley and the channels in it are invisible because they are entirely covered by windblown sand.
  It is hypothesized that the large valley was carved by one of several ancient predecessor rivers that crossed this part of North Africa, flowing westward.

- **Image 3. Wadi Kufra, Libya**
  A previously unknown branch of an ancient river, buried under thousands of years of windblown sand in a region of the Sahara Desert in North Africa. This area is near the Kufra Oasis in southeast Libya. Image reveals a system of old, now inactive stream valleys, called 'paleodrainage systems,' which, during periods of wetter climate, carried running water northward across the Sahara. The region is now hyper-arid, receiving only a few millimeters of rainfall per year, and the valleys are now dry 'wadis,' or channels, mostly buried by windblown sand.

- **Image 4. Possible string of impact craters, Chad**
  The impact of an asteroid or comet several hundred million years ago left scars in the landscape that are still visible in this spaceborne radar image of an area in the Sahara Desert of northern Chad. The concentric ring structure left of center is the Aorounga impact crater with a diameter of about 17 kilometers (10.5 miles). Scientists are using radar images to investigate the possibility that Aorounga formed as part of a multiple impact event. As well we can use this image for investigate the sedimentary formation at that area.

Recommendations

- Groundwater in Sudan is essential for now and future to the life in the northern part of Sudan, which lies on the Nubian shared aquifer.

- Sustainability of shared aquifer required Institutional collaboration and joint decision making regarding development policies.

- Net working joint studies and research programs for better understanding of the aquifer mechanism as well data exchange programs.

- Enhancing the capability of authorities by using advanced technology for data collection and Implementation of advanced methodologies such as modeling, isotopes, remote sensing and GIS

References

1. Yangxiao Zhou. *Applied Modelling groundwater flow and contaminant transport.* HH453/99/1.
2. W. Spaans. *Groundwater modeling.* Part 1 and 2. HH323/95/1.

Use of modeling

ALMOUTAZ Abdalla Mohammed. *Assessment of Groundwater Pollution from Domestic Waste Water in Khartoum Area – 1999.*

Applying groundwater modeling for optimal usage results for groundwater irrigation west Dongula north Sudan. Ministry of Agriculture, Sudan and National Consulting Bureau, Libya.

Use of Environmental Isotopes

Groundwater assessment in the transboundary aquifer at Mhlumeni Border Post Area, eastern Swaziland

Obed Mfanimpela Ngwenya

Geological Survey and Mines Department, Mbabane, Swaziland

Abstract

The Mhlumeni Border Post is located at approximately latitude 26° 16′ S and longitude 32° 05′ E, about 30 km north east of the small town of Siteki east of Swaziland. The area is semi-arid. Southeast trade winds provide summer rainfall to the area. The average annual rainfall is about 500 mm and mean temperature is about 25°C.

The main objective of the survey and drilling was to locate suitable boreholes to supply potable water for the Mhlumeni Border Post which will be opening soon between Swaziland and Mozambique. The other objective of the survey was to help us understand the hydrogeology of the area since no previous groundwater studies were conducted in the area. The Border was closed in 1975 during the outbreak of a civil war in neighbouring Mozambique. No surface water source is available in the area.

The main aquifer in the area is a fault breccia within the rhyolite formation. It extends to neighbouring Mozambique. Surveying was conducted by the Electromagnetic Instrument, EM-34. Drilling by the DTH Method using an air rotary drilling rig. Hydrogeological interpretation was based on borehole data, water levels, water chemistry and pump test results.

Borehole yields in the breccia is variable, ranging from 0.2 L/s to 1.0 L/s. The average specific capacity of the breccia is 1.42 m^3/day/m and transmissivity is of the order of 10^{-5} m^2/s. Groundwater contours were constructed using piezometric heads of the boreholes. The groundwater flow direction is generally to the east and along the breccia to the Northeast towards Mozambique. The hydraulic gradient is about 0.1. Depth to groundwater is generally shallow, ranging between 3.0 m to 14.0 m along the breccia.

The groundwater quality is good. However, there is a strong potential for pollution as indicated in one of the boreholes located inside the Border Post compound with high chloride concentration and also high EC compared to the other boreholes in the area. Since the Mhlumeni Border Post will be opened soon between the two countries, it is likely that Mozambique will also exploit the same breccia aquifer for groundwater development since there is no other source of water in the vicinity of the Border Post. The breccia is small and of limited extent, and hence groundwater development will also be limited . It also has a potential for being polluted since the groundwater level is shallow and there is likelihood of mushrooming of informal settlements over the aquifer once the Border is reopened. Therefore a groundwater monitoring programme is being conducted by the Geology Department to continuously monitor groundwater quality and fluctuations in groundwater levels in the aquifer. Also a recharge study is being planned for the area.

Introduction

The Mhlumeni Border Post is located at approximately latitude 26° 16′ S (159,6360 m) and longitude 32° 05′ E (358,820 m), about 30 km north east of the small town of Siteki east of Swaziland (Figure 1). Access to the area is easily made possible by the recently tarred road that connect Siteki town and Goba in Mozambique.

Drainage is generally to the east and southeast. Land surface elevation vary from 400 masl (metres above sea level) to 460 masl. Vegetation

IAEA, 1994.

Use of GIS and remote sensing
ELKADI, 1994.
NASA radar satellite images.

consists of mix bush and savanna. Southeast trade winds provide summer rainfall to the area. The average annual rainfall is about 500 mm and mean temperature is about 25°C.

The main objective of the study was to locate best drilling targets to supply potable water to the Mhlumeni Border Post which will open later this year between Swaziland and Mozambique. The other objective of the study was to enable the Geology Department to understand the hydrogeology of the area since no previous groundwater studies were conducted in the area. The Border was closed in 1975 during the outbreak of a civil war in neighbouring Mozambique. No surface water source is available in the area.

The main aquifer in the area is a fault brec-

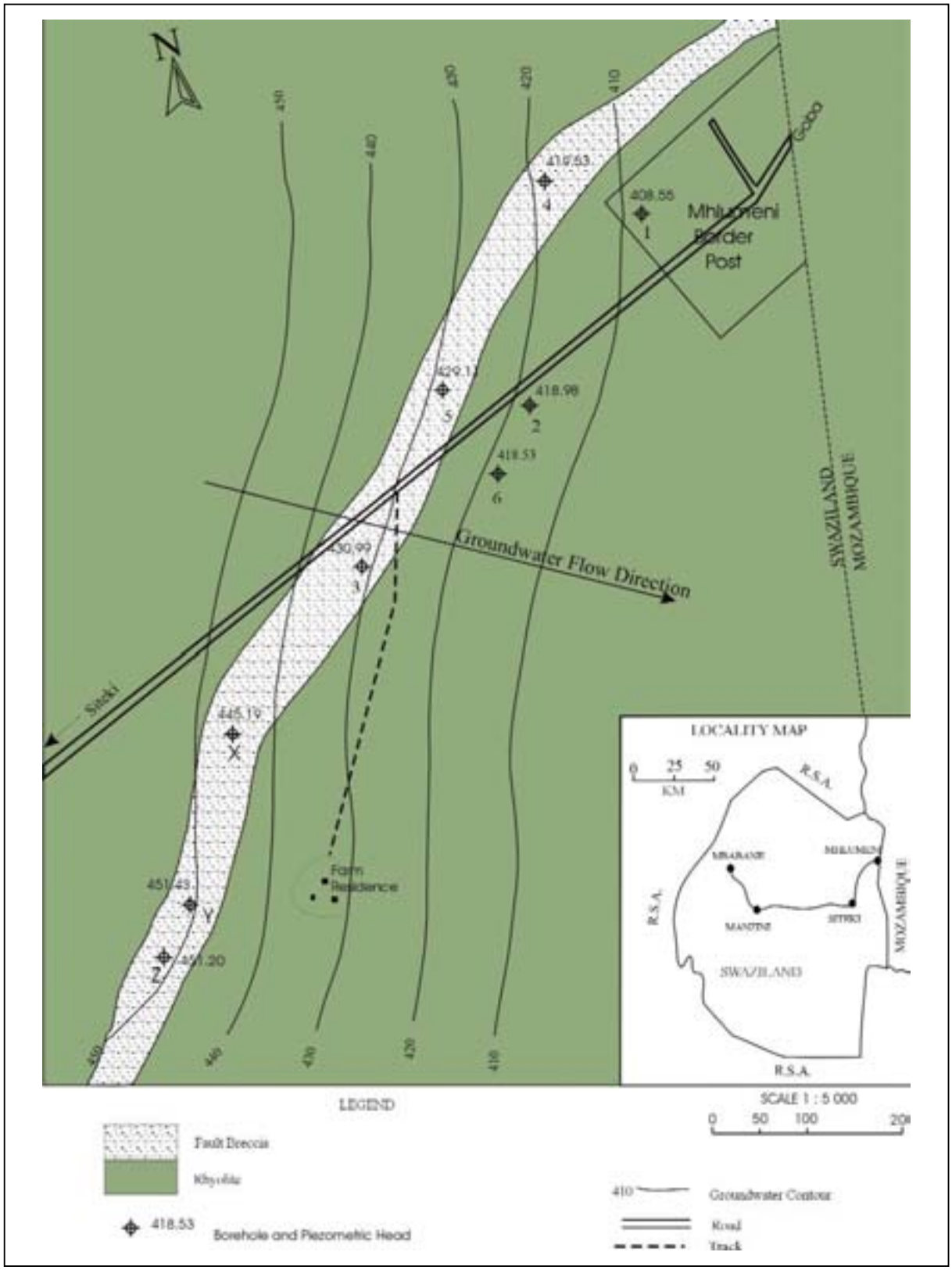


FIGURE 1

cia occurring within a rhyolite formation. The fault breccia extend to neighbouring Mozambique within the Border area (Figure 1). During the study three boreholes were drilled in the fault breccia and three in the surrounding rhyolite. Three other boreholes are existing in the fault breccia. All drilled boreholes were pump tested and also sampled for chemical analysis.

Geology

The Mhlumeni Border Post area is underlain by the acid volcanic rocks of the Karoo Supergroup. Cleverly (1977) has dated these acid volcanic rocks at 189 ± 7 m.y. (R_b-S_R). These rocks are described as 5 km thick, ranging in composition from rhyolite to dacite and contain phenocrysts of plagioclase, quartz, clinopyroxene and magnetite (Cleverly, 1977 and Wilson, 1982).

Cleverly and Bristow (1979) suggested that these rocks may have been deposited as devitrified or degassed as flows rather that normal flow, and therefore classed them as rheoignimbrites. From detailed geochemical analysis, Cleverly (1977) has concluded that the bulk of the acid volcanic rocks were derived from partial melting or differentiation from a basaltic source.

Within the massive rhyolite formation, a small fault breccia occur (Figure 1). It extend to neighbouring Mozambique. The fault breccia is the main source of groundwater in the area. The soil in the area is shallow, permeable and fersiallic.

Hydrogeology

Aquifer properties

Surface geophysical surveying was conducted by the Electromagnetic Instrument EM-34. Drilling was done by the DTH Method using an air rotary drilling rig. Hydrogeological interpretation is based on borehole data, groundwater levels, groundwater chemistry and pump test results.

The rhyolites are generally massive and unfractured. Groundwater flow and storage occur primarily in secondary porosity such as cracks, fissures, joints and zones of weathering. The main aquifer in the area is a fault breccia within the rhyolites (Figure 1). The fault breccia strikes towards the north east into neighbouring Mozambique. Its full extent is not known yet. During this study three boreholes were drilled in the fault breccia and three in the surrounding rhyolites. Three other boreholes are existing in the fault breccia .

Boreholes numbered 3, 4 and 5 together with existing boreholes X, Y and Z are in the fault breccia (Figure 1).

Air blown yields of the boreholes in the fault breccia vary from 0.2 L/s to 1.0 L/s. Table 1 summarises the drilling results .

Boreholes X, Y and Z are used by a local farm for livestock watering and for domestic purpose. These boreholes are fitted with windmills and they pump collectively into a 100,000 L reservoir. Their actual yields are unknown, but are estimated to be between 0.5 L/s and 1.0 L/s . Boreholes 3, 4 and 5 are collectively being used to supply potable water to the Border Post on the Swaziland side. Borehole yields in the massive

TABLE 1. Summary of borehole data – Mhlumeni Border Post

Borehole number	*Co-ordinates*		*Elevation*	*Depth (m)*	*Water level (m)*	*Unit*	*Blown yield (l/s)*
	Easting	*Northing*					
1	358,820	1,596,360	426	122.00	19.50	LR	0.10
2	358,245	1,596,015	424	134.20	6.52	LR	0.10
3	358,120	1,596,017	476	115.80	5.41	BR	0.20
4	358,315	1,596,465	435	115.90	13.82	BR	0.30
5	358,140	1,596,250	437	67.10	3.58	BR	1.00
6	358,165	1,596,115	428	51.80	6.08	LR	1.00

Note:
LR = Rhyolite; BR = Fault breccia

Table 2. Pump test results

Borehole number	*Static water level (m)*	*Pumping rate (l/s)*	*Duration (mins)*	*Drawdown (m)*	*Recovery (mins)*
1	19.50	0.6	240	68.55	60
2	6.52	0.8	64	77.59	200
3	5.41	0.8	64	67.04	35
4	13.82	0.8	240	73.61	225
5	3.58	0.8	1,440	30.91	35
6	6.08	0.8	720	27.46	50

Table 3. Calculated transmissivity values and specific capacity

Borehole number	*Unit*	*Specific capacity (m^3/day/m)*	*Transmissivity (m^2/s)*
1	LR	0.76	2.35×10^{-6}
2	LR	0.89	2.46×10^{-6}
3	BR	1.03	3.26×10^{-5}
4	BR	1.00	2.48×10^{-5}
5	BR	2.24	2.70×10^{-5}
6	LR/FZ	2.52	7.80×10^{-6}

Note: LR/FZ = Fractured rhyolites

rhyolite are very low except for borehole No. 6 where a fracture was encountered at depth.

Pumping tests were conducted on all boreholes drilled during this study.

Table 2 summarises the pump test results.

From the pump test results, boreholes 5 and 6 are the most reliable. It appears the two are along fracture running NW-SE.

The transmissivity (T) was calculated after the pumping tests. The T values in the breccia are of the order of 10^{-5} m^2/s, and in the rhyolites are of the order of 10^{-6} m^2/s (Table 3).

The productivity of a borehole is often expressed in terms of the specific capacity. The specific capacity of the borehole in the fault breccia vary from 1.0 to 2.24 m^3/day/m (Table 3).

Groundwater flow

Groundwater contours were constructed using piezometric heads of nine boreholes in the study area (Figure 1). The piezometric head contours are more or less parallel to the topographic contours. The groundwater flow direction is generally to the east (Figure 1). There is also flow along the breccia from southeast to northeast direction. The hydraulic gradient is about 0.1. Depth to groundwater is generally shallow ranging between 3.0 m to 14.0 in the fault breccia.

Groundwater quality

The groundwater in the area has low total dissolved solids and therefore it is of good quality for domestic use (Table 4).

The high concentration of chloride in borehole No. 1 may have been due to some contamination from human activity. This borehole is

Table 4. Quality of groundwater

Borehole number	*Cations (mg/L)*						*Anions (mg/L)*					*ALK (mg/L)*	*EC (msm)*	pH
	Ca	*Mg*	*Na*	*K*	*Fe*	*Mn*	*HCO_3*	*Cl*	*SO_4*	*NO_3*	*F*			
1	8	43	101	2.4	0	0	220	288	8	0	1	180	139	8
2	8	20	53	1.8	0	0	238	78	7	0.6	1	195	67	8
3	2	5	24	1.8	0	0	55	68	3	2	1	45	37	8
4	5	18	44	1.9	0	0	214	70	8	2	0	175	59	8
5	1	3	17	1.1	0.6	0.2	31	63	3.2	0.6	0	25	23	8
Control	89	53	14.7	1.0	0.5	0.5	153	50	36	10.4	4.2	125	141.1	7.1

located within the compound of the Border Post. There was a lot of human activity when the Border was in operation in the past. Borehole No. 1 should be avoided for use if possible. The groundwater is slightly alkaline with an average pH of 8.

Groundwater management

There is growing evidence that groundwater will be the only source of potable water in the present and future in the Border Post. Both countries are likely to exploit the same fault breccia for water supply to the Border since there is no other source of water in the vicinity. Once the Border re-opens later this year, the population will grow which may result to some informal settlements. Pollution sources will therefore, be inevitable from human activity. Therefore the fault breccia will be threatened by risk of groundwater contamination because the depth to groundwater is shallow, aquifer narrow and of limited extent, low borehole yields and the soil is highly permeable. Already there is evidence of contamination in borehole No1 located inside the Border Post compound due to past human activity when the Border was still functioning. Therefore, caution should be taken by both countries to protect the aquifer from contamination. No settlement should be allowed on the breccia. Long term monitoring of groundwater levels in the fault breccia and surrounding rhyolites is being planned by the Geology Department. Groundwater quality will also be monitored frequently. A groundwater recharge study will also be conducted in the area.

Conclusions

The fault breccia is the main aquifer for groundwater development at the Mhlumeni Border Post area. It is likely to be exploited by both Swaziland and Mozambique for water supply to the Border. The water quality is good. However, since the fault breccia is narrow and of limited extent, low borehole yields, groundwater development will also be limited. The breccia is also at risk to groundwater contamination and hence it has to be continuously monitored and protected by both countries for sustainable use.

References

CLEVERLY, R.W. 1977. The Structural and Magmatic Evolution of the Lebombo Monocline, Southern Africa, with

reference to Swaziland. Ph.D. Thesis, University of Oxford (Unpublished).

CLEVERLY, R.W. and BRISTOW, J.W. 1979. Revised Volcanic Stratigraphy of the Lebombo Monocline. Transaction of the Geological Society of Africa, 82, 227–230.

WILSON, A.C. 1982. Geological Map of Swaziland, Scale 1:250,000. Prepared by Department of Geological Survey and Mines, Mbabane, Swaziland.

Transboundary aquifers of Tanzania

Samson Mapanda

Water Resources Department, Dar es Salaam,Tanzania

Tanzania is located along eastern seaboard of Africa and shares its borders with eight countries. Kenya and Uganda to the north, the Democratic Republic of Congo (DRC), Rwanda and Burundi to the west and northwest respectively and Zambia, Malawi and Mozambique to the south. Tanzania has a land area of 945,000 sq.km and has a coastline of approximately 800 km long.

Generally, the Precambrian basement complex, Karoo supergroup, Post Karoo sedimentary formations and volcanic and alluvium deposits represents the geology of Tanzania.

Groundwater occurrence in basement complex rocks is largely limited to secondary features such as weathered zones, joints, fractures, faults etc. The transboundary aquifer type in the basement complex is metasediments aquifers that are dominant in west of Tanzania. This type of aquifer is crossing the border to Burundi, Rwanda and partially Northern DRC.

Sandstones and conglomerates of Karoo are characterized by groundwater occurrence associated with primary porosity and intergranular flow, which may locally enhanced by secondary porosity created by fracturing. This type of aquifer crosses the border in the southern part of Tanzania to Mozambique.

In the coastal sedimentary formations that attain a thickness of more than 200 m, has an aquifer lithology of limestone, sandstones, sand, marls, etc. This type of aquifer crosses to the north with Kenya and to the south with Mozambique.

The greatest aquifer potential in Tanzania lies within the volcanic pyroclastic and volcano-alluvium deposits found in the slopes of mount Kilimanjaro. This type of aquifer extends as further as to the Kenyan territory.

Last but not least the alluvial deposits that are confined in the deltas have also international significant. The country's boundary deltas of Kagera and Ruvuma that borders Tanzania with Uganda and Mozambique respectively can be included in the subject of Transboundary aquifers.

Conceptual framework of the North Western Sahara Aquifer System

Mustapha Besbes, Mohamed Babasy, Sadek Kadri, Djamel Latrech, Ahmed Mamou, Philippe Pallas, Malek Zammouri

Observatoire du Sahara et du Sahel

The North Western Sahara Aquifer System [NWSAS] designates the superposition of two main deep aquifer layers: a) the Continental Intercalaire formation, CI, which is the deepest (2,000 m in the Chotts region), b) the Complexe Terminal, CT. This System covers an extent of more than a million km^2, of which more than 60% are in Algeria, a little less than 10% in Tunisia, and 30% in Libya. This basin possesses a scale of 1,800 km E-W and 900 km N-S.

Given the conditions of saharan climate, these formations receive weak quantities of recharge: approximately 1 billion m^3/year to the total, infiltrated essentially to the Saharian Atlas in Algeria, as well as on the Dahar and the Dj. Nefoussa in Tunisia and Libya. However, the extension of the system and the thickness of layers have favored a considerable reserve accumulation, although of a quality generally rather average: the salt in these regions constitutes a risk that it is necessary to always manage. The question is then asked, to know until what limit the saharian aquifers can be solicited, in the objectives of a sustainable development.

Since forty years, a lot of studies tried to solve this problem. The last is conducted in partnership by Algeria, Tunisia and Libya, it is piloted by the Observatory of the Sahara and Sahel (OSS). This study comprises two complementary components: a) the constitution of a common database to the three countries,containing 9,000 water points and historical records over 50 years of water levels and pumping rates, b) the construction of an actualized numerical model, that could authorize simulation of development scenarios and prediction of their impacts on the system.

The Northern Sahara Aquifer System is exploited by near 7,000 points of water, drillings and springs: 4,000 in Algeria, 2,000 in Tunisia and some hundreds in Libya. The evolution of this exploitation indicates accelerating growths over the last twenty years. If this evolution, equally shared by the three countries, had to prolong, there would be without doubt to worry for the future of the saharian regions, where have been already observed the first signs of a degradation of the resource: very important decline of levels risking to entail in the near future irreversible salinisation of groundwater, mainly in the Complexe Terminal in the algero-tunisian chotts region and in the gulf of Syrte. The three countries concerned by the future of the system are obliged to conduct a certain form of joint management of the Saharian Aquifer Basin.

This paper briefly describes the first phase of the study conducted by OSS, which concerns the hydrogeological framework characterisation: geological framework, hydrodynamic framework, and will constitute a good basis for the conceptual model foundation.

Geological framework of the NWSAS

The Continental Intercalaire is defined as the set of sedimentary layers comprising mainly continental sandstone-clay formations of the lower Cretaceous, to which are associated post-paleozoic and ante-cenomanian marine or lagune sediments. This definition of the Continental Intercalaire, that constitutes the most extended aquifer formation in the region, determines the limits attributed to the study zone of the Northern Sahara Aquifer System. These limits are: the Saharian Atlas to the North-west; the Paleozoic

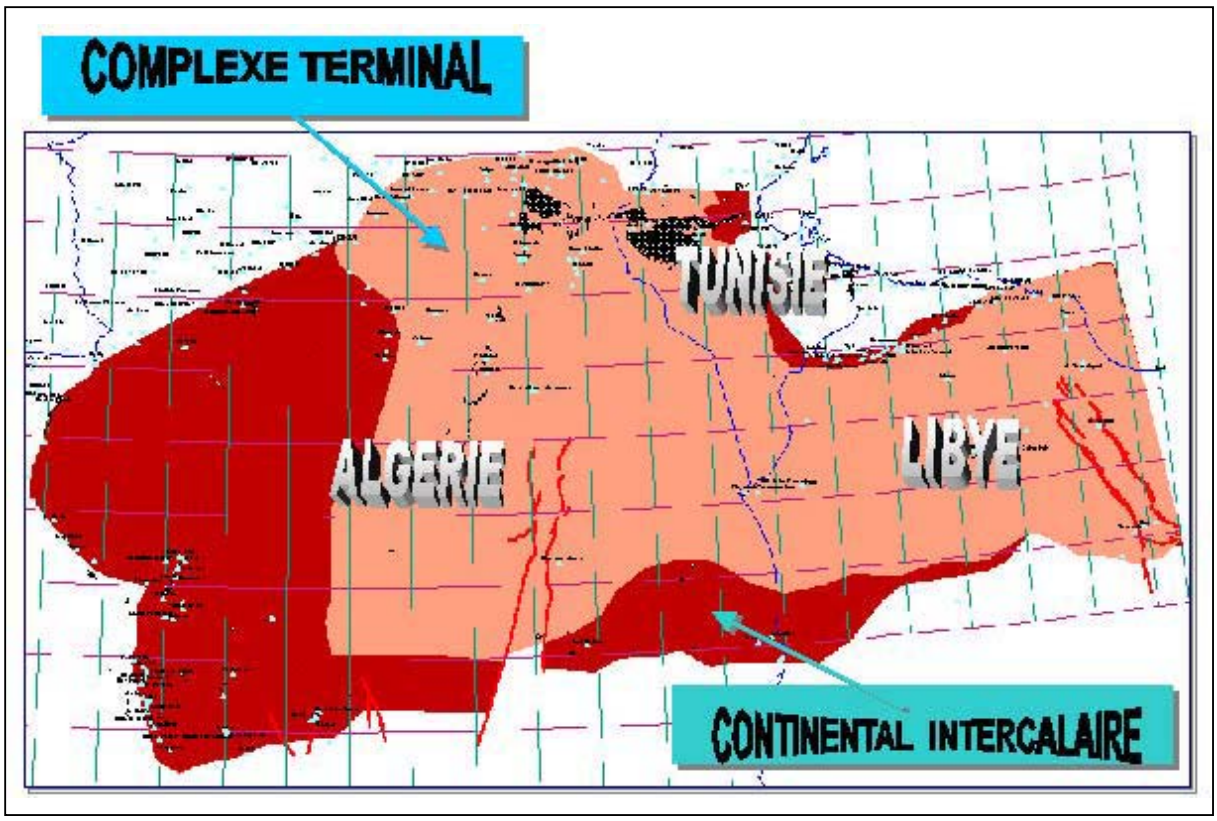


FIGURE 1. Extension of the NWSAS formations

outcrops of the Ougarta westward, Tassilis and the Dj. Hassaouna to the South, the limit to brackish water to the east of the Hun graben, the outcrops of the Continental Intercalaire on the Dj. Nefussa and the Dahar to the north, finally the south atlasic accident to the North, relayed to the gulf of Gabes by the El Hamma fault (see Fig. 2 and Fig. 3).

Classically, the 'Continental terminal' designates continental formations, sandy and clayish, in the MioPliocène. But the aquifer of the Continental Terminal is in connection with aquifers of

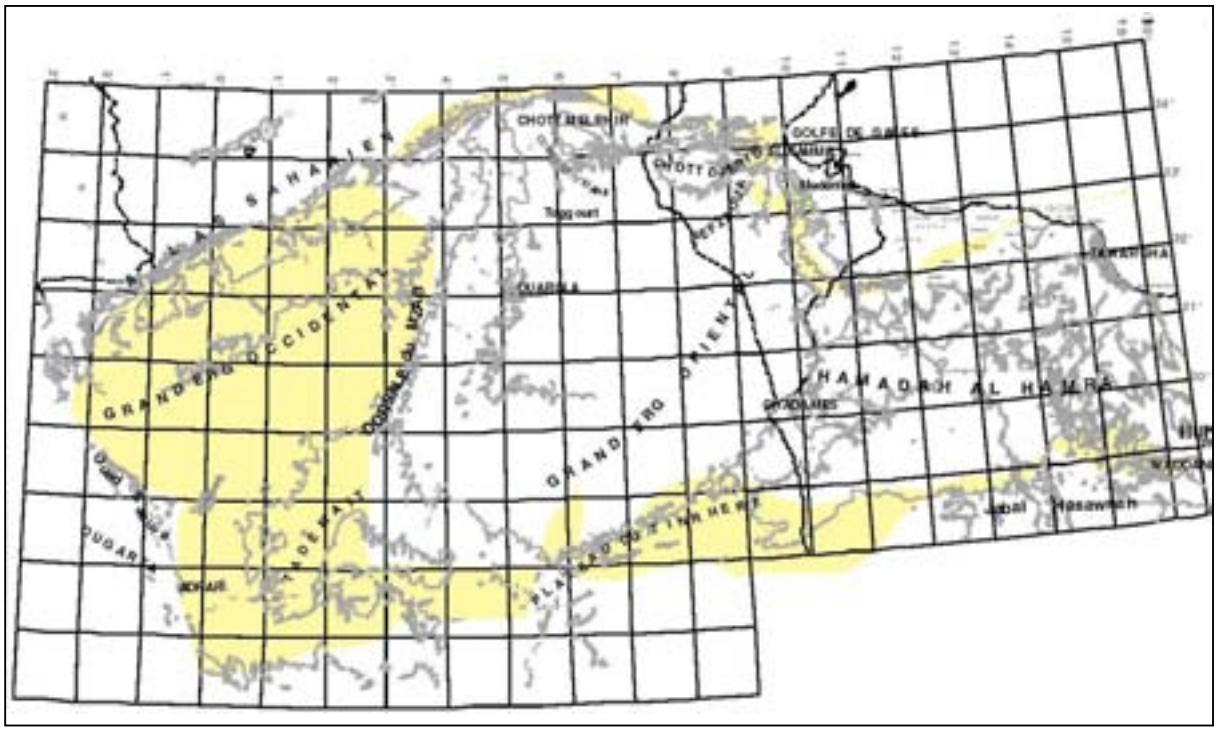


FIGURE 2. Map of North-Western Sahara

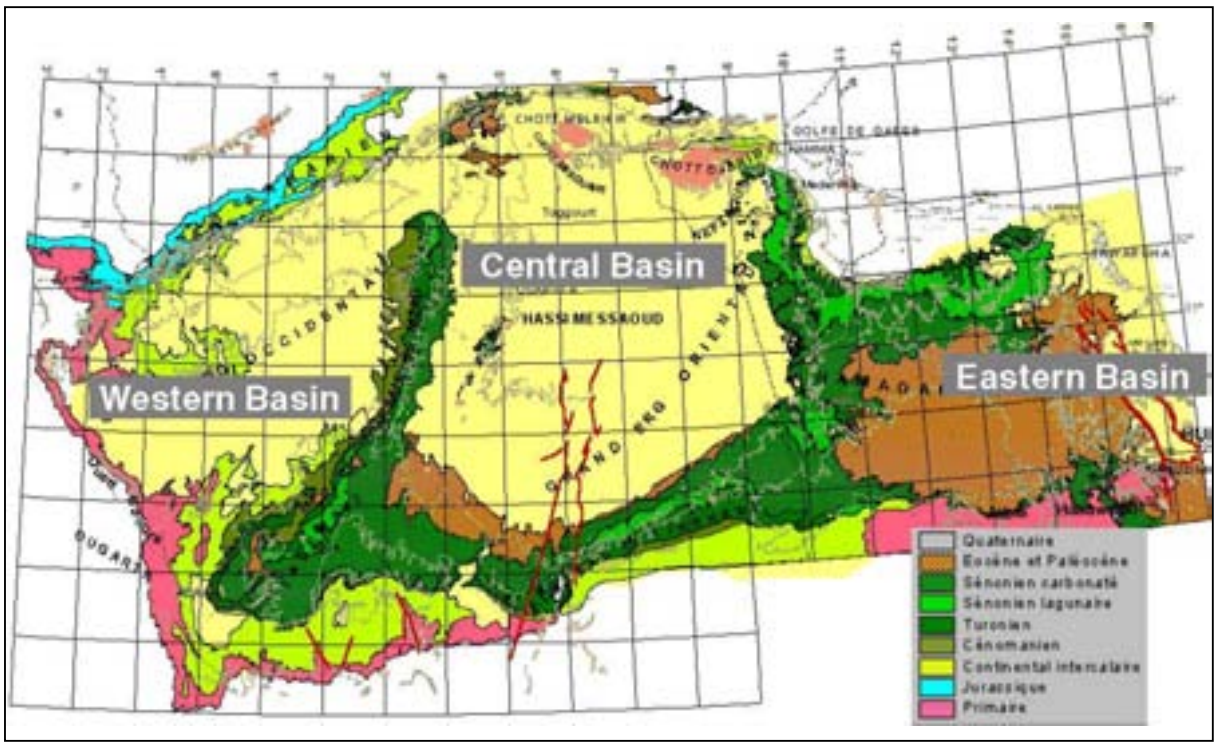


FIGURE 3. The three basins of the NWSAS defined by geological structure

the Eocene, the Senonian and the Turonian, so that considering to the whole scale of the Sahara, one can consider that these different levels form a unique aquifer, the aquifer of the 'Complexe Terminal'. Intercommunications between Senonian, Eocene and MioPliocene are evident on the whole Basin, except for the region of Chotts where the mean and upper Eocene insert. The Turonian aquifer is more individualized as a result of the low permeability of the Senonien lagunaire cover, however, its levels agree with those of the Senonien or the MioPliocene on the limits of the basin.

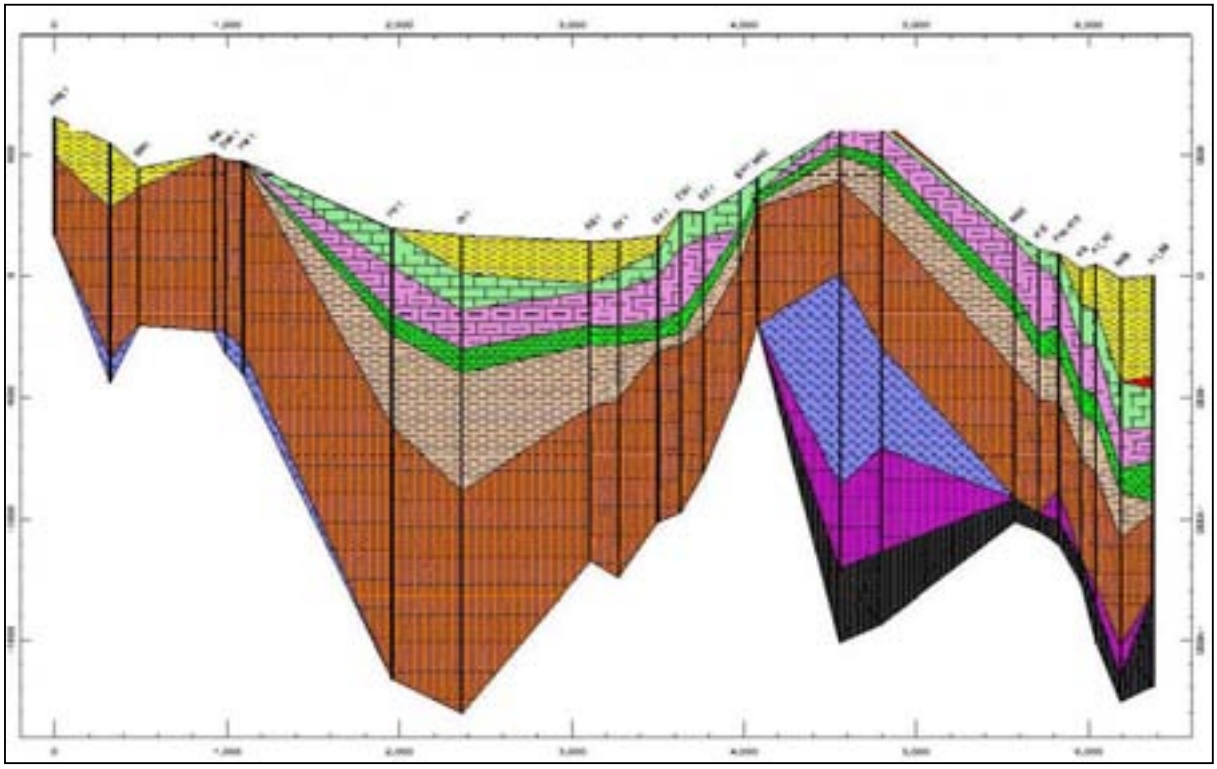


FIGURE 4. West-East median section across the NWSAS

The three basins of the NWSAS

The Conceptual Model results from a succession of simplifications having their origin in the stratigraphic subdivisions recognized on the geological outcrops confortes by the drilling logs. The result of these investigations allows to identify clearly the general structure of the NWSAS divided in three basins (Fig. 3): a) the western basin dominated by the Great Western Erg and the sector of the foggaras, b) the central basin, the most extensive in area and depth, that presents the greatest thicknesses of aquifers and whose resources are shared by the three countries, limited westward by the Mzab dorsal and to the east by the tray of the Hamadah el Hamra, c) the oriental basin characterized by the collapse of the Hun graben and the tertiary sedimentation accumulation.

Aquifers and aquitards

Due to the stratigraphic scale, that insures the time concordance and correspondence in space, and due to the whole of lithostratigraphic cross correlations undertaken, it has been possible to conjugate Algerian, Tunisian and Libyan hydrogeologies. The objective being to finally obtain a coherent framework on a hydrogeological point of view, it was necessary first, in the terminology adopted in each country, to fasten recognized lithostratigraphic formations to the universal stratigraphic scale (cf. Busson, 1970; Bishop, 1975), then to translate this formations into lithological terms to appreciate their degree of permeability, then finally to translate ten obtained lithologic formations in terms of aquifers, aquitards and aquicludes.

If we exclude the Triassic brackish aquifers, the Jurassic and Neocomien in Algeria, Triassic and Jurassic in Tunisia, generally salted, as well as the Libyan sandstone Triassic aquifer (containing sweet water, but well isolated of the other remaining aquifer systems), we find, on the litho stratigraphic criterion basis, four great superposed aquifer formations, indeed of unequal importance, and whose one perceives clearly the vertical organization and regional connections. One can distinguish from bottom to top (Fig. 5):

a) The Aquifer of the Continental Intercalaire in Algeria-Tunisia, corresponding in Libya to the Kiklah-Aquifer formation that includes Jurassic and lower Cretaceous;
b) The Turonien Aquifer in Algeria-Tunisia, corresponding in Libya to the Nalut-Aquifer formation;

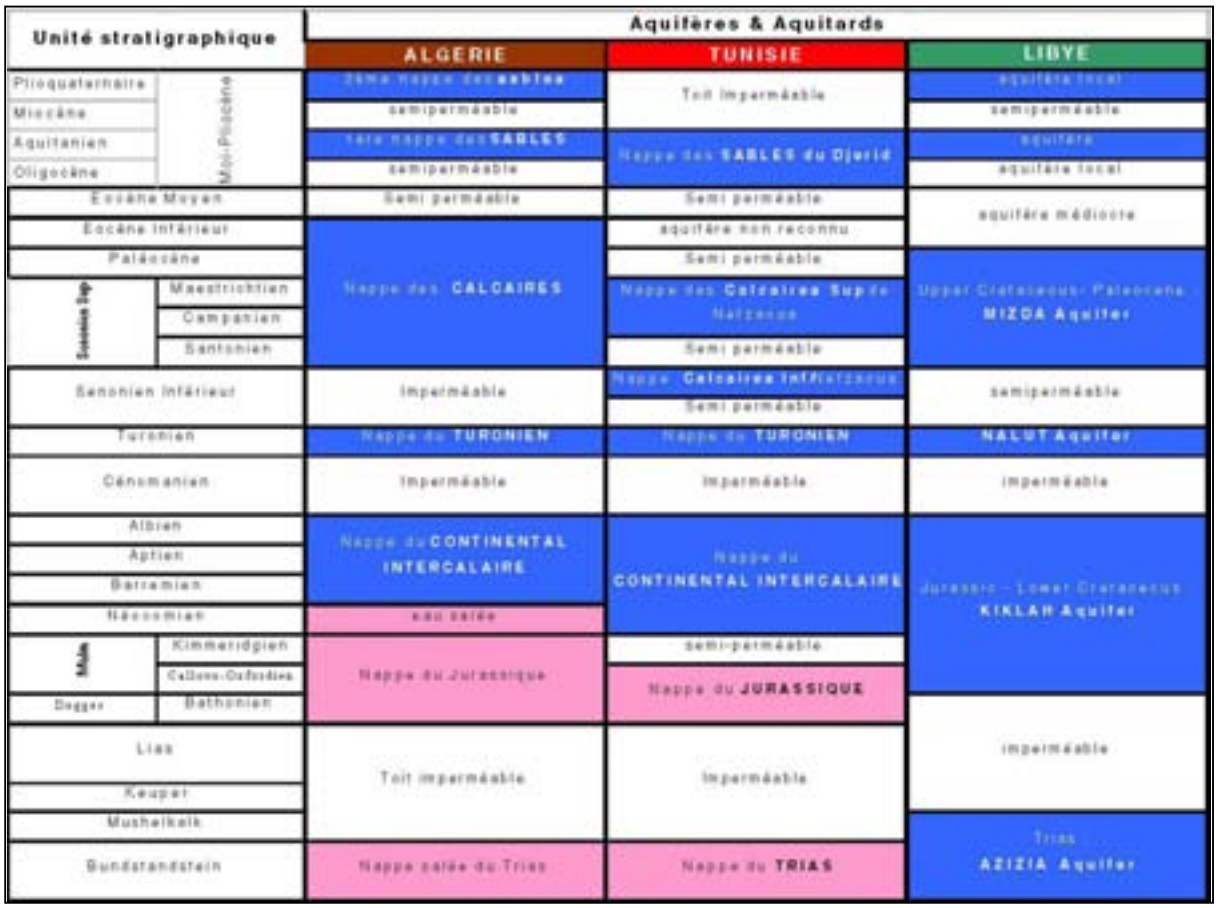


FIGURE 5. Hydro stratigraphic correlations through the Northern Sahara

c) The limestones aquifer in Algeria [Senonien carbonaté + Eocène carbonate], corresponding in Tunisia to the aquifer of limestones [inferior and superior] of Nefzaoua, equivalent in Libya to the Mizdah-Aquifer;
d) The Mio-Pliocène sands aquifer in Algeria, corresponding in Tunisia to the pontian sands aquifer of the Djerid, having for equivalent in Libya the two aquifers, respectively, the Aquitanian and the PlioQuaternary.

A supplementary simplification degree allows to get the elaboration of the diagram of the Saharian Multilayered System (Fig. 6): if one excludes the Paleozoic aquifer and Triassic sandstone in Libya, and if one regroups as that is made classically the upper Cretaceous limestones aquifer, and the aquifer of sands of the MioPliocene (resp. Mizdah and PlioQuaternary), the Multilayered NWSAS is going to appear under the form of three superposed aquifer subsystems, separated by (or communicating through) semipermeable formations or aquitards; that is: a) The Continental Intercalaire-Kiklah aquifer; b) The Turonian-Nalut aquifer; c) The Complexe Terminal–Mizdah aquifer.

Hydrodynamic framework of the NWSAS

Piezometric mapping of the CI

Plotting the piezometric map of a system as vast and complex as the CI always involves taking positions on some issues. *The first level of hydrodynamic modelling is the representation of flows in the system,* which means we must start with some ideas about the origins, direction and fate of flow. And this is not easy, even if we have measurements available. No piezometric map had yet been plotted for the whole NWSAS territory[1]. But there were such maps of parts of the territory, and each of these added its contribution to advancing knowledge on the system.

The first major contribution to understand flow in the CI was provided by A. Cornet (1964), who identified two main directions of circulation: one from the Atlas towards the drainage axis of the Gourara, Touat and Tidikelt, the other main drainage zone being 'the salt lakes of the Lower Sahara in the south of the Constantine region and southern Tunisia'. A few years later, the survey ordered by the Organisme Technique de Mise en Valeur des Richesses du Sous-sol Saharan, conducted by Burgeap (1963), concluded: 'The theory that the waters of the Intercalary Continental rise towards the south Tunisian chotts (Fejej-Djerid) where they evaporate, must be rejected. The main outlet of the IC aquifer seems to be mainly the Cretaceous and Miocene aquifers of the Gabès region, which it feeds via the great El Hamma fault'. This is the view the project adopted, taking the Tunisian Outlet to be the only outlet in the NWSAS central basin.

Flow from the Kiklah formation towards the Gulf of Sirte was described by GEFLI (1978) and then P. Pallas (1980), who confirms the Libyan Outlet, and the inflows from the Adrar ben Drich

1. M. Besbes and M. Zammouri proposed a small-scale representation in 1988: Extension en Libye du modèle du CI algéro-tunisien; int. Conf. Comput. Methods and Water Resources, Rabat.

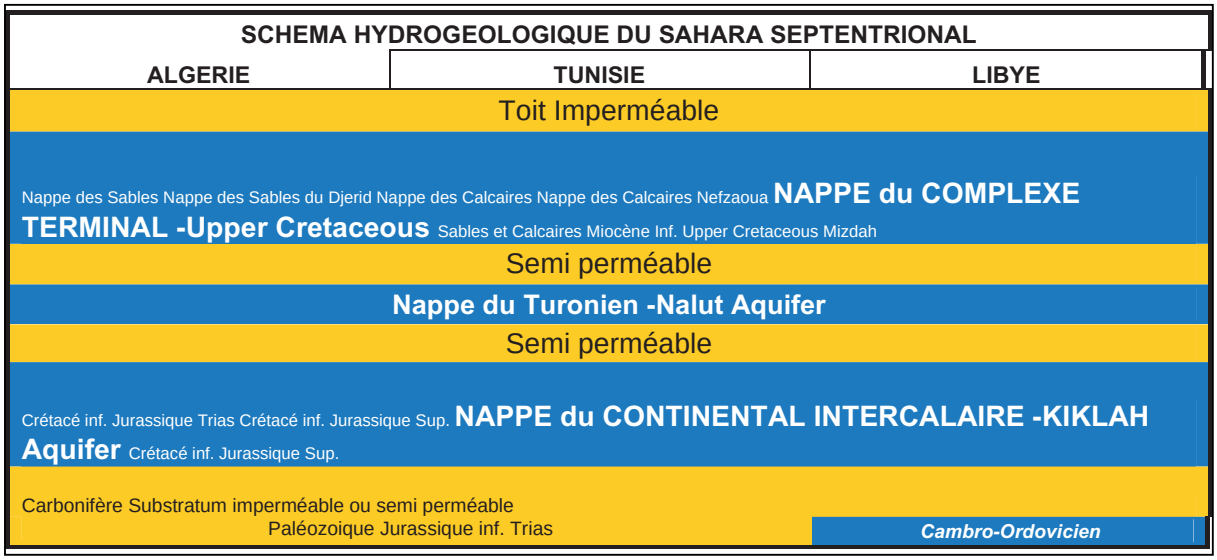


FIGURE 6. Diagram of the multilayered NWSAS

outcrop in the south and the Jabal Nefussa outcrop in the north. Later, GEOMATH (1994) took a very different view: the Kiklah and Triassic sandstone aquifers are combined and the aquifer's eastern boundary is the graben fault. Northwards, flow in the Triassic is stronger than in the Kiklah, which receives no inflow from the Jabal Nefussa, and the main outlet is considered to be the Djeffara aquifer, in Libya as well as in Tunisia.

For the NWSAS project it was necessary to plot an overall piezometric map giving a coherent picture of flows throughout the basin. The result, Figure 7, is a synthesis of all the contributions cited above. The map defines groundwater flow in the Continental Intercalaire in its 'natural' state, i.e. with little or no pumping. This spatial representation of the piezometric surface is supported by measurements, not necessarily synchronous but dating from before the most significant pumping began.

Piezometric mapping of the Complexe Terminal

As with the CI, the map of general groundwater flow throughout the Complexe Terminal is based on an accumulation of contributions from the past forty years, since A. Cornet (1964) published

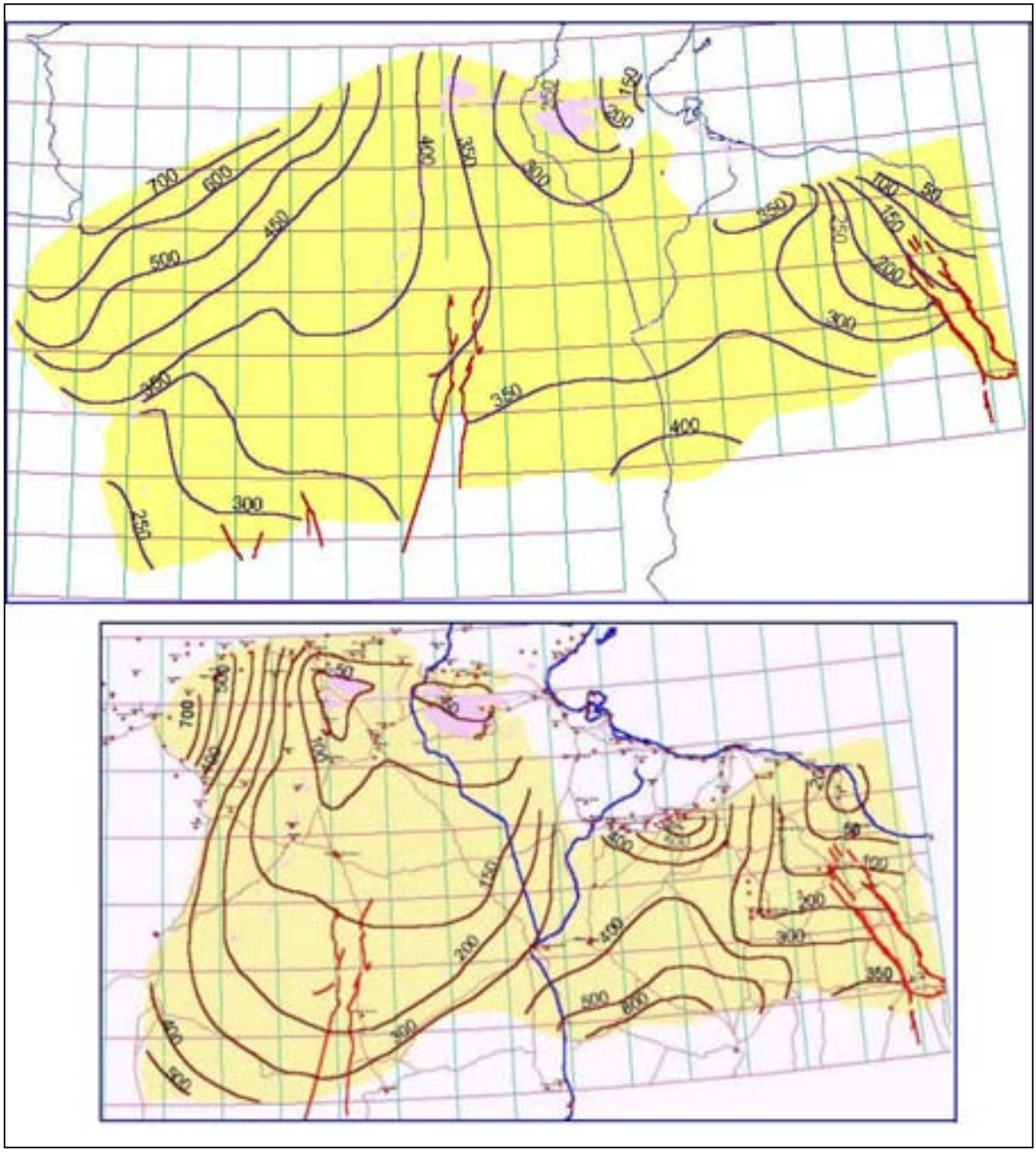


FIGURE 7. Reference piezometric maps of CI and CT

the first piezometric map covering the whole of the Saharan 'Continental Terminal'. The most significant contributions include Bel and Cuche (1969), the ERESS project (UNESCO, 1972), A. Levassor (1975), A. Mamou (1976), Armines-Enit (1984), Srivastava (1983), IDROTECNECO (1981), GEFLI (1978), P. Pallas (1980), and GEOMATH (1994). Together, this work provides the basis for an 'initial' piezometric map, i.e. before major pumping, for the entire NWSAS region (Fig. 7), which could serve as a reference for describing the system in steady state.

Conclusion

One of the objectives of the study on the North-Western Sahara Aquifer System is to build a simulation model for the aquifer system. The Model is planned to make a coherent synthesis of data and knowledge acquired on the aquifers and water resources assessment, as well as to determine the exploitable resources on the basis of development scenarios. In the beginning of the NWSAS project, there were two traditions, two outlooks, two parallel concepts of Saharan hydrogeology: a) on the Algero-Tunisian side, the thickness of the semi-permeable interlying formations and the very great difference in heads between the two main aquifers supported a well anchored tradition to treat the CI and the CT separately, and models since fourty years have designed them as single independent aquifer layers; b) on the Libyan side, the separating layers between aquifers are thinner, and a multilayer structure was adopted since 1981 when the first regional model was made.

To harmoniously combine the hydrogeological standpoints of the three countries, the general concept of the NWSAS Model replaced the CI versus CT duality by a multilayer representation that could combine Algerian and Tunisian hydrogeology with that of Libya. The 'Saharan Multilayer' rendition ensures the best simulation conditions in the long term, incorporating the Paleozoic and Turonian, and makes allowances for leakage between the CI and CT.

References

ARMINES-ENIT, 1984. *Modèle mathématique du Complexe Terminal Nefzaoua-Djerid.;* Min. Agr. Tunisie.

BESBES, M. and ZAMMOURI M. 1988. *Extension en Libye du modèle du CI algéro-tunisien*; int. Conf. Comput. Methods and Water resources, Rabat.

BEL and CUCHE. 1969. *Mise au point des connaissances sur la nappe du Complexe Terminal.* ERESS; Ouargla.

BISHOP WF. 1975. Geology of Tunisia and Adjacent Parts of Algeria and Libya. *Bull Amer. Assoc Petrol Geol,* 59, 413-450.

BURGEAP and DIRECTION DES CARBURANTS. 1963. *Etude du Continental Intercalaire Saharien.*

BUSSON, G. 1970. *Essai de synthèse des données des sondages algéro-tunisiens.* CNRS.

CORNET, A. 1964. Introduction à l'hydrogéologie saharienne; *Rev. de géogr. phys. et de géol. dyn.* (2), vol. VI, fasc. 1; 5-72.

GEFLI. 1978. *Survey for the development of the Central Wadi Zone and Golf of Sirte; Groudwater resources – Final synthesis report.* Ref: AL-WR-205.

GEOMATH. 1994. *Western Jamahirya System; Hydrogeological Modelling of Aquifers and Well Fields. Final Report.* Text and pl. Ref AW-MI-579.

IDROTECNECO. 1982. *Hydrgeological study of Wadi Ash Shati, Al Jufrah and Jabal Fezzan area. General Report.* Texte and 18 pl HT Ref. AS-751.

LEVASSOR, A. 1975. *Etab modèle de gestion et de mise en valeur des nappes aquifères du Complexe Terminal.* Rapp. int. ENSMP-INRH.

MAMOU, A. 1976. Contribution à l'étude hydrogéologique de la presqu'îlede Kébili; thèse univ. Paris.

PALLAS, P. 1980. Water resourc. Socialist People's Arab Libyan Republic. In Salem and Busrewille (ed): *The Geology of Libya.* Ac. Press; vol. II.

SRIVASTAVA, M.L. 1981. *Report on regional hydrogeological study in Ghadames-Derj-Sinawan area.* 155 p, 18 pl HT. Ref. AW-GA-682.

UNESCO. 1972. *Etude des Ressources en Eau du Sahara Septentrional. Nappe du Continental Intercalaire.* Proj. ERESS.

Managing shared aquifer resources in Africa – Uganda case

Joseph Aseka Kitakarugire

Senior Hydrogeologist
Directorate of Water Development
(Uganda)

Abstract

Uganda is in east Africa bounded by Kenya, Tanzania, Rwanda, the democratic republic of Congo, and Sudan. The climate is diverse, but generally averages up to mild equatorial with a bimodal rainfall pattern. 88% of the population live in the rural area and is distributed according to the climatic pattern and land use.

Significant formations are predominantly crystalline basement with sediments around Lake Victoria and the Western Rift Valley. groundwater occurs in the weathered mantle and the underlying fractured bedrock. The aquifer systems are as varied as the formations in which they occur. About 90% of the productive aquifers occur in the crystalline rocks while the alluvial sediments and volcanic tuffs share the remaining 10%. A commonality with all the country's aquifer is that they are highly localized and limited in aerial extent.

Studies recently conducted in the west and central regions of the country put groundwater recharge at 5–15% of the annual rainfall. During the same studies it was noted that high borehole yields occur in areas where hard rock is fractured and deeply weathered. The aquifer in the weathered formation acts as storage for the underlying fractured bedrock. The recharge flux between the two-aquifer systems is not yet understood. To address this concern a number of groundwater assessment and monitoring activities were initiated in the mid 90s. The monitoring activities were founded on a network of 16-nos. boreholes for periodic sampling to provide baseline hydrogeological and hydrochemical data. Alongside the national monitoring network, two groundwater assessment areas were initiated in central and western Uganda. The central Uganda assessment area was established to assess recharge and the impact of large groundwater abstractions. The western Uganda assessment area was established to assess the effects of mining wastes on the groundwater environment in that part of the country.

Although there is more than a likelihood of transboundary aquifers with our neighbours, in the south, north, northeast and east, so far there is no information to show weather or not problems of transboundary aquifers are likely to be experienced in Uganda. There is therefore a strong case for detailed assessment and monitoring of the potential transboundary aquifers in Uganda.

Introduction

Background

Uganda is located in East Africa, bounded by Kenya to the east, Tanzania to the south, Rwanda to the Southwest, Democratic Republic of Congo to the west and Sudan to the north. She has an area of 241,000 km^2 with a population now estimated at 22 million. The country has elevations of between 1000 and 1,500 m above sea level.

The climate o is mild equatorial with a bimodal rainfall pattern whose average annual rainfall is 1,200 mm.

More than 80% of the population live in the rural areas with population density distributed according to climatic pattern and land use. The soils are moderately fertile and this coupled with adequate rainfall ensures that throughout most of the country it is possible to sustain rain-fed agriculture.

Most of the rural water supply in Uganda is based on groundwater in the form of boreholes, shallow wells and to a lesser extent springs. Groundwater as a secure source of water supply

for urban and peri-urban areas is gaining popularity due to the low operational costs of running groundwater based water supply systems and also because it is often the only available source of water.

Geology

The geology of Uganda (Fig. 1) consists of the basement complex and cover formations of the precambrian times; the quaternary alluvial sediments in the Western Rift Valley and lake Victoria shores, and the Pleistocene volcanic ashes and tuffs.

Hydrogeology

Groundwater occurrence

Groundwater in the crystalline basement rocks occurs in two different types of aquifers, the shallow aquifer in the weathered overburden (regolith) and the deeper fractured bedrock aquifer.

The regolith has a variable thickness but is found continually over the bedrock except in a few places where out crops occur. Its average thickness is between 20–40 m across the country.

The thickness and depth of the fractures is varied. Hydrogeological studies indicate that the bedrock aquifers have poorer hydraulic characteristics than the regolith aquifers.

Aquifer systems

The occurrence of the aquifers in Uganda is closely related to the geology.

a) Crystalline aquifers

90% of the productive aquifers in the country occur in the crystalline basement complex and cover formations. They form transboundary aquifers although their dimensions have not been determined. transboundary aquifers occur in the south of the country where the Karagwe-Ankolean cover formations cross into Tanzania and Rwanda. transboundary aquifers are also possible in Karamoja region, which is in the north east of the country, extending into Kenya

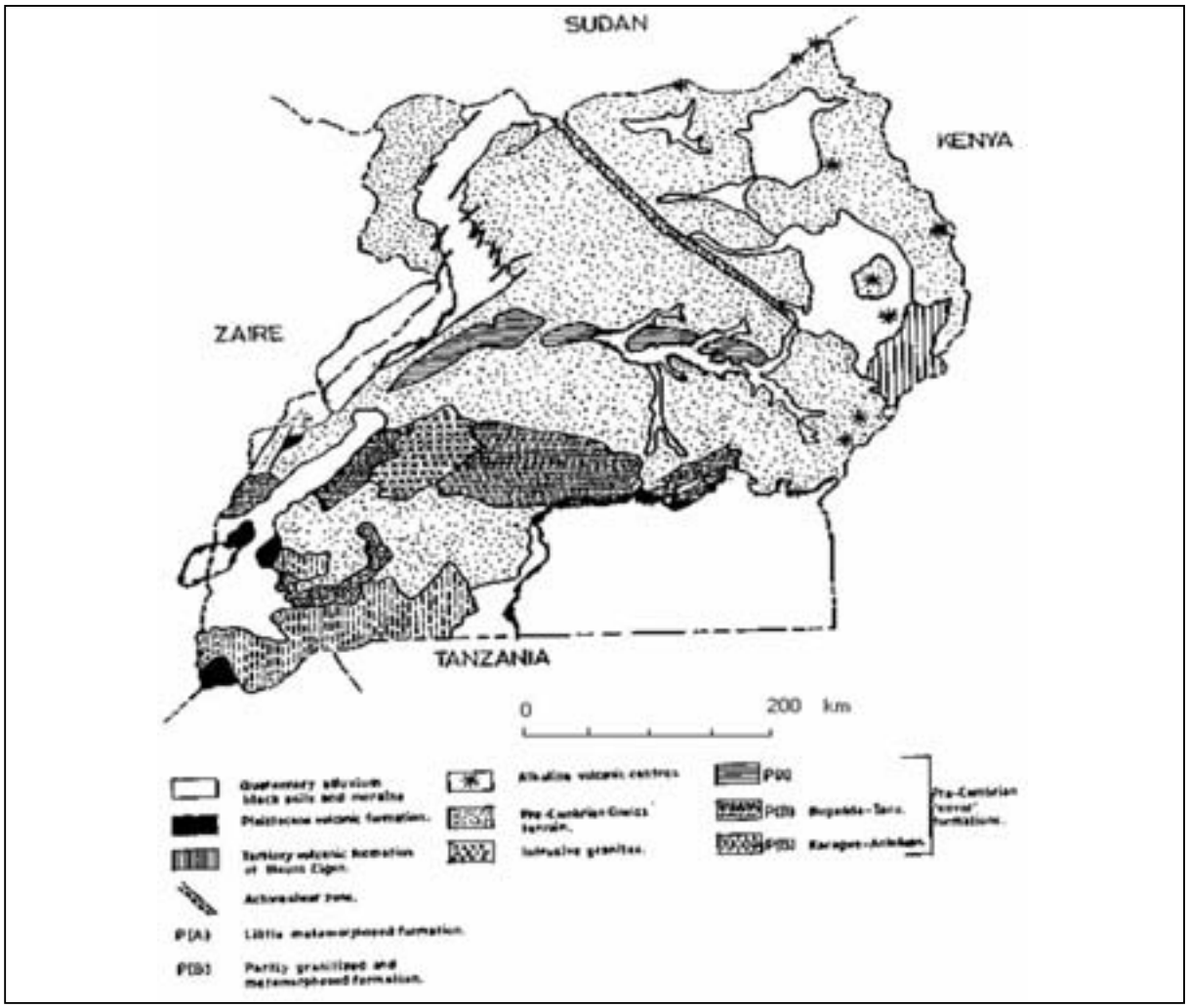


FIGURE 1. Map of the generalized geology of Uganda

and Sudan. transboundary aquifers are also possible in the northwest of the country where they extend into the Democratic Republic of Congo. A common factor with these aquifers is that they are localized and limited in extent.

b) Sedimentary aquifers
Significant aquifers exist in the western Rift sediments, which extend into Sudan and around Lake Victoria extending into Kenya. These aquifers appear to be constrained by limited storage and erratic recharge.

c) The volcanic formations
Aquifers in Volcanic formations are found on Mount Elgon on the eastern border with Kenya and on Mfumbira on the southwestern border areas with Rwanda and the Democratic Republic of Congo. The volcanic rocks are thus in areas of high relief and groundwater occurrence is often in form of springs. transboundary spring discharges occur in all the above Mountains.

Groundwater recharge

Groundwater recharge assessment has not received enough attention although present levels of groundwater abstractions warrant so. Research studies with reference to recharge have been conducted in the southwest, northern and central regions of the country. The studies indicate that recharge varies between 5 and 15% of the mean annual rainfall.

Groundwater monitoring and assessment activities

Introduction

The crystalline basement aquifer is of major importance to rural water supply in the country and supports springs, shallow wells and boreholes. They are also supporting a number of powered boreholes in many industries, several small towns and rural growth centres.

Successful high yield wells occur in areas where the hard rock is highly fractured and weathered. The regolith, which overlies the hard rock, is more permeable and provides storage for the underlying fractured bedrock. These two aquifers units are normally exploited together but their behaviours are not well known. To address this concern a number of groundwater assessment and monitoring activities were initiated in mid 1990s. So far the current National Groundwater Monitoring Network is based on 16 wells distributed in various parts of the country in consideration of the regional geology and climatic regimes. There are plans to increase the network to 30 stations to cover the various geological units.

The National Monitoring Network

The National Monitoring Network (Fig. 2) was founded on existing boreholes for periodic

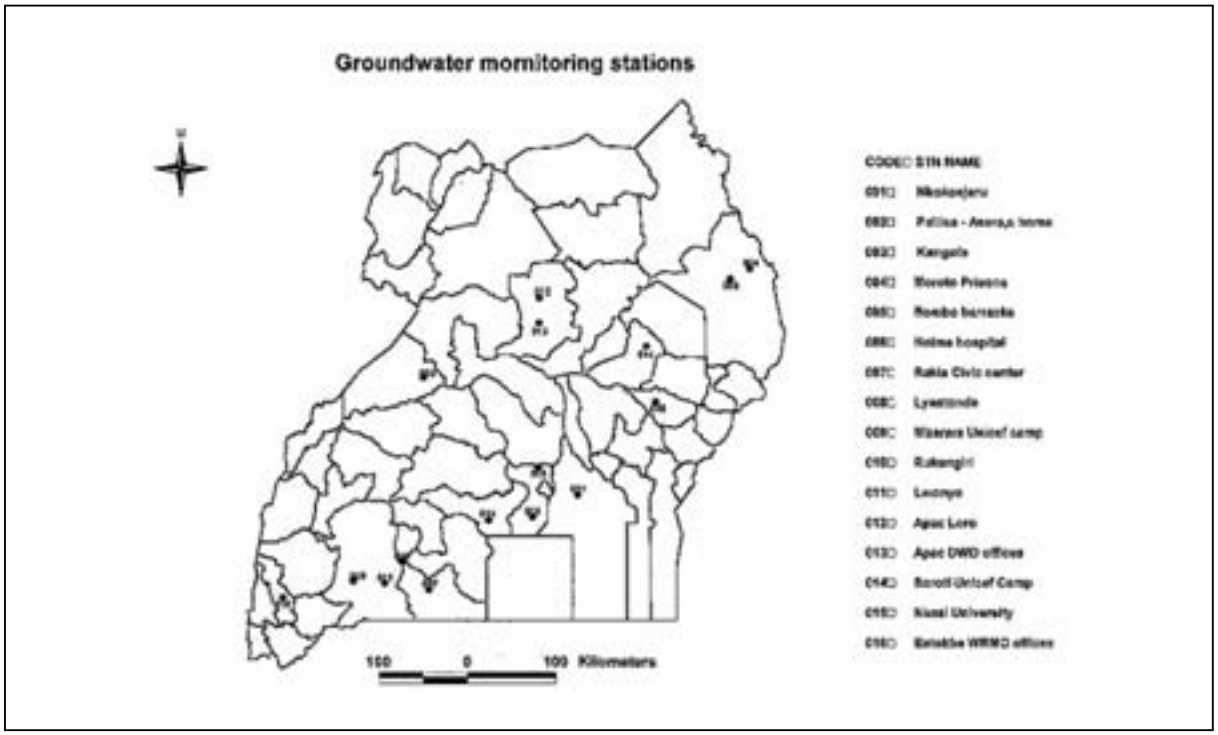


FIGURE 2. The National Groundwater Monitoring Network

sampling to provide hydrogeological and hydrochemical data. The network was established to provide baseline information, nationally and for a long time. It is used by groundwater specialists to detect trends in water chemistry and groundwater level fluctuations, which may indicate resource stress or contamination.

The data from the network supports water resource assessments and research and subsequent planning and management. The groundwater data is also used as basis for groundwater regulation and control of pollutants.

Assessment studies

Along side the running of the monitoring network two-assessment study areas were initiated.

One study is being carried out in central Uganda in the area called Wobulenzi for purposes of assessing recharge conditions and the impact of large groundwater abstraction on water resource.

Four piezometers were purpose constructed to monitor the impact of large abstractions. Groundwater monitoring is carried out using automatic water level recorders. Other measurements of hydrochemistry, spring discharge, and stream flow are carried out manually every month.

The second assessment study is carried out in western Uganda in an area called Kasese to monitor the effects of mining wastes on groundwater. For this purpose four observation wells were constructed and another 15 existing shallow and deep wells are being monitored by an International mining agency operating in the area.

The two assessment studies are about to be completed. They have not only increased knowledge on groundwater resources but also assisted in building the country's groundwater resource assessment capacity.

International significance of aquifers in Uganda

The aquifers in Uganda are highly variable in characteristics and have very limited aerial extent.

The regolith aquifer is quite shallow and is more permeable than the fractured aquifer.

Although the rift valley sediments occur both in Uganda and Sudan there is no information to date to show whether there is hydraulic connection across the border.

Although these aquifers are known to be limited in extent, high groundwater abstractions or pollution in one country may affect the aquifers in a neibouring country either directly or indirectly. This is likely to be so in areas around Lake Victoria, bordering Kenya and Tanzania and in northeastern Uganda, bordering Kenya and Sudan.

There is however no information to show whether or not problems of transboundary aquifers are likely to be experienced in Uganda. This shows there is a clear need for detailed assessment and monitoring to evaluate the extent and characteristics of potential transboundary aquifers not only in Uganda but also her neighbours.

In Uganda some studies on groundwater resource assessment and monitoring have been initiated and need a lot of support from development partners in form of capacity building, financing and materials.



Regional and basin organizations

Hydrogeological framework of the Nubian Sandstone Aquifer System

Mohamed Bakhbakhi

Regional Coordinator
Nubian Sandstone Aquifer System (NSAS) Programme

Abstract

The Nubian Sandstone Aquifer System of the North Eastern Africa covers Egypt, Eastern Libya, Northern Sudan and Northern Chad. It is differentiated here into two major systems:

- The Nubian Aquifer Systems occurring all over the area predominantly filled by approximately 3,500 m of continental clastic sediments, mainly sandstone of Pre-Upper Cenomanian. This geological succession constitutes an enormous multi layered aquifer of excellent water quality in the south and of hyper saline water in the north. This aquifer is under unconfined conditions south of latitude 25º and under confined conditions north of it.
- The other system is the Post Nubian Aquifer System; occurring to the north of latitude 26º. It is composed of marine sediments, overlain by continental clastics. This succession ranging in age from upper cenomanian to recent and it is under unconfined conditions.

The two Aquifer Systems are separated by a confining bed. A hydrogeological outline of the entire area was outlined showing in general the spatial frequency of hydraulic conductivities in the different aquifer units. The aim of the study is to develop a conceptual model suitable for the construction of a regional mathematical model.

The groundwater was formed mainly autochtonically during humid periods in the past. Recent groundwater formation is limited and insignificant.

On the base of the interpretation of hydrochemical data an Interface was delineated between the good quality water and the hyper saline water.

Over 40 billion m^3 of water was extracted in the past 40 years leading to a continuous drop of water level and to the disappearance of almost all of the naturally flowing wells and springs.

Introduction

Location of the study area

The study area occupies the NE corner of Africa (Figure 1). It is bounded by longitudes 18 and 34 from East to West and by latitude 14 and 33 from south to north. The study area covers approximately 2.2 M km^2 shared by four North African countries 828,000 km^2 in Egypt, 760,000 km^2 in East Libya, 376,000 km^2 in Northern Sudan and 235,000 km^2 in Northern Chad.

Purpose and objectives

The purpose of this study is to examine and evaluate the geological and hydrogeological data and information which has accumulated in the past decades in the study area, in order to define the geological and hydrogeological framework and analyse groundwater flow patterns and to examine the effects of development on groundwater resources and finally to develop a conceptual model of the basin suitable for the construction of a regional mathematical model.

General background

The regional geological framework of the study area was originally established in late Proterozoic times and continued into the Tertiary. This frame-

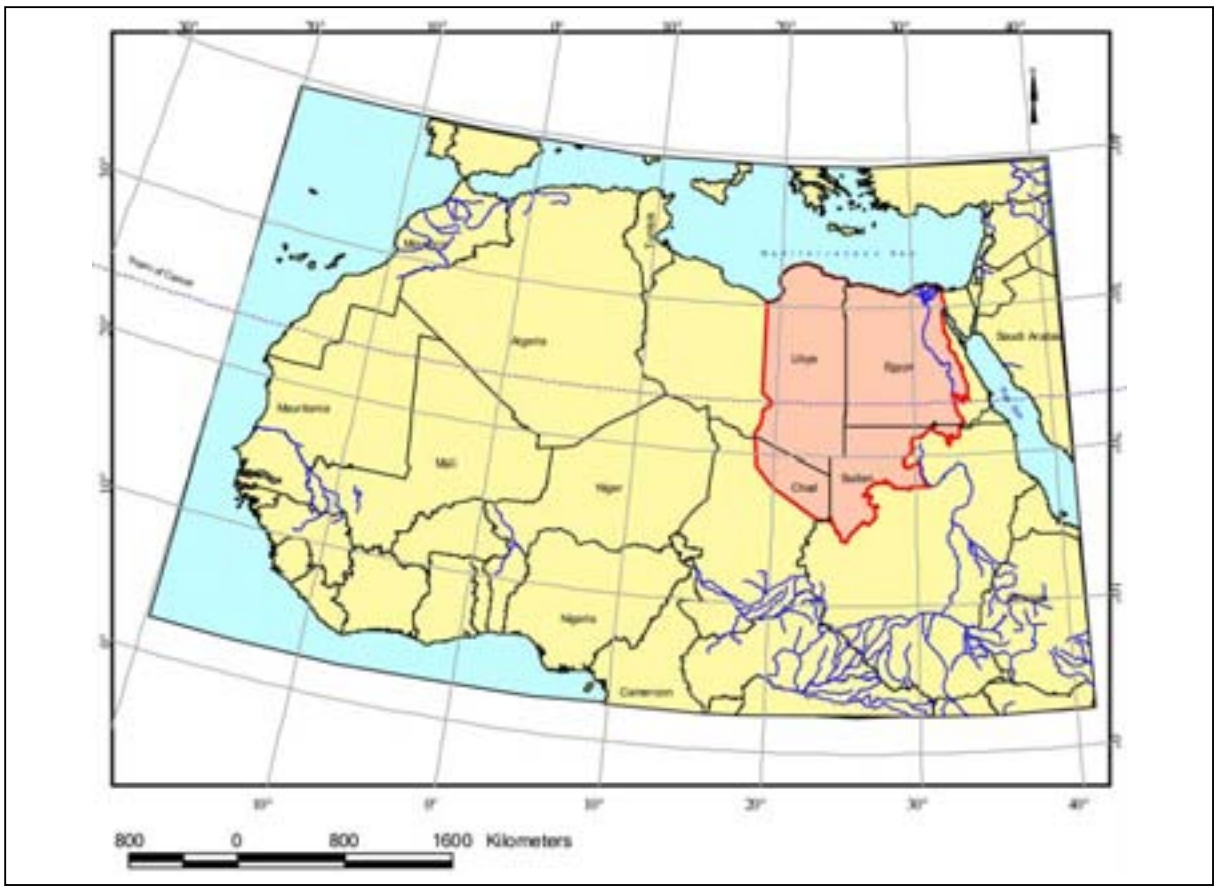


FIGURE 1. Location map of Nubian Sandstone Aquifer System

work was governed by the former plate tectonics affecting the area between Africa, Europe and Asia. The effect of the resulting stresses on the North African plate was the formation of tectonically controlled uplifts and basins. In the process of subsidence, mainly continental deposits up to several thousand meters thick were deposited in the basins. Thick continental clastic deposits of Paleozoic and Mesozoic age were deposited in Kufra and Dakhla synclinal basins, while marine carbonates dominate the northern basins. Post-Eocene continental deposits were also deposited.

The great thickness of the highly porous continental sediments formed an enormous storage volume for water resources, known in this study as the Nubian Sandstone Aquifer System. It is considered to be one of the most important groundwater basins in the whole world. The Nubian Sandstone Aquifer System extends across the borders of four African countries namely Egypt, Libya, Sudan and Chad.

Topography

The surface in this wide area is dominantly developed into extensive flat topped plateaux (Hamada type) and into gently undertaking plains (Sarir type). In the southern and eastern portion of the area, rugged mountains (Tibesti, Ennedi, Darfur, Kordofan, Arkeno, Gilf El Kebir, Oweinat, Kissu and Red Sea) characterize the landscape and rise in places to more than 3,000 m. a.s.l. The difference in relief, is therefore well pronounced in the southern and eastern portion compared to the Northern portions.

Climate

Present climate

Present climate is essentially represented by:

- Low and sporadic rainfall (Figure 2),
- Very high daily and seasonal temperature variations,
- Low relative humidity,
- High evaporation intensity,
- Strong dry winds, and
- Intense solar radiation.

Paleo climate

Previous research (Pachur (1980), Roper (1985), Kropelin (1987)), shows evidence, which point to climatic fluctuations with wet and dry intervals as follows:

- 40,000–25,000 yr. BP: semi arid climate,
- 25,000–11,000 yr. BP: hyper arid climate,
- 11,000–3,500 yr. BP: semi arid phase with

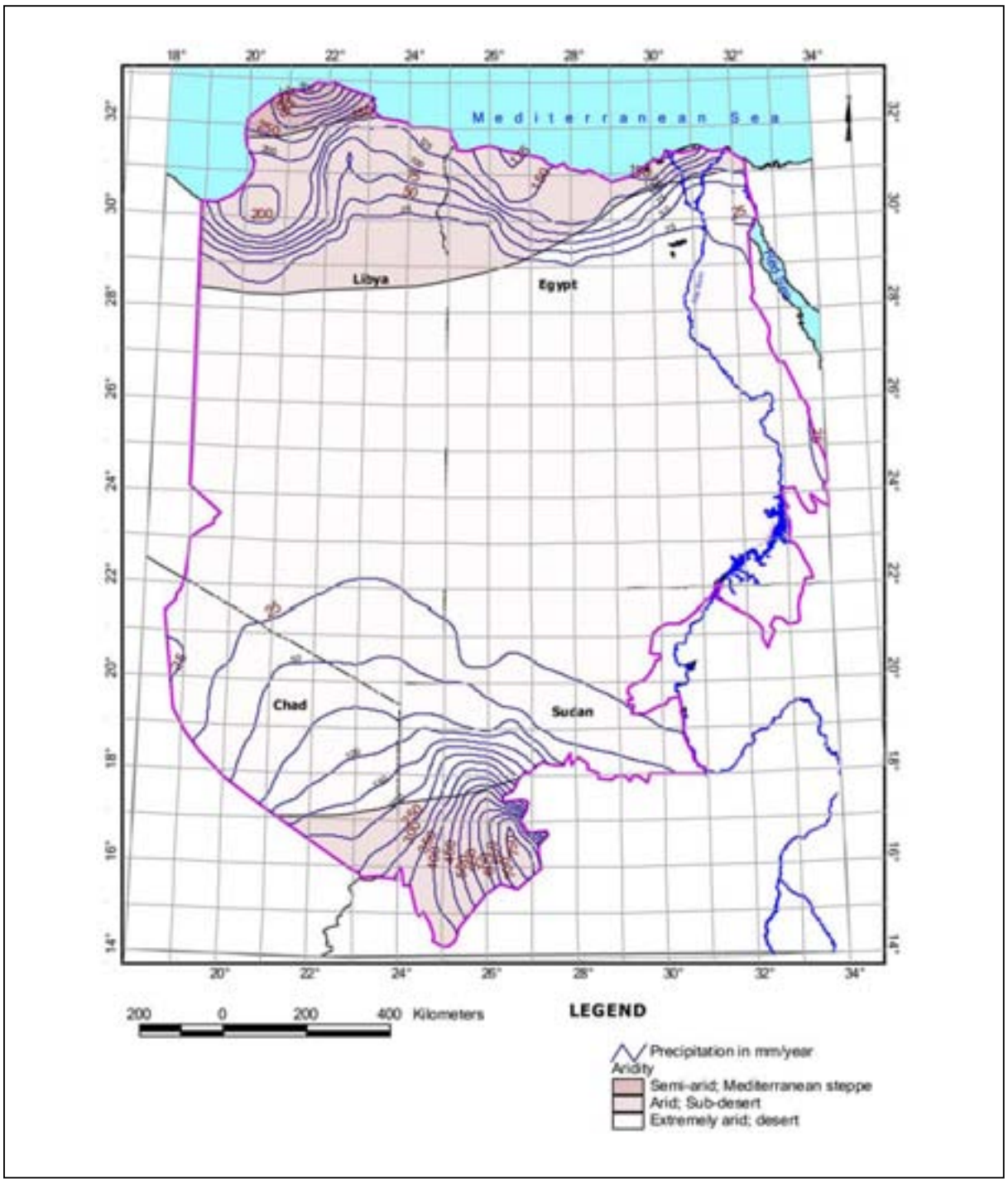


FIGURE 2. Regional surface geology

rapid rise of groundwater level and fresh water phase in the lakes; lake Selima, Laqiya Arbain, Kufra, etc.,

- 4,350 yr. BP: second desertification phase characterized by invading sands and receding floods in the Nile in Egypt,
- 2,800 yr. BP: wet phase characterized by the recovery of vegetation and extensive flooding.

The last phase characterized by relatively stable climatic arid condition has become common in the past 2,000 years.

Geology

Regional aspects

The geological framework of the study area was originally established in the late Proterozoic times and was governed by the former plate tectonics affecting the area between Africa, Europe and Asia. The effect of the resulting stresses on the North African plate was the formation of basins, troughs, grabens, ridges, blocks and uplifted areas with different orientations.

Figure 3 shows the regional surface geology of the area compiled from the available geological maps in the four countries sharing the Aquifer System.

The Precambrian Basement complex

Precambrian Basement outcrops immediately to the South, East and South West, Local exposures are found at Oweinat Area. In the subsurface the Basement relief figure (Fig. 4) was prepared using the results of aero magnetic and seismic surveys and also through the examination of the results of deep drilling. The Basement relief varies from sea level in the south to over 5,000 m b.s.l. in the North.

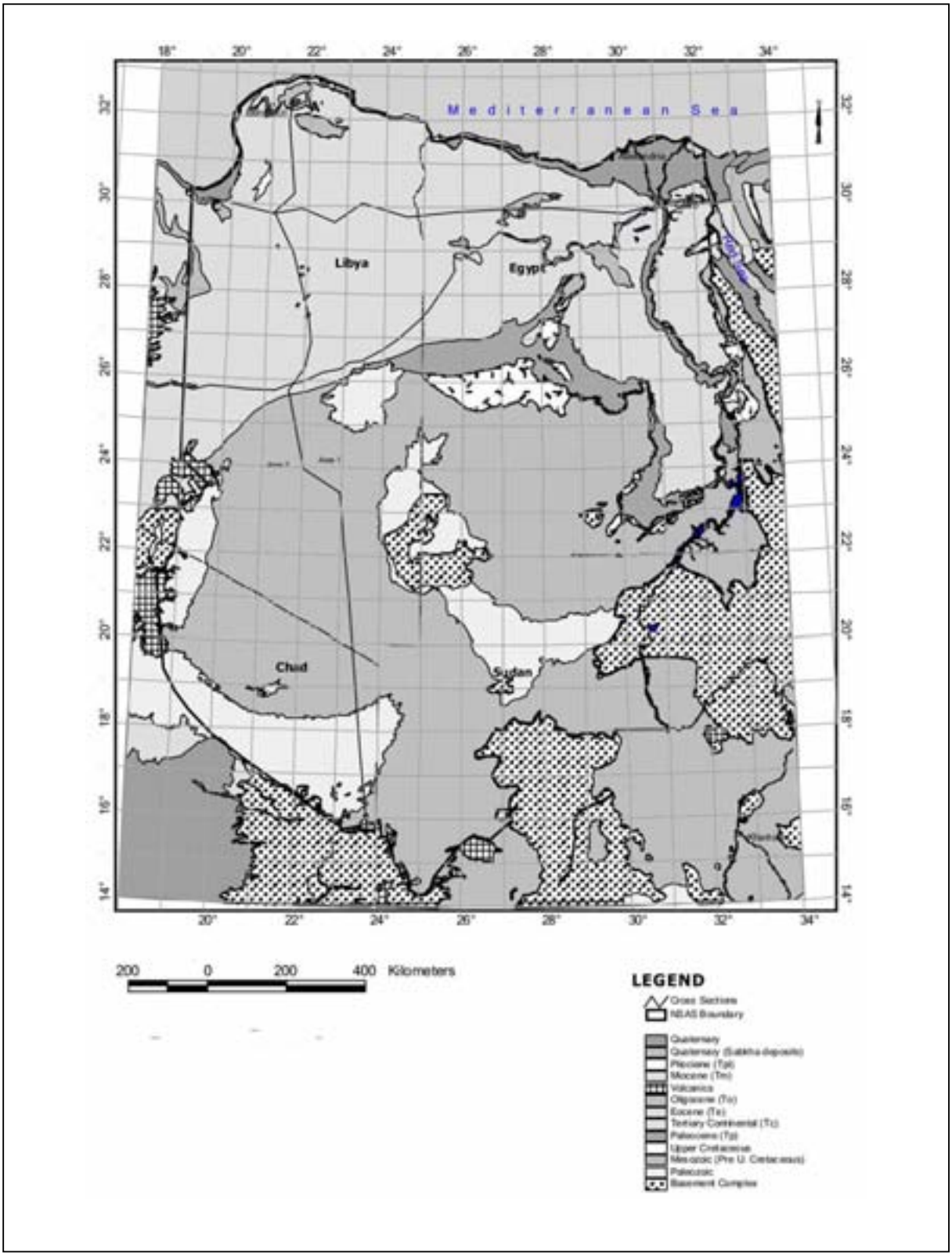


FIGURE 3. Regional surface geology

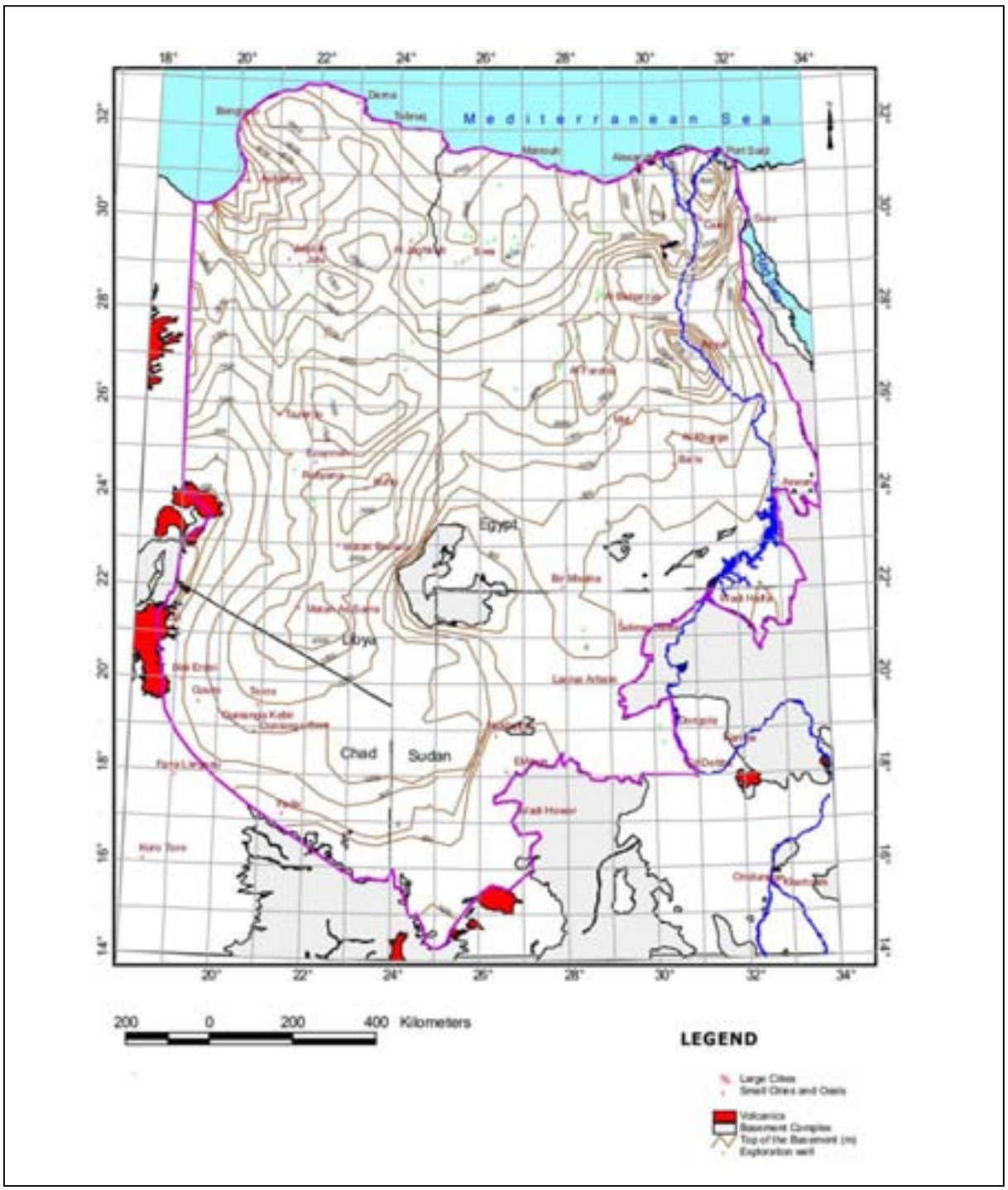


FIGURE 4. Basement relief map (datum sea level)

The configuration of the basement rocks played a significant role in determining the hydrogeological setup of the Nubian Sandstone Aquifer System. Reference is especially made to:

- Almost all the mega watershed areas in the Red Sea Region, in Darfour, in Ennedi and in Tibesti are underlain by Basement Rocks.
- The mega groundwater basins, in Kufra, Siwa, Sarir … etc. are coinciding with major troughs in the Basement Rocks.

Stratigraphy of the Phanerozoic

The Phanerozoic succession, having accumulative thickness of over 15 km, is distinct into two major unit:

- A lower unit dominated by sand facies mainly of epicontinental origin, and
- An upper unit dominated by carbonate facies of marine origin.
- This succession can be described from bottom to top as follows.

The Paleozoic

Paleozoic rocks are exposed in SE Libya, SW Egypt, NW Sudan and NE Chad with a maximum thickness of 1,500 m in Ennedi dominated by fluviatile sand facies. A thinner section of about 500 m outcrops in Gebel Haweesh (Dalma) in SE Libya. The succession in both locations is dominated by fluviatile sand facies. Paleozoic rocks are reported in the subsurface attain a maximum thickness of 2,000 m and are also dominated by sand facies. Figure 5 is a regional Isopach map of Paleozoic.

The Mesozoic

Mesozoic Sediments occupy much of the Southern portion (south of Latitude 27° N). The exposed section having a maximum thickness of about 2,000 m, is differentiated into two main units:

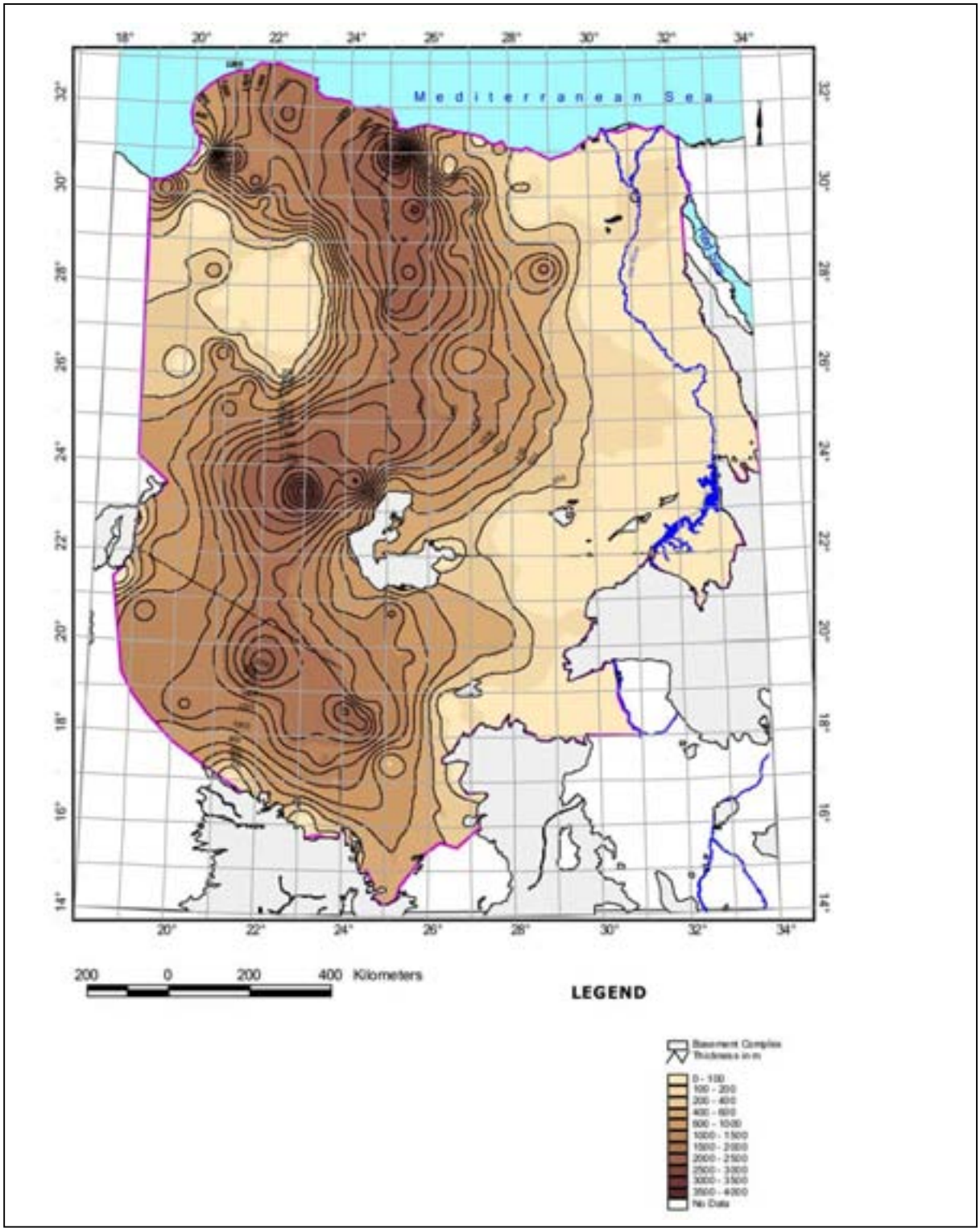


FIGURE 5. Paleozoic Isopach map

- A thick lower unit (about 1,500 m); dominated by epicontinental sediments and
- An upper unit, having a thickness of about 500 m and is developed into marine carbonates and shales.

In the northern portion (North of Latitude 27° N). The Mesozoic sediments are wide spread in the sub surface and developed essentially into marine facies (having a thickness in excess of 200 m). Local exposures are only found in the domal structures of Abu Roash in the vicinity of Cairo City and of Bahariya, 300 km to the southwest. Figure 6 is a regional Isopach map of Mesozoic.

The Cenozoic

Cenozoic sediments cover large tracts of the

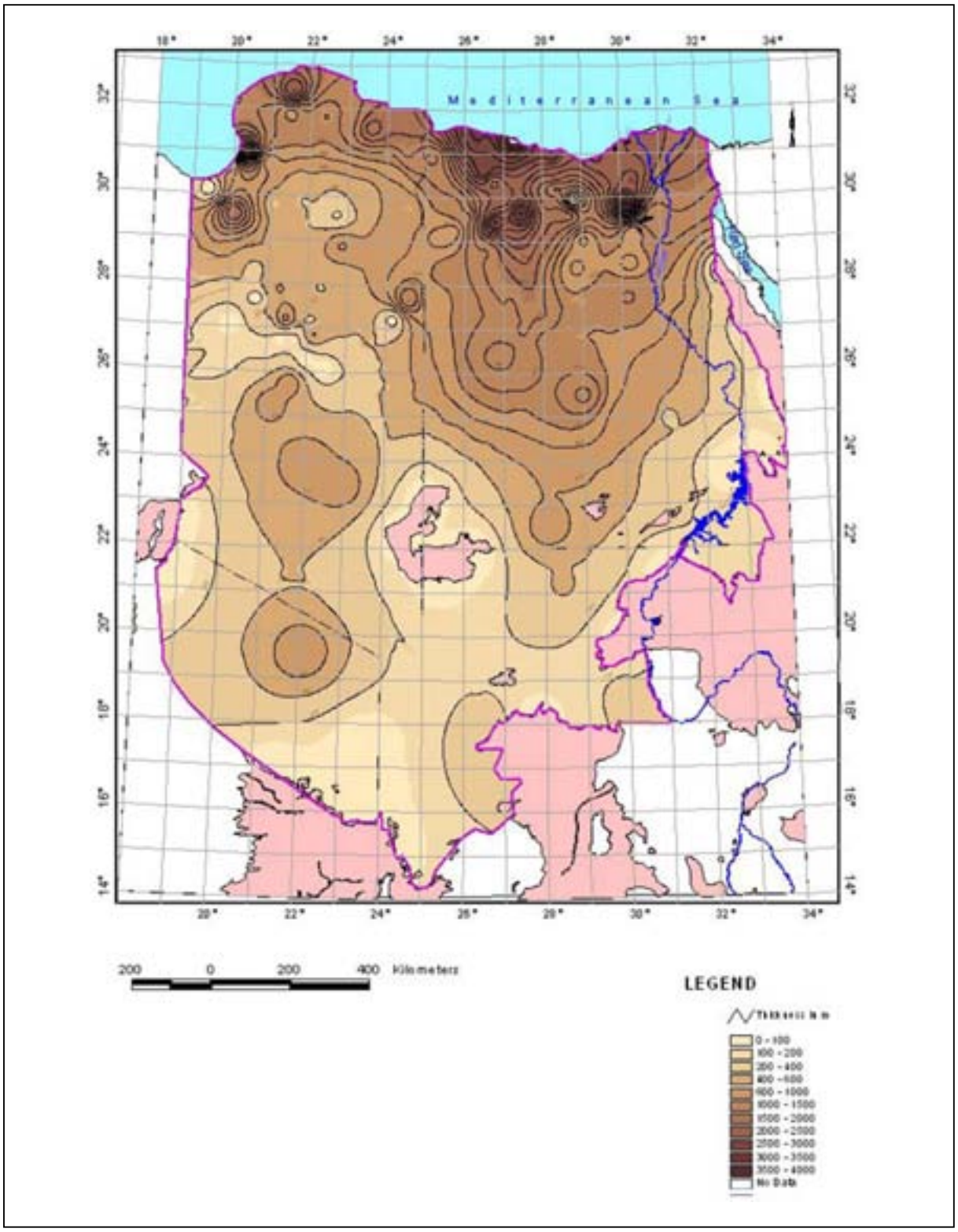


FIGURE 6. Mesozoic Isopach map

study area, south of latitude 26º. These are represented by extensive and rather thin sand sheets and elongate dunes and also by scattered lacustrine deposits and calcareous tufa. To the north of latitude 26º the Cenozoic is represented by thick marine deposits dominated by carbonate facies, having a thickness in excess of 4,000 m. Figure 7 is a regional Isopach map of Cenozoic.

Hydrogeology

The great thickness of the highly porous continental sediments that filled the synclinal basins in the area known in this study as the Nubian Sandstone Aquifer System formed an enormous storage volume for water resources. It is considered to be one of the most important groundwater basins in the whole world.

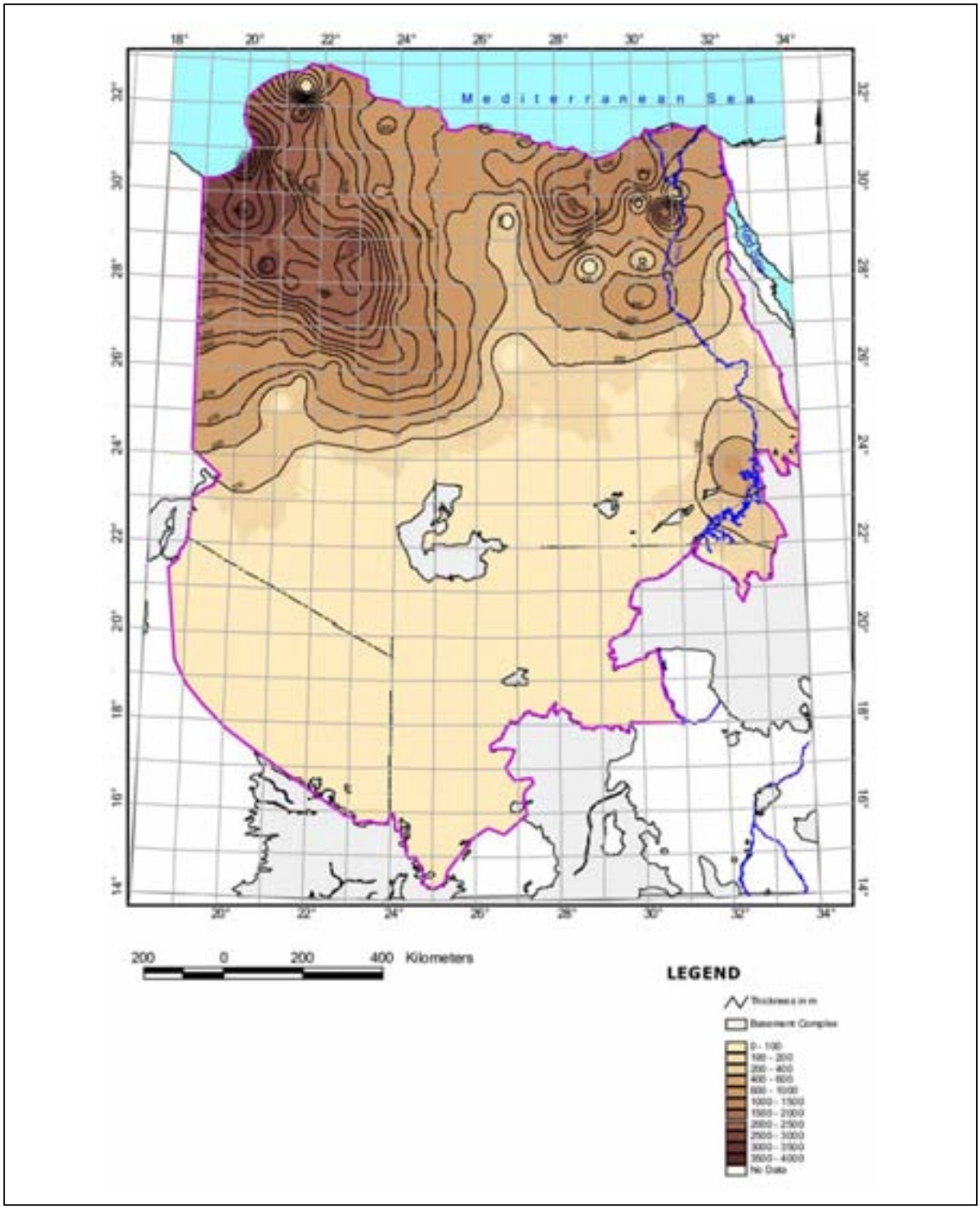


FIGURE 7. Cenozoic Isopach map

The strata of great hydrogeological interest in this geological succession are differentiated into two systems:

- *The Nubian Aquifer System (NAS):* underlying almost all the area of Egypt; Eastern Libya, Northern Sudan and Northern Chad. This consists of continental clastic sediments, mainly sandstone. It includes all the aquifers, the confining layers and the aquicludes. This system overlies the Pre Cambrian Basement complex ranging in age from Cambrian to the Pre-Upper Cenomanian.
- *The Post Nubian Aquifer System (PNAS):* occurring to the north of the 26th parallel in the Western Desert of Egypt and North Eastern Libya. It is composed of Marine Sediments generally of clay, Marl and limestone, overlain by continental clastic sediments which exhibit facies variation in the Northern parts of Egypt and Libya to pass laterally into carbonate facies. This succession ranges in age from upper cenomenian to recent.

The two systems, are separated by low permeability layers (aquitard or confining beds), belonging to the upper Cretaceous and to the lower Tertiary. These have no uniform stratigraphic definition. Local open windows between the two systems exist allowing for direct connection. This phenomenon is pronounced at the following locations:

- Tazerbo and Northwest Jabal Al Akhdar in Libya, and
- West Nile Delta: Sallum, Siwa-Qattara and Bahareya Oasis in Egypt.

Figures 8 and 9 and Figures 10 and 11 show the North-South and East-West (Figure 4, for location)

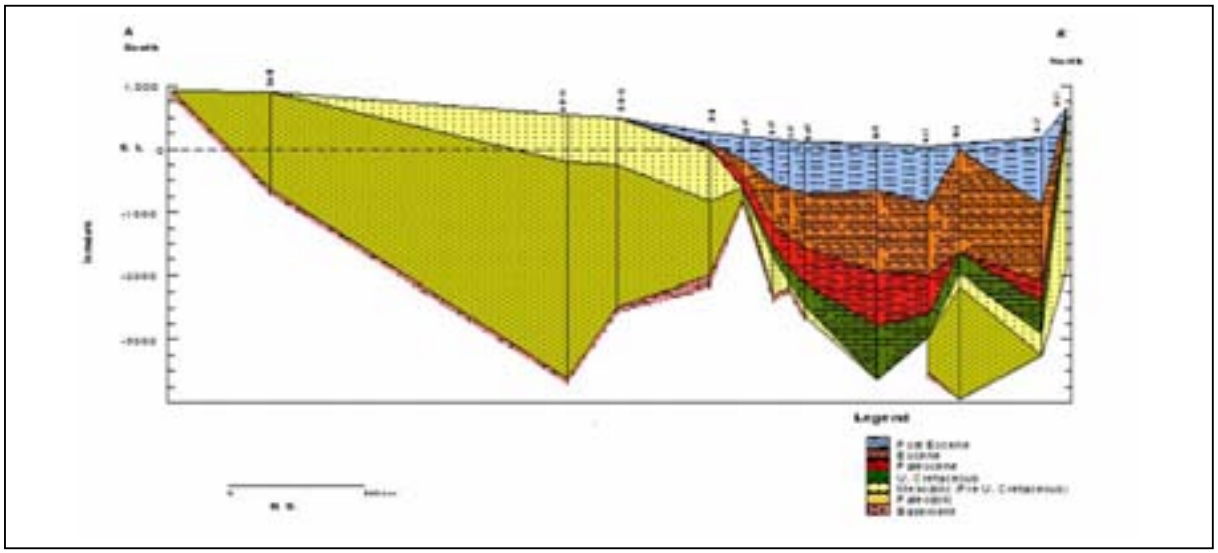


FIGURE 8. South-North geological cross-section A-A'

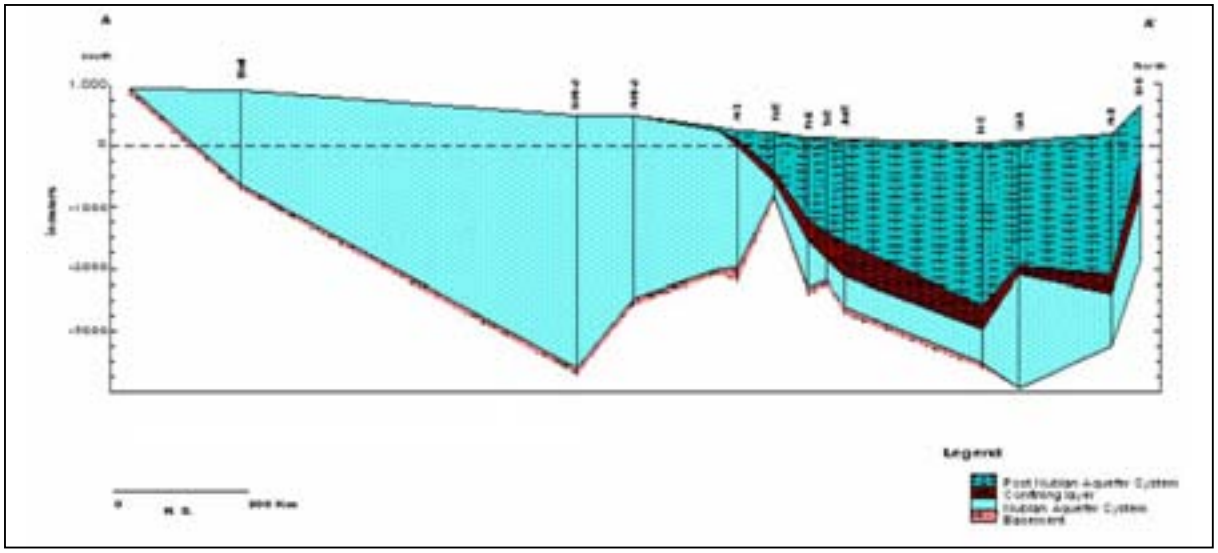


FIGURE 9. South-North hydrogeological cross-section A-A'

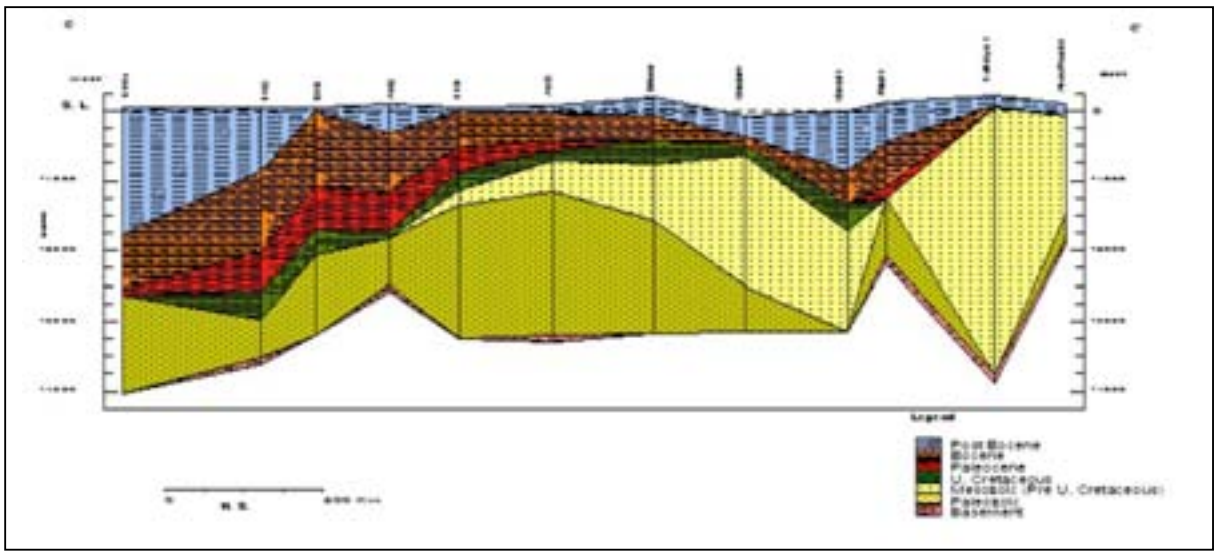


FIGURE 10. East-North geological cross-section C-C'

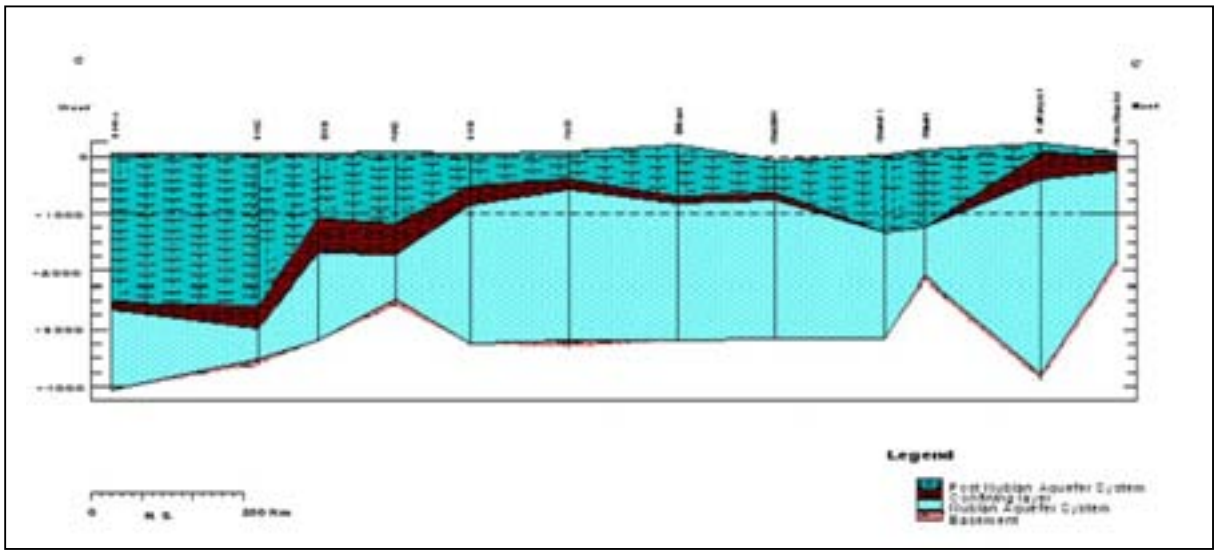


FIGURE 11. East-North hydrogeological cross-section C-C'

geological and the corresponding hydrogeological sections. They indicate the setting of the Nubian and Post Nubian Aquifer System in the study area.

The Nubian Aquifer System (NAS)

Hydrogeological Units

The Pre-Upper Cenomanian geological succession, referred to in this study as the Nubian, comprises the oldest and the most extended reservoir of supreme hydrogeological interest in Northeast Africa. This succession, having a thickness ranging from less than 500 m, to more than 5,000 m, shows a marked lateral change of facies, which plays a significant role in determining the hydraulic characteristics of the water bearing horizons. The succession can be differentiated into three distinct hydrogeological units:

a) an upper unit, dominated by clastic facies, changing in the basin-wide ward direction into carbonate facies and is assigned to the Lower and Upper Cretaceous. This unit is extensive and is also highly productive.
b) a middle unit, dominated by sand facies with interbeds of carbonates beds. It is extensive and is also moderately to very low productive; it is assigned to Late Paleozoic and to the Early Mesozoic;
c) a lower unit, dominated by sand facies with interbeds of clays, assigned to the Cambro-Ordovician, and is extensive and is also highly productive.

For the present study the above hydrogeological units, constituting the multi layered aquifer sys-

tem, have been assumed on a regional basis hydraulically connected and for all practical purposes to behave as a one layer aquifer system. This aquifer is under unconfined conditions south of 25th parallel and under confined conditions north of it (Figure 12).

The Aquifer boundaries

These comprise:

- the lateral boundaries of the aquifer (Figure 12); determined on the eastern side by the impervious Pre-Cambrian basement complex of the mountain ranges of the Red Sea and northwards the Suez Canal. The System eastern boundary is designed as a no-flow boundary. On the southern side it is determined by the outcrops of the Basement rocks of Southern Sudan (Kordfan and Darfur blocks) and Chad (Tibesti and Ennedi), which represents also a no-flow boundary. In the southeastern side, the Nile is represented at Nasser Lake and Dongola by a fixed head boundary. On the western side there is a

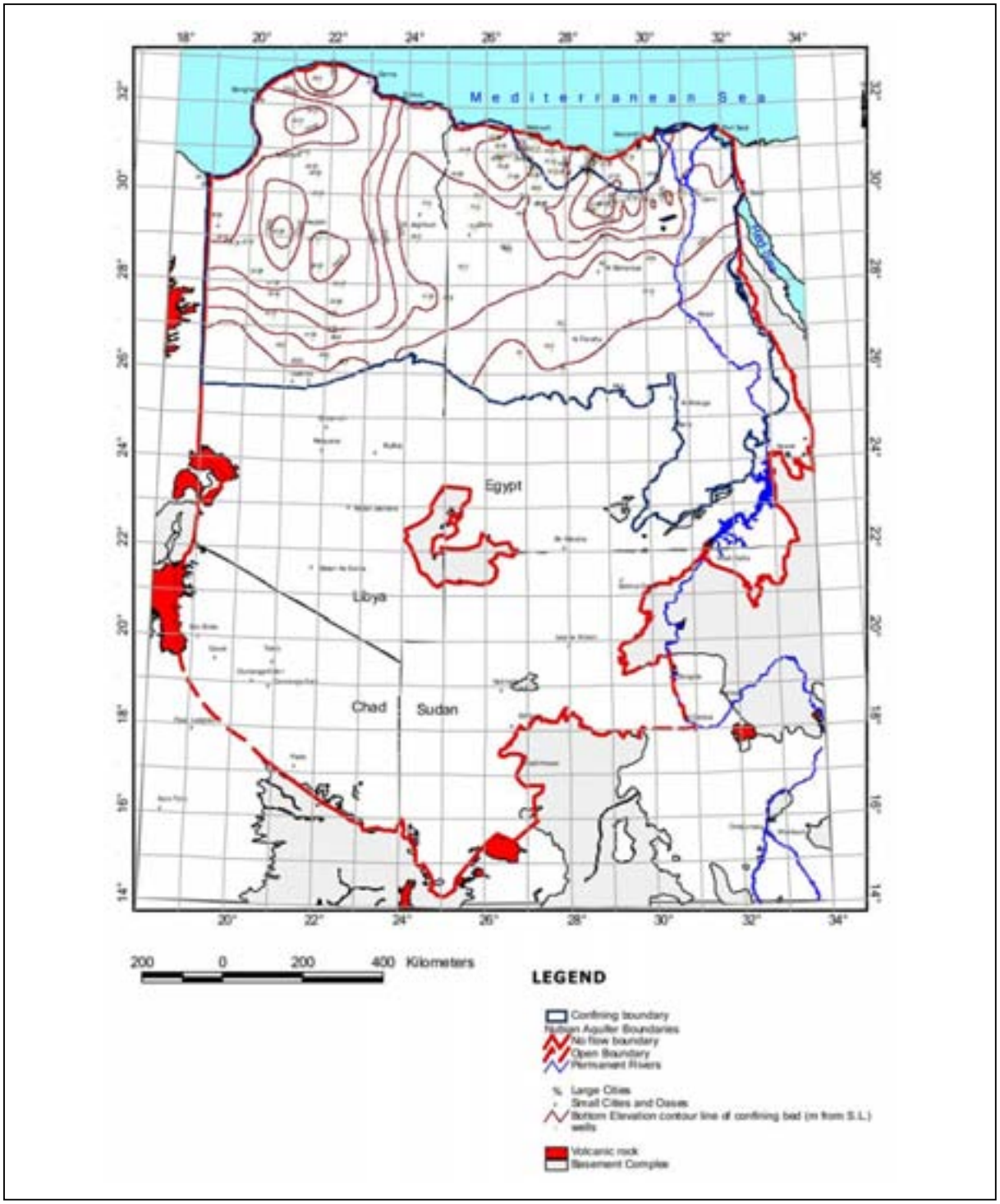


FIGURE 12. Lateral and vertical boundaries of the Nubian Aquifer System

groundwater divide extending from Tibesti mountains in the south and continuing northwards along the 19° Meridian. This boundary represents a no-flow boundary. The aquifer northern boundary coincides with the Mediterranean coastline, representing a fixed-head boundary

- the base of the aquifer is taken at the surface of the Pre-Cambrian Basement complex. The Basement surface elevations fall regionally from Sea level in the southern part of the NAS to over 5,000 m b.s.l. along the northern boundary, as shown in Figure 4.
- the top of the aquifer is represented by the water table in the vast area south of Lat. 25°N, where the system is unconfined. Northwards, the aquifer is overlain by a low permeability confining bed of shales and carbonates, with its bottom forming the top of the NAS. Figure 12 show the bottom of the confining bed. It also shows that the confining bed is missing north of a lat. 30° between Marsa Matruh and Alexandria where the NAS and PNAS are in direct contact.

Aquifer potentiometry

The data obtained from a good number of observation wells, assisted in the preparation of the initial potentiometric surface map (pre-development) Figure 13. This map gives indication to:

- the groundwater divide between Kufra and Chad basins,
- the northwest flow of groundwater from Kufra to Tazerbo and Sarir (Post Nubian),
- steep northeast flow of groundwater from Kufra to Farafra,
- a northeast flow from W. Howar area to East Oweinat area and Kharga,
- a complicated flow portion in the Nile Valley area to the north of Qena Bend (faulted),
- the lack of reliable information about the flow pattern at the border area between Libya and Egypt to the south of Siwa-Jagboub area.

The Aquifer hydraulic parameters

Data on the aquifer hydraulic parameters are only available in development project sites, leaving large areas of the aquifer with almost little or no data. Moreover, hydrogeological investigations in the study area are usually carried out very close to the surface, where most of the pump-tested wells were completed in the upper part of the aquifer (Mesozoic deposits), except for a few locations in East Oweinat in Egypt and Northern Sudan where the depth to the basement is relatively shallow and its drilled wells were fully penetrating. The system on the other hand, because of its relatively homogenous geology, where large geological units with relatively the same lithology are encountered, greater reaches can be overcome by interpolation

Table 1 shows wide variations in the values of the aquifer parameter both regionally and even locally:

- the hydraulic conductivity of the lower part (Paleozoic) estimated as 10^{-5} to 10^{-6} m/s. For the upper part (Mesozoic) it varies from less than 4×10^{-6} to more than 10^{-3} m/s. The values for the aquitard are estimated as 10^{-7} m/s. for horizontal hydraulic conductivity and 10^{-10} to 10^{-11} m/s for the vertical hydraulic conductivity;
- the storativity for the unconfined portion varies from 7×10^{-5} in Kharga to 2.7×10^{-2} in Kufra. In this study an average value of 7% for the effective porosity and of 10^{-4} for the storage coefficient is taken.

Using the above mentioned average hydraulic conductivities and the actual saturated thickness a transmissivity map shown on Figure 13 was prepared. The regional transmissivity varies from 100 m^2/d in the areas adjacent to the basement exposures to over 10,000 m^2/d in the basinal area downdip where the thickness exceeds 3,000 m.

The Post Nubian Aquifer System (PNAS)

Hydrogeological Units

The Post Nubian succession can be differentiated into four different lithostratigraphic units, which form the following hydrogeological units:

- a localized top unit belongs mainly to Quaternary and dominated by fluviatile sand, clay and near-shore deposits. Well developed in the Nile Valley, the Delta, the coastal zone and the inland depression with a maximum thickness of 1,000 m in the Nile Delta. The unit is highly productive.
- a regional top unit dominated by marl or marly limestone, with interbeds of clay and sandstone. Widely extensive in the plateau between the Nile Delta and Gebel Al Akhdar. Assigned to Middle Miocene, moderately to low productive.
- a middle unit, assigned to Upper Eocene, Oligocene and Miocene, dominated by fluvial sand and clay with interbeds of shallow marine limestone. This unit is highly productive, and is extensive in Libya and Egypt.

Proceedings of the International Workshop
Tripoli, Libya, 2–4 June 2002

- a lower unit, assigned to the Upper Cretaceous and Lower Paleocene. This unit is extensive in Egypt and is restricted in Libya dominated by carbonate facies with interbeds of clay and evaporates (locally missed in the northern portion of the area, due to erosion and/or non-deposition). The unit is generally low or non-productive.

Extent and boundaries of the Aquifer

The Post Nubian Aquifer System (PNAS) overlies the Nubian Succession north of the 26th parallel in the study area (Figure 14), and assigned to the Mesozoic-Cenozoic (Post Lower Cenomanian), having a cumulative thickness of the order of 5,000 m.

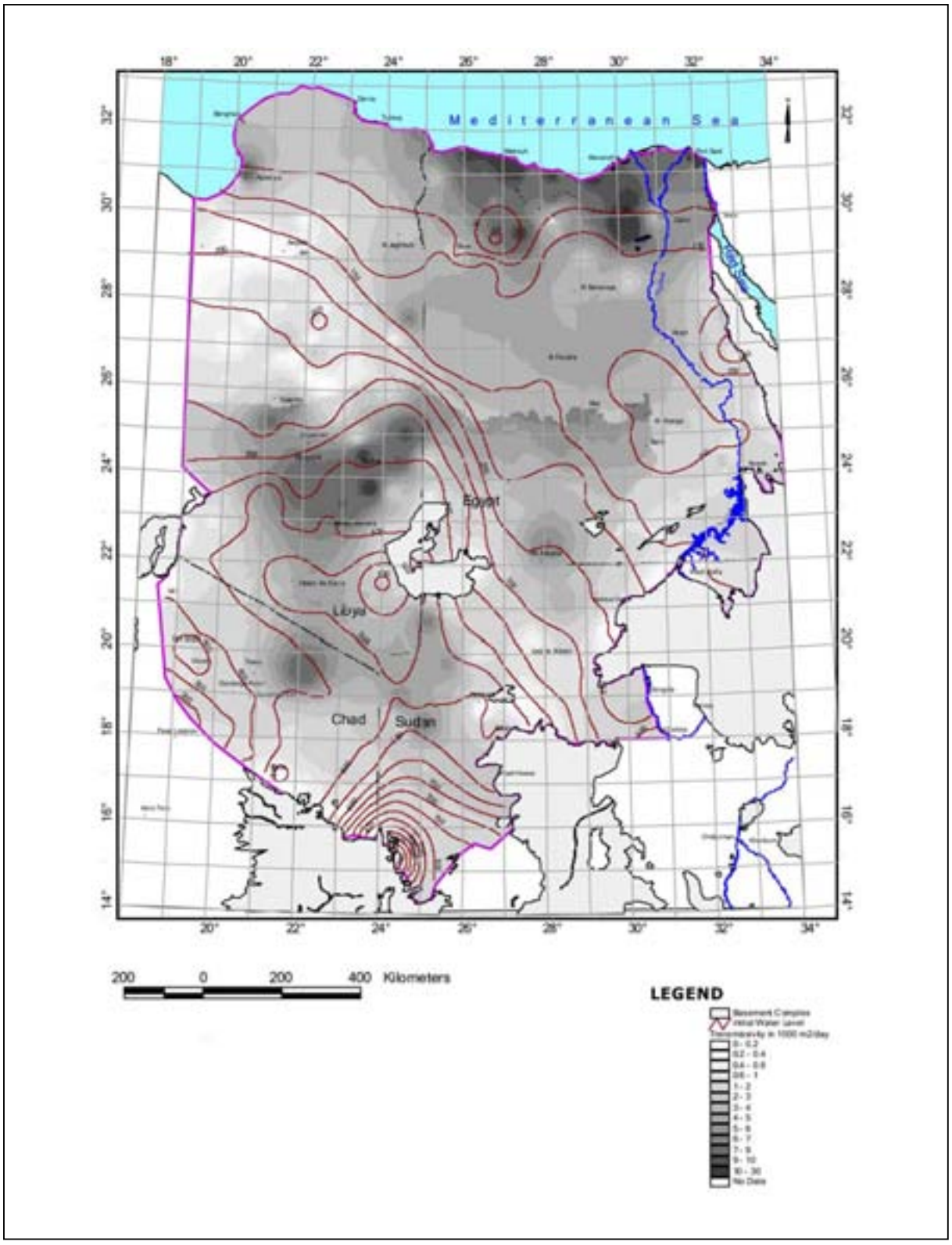


FIGURE 13. Transmissivity and water level map of the Nubian Aquifer System

Region	Country	Number of pumping tests	Saturated thickness (m)	Average screen length (m)	Transmissivity (m^2/sec)	Hydraulic cond. (m/sec)	Storage coefficient (s)
Wadi-Qena	Egypt	6	650	250	$9.905\,E^{-4}$	3.96×10^{-6}	
Wadi ElLaquita	Egypt	2	500	200	$3.975\,E^{-3}$	1.98×10^{-5}	
Bahareya	Egypt	10	1,880	196	$8.700\,E^{-3}$	4.3×10^{-5}	8.0×10^{-4}
Farafra	Egypt	8	2,600	221	$1.200\,E^{-2}$	5.4×10^{-5}	
Abu Munqar	Egypt	3	2,500	250	$5.469\,E^{-2}$	2.18×10^{-4}	
Dakhla	Egypt	21	1,850	181	$1.100\,E^{-2}$	$6.100\,E^{-5}$	6.35×10^{-4}
Kharga	Egypt	59	1,280	205	$5.900\,E^{-3}$	$2.900\,E^{-5}$	2.84×10^{-4}
East Oweinat	Egypt	6	410	185	$2.400\,E^{-2}$	$1.300\,E^{-4}$	
Siwa	Egypt		500	200	$6.944\,E^{-2}$	3.42×10^{-4}	
Aswan	Egypt	1	200	100	$2.778\,E^{-3}$	2.778×10^{-5}	
Tazerbo	Libya	5	2,500	200	$1.878\,E^{-2}$	9.4×10^{-5}	
Kufra	Libya	60	3,000	134	$8.749\,E^{-3}$	5.03×10^{-5}	2.34×10^{-3}
West Selima	Sudan		339	181	$2.600\,E^{-2}$	1.436×10^{-4}	1.43×10^{-4}
El Atrun	Sudan		210	80	$1.200\,E^{-3}$	$1.500\,E^{-4}$	
Wadi Howar	Sudan		374	39	$1.700\,E^{-3}$	$4.400\,E^{-5}$	
Um Hilal	Sudan		139	80	$2.600\,E^{-2}$	$3.300\,E^{-4}$	
El Hashi	Sudan				$1.360\,E^{-2}$	$2.390\,E^{-4}$	
Dongola Area	Sudan	29	161	9	$1.064\,E^{-2}$	1.18×10^{-3}	

TABLE 1. Average hydraulic parameters of the Nubian Aquifer System

This group is regionally missed in the southern part of the study area (with the exception of its southeastern extension in Sin El-Kadab plateau west of Aswan), and is also locally missed in the northern part.

The PNAS is bounded by:

- In the south by the 26th parallel demarking the limit of the deposition, forming a no flow boundary.
- In the west by the 19 Meridian north of Tibesti, as a no-flow boundary.
- In the east, the Red Sea basement mountains and the Suez Canal, which represents a no-flow boundary.
- In the north by the Mediterranean Sea.

The vertical boundaries of the aquifer are represented by its base, which coincides with the top of the confining bed to the underlying Nubian aquifer (Figure 14), while the top of the aquifer is represented by its water table (Figure 15). The Top and the base of the aquifer were used to evaluate the total saturated thickness.

Aquifer potentiometry

Based on the available data about depth to water of those wells tapping the PNAS and their site elevations, a potentiometric surface map was prepared (Figure 15). The map indicates that the aquifer attains a groundwater elevation of 150 m.a.s.l in the southwestern part of Sarir project areas, and decreases northward to zero at the 30° parallel. The map also shows a radial distribution of the groundwater flow from the core of Jabal al Akhdar with 400 m.a.s.l and northward to the sea and southward to the area extending from Ajadabiya in the west to Al Jaghboub in the east with water level is below Sea level (10 m.b.s.l), where it is lost by evaporation in the

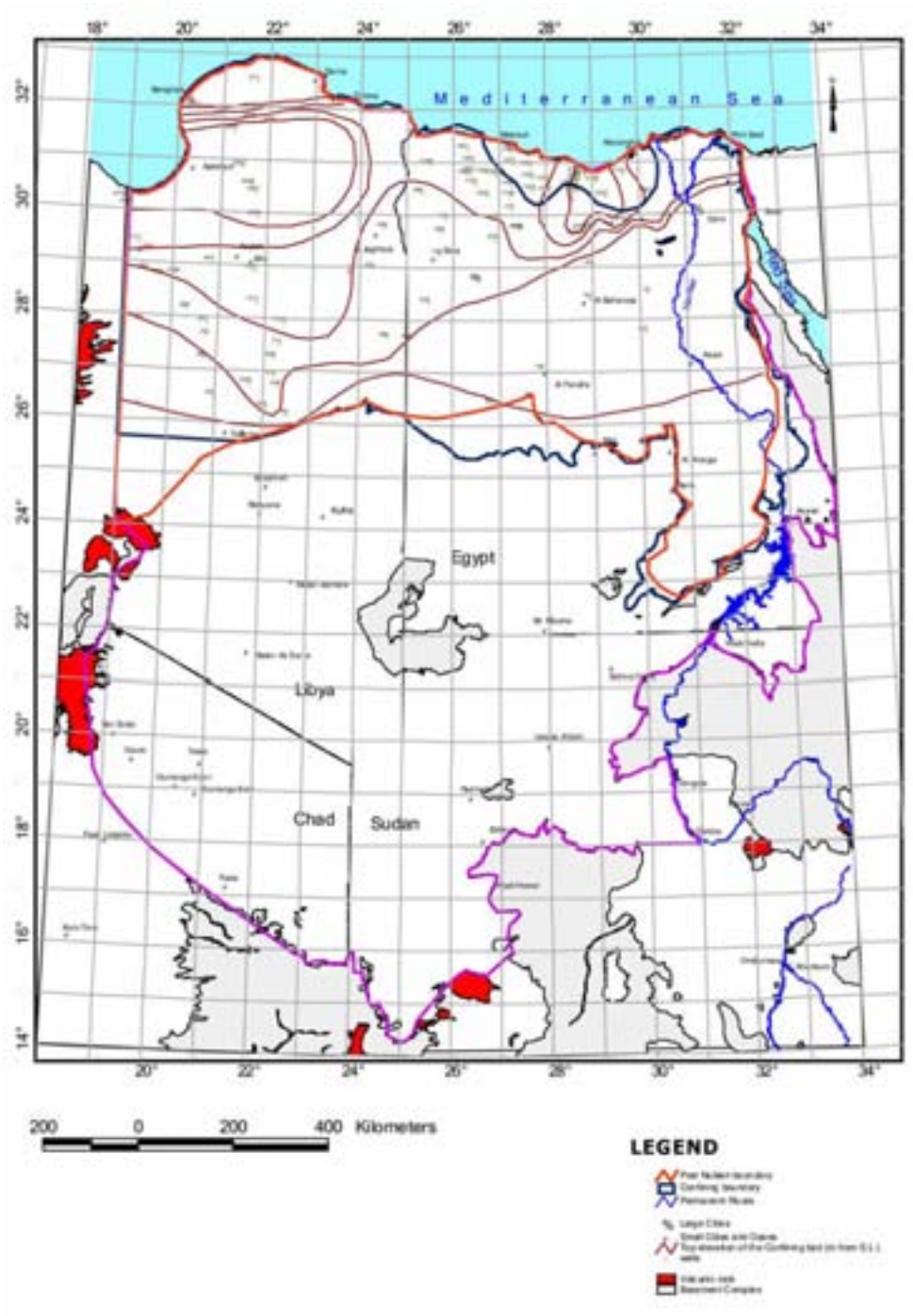


FIGURE 14. Lateral and vertical boundaries of the Post Nubian Aquifer System

Sabkhas. This groundwater depression also extends further east in the northern part of the Western Desert of Egypt between Siwa Oasis and the Qattara Depression, (40 m.b.s.l) which acts as a natural discharge area for the aquifer. In Northeastern Western Desert (Wadi El Fareigh) and the western desert fringes of the Nile Delta, the aquifer (lower Miocene Moghra aquifer) is reported to be hydraulically interconnected with Nile Delta Quaternary aquifer where it receives a considerable recharge and drains its groundwater into Wadi EL Natrun lakes (RIGW/IWACO, 1998).

Hydraulic parameters

Table 2 represents the results of the interpretation of the pumping tests conducted in those wells tapping different aquifers of the PNAS (48 wells in Sarir well field in Libya and 18 wells in the Western Desert of Egypt). It indicates that the

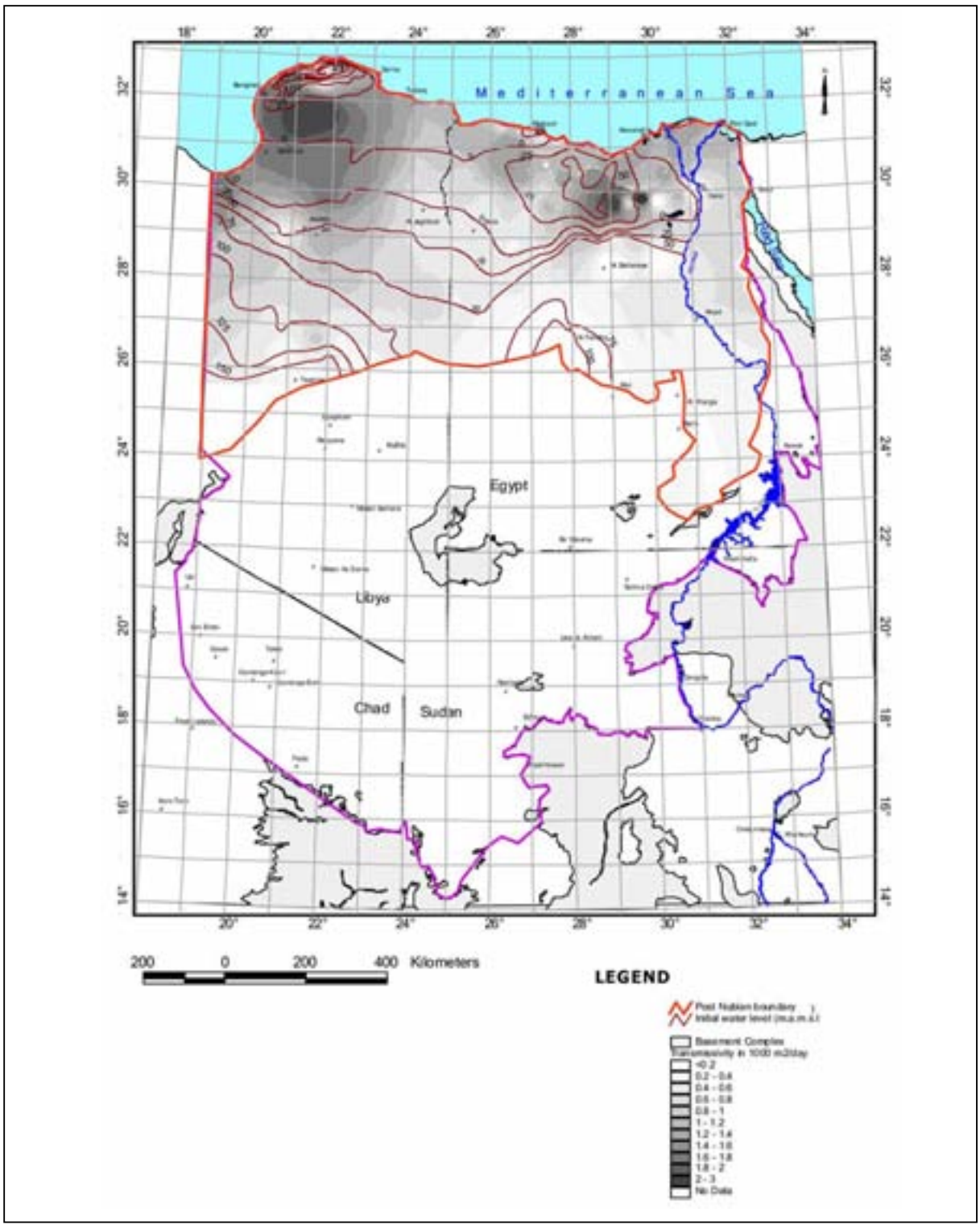


FIGURE 15. Transmissivity and water map of the Post Nubian Aquifer System

Post Nubian Aquifer Hydraulic conductivity ranges between 3.6 x 10^{-5} m/s in the area between West Delta and Qattara Depression, 6.4 x 10^{-5} m/s. in northwestern Western Desert and 3.1 x 10^{-4} m/s to 8 x 10^{-5} m/s in Sarir.

Using the above mentioned average hydraulic conductivities and the actual saturated thickness a transmissivity map was prepared (Figure 15).

The aquifer transmissivity ranges between 1.6 x 10^{-2} m^2/s. in Sarir area, 2.8 x 10^{-4} to 2 x 10^{-3} m^2/s. for the moghra aquifer in West Delta–Qattara depression Zone and 6 x10^{-5} to 8 x10^{-4} m^2/s. for the middle Miocene limestone aquifer in El-Diffa plateau.

Region	*Country*	*Number of pumping tests*	*Saturated thickness (m)*	*Average screen length (m)*	*Transmissivity (m^2/sec)*	*Hydraulic cond. (m/sec)*	*Storage coefficient*
West Sarir	Libya	3	615	260			
Pr1	Libya		720	9	7.5×10^{-2}	2.88×10^{-4}	2×10^{-2}
Pr2	Libya		706	206	1.25×10^{-2}	1.38×10^{-3}	5×10^{-4}
Pr3	Libya			130	1.27×10^{-2}	6.16×10^{-5}	3×10^{-2}
North Sarir	Libya	6		130	5.8×10^{-2}	4.4×10^{-4}	5×10^{-4}
South Sarir	Libya	39			1.435×10^{-2}	1.1×10^{-4}	5×10^{-4}
Marada	Libya						
Shallow					2.3×10^{-3}	2.3×10^{-3}	0.1–0.44
Deep					1.3×10^{-4}	1.3×10^{-4}	5×10^{-4}
Jalo/Ojla	Libya				1.731×10^{-2}	1.73×10^{-2}	2×10^{-2} 2×10^{-2}
Moghra	Egypt	11		31	2.75×10^{-4}	2.75×10^{-4}	
Moghra	Egypt	3		26	2.1×10^{-3}	2.1×10^{-3}	
Marmarica	Egypt	3		35	8.0×10^{-4}	8.0×10^{-4}	
Western Plateau	Egypt	1		46	6.4×10^{-5}	6.4×10^{-5}	

TABLE 2. Average hydraulic parameters of the Post Nubian Aquifer System

Groundwater extraction

Groundwater from the Nubian Sandstone Aquifer System that is Nubian and Post Nubian has been utilized since centuries in the Oases all over the area through springs and shallow wells. Intensive groundwater development for different purposes (Irrigation, mining, medical tourism and water supply) was initiated in 1960 in the Western Desert Oases of Kharga, Dakhla, Bahareya and Farafra while it started in 1990 in Siwa Oasis and East Oweinat areas, and lately in Darb El-Arbain area. In Libya, large-scale groundwater extraction started in 1970 in Kufra Production Project (KPP) and later in Kufra Settlement Project (KSP), in South Sarir, North Sarir, West Sarir and Jalu area. Figure 16 shows the locations of the extraction zones from the aquifer in Egypt, Libya and Sudan.

The total extraction from the Nubian Sandstone Aquifer System within the study area in 1998 is 911 mcm from the PNAS and about 1,376 mcm from NAS, of which 1,029 mcm in

Proceedings of the International Workshop
Tripoli, Libya, 2–4 June 2002

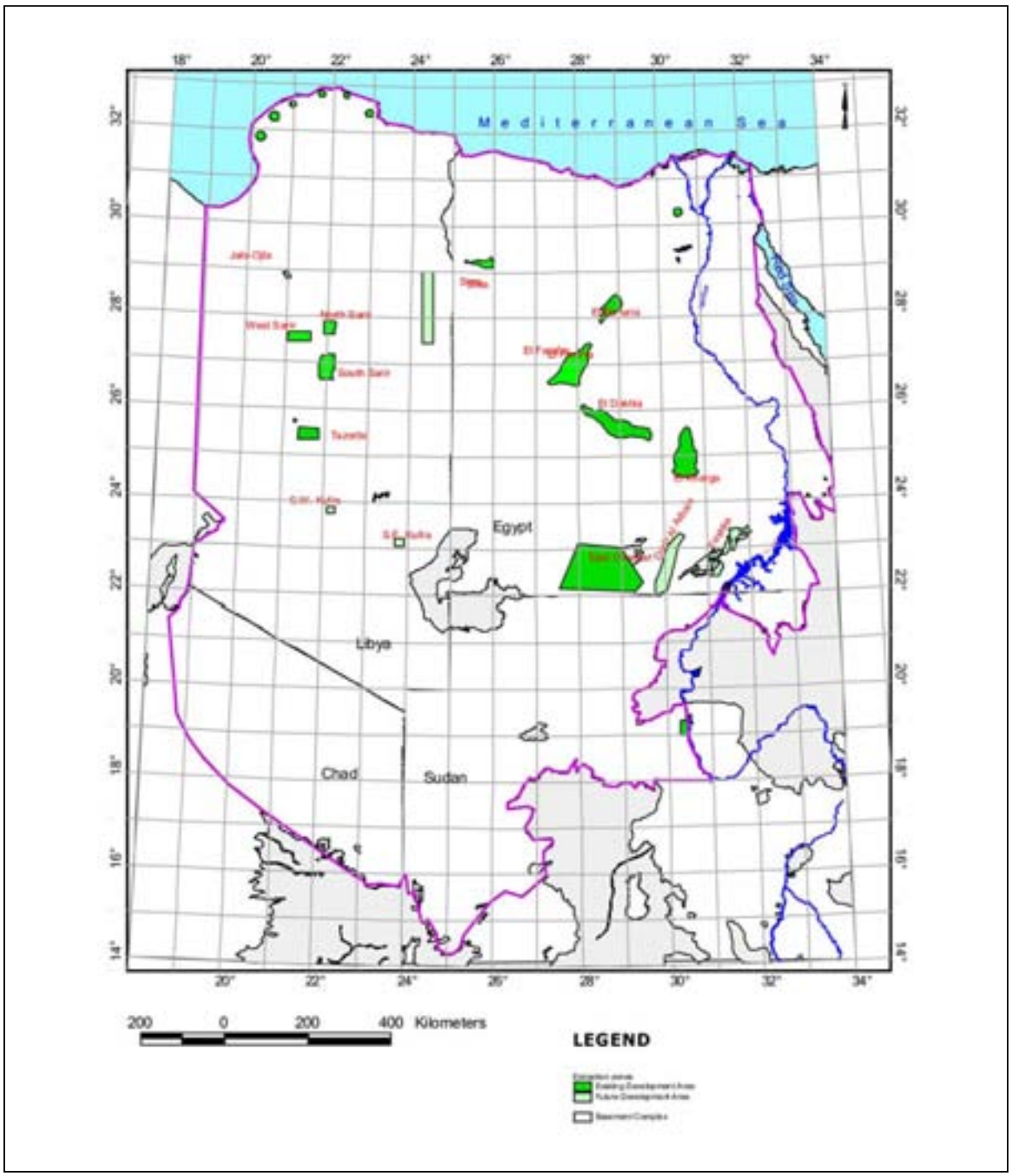


FIGURE 16. Extraction zones of the Nubian Sandstone Aquifer System

Egypt, 857 mcm in Libya and 407 mcm in Sudan. In Sudan, the figure includes extraction east of the study area i.e. east of The Nile River in Dongola area and may be even further south. Historical groundwater extraction in the different development areas from the Nubian Sandstone Aquifer System in Egypt and Libya is indicated in Figure 17, show a total of 40 Bm^3 of water that has been extracted in the past 40 years in Egypt and Libya. No historical data available regarding extraction for Sudan and Chad.

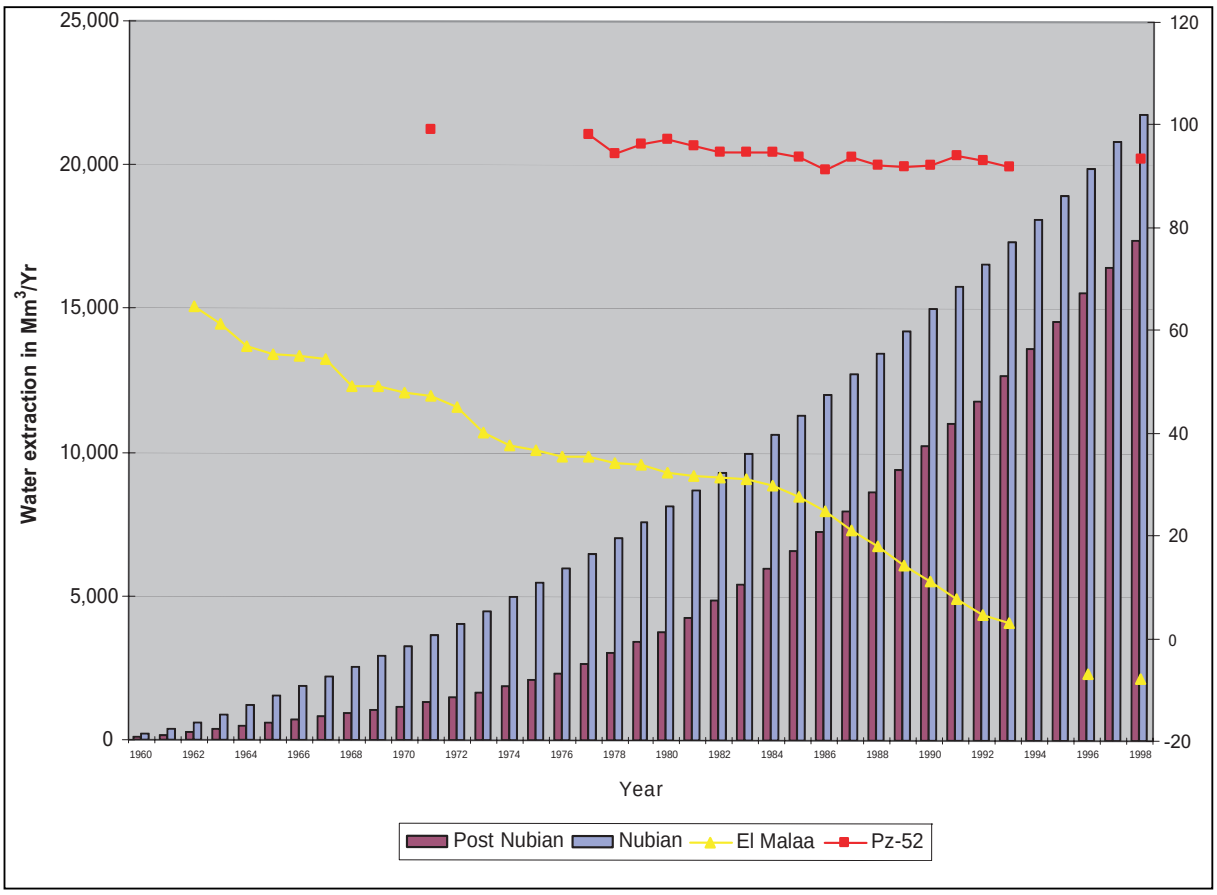


FIGURE 17. Cumulative extraction from the NSAS in Egypt and Libya and the corresponding aquifer response

Aquifer response to extraction

Water level fluctuations as a response to groundwater extraction in the development areas are shown in Figures 18, 19, 20. Figure 18 indicates that the water extraction in Kharga Oasis created a groundwater depressions in the Northern part of the Oasis with a maximum drop of water level of 60 m and 35 m in the Southern part during the period 1960 to 1998. In 1960 the groundwater was extracted mainly from naturally flowing shallow wells and springs, while now 97% of the extracted water is pumped from deep wells.

Figure 19 shows a decline in water level ranging between 10–20 m in Kufra production project and to less than 5m in kufra settlement project during the period 1972–1998, creating a drawdown circle of less than 25 km in radius.

Figure 20 indicates a decline of water level between 5–8 m within North Sarir project, 3–8 m in the South Sarir project and from 1–4 m in the West Sarir Transport project. The figure also shows that the cones of depression are connected and form a unique large depression enclosed by the 1m isodecline contour line.

Groundwater quality

The groundwater chloride salinities data obtained from Drilling Stem Test (DST), and calculated

Proceedings of the International Workshop
Tripoli, Libya, 2–4 June 2002

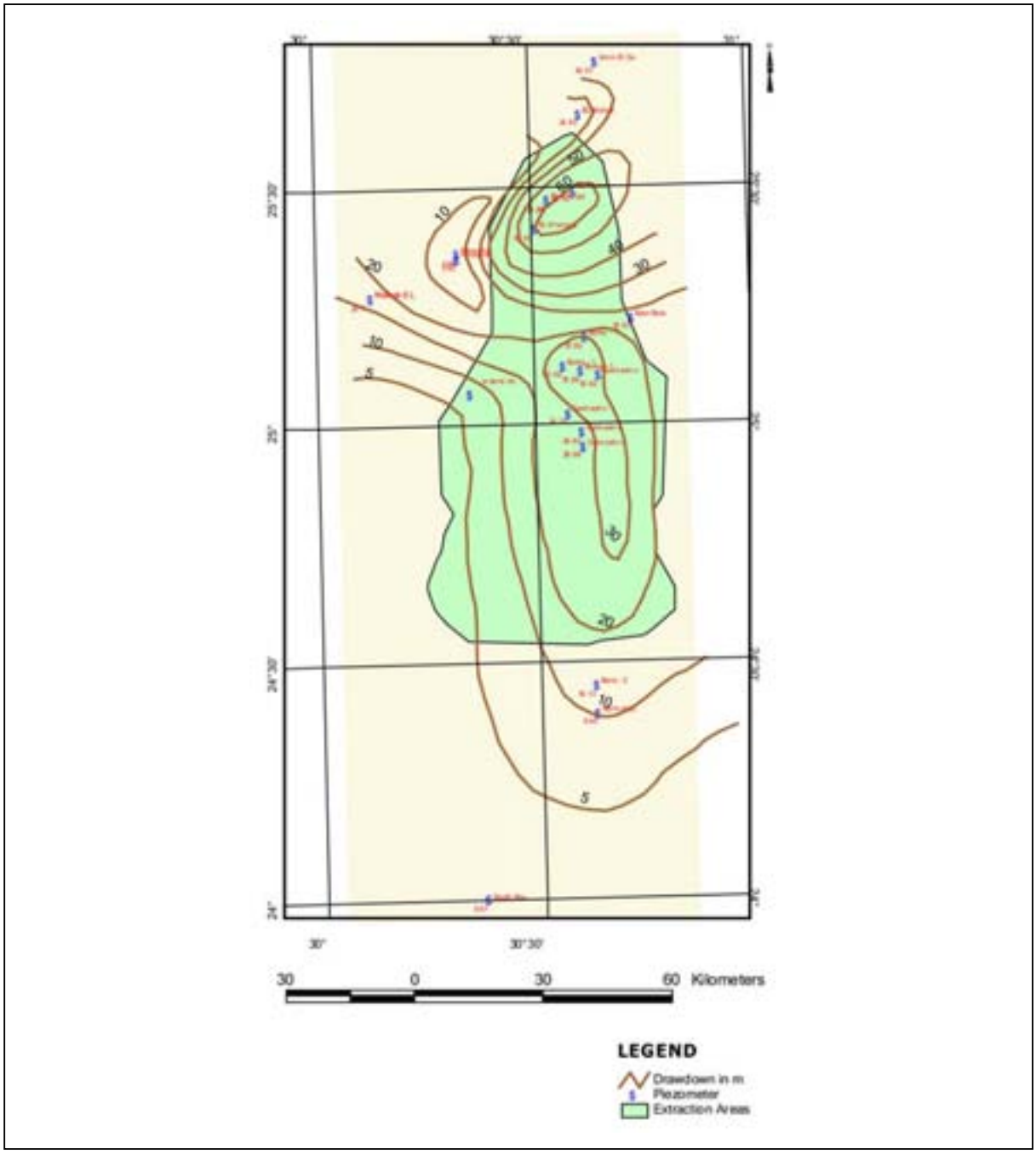


FIGURE 18. Water level iso decline contour map from 1996 to 1998 in Kharga Oasis

from SP logs for a large Number of oil wells taping the Nubian were used to draw the Isosalinity map shown in Figure 21.

This map and a large number of water quality measurements in water wells show that the water quality varies laterally and vertically as follows:

- Water quality in the unconfined part of the Nubian Aquifer System is good (TDS less than 1,000 ppm) to excellent (TDS less than 500 ppm) all over the area.
- For the confined part of this system particularly in the area up to Lat. 30° in Egypt and Lat. 26° in Libya, the water quality changes

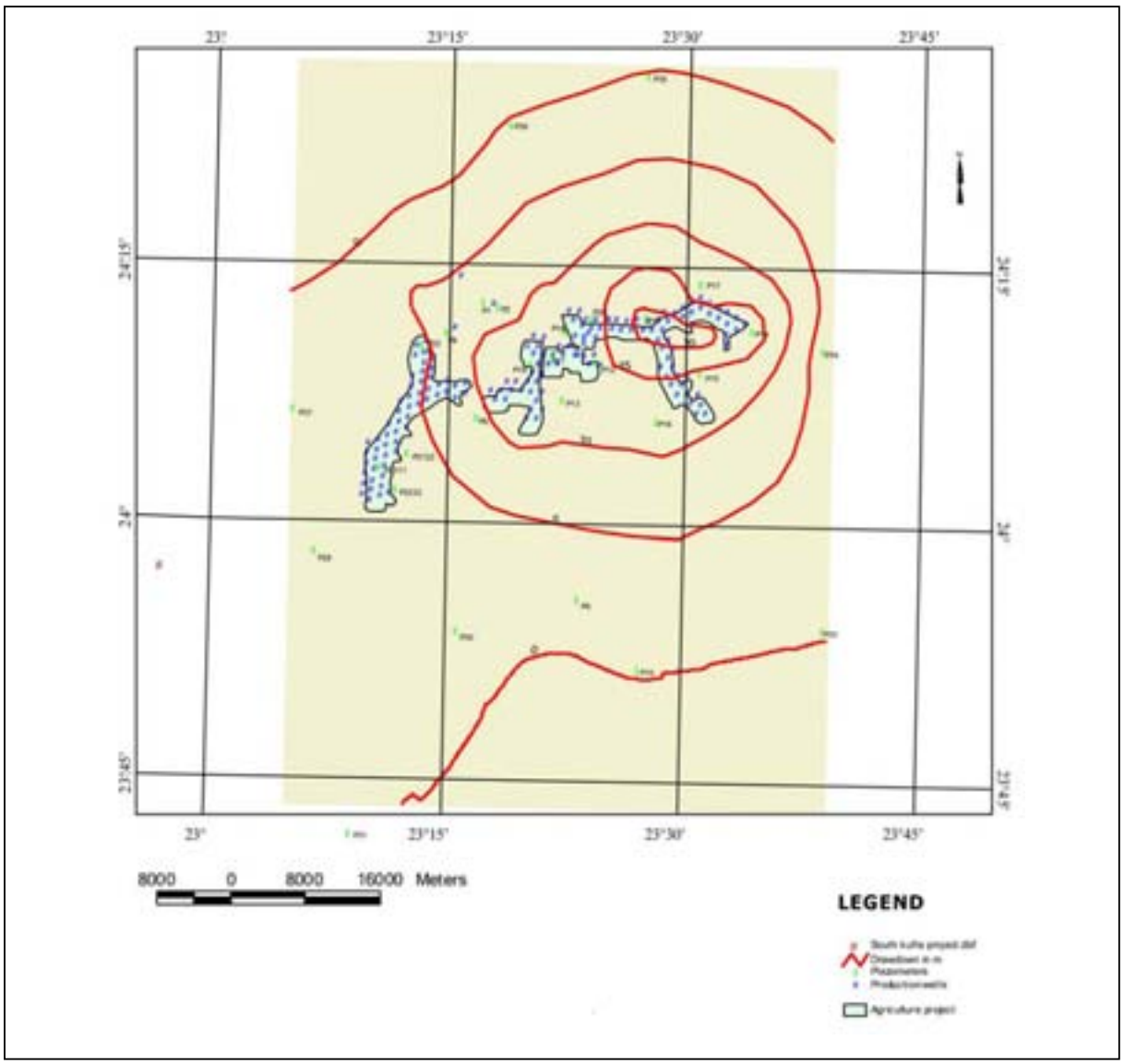


FIGURE 19. Water level iso decline contour map from 1972 to 1998 in Kufra Projects Area (from deep piezometers readings)

laterally and vertically where the upper part of the aquifer system (Mesozoic) contains fresh water (TDS less than 2,000 ppm), while the lower part of the aquifer system (Paleozoic) becomes saline very rapidly till it reaches the freshwater-saline water interface where the whole aquifer becomes saturated with hypersaline water as high as 200,000 ppm. The occurrence of such saline water-freshwater Interface was attributed (El-Bishlawy, 1970) to the Post Cenomanian tectonic movements that initiated permeability barriers and prevented further northward freshwater flushing of the saline formation water. Part of the highly saline water can also be explained by sea water intrusion induced by the deep topographic depressions (below sea level) along the Lat. 30° and by the missing aquitard in the northern part of Egypt (between Marsa Matrouh and Alexandria) which may have contributed to the salinisation of the Nubian Aquifer. However an important part of saline water in the Nubian and the deep Post Nubian Aquifer system

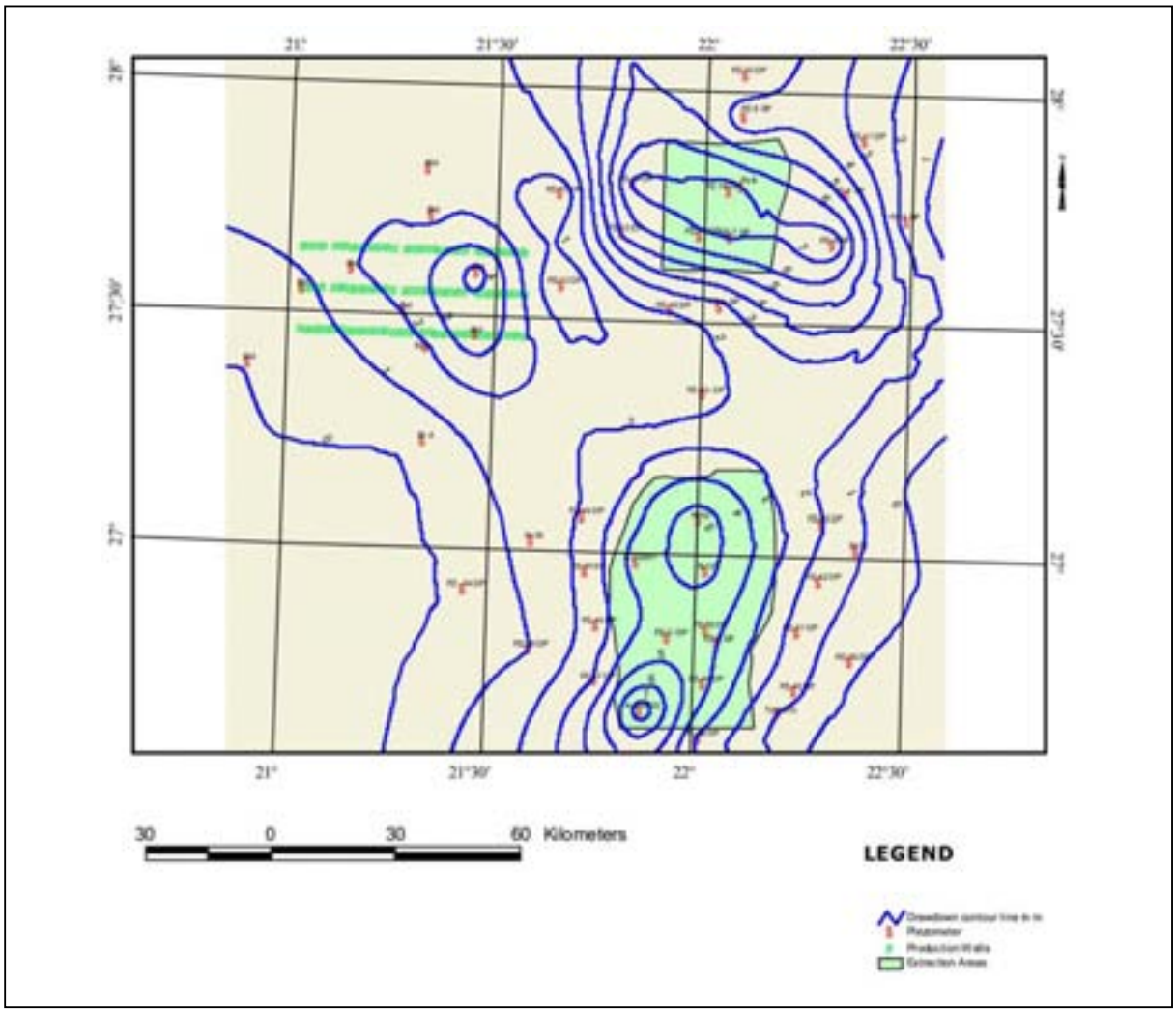


FIGURE 20. Water level iso-decline map from 1975/1977 to 1998 in Sarir water production projects

north of the Lat. 26° N in Libya is likely due to the presence of evaporates in the matrix of the water bearing formations.

- Groundwater of the Post Nubian Aquifer System shows a wide variation in chemical quality. In areas of intensive development as Sarir, Jalo, Siwa and W. El Fareigh the good quality of the water is endangered by the upconing and/or the lateral flow of saline water. There is lack of detailed information to make synthesis of the problem even on the regional level.

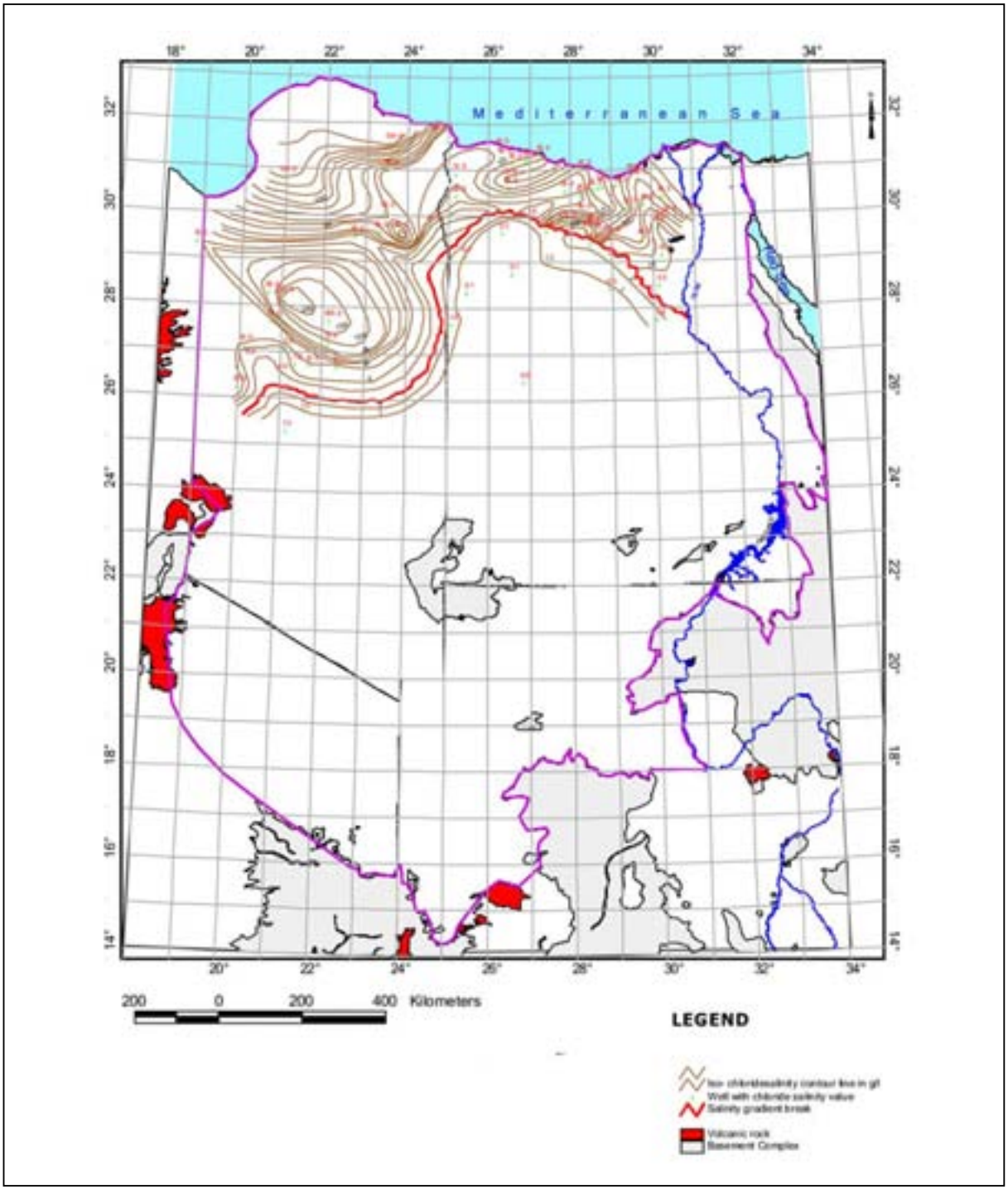


FIGURE 21. Iso salinity contour map of the Nubian Aquifer (Lower Cenomanian Aquifer)

Groundwater genesis

In the modern literature (mainly Butzer, 1964; Pachur et al., 1986; Thorweihe in Said, 1990; Shata, 1992; ... etc.) there are facts of significant importance, which have a direct bearing upon this subject. These include: the facts related to the evolution of the landscape since Late-Miocene times, the facts about the fluctuations of the climatic conditions in Pleistocene and Holocene times, and eventually the facts regarding the results of the applications of isotope hydrology.

Within this area, the discovery of Late-Miocene rivers was made, particularly in E Libya, S Egypt and N Sudan. The lowland portions of such rivers are occupied generally by extensive

sand sheets. The level of such areas was lowered topographically. In S Libya, S Egypt and N. Sudan, the Nubian Sandstone sediments essentially underlie the surface area of such rivers. It is, therefore, expected that the paleo-river system in addition to the Nile, should have played a significant role in the recharging history of the Nubian Sandstone Aquifer System (for quantification purposes, special studies in the fields of quantitative geomorphology, paleography, sedimentology and subsurface geology are wanted).

The fluctuations of the climatic conditions during Pleistocene and Holocene times included a number of wet and dry periods. Such events together with the existing river systems contributed, essentially, to the replenishment and depletion of the aquifer respectively. The filling process ends when recharge and discharge balance each other. Such state probably existed 8,000 years ago. No significant recharge had taken place afterwards and the aquifer system is assumed to be in a transient state, depleting slowly through natural and artificial processes. Modern rain events as well as the seepage from the Nile proper and the High Dam Lake most likely contributed to the recent formation of groundwater but in a very limited scale. Latest radio isotope hydrogeological studies indicated that no recent significant groundwater formation is detectable.

References

ALI HESSENE MAHMOUD 1986, *Geologie Und Hydrogeologie des Erdis-bchen, NE-Tchad.* Berliner Geowiss. Reihe A/B 76, Berlin.

BUTZER, K.W. 1980. Climatic changes in the arid zones of Africa during early to mid-Holocene Time. In: *Royal Meteorological Society, Proceedings of the International symposium on world climate for 8,000 to 000 BC.*

CEDARE, 2002. *Regional Strategy for the Utilization of The Nubian Sandstone Aquifer System*, Volume II. CEDARE, Heliopolis Bahry, Cairo, Egypt.

EDMUNDS, W.M. and WRIGHT, E.P. 1979. Groundwater Recharge and Paleoclimate in the Sirte and Kufra Basins. Libya, *Jour. Hydrol*, 40, pp. 215–41.

EL-BISHLAWY, S. 1970. Formation Water Salinities of the Cretaceous and Jurassic Sand. AMOCO, Internal Report.

EL RAMLY, I. 1983. *Water Resources Study of Zone V-Al Kufra and Sirte Basins Socialist Peoples Libyan Arab Jamahiriya.* Technical report of the Secretariat of Agricultural Reclamation and Land Development, Tripoli, 136 pp. + appendices.

EZZAT, M.A. 1974. *Groundwater Series in the Arab Republic of Egypt; Exploitation of Groundwater in El-Wadi El-Gadid Project Area. Part I to IV*. General Desert Development Authority/Ministry of Irrigation, Cairo.

GEYH, M.A 1978. *Interpretation of Environmental Isotope Data of Groundwater, Arid and Semi-Arid Zones*. Prog. IAEA Advisory Group Meeting on the Application of Isotope Techniques to Arid Zone, Hydrology, Vienna, Nov. 1978.

ISSAWI, B. et al. 1999. *The Phanerozoic Geology of Egypt*. Special Publication No. 76 by the Egyptian Geological Survey, 462 pp.

JVQ (JOINT VENTURE QATTARA). 1978. Study Qattara Depression, Special Volume: Regional Geology and Hydrogeology. Unpublished report of Lahmeyer GMBH, Salzgitter Consult GMBH, Deutsche Projeckt Union, GMBH.

———. 1979. Study Qattara Depression, Vol. III. Part 1: Topography, Regional Geology and Hydrogeology. Lahmeyer International, Salzgitter Consult and Deutsche Project Union, GMBH, German Federal Republic.

KHOURI, J, 1996. *Synthesis of National Reports and Definition of Gaps in Knowledge.* ACSAD, Damascus Syria.

KLITZCCH, E. et al. 1987. *Geology of the Sedimentary Basins of Northern Sudan and Bordering Areas.* Proceedings of the Special Research Project in Arid Areas, Berlin.

NOUR, S.E. et al. 1983. Hydro-agriculture Study Project, East Oweinat Region, Western Desert, Egypt – Groundwater Resources. Interim Report submitted to the General Petroleum Company, Cairo.

———. 1984. Groundwater Resources in the East Oweinat Region, Hydrogeological Condition. Unpublished final report of General Petroleum Company, Cairo, Egypt.

OSS. 1996. *Groundwater resources of the Nubian Aquifer System*. OSS-Technical report, Ulf. Thorweihe and M. Heinl, Paris, 1996, asp.

PACHUR, H.J. 1980. Climatic History in the Late Quaternary in Southern Libya and the Western Libyan Desert. In: *Salem, M.J. and*

Busrewill, M.T. (eds.) 2nd Symp. Geology of Libya. V. III, pp. 781–8. Academic Press, London.

PALLAS, P. 1978. Water resources of the Socialist Peoples Libyan Arab Jamahiriya. Technical report of the Secretariat of Dams and Water Resources, Tripoli, 80 pp.

BRINKMAN, P.J., HEINL, M., HOLLANDER and REICH, G. 1987. *Retrospective Simulation of Groundwater, Flow and Transport in the Nubian Aquifer System.* Berliner Geowiss. Abh (A) 75.2, 465-519 Berlin.

RIGW/IWACO. 1988. Hydrogeological Map of Egypt (1:2000 000). Cairo, Egypt.

———. 1998. Environmental Management of Groundwater Resources. TN/70.00067/WQM/97/20, Cairo.

SAID, R. 1981. *The geological evolution of the River Nile.* Springer Verlag, 151 pp.

———. 1990. *The Geology of Egypt.* Balkema/ Rotterdam and Brookfield, 733 pp.

SHATA, A. et al. 1962. *The Geology, Origin and Age of Groundwater Supplies in Some Desert Areas of U.A.R.* Bull. De l'Int. de Desert D'Égypte, pp. 61-120.

SHATA, A. 1982. Hydrogeology of the Great Nubian Sandstone Basin, Egypt. Q.J. *Eng. Geol.* London, Vol. 15, pp. 127–33.

———. 1995. Climatic Changes and Tectonic Activities and the Development of the Nile Drainage Basin in Egypt. In: *The climatic fluctuations and water management*, by Abu Zeid and Biswas, Butter worth-Heinemann.

SONNTAG, C. 1984. *Autochthonous Groundwater, in the Confined Nubian Sandstone Aquifer.* Berliner Geowiss Abh, Vol. 50, pp. 217–20.

THORWEIHE, U. 1986. Isotopic Identification and Mass Balance of the Nubian Aquifer System in Egypt. In: Thorweihe, V. (ed.): *Impact of climatic variations on East Sahara,* Berliner Geowiss Abh., Vol. 72, pp. 87–97.

———. 1990. *Studies on Aquifer Properties the Dongola Area.* Berliner Geowiss Abh, Vol. 120,1.

———. U. 1990, Nubian Aquifer System. In: Said, R. (ed.): *The geology of Egypt.* 2nd Edition, Elservier, Amsterdam.

UNDP/UNESCO. 1972. *Study of Water Resources in the Lake Chad Basin* (1966–1970).

WILLIAMS, M.A and HALL, D.N. 1965. Recent Expeditions to Libya from Royal Military Academy, Sans hyrst, *Geog. Jour.* Vol.131, pp. 487–501.

WRIGHT, E.P. 1986. Review of the Hydrogeology of the Kufra Basin, North Africa. In: *Proceedings of the Workshop on Hydrology*, organized by the Special Research Project Arid Areas at the Technical University Berlin.

WRIGHT, E.P. and EDMUNDS, W.M. 1971. Hydrogeological Studies in Central Cyrenaica, Libya. In: *Symposium on the Geology of Libya,* 522 pp.

Management of transboundary aquifer systems in Africa
A case study of the Lake Chad Basin Commission

J. A. Oguntola

Chief, Water Resources Unit, Lake Chad Basin Commission,
N'Djaména (Chad)

Introduction

■ Lake Chad Basin

(i) Inland Drainage Basin;
(ii) Hydrographic Basin = 2,355,000 km^2;
(iii) Conventional Basin = 967,000 km^2.

■ Lake Chad

- third world largest lake behind the Caspian and Aral Seas, but a freshwater lake;
- 'Mega Lake' used to cover 350,000 km^2 in medieval periods;
- Could be drained towards the Nile basin at high stages through the Bahr El Ghazal;
- 'Great Lake' covered about 25,000 km^2 in the 1960s then at about 284 m altitude;
- 'Small Lake' presently covering less than 3,000 km^2 now below 280 m altitude.

■ Climate/Rainfall

- Regulated by the ITCZ (front between hot and dry air mass centred on the Sahara and the humid St Helena Anticyclone.
- Distance travelled by the ITCZ to the north influences the start, duration and end of rains, as well as amount, distribution and type of rainfall.
- Annual rainfall between 1,500 mm in the southern parts to less than 100 mm in the northern parts.
- Problems of temporal and annual intensity variations.
- Southwards shift of the isohyets over variable distances depending on the place.
- Drought forecasting research efforts show influence of abrupt changes in sea-surface temperatures caused by El Nino/La Nina events in the Pacific.
- Using aridity index, the basin three large climatic zones can be recognized:
  - The humid tropical zone.
  - The semi-arid sahelian zone, and
  - The arid saharan zone.

  The limit between the humid tropical zone and the sahelian zone corresponds to a value of 0.2 while that between the sahelian and saharan zones to 4 on the aridity index defined by Schneider (1991).
- One particularity of the Sahelian zone is the presence of numerous closed hydraulic basins with large piezometric depressions connected to aquifers of fluvio-lacustrine or lacustrine origin.

Geological/hydrogeological context

■ Basin formed during the Mesozoic (Cretaceous)

- opening of large troughs along the pan-African trends (NE and NW) i.e Doba and Bousso troughs
- followed by flooding and deposition of sedimentary sequences (continental intercalaire, continental hamadien, continental terminal, lower pliocene and quaternary sequences).

■ Groundwater quality

Quaternary – classified as bicarbonate type with low mineralization
  - important nitrate concentrations attributed to agricultural or faecal origin.

Lower Pliocene – classified as bicarbonate type
  - TDS greater than 700 mg/l
  - high conductivity

Continental Terminal – classified as sodium bicarbonate type
- TDS range between 75 and 600 mg/l
- high conductivity and high temperature (40°C–46°C)

Waters of the Lower Pliocene and Continental Terminal Aquifers present the risk of salinization of irrigation fields.

- There was a sharp piezometric pressure head decline of about 4.5 meters in the lower pliocene aquifer within a period of one year (1999–2000) attributable to the general decline in the artesian pressure within the basin.

- Recharge of these groundwater aquifers from rainfall is reported to be less than 5%. Rather, it is believed to be essentially from rivers influent into the lake Chad, the lake Chad itself and other lakes as well as wetlands within the basin.

Surface water

Rivers

- *Chari-Logone*

- catchment area = 600,000 km^2;
- average discharge over 59 years (1932–1992) = 33.5 x $10^9 m^3$;
- highest discharge = 54 x $10^9 m^3$ in 1955–1956;
- least discharge = 6.7 x $10^9 m^3$ in 1984–1985;
- average discharge since 1972 low (20.7 x $10^9 m^3$ compared to 39.6 x $10^9 m^3$ before then).

- *Komadougou-Yobe*

- catchment area = 150,000 km^2;
- runoff generated in 32% upstream part = 4,552 x $10^6 m^3$ in the ratio 55:45 at Foggo and Wudil respectively;
- major runoff losses in the middle and lower parts due to inundation plains, infiltration and evaporation, leaving only 1,147 x $10^6 m^3$ (1963–1996) at Gashua (confluence).

Human health aspects

- Water supply is groundwater based in most parts of the basin, except for the headwater areas where large dams have been constructed for urban water supplies.
- Water related diseases such as diarrhea in the most vulnerable group (children below 5 years and the elderly), cholera, typhoid fever as well as iodine defficiency are very common occurrences in the basin.

Water uses

- Major water use sectors within the basin are ecological, agricultural, domestic and industrial, livestock, fisheries, wildlife, navigation and cooling of thermal generating plants.
- Out of an annual total water use of the order of 19.933 x $10^9 m^3$, ecological water uses at the lakes and wetlands account for about 86.7%, These constitute 'losses' in form of evaporation that accounts for about 42% and infiltration that accounts for about 44.1%.
- Agricultural uses account for about 11.1%, domestic and industrial 1.8%, livestock 0.3%, and cooling of thermal generating 0.01%.
- Fisheries and navigation uses are non-consumptive, while the wildlife uses are part of the ecological uses.

Management challenges

- Rainfall deficits, southwards shift of the isohyets, reduced runoff on the rivers influent into Lake Chad and shrinkage of the Lake Chad from 25,000 km^2 in the sixties to barely 2,000 km^2 in present times.

- High evaporation and evapotranspiration.

- Drought and desertification.

- Definition of Water Type-Years:
  - based on the historical flow records at N'Djamena;
  - assumption that 'good', 'average' and 'poor' years correspond to hydrological conditions having probability which meet or exceed 75%, 50% or meet or are below 25% respectively.
  - a 'good' year within the basin is characterised by a maximum discharge at N'Djamena Q75% = 3,875 m^3/s as in 1975, an 'average' year by Q50% = 3,450 m^3/s as in 1949 and a 'poor' year by Q25% = 2,130 m^3/s as in 1973.

- Reduction of human impacts on streams rivers and wadi channels due to urbanization, roads, upstream dams and/or diversions.

With respect to groundwater:

- Continuous monitoring of the artesian pressure in the confined aquifers as well as capping of free-flowing degraded artesian boreholes of the lower pliocene aquifer in order to conserve the fossil resource. Related to this is the possibility of over-exploitation of shallow groundwater particularly from fadama irrigation schemes along river courses using tube wells.

- Monitoring of groundwater abstraction rates and potential sources (point and non-point) of pollution of groundwater resources, including mining and petroleum exploitation.

From the wider environmental point of view:

- Reduction of sheet erosion of soils, wind erosion of top soil, abrasion of plant life by blown sand, fertility and tilth reduction, alkalinization, salinization, soil crust formation, sand barrier formation and compaction of top soil.

- Floristic degradation such as:
  - reduced canopy coverage that increases ground temperature, increases soil water evaporation and opens up the soil surface to rain drop and wind erosion;
  - change of species from perennials to annuals;
  - reduced biomass of forest products from lowered water tables or overexploitation;
  - loss of root volume that increases soil erosion;
  - reduced numbers of deep-rooted trees that recycle minerals locked in soil.

- There are about 130 species of fish. Symptoms of degradation include:
  - loss of prized food species (Alestes Daremoze);
  - drying up of fishing areas;
  - increased fishery effort by displaced farmers and normads;
  - smaller mesh sizes and increased juvenile catch.

- There are about 60 to 65 medium- to large-sized mammals in the conventional basin. Civil strife, spread of automatic weapons, need for drought fallback meat, clearing of habitat and drought have combined to devastate many of these species.

Basin-wide policy and plans

- Promotion of environmentally sound socio-economic development within the basin by allowing the growth of irrigated agriculture, fisheries, animal husbandry, domestic and industrial water supply and of infrastructures in support of food production and self-sufficiency.

- Preservation of the environment, in particular, control of desertification.

- Restoration of the level of Lake Chad to the degree possible, within the existing resources in the conventional basin.

Legal aspects

- In the Statute annexed to the Convention establishing LCBC, member states undertook to consult the Commission prior to implementing any measure likely to affect the quantity and quality of surface and groundwater resources in the basin and to abstain from carrying out such activities in their respective jurisdictions.

- The LCBC Draft Agreement on Harmonization of Regulations of Member States on Fauna and Flora further provides in Article 11 of Section B that 'member states commit themselves to prohibiting the pollution of all water frequented by fish for their subsistence'.

- In the Annex to the draft Agreement, para. 24 of part III provides that all territorial waters belong to member states and fishing can be freely carried out except in private properties, recognised as such, or for security reasons while commercial fishing is subject to issuance of permit.

- Para. 25 prohibit fishing using

  - fire arms and explosives,
  - electric gadgets,
  - obnoxious or toxic products and pollu tants.

- Para. 26 prohibited the construction of dykes, dams or other obstacles to fish migration.

- Para. 27 provides that untreated industrial effluents, poisons, pharmaceutical products or other toxic products shall not be discharged in water courses, ponds, creeks and lakes.

The problems are that:

- Good as these draft basin-wide provisions are, there is no evidence that they are being applied in member states particularly where there are in existence neither a water law nor an environmental law.

- There is presently no effective mechanism for basin-wide monitoring of compliance of member states

- There is need for cooperation, consultation and coordination between water resources and environment sectors to harmonize water and environmental protection laws in member states for better protection of the resource:
  - beneficial use *versus* abuse;
  - quantity *versus* quality;
  - discharge of contaminants and pollution could be regarded as consumptive water uses while reduction of flow which dilutes downstream influx of contaminants and thus increase its concentration of the substance to intolerable limits on rivers should be recognised.

Activities of the Lake Chad Basin Commission

The regional sustainable development strategy of LCBC commenced with

(a) The diagnostic study of environmental degradation

The diagnostic study identified causes of environmental degradation and recognized defining 'type years' according to rainfall, channel flow, lake levels and flooding as a necessity for a flexible development policy which can adjust rapidly to water supply changes. The study recommended (i) integration of irrigated cropping with food storage and famine prevention programmes, (ii) improving water and soil conservation through incorporation of tree regeneration, forage production and other agroforestry techniques in irrigated agriculture, (iii) imposing a moratorium on large-scale water projects, (iv) undertaking a review of existing water projects, (v) correcting the environmental impact of specific projects to downstream and floodplain users, and (vi) according priorities to downstream users (fishery, recession agriculture, pasture, groundwater recharge) and to multiple use of wetlands (wildlife tourism and economic production).

(b) The master plan for the environmentally sound management of the basin

To address the issue of projects, cost estimates, environmental and socio-economic assessments, national government priorities and methods of attracting donors, a master plan was prepared. The master plan recommended thirty six projects to address the problems identified in the diagnostic study. Among these, eighteen are water related projects built around network installation and monitoring, water resources assessment and management including interbasin water transfer project from the Oubangui basin (Congo river) into the lake Chad basin.

(c) The strategic action plan

To mobilize resources for the implementation of the master plan, a strategic action plan (SAP) was also prepared with the assistance of GEF. The SAP was broken into two components, namely a 20-year SAP with six priorities and an eight-year SAP based essentially on institutional coordination. The implementation of the SAP has already commenced with the selection of six pilot projects for funding within GEF PDF-C phase. The projects were selected to address themes such as protected areas, aquatic ecosystems, demand management, pollution risks analysis and control, and integrated wetland management. During this phase, GEF is set to prepare TDA and to solicit additional donor support in project funding.

(d) Data collection

The Commission collects water resources (climatological, hydrological and hydrogeological) data from member states for purposes of carrying out regular assessment of the available resources, running the mathematical model and publishing the hydrological yearbook.

(e) Management of groundwater resources for sustainable development

There is also an on-going UNESCO/BMZ project to improve existing knowledge and quantification of the recharge and reserve of the underlying aquifers under the different climatic scenarios of humid, medium and dry years. The project involves groundwater level monitoring, rain-, surface- and ground-water sampling for physical, chemical and isotopic analysis. A groundwater model is to be developed afterwards. The final hydrogeologic report of the project which commenced in 1997 is presently being finalized to pave way for the groundwater modelling phase.

(f) Existing HYDRO-CHAD Model

This has been developed to investigate alternative water resources planning scenarios. The hydrodynamic model is based on the St Venant equations. Field topographic data are being collected to improve the accuracy of the model which was initially calibrated with synthetic data on cross sections derived from stage and discharge measurements at hydrometric stations.

(g) Coordination meetings of thematic technical committees

The process of decision-making at the regional level within the lake Chad conventional basin commences with sectoral consultations. Meetings of experts of member states in specific thematic areas such as water resources, crop protection, animal husbandry, fisheries, etc. are organized at least once a year to harmonize programmes and projects of member states and address topical technical and operational issues in those respective areas as well as profer recommendations to the Commission. The programmes and recommendations by the experts are then deliberated upon by the Ministerial Session which gives final approval. There are, however, certain issues which are referred to the Summit of Heads of State.

(h) World Water Vision Follow-up actions

A Regional presentation was made on the Lake Chad Region at the Second World Water Forum held in the Hague, The Netherlands, in March, 2000. The presentation highlighted important issues deduced from existing situation within the basin. The vision of the Lake Chad Region representing a sustainable world scenario, identified three areas of objectives, namely (i) maintenance of the lake Chad and other wetlands of the region at sustainable levels for economic security of the freshwater ecosystem resources, sustained biodiversity and aquatic resources of the basin and their equitable use and alleviation of poverty; (ii) acceptance of responsibilities for freshwater, ecosystem and biodiversity conservation and judicious integrated river basin management by regional and national authorities; and (iii) equitable access by member states to safe and adequate water resources to meet their needs and rights. Actions were also proposed that require follow-up. These include:

- Mobilization of political will and ensuring good governance.
- Enlisting the broad based support and commitment of all the basin's donors and technical support agencies so that sacrifices and investments can be made to achieve the desired vision goals.
- Institutional strengthening at national and regional levels.
- Implementation of the LCBC Strategic Action Plan.
- Initiation of shared management of water resources within and between countries and at national, sub-basin and basin levels.
- Setting up of viable network for basic data on water resources and ecosystem management.
- Water demand management to combat desertification and loss of biodiversity.
- Control and prevention of pollution and contaminant load and preservation of fisheries resources.
- Improve methods of exploiting aquatic ecosystems and protect flood plains in relation to regional development.
- Begin feasibility studies and environmental impact assessment of intra- and inter-basin water transfer for the restoration of the lake Chad water level and ecosystem conservation.

(i) Other projects

Other on-going activities of LCBC include:

- Integrated Pests Management project in the conventional basin jointly funded by ADB and LCBC;
- the control and eradication of neem tree diseases by the member states coordinated by LCBC;
- the development of regional policy on continental fishery within the conventional basin jointly with the University of Portsmouth; and

- the conservation of the endangered Kuri cattle within the Lake Chad with FAO assistance.

Conclusions and recommendations

The initiative behind this UNESCO International Workshop on the Management of Transboundary Aquifer Systems in Africa is laudable given that up to now, groundwater being a hidden resource, has been marginalized. This may be attributable to the fact that compared to surface water where the downstream impact of upstream abstraction or pollution is felt within a very short time (few days), there is general poor understanding of the characteristics and behaviours of groundwater aquifers. The management rules are also quite different. For instance, while we talk of riparian and appropriative doctrines in the case of surface water, the correlative right in groundwater management asserts the right of any landowner to pump water from under his property co-equal to his neighbour's right. The Helsinki Rules on equitable sharing of the resource, however, includes groundwater in its definition of 'international drainage basin', even though there do not seem to be any case where this has been applied to groundwater so far.

It is therefore not surprising that most of the existing Commissions established for the management of shared resources have given focus essentially to surface water. **We are therefore recommending that countries be encouraged to forge more international cooperation in the Management of groundwater basins by establishing Commissions.**

One of the objectives of the Workshop is the establishment by UNESCO of a Register of shared aquifer systems in Africa. **We are recommending that UNESCO includes the above listed regional aquifers of the Lake Chad basin in the Register.**

From all indications, the Lake Chad basin may face more pressure in the future (2025). The population growth rate is projected to be around 2.5%. Due to population growth, higher demands are expected in the basin for agricultural products, fisheries, higher pressure on the forest resources, water use and groundwater reserve. FAO forecasts the GDP of most Member States of LCBC are expected to shrink. Considering the potential threat of climate change postulated by WMO/UNEP Inter-governmental Panel on Climate Change using various scenarios for the emission of carbon dioxide and other greenhouse gases over the twenty first century, a rise in global mean temperature, leading to more severe drought, the Lake Chad basin may experience aggravation of existing ecological problems, loss of wetlands, upsetting of fisheries potentials, greater influx of diverse pollutants and the impact on the population.

While LCBC continues to pursue more aggresive policies on sustainable development including sustainable management of natural resources, UNESCO is called upon to include our shared aquifers in the UNESCO Heritage sites and spare-head more aggresive projects of groundwater studies for a better understanding of the aquifers and development of decision support tools for better management.

Impact of climatic change on river Niger

Ibraheem A. Olomoda

Water Resources Development Engineer
Niger Basin Authority, Niamey, Niger

Introduction

River Niger is situated between latitude 4 and 17° North and between longitude 12° West and 15° East. It is the third longest river in Africa after the Nile and the Congo, and the most important in West Africa. It is about 4,200 km long with an active catchment's area of about 1.5 million km^2 shared among nine countries according to the following approximate proportions: Benin (2.5%), Burkina Faso (3.9%), Cameroon (4.4%), Côte d'Ivoire (1.2%), Guinea (4.6%), Mali (30.3%), Niger (23.8%), Nigeria (28.3%), and Chad (1.0%) (see Fig. 1).

The river also takes its source from the Fouta Djallon Mountains in Guinea at an altitude of about 800 m and flows North-Eastwards towards the fringes of the Sahara which it uireaches after having traversed its own delta across a vast plain spreading over an area of about 80,000 km^2 with an appreciable loss of water through evapotranspiration.

Here it forms a great bend and flows South-Eastwards towards the Gulf of Guinea which it reaches after being joined by its largest tributary, the river Benue at Lokoja in Nigeria.

The population of the Basin is estimated at more than 100 million inhabitants (1995) with a growth rate of 3% per year. The river is also the major source of hydropower generation and irrigational food crop production in the sub-region. It also provides avenue for intensive fishing and

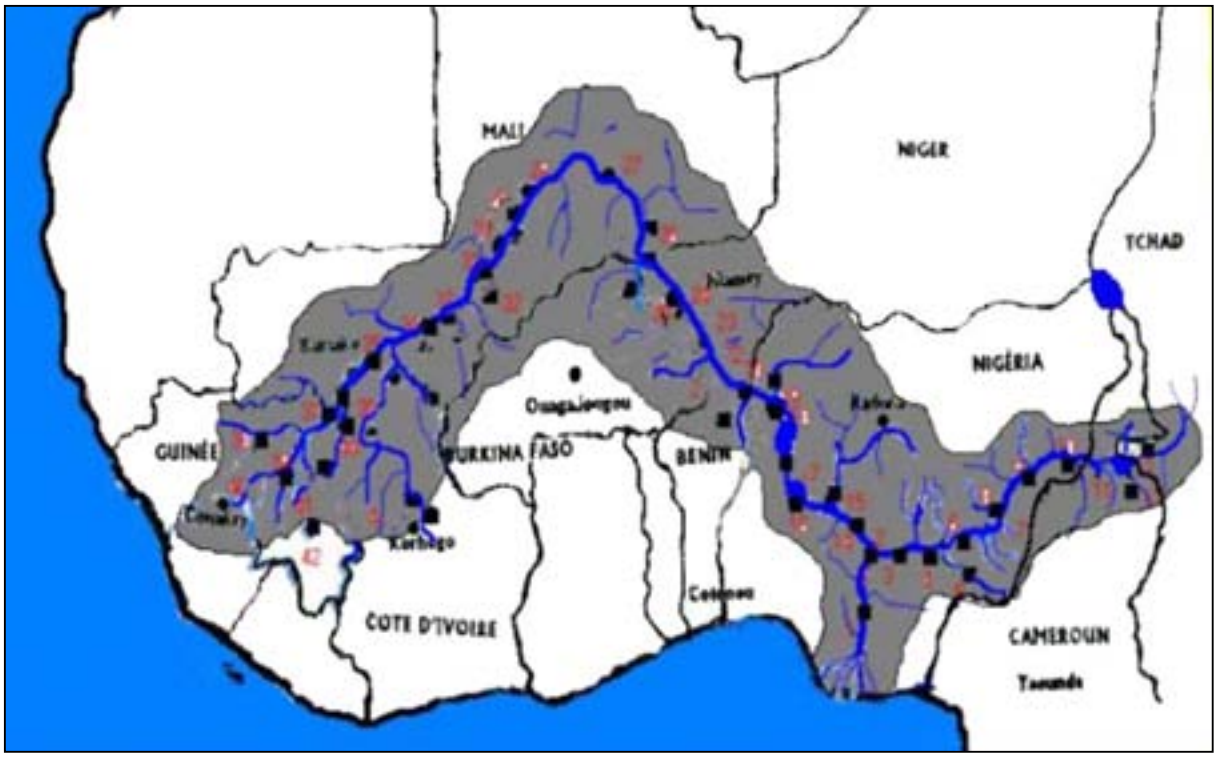


FIGURE 15. Transmissivity and water map of the Post Nubian Aquifer System

navigation that improve the socio-economic development of the people.

The Niger Basin Authority, NBA, created first as Niger River Commission in 1964, is the custodian of the river Niger and an instrument of cooperation and development in the sub-region. The NBA member countries are Benin, Burkina Faso, Cameroon, Côte d'Ivoire, Guinea, Mali, Niger, Nigeria and Chad.

The NBA primary objective was the promotion of cooperation among the member countries and insuring integrated development of the basin in all fields notably; energy, water resources, agriculture, animal rearing, fish breeding, sylviculture, transportation, communications and industry.

The objectives of NBA can also be summarized as follows:

- To harmonize and coordinate national policies on resources in the Basin;
- To plan the development of the Basin by preparing and executing an integrated development plan of the Basin;
- To design, realize, exploit and maintain common work projects

The Niger basin faces series of sub-saharan climatic changes that causes problems hampering the progress of most initiated integrated developmental projects.

The Niger Basin climatic characteristics

Air mass characteristics

The climate of the Basin exhibits a definite wet season and a marked dry season in response to the pressure pattern resulting in the seasonal shifts of pressure belt with the apparent movement of the overhead sun.

Belts of distinctive weather have been observed to show a pronounced migration across the Basin, that is strongly associated with the north-south movement of a zone of sharp discontinuity between the dry continental (Sahelian) air and the humid maritime (Atlantic) air. At the surface, it forms a boundary referred to as the Inter-Tropical Discontinuity (ITD) which determine the zone of approximate penetration of the moist maritime air mass (JICA).

Sunshine hours

On an annual basis there is a general increase in the sunshine hours from the Atlantic coast to the interior. The amount of annual sunshine ranges from a minimum of about 1,300 hours in the Coastal areas to over 3,200 hours in the extreme north. The rate of increase is, however, not constant and there is a steeper gradient in the area south of latitude 9°N than to the north where there appears to be a more even distribution. This distinct break in gradient is related to the surface location of the ITD (JICA).

Evaporation

Since the dry season is much longer in the north than in the south, the measured evaporation values are greater in the north than in the south. Evaporation using 'Class A pan' measurement, decreases from extreme North to Southern part as shown in Nigeria, in Table 1. The Basin's Evapotranspiration rate is estimated at between 1,800 mm and 2,200 mm/year.

Humidity

There are considerable spatial and seasonal variations in the relative humidity throughout the Basin within West Africa. In the coastal region the months of June to October have monthly means of over 90 percent while in the north, during January to April, mean values are close to 20 or 25 percent. Diurnal values may fall from 30 percent at dawn to 10 percent in the afternoon. This is a characteristic of the Harmattan season when the dry and dust-laden North-East Trade Winds are blowing from the Sahara under cloudless but dusty conditions (JICA).

Table 1. Mean annual evaporation (mm)

Station	*Coordinates*	*Class A pan*	*Comments*
Maiduguri	11°51′ N 13°05′ E	4,047 mm	Extreme North
Yola	9°14′ N 12° 28′ E	2,971 mm	Middle Belt
Port Harcourt	4°51′ N 7°01′ E	1,630 mm	South

Temperature

Because of latitudinal location within the tropics, the Niger basin experiences relatively high temperatures all the year round. The mean daily Temperature for most areas is about 27°C. Seasonal and latitudinal variations affect the extreme and the diurnal as well as seasonal ranges.

The highest air temperatures are normally in April most especially in the Extreme northern part, with a minimum temperature especially in Nigeria, usually recorded around December as a result of harmattan breeze. In the south along the coastal areas, there is little difference between the December temperature and the relatively low temperatures of the rainy season; the lowest temperature of the year may be recorded during the rainy season (JICA).

Mean maximum temperatures increase from the coast northward; the highest monthly mean of 32.2°C for the coastal region to a mean of 40.6°C in the extreme north. Mean minimum temperatures on the other hand, decreases northward with the lowest of 21.1°C on the coast to less than 12.8°C in north. The monthly means of daily temperatures at selected stations in Nigeria is shown in Table 2.

Rainfall

The major factors that influence the regional weather include the ITD, easterly waves, tropical storms, low level troughs, jet storms and extra-tropical weather systems. Most rainfall in Tropical Africa is received during the rainy season, which varies in length in different climatic regions. The most common explanation for the climatic variations and their causes, is the control established by the seasonal migration of the ITD with its contrasting two air masses.

The rainfall pattern in Nigeria for example, is a good reflection of the seasonal variation of surface location of the ITD with the rainfall decreases both in duration and amount from the coast to the interior except where altitudinal effect create island of higher rainfall, as shown in Jos Plateau. The coastal areas receive over 3,000 mm spreading over 8–10 months whilst the extreme north receives less than 100 mm spreading between 3 to 4 months. The incidence of rainfall can be linked to one or more of four causes: the coastal effect; the monsoon effects which are generally widespread; the thunderstorms that are sporadic; and the disturbance lines which are belt of intense thunderstorms moving East-West and giving heavy rains of short duration (JICA).

Table 3 shows the mean monthly rainfall patterns in some major cities within the Niger Basin. In the Inland Delta for example, the annual rainfall varies from 700 mm (Ké-Macina in Mali) to 200 mm (Diré in Mali) few kilometres away.

Similarly at the Middle basin, from Tossaye (Mali), Mallanville (Benin) to Niamey (Niger), rainfall varies from 200 mm to 900 mm. Rainfall in the lower basin varies from 900 mm to more than 3,000 mm over the Gulf of Guinea.

The maximum rainfall occurs in the month of September or October in most part of the Basin as shown in Table 3. The dry seasonal periods are usually from November to April, while the hydrological year is with effective from June for most areas. In the Upper Niger basin for example, most of the flows come from the Guinea plateaus where the average rainfall is about 1,200 mm/year.

Table 2. Monthly means of daily temperatures at selected stations in Nigeria (°C)

Station	*Maximum*	*Minimum*	*Range*
Sokoto	35.3	20.9	14.4
Maiduguri	34.43	19.3	15.1
Jos	27.8	16.6	11.2
Kano	33.3	19.2	13.9
kaduna	31.3	17.8	13.5
Ilorin	32.8	21.3	11.5
Lagos	30.7	21.8	8.9

Source: JICA.

TABLE 3. Mean monthly rainfall patterns in some major cities within the Niger basin (mm)

	Farana	*Bamako*	*Ouagadougou*	*Niamey*	*Ndjamena*	*Sokoto*	*Abuja*	*Kano*
January	4	1.2	0	0	0	0	3	0
February	7	0.2	0	0	0	0	3	1
March	28	1.3	3.6	0	0.1	3	33	0
April	74	18.7	29.6	0	5.5	1	47	8
May	156	51.5	72.6	30.4	26.8	31	117	41
June	223	119	114.1	84.8	42.2	96	188	93
July	174	213	189.9	152.4	143.9	140	227	182
August	212	280	240.3	185.7	166.5	170	297	241
September	305	184	133.9	96.7	76.2	86	301	96
October	189	61	1.6	13.4	18.8	8	125	22
November	50	3.1	0	0	0	0	6	0
December	6	0	0	0	0,3	0	0	0
Total	**1,630**	**933**	**821.3**	**563.4**	**480**	**535**	**1,347**	**684**

Climatic effect on Niger basin hydrology

- The Niger basin, subjected to the influence of climatic variations from North to South and characterized by a rainy and dry seasons, has the following circulatory air masses governing the passage of the seasons;
- The tropical continental air mass which blows from the Sahara, dry air mass with high temperature in Summer, generally blowing North-Eastward, and commonly referred to as Harmatan and,
- The humid and unstable maritime equatorial air mass with relatively cool temperature blowing from Saint Helen anticyclone to South-East and commonly referred to as monsoon wind.

These consequently create three identified climatic zones in the basin as follows (Fig. 2);

a) The Guinea climatic zone with an annual rainfall ranging from 1,200 mm to over 3,000 mm in the South,
b) The Sudanese climatic zone with an annual rainfall ranging from 500 mm to 1,200 mm, within the middle belt,
c) The Sahel zone climatic with an annual rainfall ranging from less than 100 mm to 500 mm, within the extreme North.

River Niger flow rate reduction

The entire Niger basin is usually sub-divided into 4 zones namely, the Upper, the Inland Delta, the Middle and the Lower Niger, based on their topographical and hydrological characteristics.

The Upper Niger

The Upper Niger covers a drainage area of about 138,500 km^2, with the main river tributaries from rivers; Tinkisso, Niandan, Milo, and Sankarani. The mean annual flows recorded at Kouroussa in the Upper Niger along the river Niger in Guinea was 239 m^3/s. The hydrological gauge station at Koulikoro in Mali also along the river Niger, which was establish since 1907, has the maximum discharge of about 9,670 m^3/s, recorded in 1925, while the minimum was 13 m^3/s was recorded in 1973 and 1982, as shown in Table 4.

The Inland Delta

The Inland Delta of the Niger Basin is characterized by wide plain area having gentle slope, large channel width with the absence of major tributaries for over 300 km stretch, i.e. from the town of Douna to Mopti and Dire in Mali, with a total catchment's area of about 80,000 km^2.

The gauge station at Douna was established

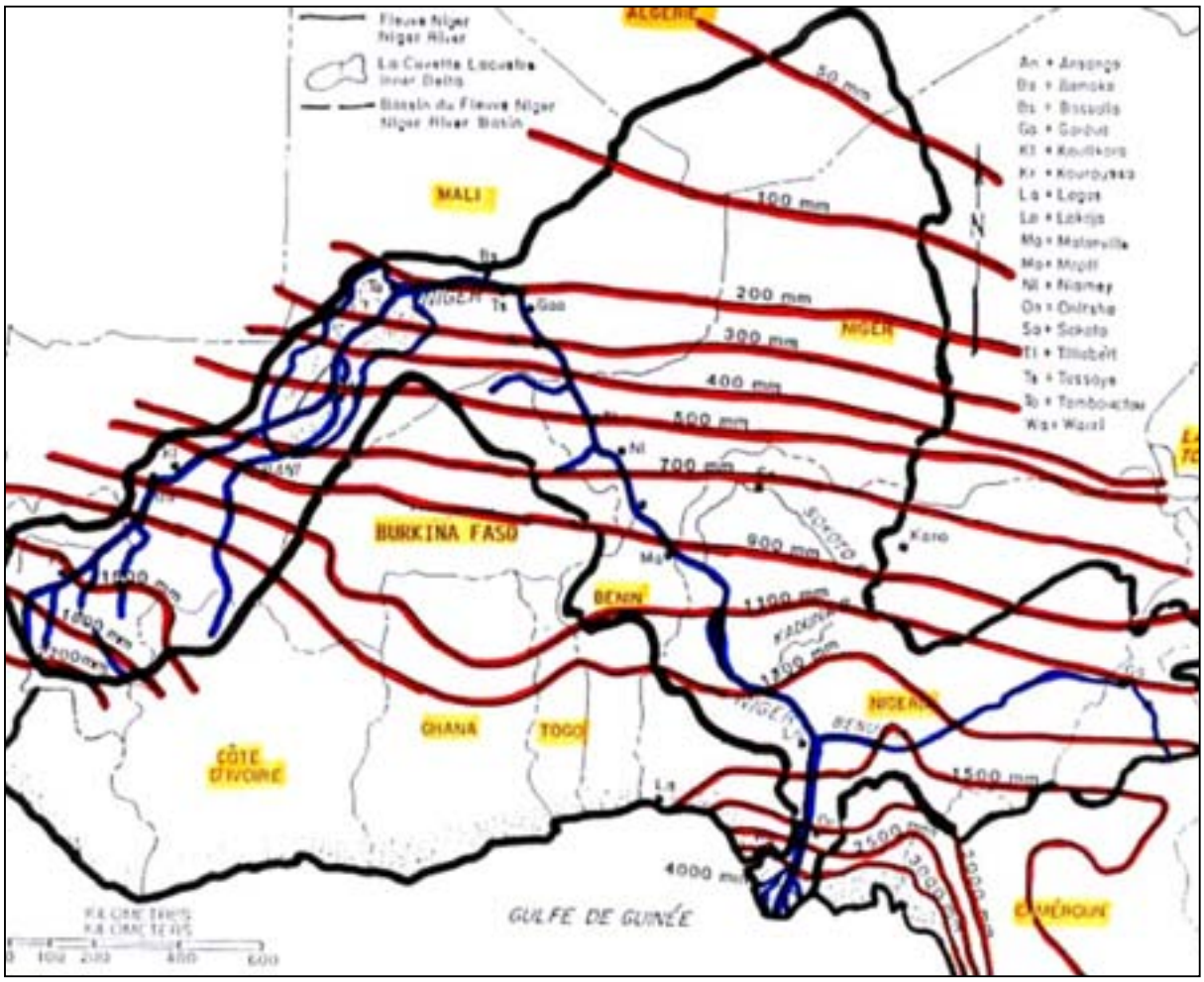


FIGURE 2. Isohytal map of the rainfall pattern of the Niger basin

in 1922 along the river Bani a tributary of River Niger and has a maximum discharge recorded of 4,460 m^3/s in 1929 and a minimum of 0 in 1983, 1984 and 1987. At Mopti which is along the river Niger, the gauge station was also established in 1922 with the maximum discharge recorded as 3,890 m^3/s in 1954 and the minimum of 6.3 m^3/s in 1979. At Dire which is also along the river Niger, the gauge station was established in 1924 with maximum discharge recorded as 2,710 m^3/s in 1967 and the minimum of 4.0 m^3/s in 1979, as shown in Table 4.

TABLE 4. Annual flow

Stations	*River*	*Period*	*Q. mean* (m^3/s)	*Q. max* (m^3/s)	*Year*	*Q. mini* (m^3/s)	*Year*
Koulikoro	Niger	1907–2000	1,385	9,670	1925	13	1973 et 1982
Douna	Bani	1922–2000	498	4,460	1929	0	1983-84 et 87
Mopti	Niger	1922–2000	1,090	3,890	1954	6.3	1979
Diré	Niger	1924–2000	998	2,710	1967	4.0	1979
Niamey	Niger	1928–2000	870	2,360	1968	(0)	1985
Makurdi	Bénoué	1955–2000	3,060	20,000	1969	65	1961
Lokoja	Niger	1915–2000	5,590	26,300	1956	599	1974

The Middle Niger

The Middle Niger covers part of Mali, Burkina Faso, Niger and Benin, with hydrological automatic gauge stations established in these countries.

From records of gauge station in Niamey which was established in 1928, the maximum discharge of 2,360 m^3/s was recorded in 1968 and a minimum of 0 in 1985 as shown in Table 1.

Figure 3 shows the monthly hydrograph of the river Niger in Niamey, showing the years of highest record (1967/68), lowest (1984/85), mean (1994/95), 2001/2002 and 2002/2003.

The Lower Niger

The river flows into the lower Niger in Nigeria isr through Jiderebode to the Kainji dam and then into Jebba Dam. The river Benue joined the river Niger at Lokoja in Nigeria. At the lower Niger along the river Benue at Makurdi in Nigeria, the gauge station was established in 1955 while that at Lokoja was established in 1915. The maximum flows recorded are 20,000 m^3/s in 1969 for Makurdi and 26,000 m^3/s in 1956 for Lokoja. The minimum flow at Markudi was 65 m^3/s in 1961 and at Lokoja it was 599 m^3/s in 1981 as shown in Table 4.

Besides the river Benue, the other important tributaries of river Niger in Nigeria are river Sokoto and river Kaduna.

However, the maximum flow along the main course of Niger from upstream to downstream in Niger Republic ranges from 2,360 m^3/s in Niamey in 1968 to 9,670 m^3/s at Koulikoro in 1925. The maximum flow of 20,000 m^3/s was recorded along the Benue in 1969 and at Lokoja, the maximum flow was 26,300 m^3/s recorded in 1956. This also clearly showed that most of the flows in Lokoja emanated from the Benue mostly during the rainy season.

Other consequences of climatic change

Decrease in rainfall southwards

From the isohetal rainfall changes shown in Fig. 4 there is a clear indication of the movement of desertification southwards. For example the isohytal line of 200 mm is shown to have shifted southward at a distance of about 100 km range. The same shift applies to lines 500, 700 and 1,000.

From Table 4, the minimum flow recorded along the river Niger upstream at Koulikouro in Mali down to Niamey is between 0 and 13 m^3/s recorded. The least flow at Lokoja, the confluence of river Niger and Benue, was 599 m^3/s. It was just 65 m^3/s along the Benue in Makurdi, Nigeria. These low flows are the reflection of the effect of low rainfall pattern in the last 30 years that resulted to drought and desertification encroachment in the Basin. These are showing the reality and possibility of the river Niger totally drying up.

Increase in evapotranspiration rate

Another contributing factor to the continued effect of low flow is the high Evapotranspiration rate as a popularly said to be due to global warm-

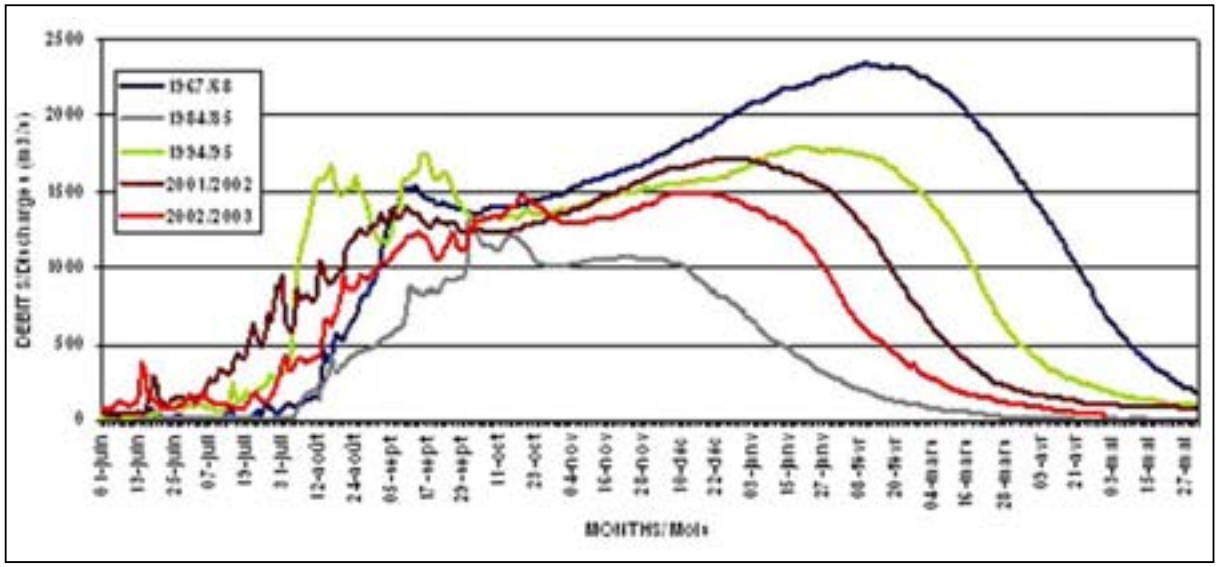


FIGURE 3. Comparative hydrographs in river Niger in Niamey

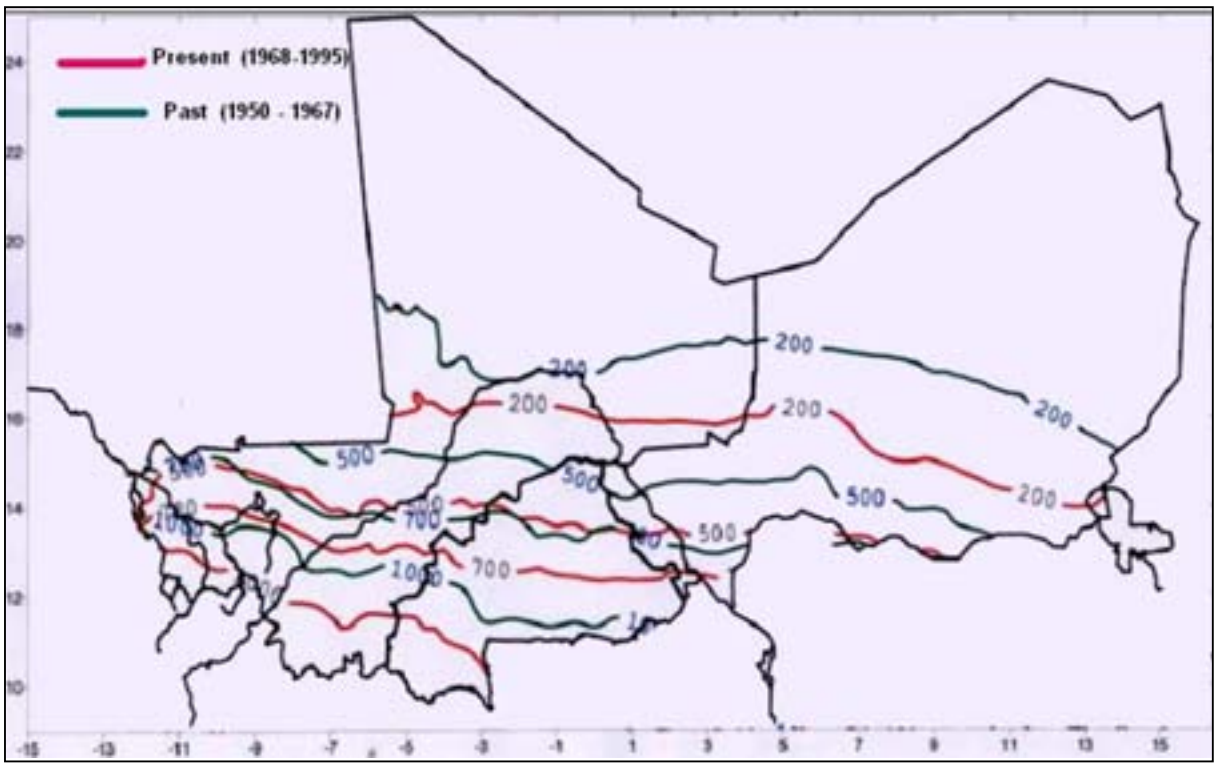


FIGURE 4. Isohytical changes in Niger basin

ing. The evopotranspirate rate is now estimated at between 1,800 mm and 2,200 mm/year.

Drought encroachment

The effect of drought encroachment is seen from the reduction from the North to the South at the rate of about 200 mm in range of 100 km as shown by the isohetal map.

Reduction in catchments area of the river Niger

The effect of climate is directly felt in the entire catchments area by the quickly drying up of the seasonal river and flow reduction of the perennial ones which consequently have now reduced the active basin area from 2 million km^2 to just about 1.5 million km^2 with areas mostly from Algeria excluded from the active catchment's area of the river Niger basin.

Excessive river siltation

Sedimentation rate along the main course of the river have developed into alarming proportion due to poor agricultural management practices. This is also causing the meandering of the river and flooding that is another serious menace to the population.

Groundwater depletion

There is currently high rate of groundwater depletion due to mining through borehole, high evapotranspiration rate, etc.

Demographic pressure

Movement o people from low water zone areas most especially among the nomad is now a major problem. Conflicts between farmers on land ownership and tenure-ship is a common occurrence.

Socio-economy

Socio economic development is grossly affected as a result of displacement of people from one place to the other due to inadequate water, reduction fisheries, harsh weather etc.

Recommendations

To effectively protect and develop the surface and the groundwater resources from the menace of climate change in the Sahelian region, the following are hereby recommended:

a) Provision of financial support for the establishment of groundwater monitoring

mechanism for regional organisation such as the NBA, for the enhancement of an effective transboundary groundwater resources management.

b) Encouragement of modern land use practices, tree planting and prohibition of bush burning and tree cutting.
c) Intensification of village water project for the drought proned areas.
d) Intensification of hydrometeorological data collection and monitoring system using latest methods and modern equipments.
e) Encouragement of manpower development, research and training on groundwater monitoring, prospecting and development.
f) Reduction of effect of global warming.

Conclusion

Niger basin is progressively facing the adverse effect of climate that result into environmental degradation, drought, desertification encroachment, population pressure etc. These, coupled with the present high rate of mining groundwater without monitoring and control, has continued to have negative impact on the long-term sustainability of groundwater resources.

There is therefore, urgent need to fully encourage and support regional river basins in their efforts to mitigate the impact of climatic changes and improving the socio-economic development of the people through the groundwater development, monitoring and management.

References

Yaya IDRISSA. Étude pour l'organisation d'un Colloque sur la sauvegarde du Fleuve Niger, 1995.

Housseini A. MAÏGA. Ensablement de la vallée du cours moyen du Fleuve Niger (Colloque sur la sauvegarde du Fleuve Niger, Bamako, Avril 1999).

Yatabary DANTE. Le Fleuve Niger au Mali - Problématiques et acteurs (Colloque sur la Sauvegarde du Fleuve Niger, Bamako, Avril 1999).

Oumar O. ALY. Rapport technique final. HYDRONIGER, 1991.

Convention révisée de création de l'ABN. ABN, 1989.

Plan d'Action 2000 - 2002. ABN, 1999.

Jean-Michel CHENE. Synthèse de la vision des problématiques par les acteurs du Fleuve Niger (résultats de l'Assistance Préparatoire FEM 'A'), NU-DAESG, 1996.

Bulletins d'Information de l'ABN. ABN-INFO.

Publications hydrologiques du CIP/HYDRONIGER.

Comptes-rendus de réunion du WATAC, Ouagadougou (Février 2000).

Rapports finaux des 17ème et 18ème Sessions du Conseil des Ministres de l'ABN. ABN, 1997 - 1998.

JAPANESE INTERNATIONAL COOPERATION AGENCY (JICA), Nigerian National Water resources Master plan, 1992.

Le Système d'Information sur les Ressources en Eau des Pays de l'Afrique du Nord (SERIPAN): un outil de gestion concertée des ressources en eau

Mohamed Safar Zitoun

Consultant auprès de l'OACT

Résumé

Le Système d'Information sur les Ressources en Eau des Pays de l'Afrique du Nord (SERIPAN) a pour ambition de doter les États de l'Afrique du Nord d'un outil fiable pour gérer de manière concertée leurs ressources. La première phase de ce programme est en voie d'achèvement. Les phases 2 et 3 ainsi que l'extension du programme aux autres régions du continent nécessiteront dans le futur une mobilisation et une participation plus grandes de la communauté internationale.

Abstract

The Water Resources Information System of North African States (SERIPAN) have the ambition to dower North African States with a reliable tool for managing theirs common resources. The first phase of this programme is in process of completion. The Phases 2 and 3 as well as the extension of the programme to other regions of the continent in the future will necessitate more mobilization and participation of the international community.

Introduction

De toutes les régions géopolitiques du Monde, les pays de l'Afrique du Nord sont, avec le Moyen Orient, situés dans la région la plus pauvre en eau. Tous ces pays disposent de seulement 1000 m^3/an et par habitant de ressources en eau naturelle, ce qui représente le seuil au dessous duquel des tensions apparaissent entre les besoins et les ressources, avec des risques de pénurie d'eau locale ou conjoncturelle. Cette situation alarmante ne peut que s'accentuer avec l'accroissement de la population[1].

C'est aussi une région fortement perturbée par les changements climatiques de ces dix dernières années puisqu'on y observe des anomalies de –50 % dans les précipitations moyennes par rapport à la moyenne calculée entre 1961 et 1990 avec une période mai-octobre anormalement sèche, ce qui n'est pas sans conséquence sur l'écoulement des eaux de surface et l'alimentation des nappes souterraines. Les projections de l'OMM à l'horizon 2050 d'après le modèle de circulation générale atmosphèreocéan montrent une diminution du ruissellement annuel pouvant atteindre – 25 mm[2]. Ramenée à la surface de la partie arrosée par les pluies, cela représente une diminution du ruissellement allant de 0 à 27 km^3. L'alimentation des nappes phréatiques sera altérée de la même manière. Les périodes de sécheresse y sont fréquentes provoquant des situations de crise poussant les décideurs à faire appel aux eaux souterraines non renouvelables, à la désalinisation de l'eau de mer et d'envisager, comme pour les zones insulaires, l'importation de l'eau potable par bateaux-citernes.

La conjonction de cette situation avec :

1. la nécessité de réactualiser la carte hydrogéologique internationale de l'Afrique (éditée en 1992 par l'OACT en six feuilles et cinq notices à l'échelle du 15.000.000-ième) eu égard à l'amélioration des techniques et des connaissances sur les ressources en eau du continent ;
2. le bouleversement technologique provoqué par les nouvelles techniques de l'information en particulier Internet, qui permet aujourd'hui une circulation des données et de l'information avec une fluidité exceptionnelle ;

3. les images quasi-quotidiennes captées par les satellites ainsi que les systèmes d'information géographique qui « interconnectent » les techniques de dessin assistées par ordinateur avec les bases de données objets et donnent désormais à la cartographie un caractère plus dynamique, actualisable et adaptable aux besoins des utilisateurs ;
4. la nécessaire vision globale des ressources en eau à l'échelle régionale et leur évolution future.

L'eau, ressource à la fois vitale, rare et, très souvent partagée par plusieurs pays est à gérer dans un esprit de développement durable profitable aussi bien aux générations actuelles que celles à venir.

État des lieux

Il existe une dizaine de cartes « de type classique » sur les ressources en eau souterraines couvrant totalement ou partiellement l'Afrique. Ces cartes ont été dressées à des fins diverses : prospection, planification, gestion des systèmes aquifères, etc. Elles ne sont pas, a priori, sous une forme numérisée. Par ailleurs plusieurs pays africains (une vingtaine) disposent à l'échelle nationale ou locale de cartes hydrogéologiques [3]. L'intégration de la dimension eau superficielle n'y est pas toujours prise en compte.

De nombreux pays disposent maintenant de systèmes d'information géographiques utilisant les standards actuels du marché (Agis, ArcInfo, MapInfo, IlWis, etc.) mais se heurtent à l'inexistence de fonds topographiques de base numérisés sauf pour certaines échelles moyennes locales (1/200.000 ou 1/250.000). La difficulté est plus grande quant il s'agira de faire une cartographie à l'échelle régionale par manque de référentiel et spécifications (légendes) communes. Ceci explique les travaux d'harmonisation en cours conduits par la FAO (Africover), l'OACT (NAFREF) et l'OSS (projet SASS) en partenariat

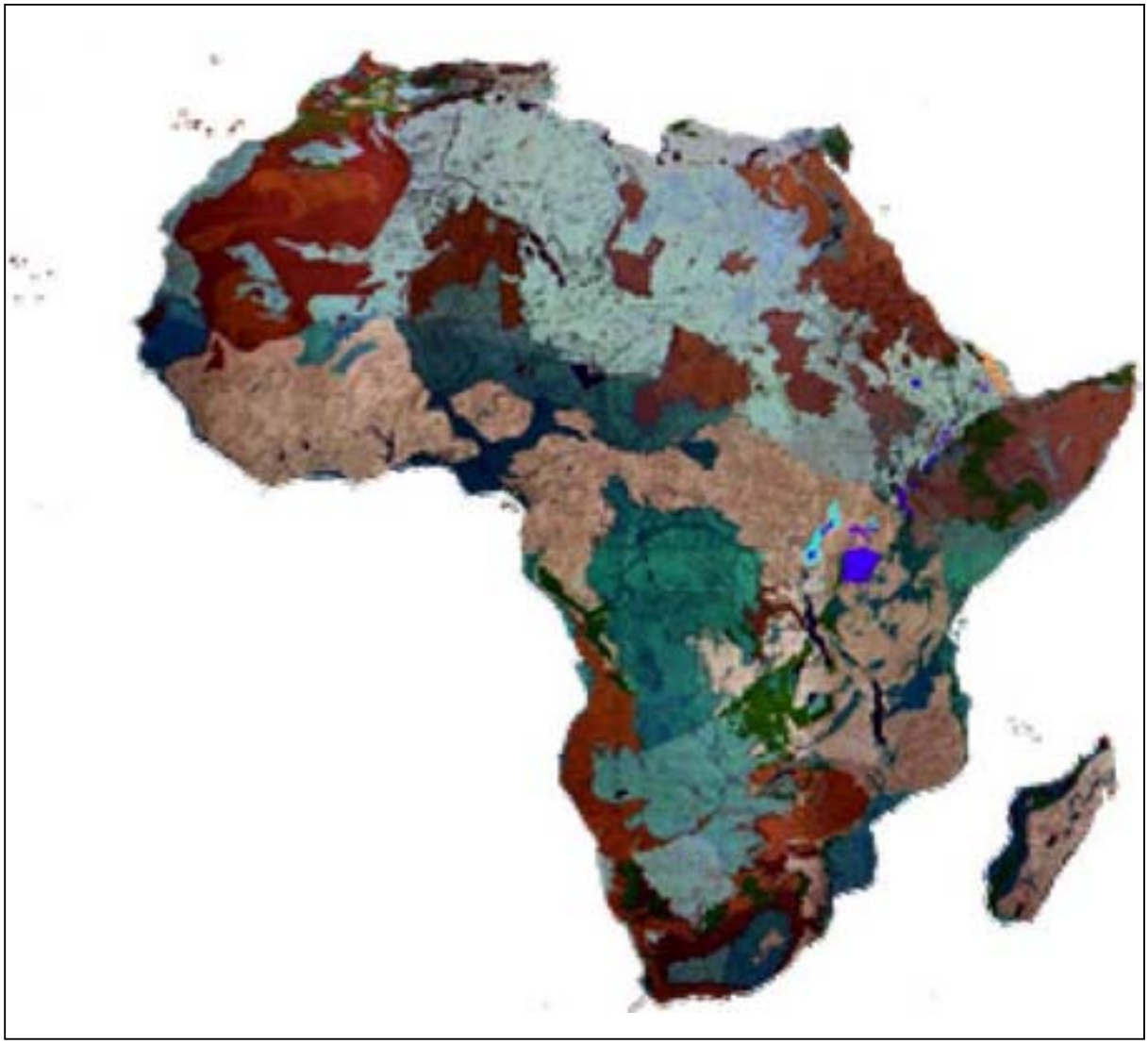


FIGURE 1. Image de la carte hydrogéologique internationale de l'Afrique éditée par l' OACT (1988 - 1992)

avec plusieurs autres organisations. Des fonds à des petites échelles sont tout de même accessibles gratuitement par Internet.

La nécessité d'aboutir à « une conscience de bassin » a poussé les États partageant l'eau des systèmes aquifères des grands bassins sédimentaires à lancer des actions d'évaluation, de modélisation et de simulation de l'évolution de ces ressources à différents horizons et suivant différents scénarios. Il s'agit en particulier des programmes SASS piloté par l'OSS concernant le bassin sédimentaire du Sahara septentrional partagé par l'Algérie, la Tunisie et la Libye et le NSAS piloté par CEDARE concernant le grand bassin de Nubie partagé par la Libye, l'Égypte, le Soudan et le Tchad. Des opérations similaires sont en gestation pour les grands bassins de l'Iumelleden et Sénégalo-Mauritanien. L'évolution vers des structures permanentes de concertation est envisagée.

Le SIREPAN : vision novatrice initiée par l'OACT

Dès juin 2000, l'OACT, forte de son expérience de cartographie des ressources en eau souterraines à l'échelle du continent africain [4] a pris l'initiative de lancer un programme dont les objectifs ont été arrêtés comme suit :

- Réactualiser la Carte Hydrogéologique Internationale en tenant compte des nouvelles technologies (Systèmes d'Information Géographique, Internet, Télédétection) ;
- Définir les bases d'une cartographie « dynamique » réactualisable régulièrement par les producteurs de l'information (les services nationaux) suivant des procédures et normes convenues d'un commun accord.
- Définir des procédures de consultation et d'édition sur Internet de cartes thématiques sur les ressources en eau à différentes échelles par région hydrologique ou hydrogéologique homogène ou par unité administrative.

Cette initiative a été soutenue dès son lancement par l'Union du Maghreb Arabe (UMA), l'Observatoire du Sahara et du Sahel (OSS) et l'UNESCO avec lesquels il fut décidé de lancer le programme sur la partie nord de l'Afrique (UMA + Égypte) et de l'étendre par la suite aux autres régions (CILSS, SADC, IGAD, CEDEAO). Le SADC et le CILSS ont d'ailleurs exprimé leur intérêt. Le SIREPAN (Système d'Information sur les Ressources en Eau des Pays de l'Afrique du Nord) est alors individualisé.

Structure du programme

Le programme est structuré en trois phases principales résumés dans le Tableau 1 ci après.

Tableau 1. Phases de réalisation du SIREPAN

■ **Phase 1** (à très court terme) : • carte des Ressources en Eau • Type de carte : carte numérisée informative sur les ressources en eau • Groupes ciblés : Décideurs politiques de l'UMA + Égypte, planificateurs et autres • Échelles de représentation (sortie) : 1/5.000.000 avec possibilité d'autres échelles • Échelles de travail : variables suivant l'information fournie par les experts des pays.
■ **Phase 2** (Document programme comprenant les points suivants) : • Définition de l'objectif, justification et avantages attendus • Revue et analyse des systèmes similaires sur les Ressources en Eau en fonctionnement et en cours : en particulier SIMEDE de l'espace euro-méditérranéen, du DSS du WWAP-UNESCO, du SIREPAN et AWAP • Revue des systèmes intégrant la dimension Ressources en Eau dans la région : SID-SISEI de l'OSS, le Programme Régional pour un Développement Durable de la WANA région, etc. • Revue des Systèmes d'Information existant au niveau national tel que SIPPE de la Mauritanie • Structuration du projet : Définir le fonctionnement interne du système et ses connexions éventuelles avec les systèmes émetteurs et récepteurs de l'information aussi bien nationaux qu'internationaux. • Analyse des impacts au niveau régional et national. • Rédaction de la Charte informationnelle. • Planning de réalisation sur trois ans, • Recherche des partenaires scientifiques et techniques.
■ **Phase 3** : Mise en œuvre du système • Désignation de la structure d'accueil et mise en place des moyens humains et matériels • Lancement du site web spécialisé • Organisation d'ateliers thématiques et techniques • Connexion avec les systèmes nationaux et renforcement de ceux-ci • Connexion avec les systèmes des nations Unies et autres traitant des ressources en eau.

La réalisation du programme est schématisée dans la Figure 2 ci après.

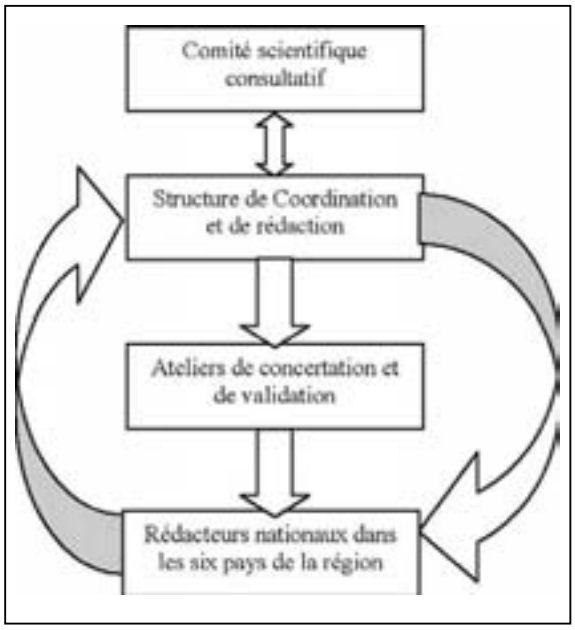


FIGURE 2. Schéma structurel de réalisation

Spécifications de la carte (première phase)

La première tâche dans la mise en place du programme a consisté à définir le type de carte normalisée à réaliser, arrêter une légende générale et structurer les bases de données par le biais d'ateliers. Le premier de ces ateliers s'est tenu à Tunis les 24-25 avril 2002 à l'initiative de l'OACT en partenariat avec l'OSS sous l'égide de l'Union du Maghreb Arabe (UMA) avec la participation de tous les Pays concernés (UMA + Égypte) ainsi que les Organisations suivantes : UNESCO, ALESCO, UMA, OSS et OACT. Le deuxième atelier s'est tenu à Alger du 30 septembre au 1er octobre 2002 et a été organisé par l'Agence Nationale des Ressources Hydrauliques d'Algérie (ANRH) et l'OACT avec la participation des pays concernés, de l'UMA, de l'OSS et de l'ACSAD.

La carte sera informative et traitera de toutes les ressources en eau, conventionnelles ou non (Fig. 3).

Le fonds topographique numérique de base sera le Digital Chart of the World (DCW) développé en 1991/1992, disponible gratuitement sur Internet [5] et dont l'échelle est le 1/1.000.000ième. Les coordonnées géographiques en longitude/latitude suivent la projection WGS 84 (World [6] Geodetic System 1984).

Les logiciels S.I.G de report sont Arc View (v. 3 et plus) et /ou Map Info (v. 6.0 et plus).

Les tables (ou couches d'information) retenues dans la carte sont résumées dans le Tableau 2 ci après.

La toponymie et les données quantitatives, etc. sont données par les étiquettes propres aux différentes couches.

La légende retenue pour les eaux souterraines est fonction de l'exploitabilité de la ressource et de sa capacité à se renouveler (Fig. 4).

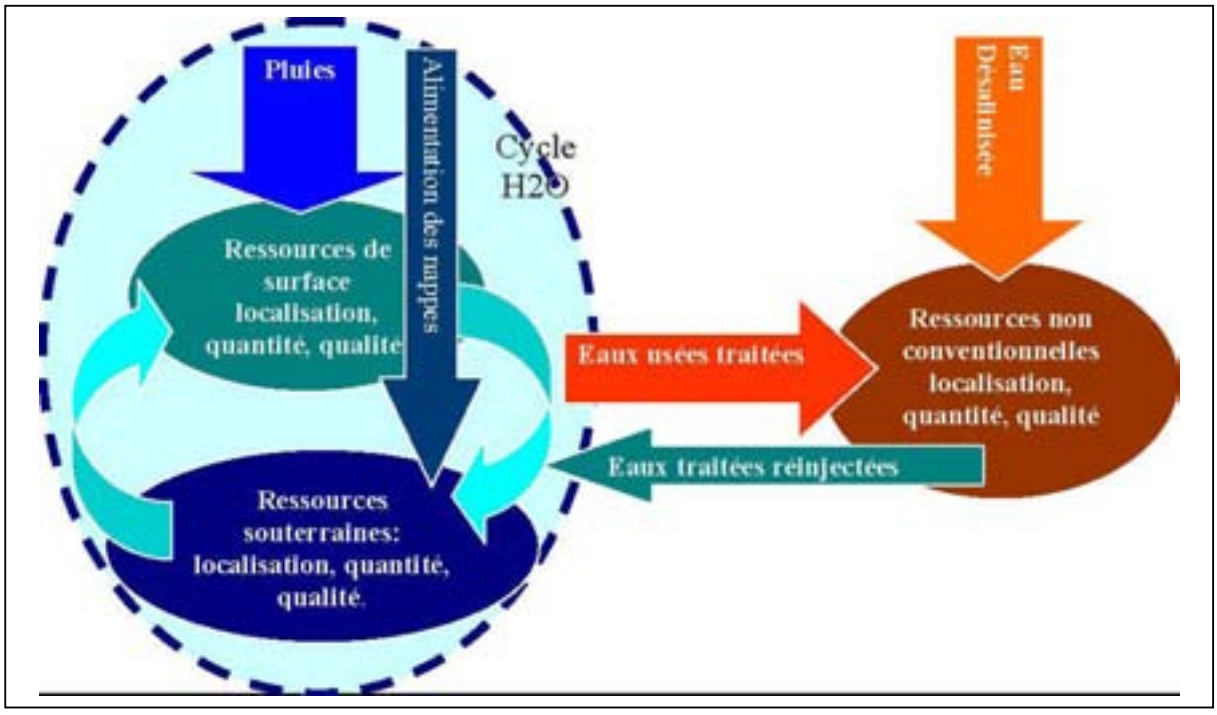


FIGURE 3. Contenu de la carte et des bases de données du SIREPAN

Nom de la table	*Type d'objet*	*Réalisation*
Li mites_ad ministratives	ligne	DCW
Villes	point	DCW + rédacteurs
Réseau_routi er	ligne	DCW
Réseau_h ydrographique	ligne	DCW + rédacteurs
Lacs_sebkhas	polygone	DCW + rédacteurs
Nappes_aquifères	polygone	rédacteurs
Barrages_r éalisés	point	rédacteurs
Barrages_ en_cours	point	rédacteurs
Grands_transferts	ligne	rédacteurs
Salinité	polygone	rédacteurs
Qualité_eau	point	rédacteurs
Usines_désali nisation	point	rédacteurs
Usines_épuration	point	rédacteurs

TABLEAU 2. Les tables (ou couches d'information) retenues dans la carte



FIGURE 4. Légende de la Figure 5

Conclusion

La phase 1 du programme est pratiquement achevée (Fig. 5, page suivante). Les phases 2 et 3 ainsi que l'extension du programme aux autres régions du continent nécessiteront dans le futur une mobilisation plus grande de la communauté internationale autour de cette mission, oh combien exaltante de la connaissance, de la maîtrise et de la protection de nos ressources naturelles.

Références et notes bibliographiques

1. J. MARGAT. 2001. *D'après les ressources en eau des pays de l'OSS, évaluation, utilisation et gestion.* OSS-UNESCO.
2. OMM. 2001. *Déclaration de l'OMM sur l'état du climat mondial.* Rapport OMM n°920 et Rapport d'évaluation du GIEC n°19.
3. STRUCKMEIER, W. et MARGAT, J. 1995. *Hydrogeological Maps, a Guide and a Standard Legend.* AIH, éditions Hesse, vol. 17.
4. OACT. 1988-1992. Carte Hydrogéologique Internationale de l'Afrique, échelle du 1/5.000.000ième, 5 feuilles et 4 notices explicatives. Coordinateur scientifique: Mohamed Safar Zitoun.
5. The Digital Chart of the World (DCW) is an Environmental Systems Research Institute, Inc. (ESRI) product originally developed for the US Defense Mapping Agency (DMA) using DMA data at 1:1,000,000 scale. Voir aussi le site http://www.maproom.psu.edu/dcw.
6. Pour de plus amples informations concernant le WGS 84 voir le site http://www.wgs84.com.

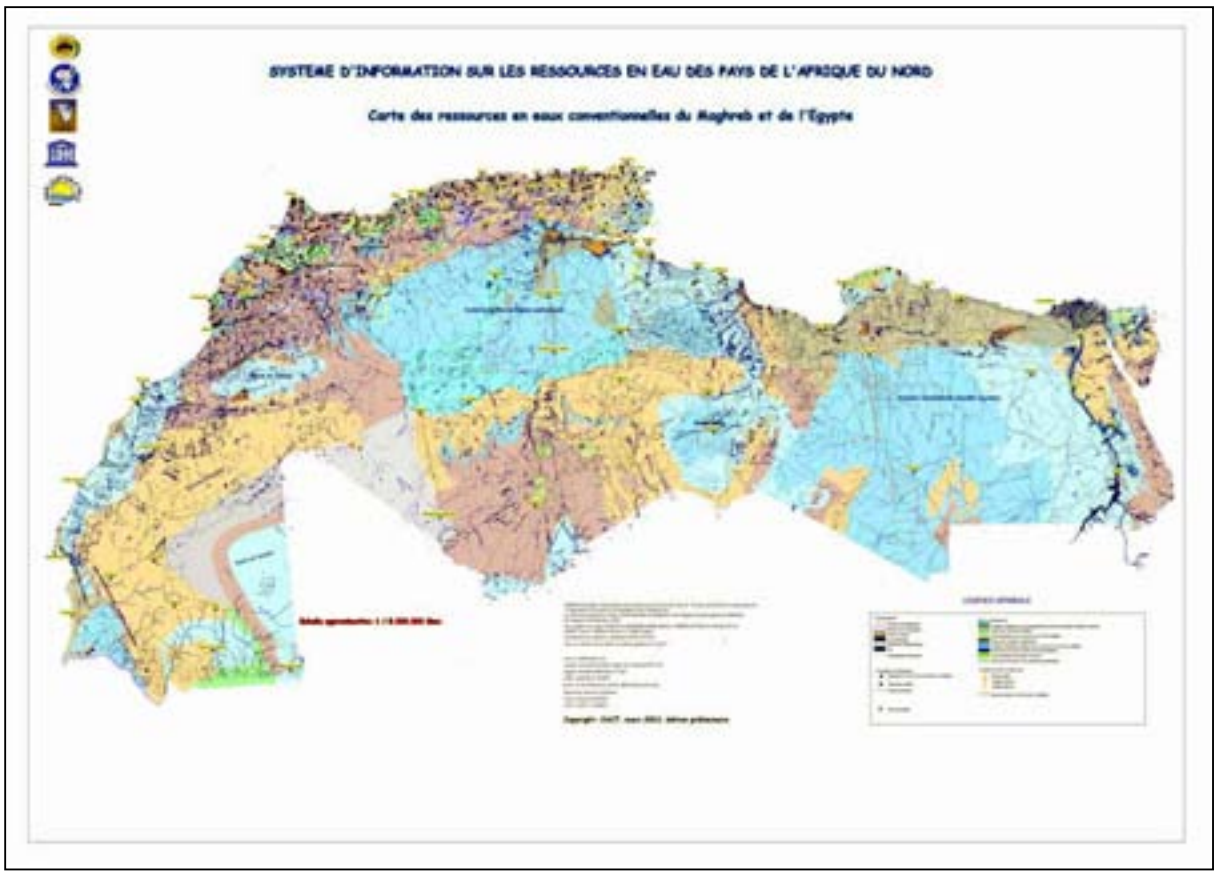


FIGURE 5. **Épreuve d'essai de la carte des ressources en eau conventionnelles du Maghreb et de l'Égypte**



Appendices

APPENDIX 1

TABLE 1
Transboundary aquifers in Africa; identified in the Workshop (compiled by Bo Appelgren)

The aquifer systems in Africa. As a result of the workshop the thirty-two transboundary aquifer systems and sub-basins – large and small – identified in the workshop papers are presented in Table 1. The table, which includes necessary generalizations and reconciliation of aquifer names, organizes the aquifers in sub-regions, in large basins, coastal and other aquifer systems.

Aquifer Name	Countries	Size	Reference: Author(s)/Papers in the Proceedings
Nubian Sandstone Aquifer System (NSAS)	Chad, Egypt, Libya, Sudan	storage 3,730,000 km^3 renew 15,340 km^3 3,096,000 km^2 use 2,173 km^3/yr	O. Salem, P. Pallas A.A. Mohammed - Sudan M. Bakhbakhi - CEDARE
Northern Sahara Aquifer System (NSAS) [Grand Erg Oriental]	Algeria, Libya, Tunisia	780,000 km^2	B. Appelgren A.S. Moulla et al. - Algeria M. Besbes - Tunis
SADC			
Coastal Marine Sedimentary basins	Angola, DRC, Mozambique, Namibia, South Africa, Tanzania		P. Molapo, S. Puyoo - SADC
Coastal Marine Sedimentary basins	Kenya, Tanzania		S. Mpanda - Tanzania
Basement complex aquifers	Tanzania, with Burundi, Rwanda, DRC		S. Mpanda - Tanzania
Volcanic aquifer systems (Kilimanjaro)	Kenya, Tanzania		S. Mpanda - Tanzania
Alluvial deposits in deltas (Kagera, Ruvuma	Tanzania with Uganda resp Mozambique		S. Mpanda - Tanzania
Congo Intra-cratonic - Continental basin	DRC, Angola		P. Molapo, S. Puyoo - SADC
Northern. Kalahari/ Karoo basin	Angola, Botswana, Namibia, Zambia		P. Molapo, S. Puyoo - SADC
South-Eastern Kalahari/ Karoo basin	Namibia, Botswana, South Africa		P. Molapo, S. Puyoo - SADC C. Chilume - Botswana S. Ndengu - Namibia

Table 1 (continued)

Aquifer Name	Countries	Size	Reference: Author(s)/Papers in the Proceedings
SADC (Continued)			
Karoo Sedimentary Aquifer	Lesotho, S. Africa		B. Appelgren
Nata Karoo sub-basin	Botswana, Namibia, Zimbabwe		C. Chilume - Botswana
Tuli Karoo sub-basin	Botswana, South Africa, Zimbabwe		C. Chilume - Botswana
Karoo Sandstone aquifer	Mozambique, Tanzania		S. Mpanda - Tanzania
Ramotswa Dolomite basin	Botswana, South Africa		S. Ndengu - Namibia
Shire Valley Alluvial aquifer			P. Molapo, S. Puyoo - SADC
Suture zones, Medium Zambezi	Botswana, Mozambique, South Africa, Zimbabwe		P. Molapo, S. Puyoo - SADC
Limpopo Basin	Mozambique, Swaziland		P. Molapo, S. Puyoo – SADC
Rhyolite-Breccia aquifer (Mhlumeni Border Post)	Mozambique, Swaziland		O.M. Ngwenya - Swaziland
Merti Aquifer	Kenya, Somalia	Groundwater Flow 7,200 m^3/day.	F. Mwango - Kenya
Volcanic Aquifers (Mount Elgon, and Mfumbira)	Uganda with Kenya and Rwanda, DRC		A. Kitakarugire - Uganda
Regolith and Rift Aquifers	Uganda with Sudan and with Kenya and Tanzania	Limited aquifers	A. Kitakarugire - Uganda
Shallow Aquifers	Burkina Faso, Côte d'Ivoire, Mali, Senegal		M. Alhouseini - Mali
Coastal Sedimentary Aquifer System (continental, quaternary, limestone)	Ghana, Côte d'Ivoire	About 500 km, along the coast	W.A. Agyekum - Ghana J.P.R. Jourda - Côte d'Ivoire
Coastal Sedimentary Aquifer System (continental, limestone, quaternary) (Dahomeyan Basin)	Benin, Nigeria, Togo		F. Azonsi - Benin C. M. Maduabuchi

Table 1 (continued)

Aquifer Name	Countries	Size	Reference: Author(s)/Papers in the Proceedings
SEDIMENTARY BASINS SOUTH OF THE SAHARA			
Senegal		34,000 km^2	B. Diagana - Mauritania
Gambia		80,000 km^2	B. Diagana - Mauritania
Chad		2,500,000 km^2	B. Diagana - Mauritania A. Dodo - Niger
Senegal- Mauritania	Gambia, Guinea-Bissau, Mauritania, Senegal	200,000 km^3	B. Appelgren B. Diagana - Mauritania
Toudéni	Algeria, Mali, Mauritania	500,000 km^2	B. Diagana - Mauritania
Iullemenden Continental Sedimentary Aquifer (Sokoto basin, Nigeria)	Mali, Niger, Nigeria (Algeria, Benin)	5,000 km^3 500,000 km^2	P. Pallas, J. Margat B Appelgren M. Alhouseini - Mali A. Dodo - Niger B. Ousmane - Niger C. M. Maduabuchi - Nigeria
Tin-Séririne basin in the Tassili Oua N'Ahaggar mountain complex (*bassin du Tafassasset)*	Algeria, Niger	45,000 km^2 captive- artesian in Niger	A.S. Moulla et al. - Algeria A. Dodo
Djado - Bilma Basin	Niger, Libia, Chad		A. Dodo - Niger B. Ousmane - Niger
l'Aïr (discontinued) cristalline basement aquifer	Algeria, Mali, Niger		A. Dodo - Niger
Liptako-Gourma, (discontinued) cristalline basement aquifer	Burkina Faso, Niger		A. Dodo - Niger
Chad Aquifer Basin	Central African Republic, Cameroon, Niger, Nigeria	1,400,000 km^3	B. Appelgren B. Diagana - Mauritania C.M. Maduabuchi - Nigeria J.A Oguntola - LCBC

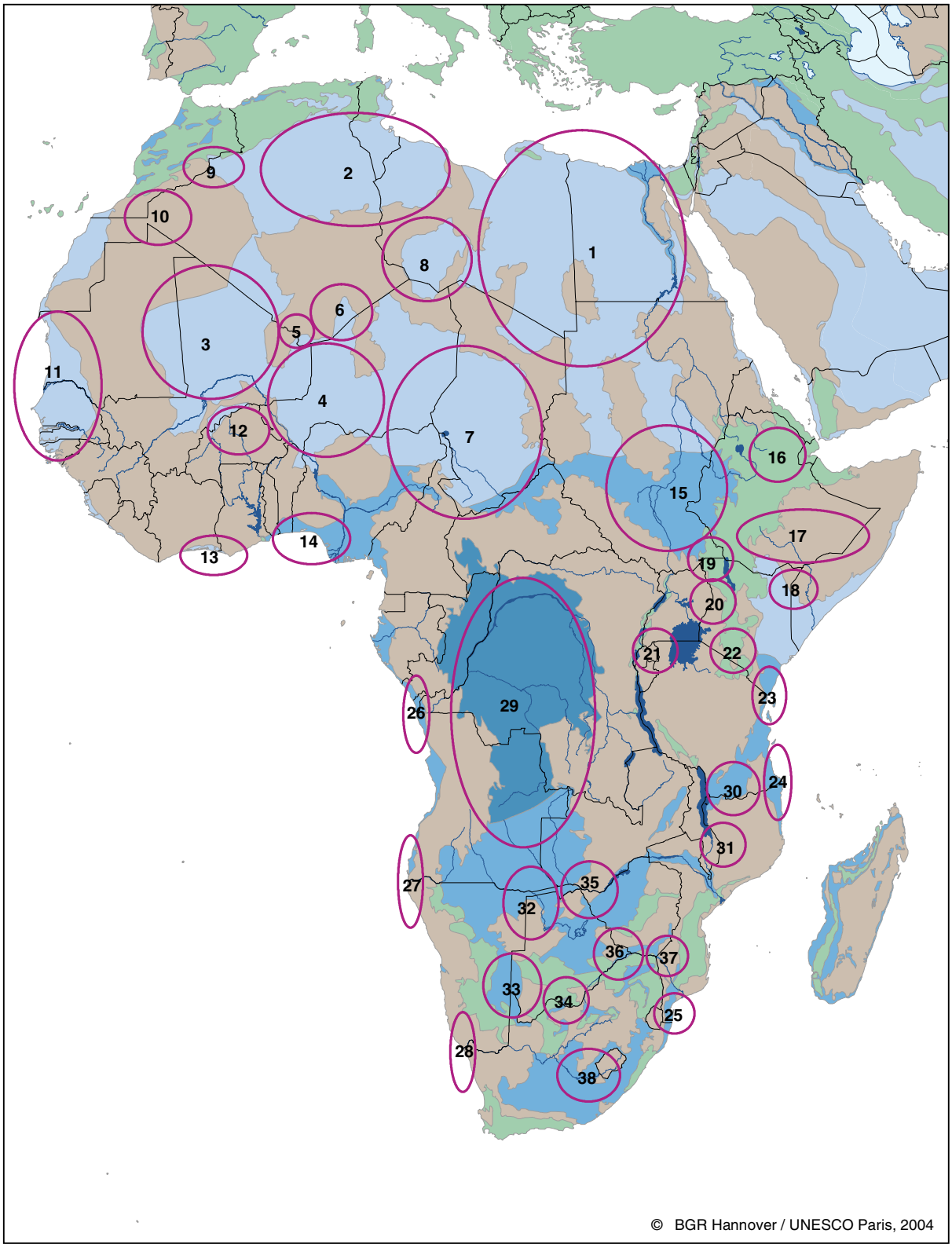
APPENDIX 2

TABLE 2

Transboundary aquifers in Africa
Cross-reference between African countries sharing individual aquifer systems

African Transboundary Aquifers/ Countries	Algeria	Angola	Benin	Botswan	Burundi	Bk Faso	Camroun	C. Africa	Chad	C. d'Ivoire	DRC	Egypt	Gambia	Ghana	Guinea	Kenya	Lesotho	Libya	Mali	Mauritania	Mozamb.	Namib	Nigeria	Niger	RSA	Rwanda	Senegal	Somalia	Sudan	Swaziland	Tanzania	Togo	Tunisia	Uganda	Zambia	Zimbabwe	Countries
Nubian Sandstone Aquifer									1			1						1											1								4
Northern Sahara Aquifer	1																	1				1											1				3
South West Coastal Marine Sediment		1									1												1		1												4
Eastern Coastal Marine Sediment																1					1										1						3
Basement complex aquifers					1						1																1				1						4
Volcanic aquifer (Kilimanjaro)																1															1						2
Alluvial delta deposits (R.Kagera)																															1			1			2
Alluvial delta deposits (R. Ruvuma)																					1										1						2
Congo Intra-cratonic,Continental		1									1																										2
Northern. Kalahari /Karoo basin		1		1	1																	1															4
South-Eastern Kalahari /Karoo basin				1																		1			1												3
Karoo Sedimentary Aquifer																	1								1												2
Nata Karoo sub-basin					1																	1														1	3
Tuli Karoo sub-basin					1																				1												3
Karoo Sandstone aquifer																					1																2
Ramotswa Dolomite basin,					1																				1						1						2
Shire Valley Alluvial aquifer																			1		1																2
Suture zones, Medium Zambezi					1																1																4
Limpopo Basin																					1									1							2
Rhyolite-Breccia aquifer (Mhlumeni)																					1									1							2
Merti Aquifer																1												1									2
Volcanic Aquifers EA (Mount Elgon)																1																			1		2
Volcanic Aquifers EA (Mfumbira)											1															1											2
Regolith, Rift Aquifers Ken-Tan																1															1						2
Regolith, Rift Aquifers Sud-Ug																														1				1			2
"Shallow Quartenary Aquifers" I						1				1																											2
"Shallow Quartenary Aquifers" II																				1									1								2
Coast. multi-Aquifers G.of Guinee I										1				1																							2
Coast. multi-Aquifers G.of Guinee II		1																					1									1					3
Senegal- Mauritiania															1		1				1								1								4
Toudéni	1																			1	1																3
Iullemeden multiaquifer system																				1			1	1													3
Tin-Séririne basin, Tassili	1																							1													2
Djado- Bilma Basin									1									1						1													3
I'Aïr basement aquifer	1																			1				1													3
Liptako-Gourma basement aquifer						1																		1													2
Chad Aquifer Basin							1	1	1									1					1	1													6
No of shared aquifers	4	3	1	6	1	2	1	1	3	2	4	1	1	1	1	5	1	4	5	2	7	4	3	6	6	2	2	1	2	2	7	1	1	3	1	3	

APPENDIX 3
Map of transboundary aquifers in Africa



Transboundary aquifers in Africa

No.	*Aquifer Name*	*Countries*
1.	Nubian Sandstone Aquifer System	Chad, Egypt, Libya, Sudan
2.	Northwest Sahara Aquifer System	Algeria, Libya, Tunisia
3.	Taoudéni Basin	Algeria, Mali, Mauritania
4.	Irhazer-Iullemeden Basin	Mali, Niger, Nigeria
5.	l'Air Cristalline Aquifer	Algeria, Mali, Niger
6.	Tin-Séririne Basin	Algeria, Niger
7.	Chad Basin	Central African Republic, Chad, Cameroon, Niger, Nigeria
8.	Mourzouk-Djado Basin	Chad, Libya, Niger
9.	Errachidia Basin	Algeria, Morocco
10.	Tindouf Aquifer	Algeria, Morocco
11.	Senegalo-Mauritanian Basin	Gambia, Guinea-Bissau, Mauritania, Senegal
12.	Liptako-Gourma Aquifer	Burkina Faso, Niger
13.	Coastal Sedimentary Aquifer	Ghana, Côte d'Ivoire
14.	Coastal Sedimentary Aquifer	Benin, Nigeria, Togo
15.	Upper Nile Basin	Ethiopia, Sudan
16.	Awash Valley Aquifer	Djibouti, Ethiopia
17.	Ogaden-Juba Aquifer	Ethiopia, Kenya, Somalia
18.	Merti Aquifer	Kenya, Somalia
19.	Rift Aquifers	Kenya, Tanzania, Uganda
20.	Mount Elgon Aquifer	Kenya, Uganda
21.	Kagera Aquifer	Tanzania, Uganda
22.	Kilimanjaro Aquifer	Kenya, Tanzania
23.	Coastal Sedimentary Basin	Kenya, Tanzania
24.	Coastal Sedimentary Basin	Mozambique, Tanzania
25.	Limpopo Basin	Mozambique, Swaziland
26.	Coastal Sedimentary Basin	DR of Congo, Angola
27.	Coastal Sedimentary Basin	Angola, Namibia
28.	Coastal Sedimentary Basin	Namibia, South Africa
29.	Congo Intra-cratonic Basin	DR of Congo, Angola
30.	Karoo Sandstone Aquifer	Mozambique, Tanzania
31.	Shire Valley Alluvial Aquifer	Malawi, Mozambique
32.	Northern Kalahari/Karoo Basin	Angola, Botswana, Namibia, Zambia
33.	SE Kalahari/Karoo Basin	Botswana, Namibia, South Africa
34.	Ramotswa Dolomite Basin	Botswana, South Africa
35.	Nata Karoo Sub-basin	Botswana, Namibia, Zimbabwe
36.	Tuli Karoo Sub-basin	Botswana, South Africa, Zimbabwe
37.	Medium Zambezi Aquifer	Botswana, Mozambique, South Africa, Zimbabwe
38	Karoo Sedimentary Aquifer	Lesotho, South Africa

APPENDIX 4
List of Workshop participants

The Workshop participants included:

- Representatives and experts of countries and institutions in African Countries, and
- Representatives and experts of regional and international communities and institutions.

The following list includes the participants and the authors of the contributions to the Workshop, as well as the country experts/representatives of the ISARM-Africa Network, and the representatives of the participating institutions.

African Countries which have confirmed their participation and nominated country experts in the ISARM-Africa Network:

Algeria	Kenya	Nigeria
Benin	Libya	South Africa
Botswana	Malawi	Sudan
Chad	Mali	Swaziland
Côte d'Ivoire	Mauritius	Tanzania
Djibouti	Mauritania	Tunisia
Egypt	Namibia	Uganda
Ghana	Niger	

Expert/Country-Organization

ALGERIA

■ ***Ali LARBES***
Ingénieur hydrogéologue à l'Agence Nationale
des Ressources Hydrauliques
Email: hrna@wissal.dz

■ ***Adnane S. MOULLA***
Head of Dept
Applied Hydrology and Sedimentology Dept.
Nuclear Application Division
Algiers Nuclear Research Center
02, Bd. Frantz Fanon, P.O. Box 399
16000 Alger-Grae
Tel.: +213 21 43 44 44; Fax: +213 21 43 42 80
Email: asmoulla@hotmail.com;
as.moulla@comena-dz.org

BENIN

■ ***Félix V. AZONSI***
Chef du département des ressources en eau
Direction de l'Hydraulique
01 BP 385 Cotonou
Tél. : +229 31 32 98/31 34 87
Fax : +229 31 08 90
e-mail: dre.dh@intnet.bj; felyazonsi@yahoo.fr

BOTSWANA

■ ***Chakalisa CHILUME***
Tel.: +267 3607355
Tel/Fax: +267 303508

CHAD

■ ***Zakaria Fadoul***
Directeur Adjoint de l'Hydraulique
Ministère de l'Environnement
et de l'Hydraulique
Fax: +235 52 56 68

CÔTE D'IVOIRE

■ ***Jean Patrice Roger JOURDA***
Directeur du Laboratoire
des Sciences et Techniques de l'Eau
et de l'Environnement
Universite de Cocody-Abidjan
UFR-STRm, 22 BP 582 Abj 22
Tél. : +225 22 42 03 45/22 44 35 00
Fax : +225 22 44 35 00
Email: jourda_patrice@yahoo.fr

DJIBOUTI

■ ***Houssein Ali GAMAL-ELDINI***
Office National des Eaux de Djibouti
Fax: +253 35 44 23

EGYPT

■ ***Mohamed Hassan TAHER***
Groundwater Research Institute
National Resource Center
Email: ps8@mwri.gov.eg

GABON

■ ***Christian Olivier LASSENY***
Directeur de l'Hydraulique
Direction générale de l'Energie
et des Ressources Hydrauliques
BP 1172
Tél. : +241 76 15 04/76 15 05/76 32 90
Fax : +241 72 49 90/76 32 42
Mobile: +241 24 93 29

GHANA

■ ***William A. AGYEKUM***
Hydrogeologist
CSIR Water Research Institute
P.O. Box M 32, Accra
Fax: +233 21 77 71 70
Email: wri@ghana.com

KENYA

■ ***Fred K. MWANGO***
Deputy Director of Water Development
P.O. Box 30521, Nairobi
Fax: +254 2727622 ;
Email: thandigithae@hotmail.com

LESOTHO

■ ***Motlasi John LESUPI***
Tel.: +266 313602 and 266 313603
Fax: +266 310437
Email: gwd@ilesotho.com

LIBYA

■ ***Omar SALEM***
Director General Water Authority
P.O. Box 5332
Tripoli
Tel.: +218 21 432 129
Fax: +218 21 4832 124
Email: gwalibya@hotmail.com

MALAWI

■ ***Peter P. MKANDAWIRE***
Ministry of Water Development
Private Bag 68; Mzuzu, Malawi
Fax: 265 33 26 07 ; Email:
hydrology@malawi.net

MALI

■ ***Malick ALHOUSSEINI***
DNH
BP 66, Bamako
Fax: +223 21 46 76
Email: dnh@afribone.net.ml

■ ***Moussa DIENG***
Ingénieur Hydrogéologue sénior

MAURITIUS

■ ***Rajeshwar POKHUN***
Vice Chair of the SADC
Sub-Committee for Hydrogeology
Tel.: +230 465 95 40
Fax: +230 465 71 77
Email: slg@intnet.mu and wru@intnet.mu

MAURITANIA

■ ***Bassirou DIAGANA***
Directeur du CNRE
BP 899
Email: mbdiagana@yahoo.com
Fax : +222 525 30 07

MOROCCO

■ ***Boubker EL HOUADI***
Agence du bassin hydraulique de la Moulouya
B.P. 703 Oujda
Tél. : +212 56 68 38 15/56 68 68 99
Fax : +212 56 68 38 48
Email: drhouj@mtpnet.gov.ma

MOZAMBIQUE

■ ***Lucas CHAIRUCA***
Geohydrologist
National Directorate of Water
Email: pcambula@tropical.co.mz

NAMIBIA

■ ***Swama NDENGU***
Tel.: +264 61 208 71 45
Fax: +264 61 208 71 49
Email: ndengus@mawrd.gov.na

NIGER

■ ***Abdulkader DODO***
Directeur National
Ministère de l'Hydraulique
et de l'Environnement
BP 257, Niamey
Fax: +227 72 40 15
Email: mre@intnet.ne; dregef@intnet.ne;

■ ***Boureima OUSMANE***
Université Abdou Moumouni
BP 13609, Niamey
Tél. : +227 75 35 58
Fax: +227 75 28 04/75 20 55
Email: ousmane@ird.ne

NIGERIA

■ ***Christopher MADUABUCHI***
Assistant Director (Hydrogeology)
Email: maduchristo@yahoo.com

REP. DEM. CONGO

■ ***Willy E. MUSOYI BAYIPOKE***
Point focal VIème Phase du PHI
Chef de Division de Gestion des eaux
Direction des Ressources en eau
35, Av Pumbu n° 35 C/Gombe
B.P.12348 ou 16312 Kinshasa 1

SOUTH AFRICA

■ ***Boniface ALEOBUA***
Deputy Director/NORAD Program Manager
Directorate: Geohydrology
Department of Water Affairs and Forestry,
Bag X 313, Pretoria 0001
Tel.: +27 12 336 8262
Cell: +27 82 807 5719
Fax: + 27 12 328 6397
Email: wad@dwaf.gov.za
Priv email: baleobua@mweb.co.za

■ ***Edwin THABILE NCUBE***

SUDAN

■ ***Almoutaz Abdalla MOHAMMED***
UNESCO Chair in Water Resources
Email: mamah66@hotmail.com

SWAZILAND

■ ***Obed Mfanimpela NGWENYA***
Hydrogeologist
Geological Survey and Mines
Department
P.O. Box 9, Mbabane
Fax: +268 404 52 15
Email: geoswz_lib@realnet.co.sz

SENEGAL

■ ***Abdoulaye FAYE***
Maître de Conférence
au Département de Géologie
de l'Université Cheikh Anta Diop de Dakar
Fax: +221 822 95 81
Email : abfaye@sentoo.sn

TANZANIA

■ ***Samson MPANDA***
P.O.Box 35066
Dar es Salaam
Email: smpanda4@yahoo.com

TUNISIA

■ ***Y. BENSALAH***
Direction générale des ressources en eau
Tunis
Email: y_bensalah@yahoo.com

UGANDA

■ ***Aseka Joseph KITAKARUGIRE***
Senior Hydrogeologist
Directorate of Water Development
P.O.Box 19, Entebbe
Tel.: +256 41 321342/256 77 521413
Fax: +256 41 321368
Email: ctindi.wrmd@dwd.co.ug

ZAMBIA

■ ***Simon KANG'OMBA***
Tel.: +218 21 361 48 33/34
Email: jingu@water-forum3.com
Lusaka

ZIMBABWE

■ ***Jeffrey MAZONDE***
Principal Engineer
Ministry of Rural Resources
and Water Development,
Private Bag 7712, Causeway, Harare
Tel.: +263 (04) 793914
Fax: +263 (04) 722733
Email: hydro@icon.co.zw
Email: musoyibay@yahoo.fr

AFDB

■ ***Gustave ABOUA***
NESDA
24 BP 95 Abidjan 24
Guichet Annexe BAD
Côte d'Ivoire
Tél. : 225 20 20 54 19
Fax: 225 20 20 59 22
Email: f.coulibaly@afdb.org

AGRHYMET
(Permanent Interstate Committee for Drought Control in the Sahel)

■ ***Madiyara NGUETORA***
Responsable de la Filière Hydrologie
Programme Majeur Formation
Centre Régional AGRHYMET
11011 Niamey - Niger
Tél. : +227 73 31 16
Fax : +227 7324 35
Email: nguetora@sahel.agrhymet.ne

BGR

■ ***Gerhard SCHMIDT***
Referat B 1.27 - Grundwasserdynamik,
Grundwassermodellierung
Section B 1.27 - Groundwater dynamics and
modelling
Bundesanstalt fuer Geowissenschaften und
Rohstoffe (BGR)
Federal Institute for Geosciences and Natural
Resources (BGR)
Stilleweg 2 - 30655 Hannover
Postfach / POB 510153 - 30631 Hannover
Germany
Email: g.schmidt@bgr.de

CEDARE

■ ***M. BAKHBAKHI***
NSAS,CEDARE
Cairo, Egypt
Email: mbakh@cedare.org.eg

COMMUNITY OF SAHEL SAHARAN STATES

■ ***Mohamed AL-MADANI AL-AZHARI***
The Secretary-General
Community of Sahel Saharan States
Aljazaer Square Tripoli – Great Jamahirya
Tel.: +218 21 361 48 33/34
Email: halilou_as@yahoo.fr

CSIR

■ ***Christine COLVIN***
Hydrogeologist, CSIR.
Tel.: +27 21 888 2432
Fax: +27 21 888 2682
PO Box 320, Stellenbosch,
7599, South Africa
Email: ccolvin@csir.co.za

■ ***Wolfgang KINZELBACH***
Swiss Federal Institute of Technology
Institute of Hydromechanics and
Water Resources Management
HIL G 37.3
ETH-Zurich
CH-8093 Zurich-Hoenggerberg
Switzerland
Tel.: +41 1 633 3066
Fax: +41 1 633 1061
Email**:** kinzelbach@ihw.baug.ethz.ch

FAO

■ ***Stefano BURCHI***
Senior Legal Officer
Development Law Service
FAO
Via delle terme di Caracalla
00100 Roma
Italy
Fax: +39 06 57054408
E-mail: stefano.burchi@fao.org

IAEA

■ ***B. WALLIN***
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna
Austria
Tel.: +43 1 2600 217 32
Fax: +43 1 26007
Email: B.G.Wallin@iaea.org

IAH

■ ***Shammi PURI***
Chairman, IAH Commission
on Transboundary Aquifer
Resource Management (TARM)
Avalon House, Marcham Rd
Abingdon, Oxon, OX 14 1UG, UK
Tel.: +44 1235 555 535
Fax: +44 1235 553 203
E-mail: shammypuri@aol.com

IGAD (Intergovernmental Authority on Development for Africa)

■ ***Maina KARABA***
Chief Natural Resources and Energy
Email**:** maina.karaba@igad.dj
Fax: +253 356994/+253 353520

INSTITUT MÉDITERRANÉEN DE L'EAU

■ ***Abderrahmane SALEM***
Les Docks - Atrium 10.3 - 6ème étage
10, Place de la Joliette - 13002 Marseille
France
Tél. :+33 4 91 59 87 77
Fax: +33 4 91 59 87 78
Email: info@ime-eau.org
Site Web: http://www.ime-eau.org

IRD - UMR HYDROSCIENCES MONTPELLIER

■ ***Christian LEDUC***
BP 64501,
34394 Montpellier Cedex 5
France
Tél. : + 33 (0)4 67 14 90 45
Fax:+33 (0)4 67 14 47 74
Email: christian.leduc@msem.univ-montp2.fr

LAKE CHAD BASIN COMMISSION
COMMISSION DU BASSIN DU LAC TCHAD

■ ***J.A. OGUNTOLA***
Chief of Water Resources Unit
Lake Chad Basin Commission
N'Djamena, Chad
Email : johnogun@intnet.td

NIGER BASIN AUTHORITY (NBA)

■ ***Ibraheem Alabi OLOMODA***
For: the Executive Secretary NBA
Email: olomoda@gw.abn.ne

OACT

■ ***Muftah UNIS***
Secrétaire General
Email : oact@wissal.dz

OSS

■ ***Chedli FEZZANI***
Directeur exécutif
Observatoire du Sahara et du Sahel (OSS)
Boulevard de l'Environnement BP 31
1080 Tunis
Tunisie
Fax: +216 1 807 310

PALESTINIAN WATER AUTHORITY

■ ***Madhat AL MASRY***
Tel.: +972 8 2822696
Fax: +972 8 2822697
Email: ghbn98@hotmail.com
or: dinahed@p-i-s.com

SADC

■ ***Serge PUYOÔ***
Water Coordination Unit
Hydrologue
Private Bag A440
Maseru 100, Lesotho
Fax: +266 310465
Email: spuyoo@lesoff.co.ls

■ ***Palesa MOLAPO***
Water Coordination Unit
Tel.: +266 320719/310022
Fax: +266 310465
Email: pmolapo@sadcwscu.org.ls

SOCIÉTÉ DES EAUX DE MARSEILLE

■ ***Michel NALBANDIAN***
Directeur de la filiale tunisienne SOMEDEN
■ ***Emmanuel GAILLARD***
Ingénieur hydrogéologue
■ ***Claude-Nicole FAUCHON***
Administrateur territorial

Email : benedicte.williamson@eauxdemarseille.fr

UMA

■ ***Abdessalem KALLALA***
Secrétariat Général de l'UMA
Tél : + 212 37 67-12-78/80/85
Fax : + 212 37 67 12 53
E-mail : kallala2000@yahoo.fr

UNECE

■ ***Geo ARNOLD***
RIZA
P.O. Box 17, 8200 A A Lelystad
The Netherlands
Tel.: +31 320 298435;
Fax: +31 320 249218
Email: g.arnold@riza.rws.minvenw.nl

UNESCO

■ ***Alice AURELI***
Hydrogeologist
Program Specialist
International Hydrogeological Program
UNESCO Paris
Tel.: +33 1 45683995
Email: a.aureli@unesco.org

■ ***Emmanuel NAAH***
Environmental Sciences Specialist
Regional hydrologist
UNESCO Office Nairobi
Tel.: +254 20 62 12 34
Email: e.naah@unesco.org

UNESCO Consultant

■ ***Bo APPELGREN***
Senior Water Economist Expert
VI Colesanti 13
I-10230 Bolsena, Italy
Fax: +39 0761 797112
Email: bo.appelinvpl@flashnet.it

UNESCO-FAO - Consultant

■ ***Philippe PALLAS***
Viale della Tecnica 177
00144 Rome
Italy
Tel+Fax: (+39) 06 5910153
Email: phpallas@tin.it

THIRD WORLD WATER FORUM

■ ***Makoto JINGU***
Chief officer of the Secretariat of the
3rd World Water Forum
Japan
Fax: +81-3-5212-1649
Email: jingu@water-forum3.com

WORLD BANK

■ ***Marcella NANNI***
GWMATE
(WORLD BANK - Global Water Partnership)
Email: marcellananni@libero.it

WORLD WATER COUNCIL

■ ***Marlies SCHUTTELAAR***
Water Action Unit
World Water Council
Atrium 10.3, quai de la Joliette
Marseille, France
Tel.: + 33 (0) 4 91 99 41 00
Fax: + 33 (0) 4 91 99 41 01
Email: schuttelaar@worldwatercouncil.org