PhD THESIS
In "co-tutelle"

THESE
de co-tutelle

For obtaining the Rank of - Pour l'obtention du Grade de

DOCTOR OF PHILOSOPHY
UNIVERSITY OF GLAMORGAN
School of Technology
Division of Civil Engineering
UK.

DOCTEUR DE L'UNIVERSITE DE
POITIERS, FRANCE
Faculté des Sciences Fondamentales et Appliquées
Diplôme national – Arrêté du 30 mars 1992
Ecole doctorale : Ingénierie Chimique,
Biologique et Géologique (ICBG)

Secteur de Recherche : Terre solide et
enveloppes superficielles

Submitted by - présentée par

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The Use of Remote Sensing and GIS for Water Resources Management of Large Semi-Arid Regions: a Case Study of the Lake Chad Basin, Africa.

Gestion des ressources en eau des grands bassins semi-arides à l'aide de la télédétection et des SIG. Application à l'étude du bassin du lac Tchad, Afrique.

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Defended on 24 january 2002 - Soutenue le 24 janvier 2002

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List of Acronyms

Institutions

DREM	Direction des Ressources en Eau et de la Météorologie, N'Djamena, Chad
DHA	Direction de l'Hydraulique et de l'Assainissement, N'Djamena, Chad
CNAR	Centre National d'Appui à la Recherche, N'Djamena, Chad
DRGM	Direction des Ressources Géologiques et Minières, N'Djamena, Chad
STEE	Société Tchadienne d'Eau et d'Eléctricité, N'Djamena, Chad

DRE	Direction des Ressources en Eau, Niamey, Niger
DDH	Direction Departementale de l'Hydraulique, Niger

IRD	Institut de Recherche pour le Développement, Montpellier, France
BRGM	Bureau des Ressources Géologiques et Minières), Orleans, France
BGS	British Geological Survey, UK
CEH	Centre of Ecology and Hydrology, Wallingford, UK

NASA	National Aeronautics and Space Administration, USA
NOAA	National Oceanic and Atmospheric Administration, USA

UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNDP	United Nations Development Program
FAO	Food and Agriculture Organisation

Remote sensing

ERS	European Remote sensing Satellites
SPOT	Satellite Pour l'Observation de la Terre
AVHRR	Advanced Very High Resolution Radiometer
LAC	Local Area Coverage
MODIS	Moderate Resolution Imaging Spectroradiometer
SAR	Synthetic Aperture Radar
TRMM	Tropical Rainfall Measuring Mission
TM	Thematic Mapper
MSS	Multi-Spectral Scanner

NDVI	Normalised Difference Vegetation Index
MVC	Maximum Value Composite

Acknowledgement

This study spans different disciplines and continents, it is the fruit of exchanges of data, expertise and ideas.

I am most grateful for the constant guidance, advice, help and teamwork support I received throughout this project from my directors of studies - Dr Linus A Mofor (University of Glamorgan) and Prof Moumtaz Razack (University of Poitiers, France), and my supervisors - Prof Chris B Jones (formerly of University of Glamorgan and now of Cardiff University), and Dr Christian Leduc (of IRD, France).

Many thanks go to all the people and friends at the various institutions in Chad (the Lake Chad Basin Commission, DHA, DREM, CNAR) and Niger (DDH Niamey and Diffa). We are extremely grateful for all the data they provided and the discussions we had; they provided us the main part of the documentation we needed for this study - not to mention their kindness and friendliness. In particular, we wish to express our gratitude to the Secretary General of the LCBC. Also from the people we met at the LCBC we wish to thank Tam Lambert, Dr J.A. Oguntola, Afrika Olojoba, M.Pondo and A. Saleh. At the DHA, we were warmly received by the director, J.J. Donnat, S. Abderamane and J. Le Priol. We show our appreciation to the director of the DREM, as well as Alainaye Djogromel and Nadji Wai. From the CNAR, we thank the director Baba El-Hadj Mallah, Joseph Libar of the remote sensing department, and all the remarkable documentation service. We cannot forget the DDH Diffa where we were received by the director and my special thanks to Laouali Maroussa.

Dr Dominique Dagorne provided us with many data acquired in the framework of the "Veille Climatique Satellitaire" program, a collaboration between the IRD (formerly ORSTOM) and Météo-France based at the CMS Lannion, France. But above all, he must be acknowledged for his patience and his kindness in explaining the tricks of remote sensing to a hydrogeologist! Thank you Dominique.

I very much appreciated the frank and professional discussions I had with Dr Richard Carter (Cranfield University) and Dr Mike Edmunds (BGS). The exchanges were very useful in appraising and interpreting the recharge and discharge processes in the Quaternary aquifer of the Lake Chad Basin.

Jacques Lemoalle was very kind and helpful to me, especially with remote sensing data interpretation and sharing with me his knowledge of the Lake Chad Basin.

General discussions and exchange of ideas with Dr J.L Schneider, Dr J.C Olivry were very informative and useful. Thank you.

During our two field visits (one in Niger and the other in Chad) we received a lot of help and kindness from a number of people too many to mention by names. I thank them all.

The IRD was involved since the beginning of the project. It has significantly contributed to this project by providing satellite data, scientific expertise of the Basin and a technical support on the field.

Finally and most of all, I am extremely grateful to my family and my friends for all their love and support.

Résumé étendu

La problématique

L'objectif de cette thèse est d'examiner les bénéfices de l'utilisation des SIG et de la télédétection pour la gestion des ressources en eau en milieu semi-aride. Pour ce faire, le bassin du Lac Tchad en Afrique a été choisi comme étude de cas. 32% de l'ensemble des continents est affecté par l'aridité (UNEP, 1992). Dans cet ensemble, les zones semi-arides se caractérisent par de faibles précipitations et une forte évapotranspiration, si bien qu'à l'échelle de l'année la plupart des mois montre un déficit en eau. Les eaux de surface sont en général temporaires et seule l'eau souterraine offre un accès permanent à la population. Dans tous ces environnements l'eau est donc une ressource limitée et précieuse. C'est pourquoi comprendre et quantifier les ressources en eau souterraine est d'une importance cruciale. Malheureusement estimer la recharge des aquifères est une tâche difficile car les processus de recharge sont complexes et les méthodes développées pour les milieux tempérés sont souvent inadéquates (Allison et al., 1994; Lerner et al., 1990; Simmers and Hendrickx., 1997). Par ailleurs, l'immensité et l'isolation qui caractérisent bon nombre de régions semi-arides ont très souvent limité les études hydrologiques et hydrogéologiques. La télédétection et les systèmes d'information géographiques (SIG) offrent une alternative séduisante à ce problème. Néanmoins l'utilisation de ces outils reste un fait rare et ce particulièrement en hydrogéologie des milieux semi-arides. C'est pourquoi nous avons choisi d' explorer ce sujet.

Les travaux de recherche présentés dans cette thèse se concentrent sur la partie centrale du basin du Lac Tchad où l'aquifère quaternaire, qui couvre près de 500,000 km^2, constitue la principale ressource en eau pour la population. En plus de la difficulté à estimer la recharge mentionnée ci-dessus, le centre du bassin du Lac Tchad et l'aquifère quaternaire présentent, en matière de recherche scientifique, de nombreux challenges dont: l'échelle du bassin, le peu de moyens pour la collecte des données, de remarquables caractéristiques hydrologiques et hydrogéologiques dont de larges dépressions piézométriques, et d' importants changements hydro-climatiques (sécheresses depuis les années 1970).

La méthodologie

La méthodologie employée réside dans l'utilisation combinée d'un SIG et de la télédétection pour l'estimation et la gestion des ressources en eaux. En sciences, les SIG sont appréciés pour la capture, la manipulation, l'interprétation et la communication de données spatialisées, quelles soient d'origines diverses ou d'échelles multiples (*e.g.*, Singh, 1996). Par ailleurs, la télédétection fournit une vaste gamme de données qui peut s'avérer très utile en matière de connaissance et de gestion des ressources en eau. L'utilisation couplée d'un SIG et de la télédétection permet donc l'acquisition de nouvelles informations et une exploitation optimale de l'ensemble des données (existantes et nouvelles). C'est cette approche qui doit permettre, dans la partie centrale du bassin du Lac Tchad, l'amélioration de nos connaissances sur les ressources en eau.

L'approche employée tout au long de la thèse fait ainsi appelle à deux disciplines, d'un côté l'hydrogéologie et de l'autre les SIG et la télédétection. C'est donc grâce à une co-opération entre experts dans ces différentes disciplines que le projet a pu être mené à bien. Concrètement la thèse a été effectuée en co-tutelle entre l'Université de Glamorgan, spécialisée dans la télédétection et les SIG, et le laboratoire d'hydrogéologie de l'Université de Poitiers. A ce groupe de recherche vient s'ajouter l'Institut de Recherche pour le Développement (IRD), France, qui a été impliqué depuis le début du projet. L'IRD a grandement contribué à ce projet et a notamment fourni des données satellitaires, une expertise scientifique du milieu de l'étude et un appui technique sur le terrain.

Les résultats

Un chapitre est consacré à une revue critique des diverses estimations proposées à ce jour pour les processus de recharge et de prélèvement de l'aquifère quaternaire. Il apparaît que les estimations sont divergentes et que par conséquent il y a un réel besoin de plus d'efforts scientifiques à ce sujet (*cf.*, Ch 3).

Une analyse des données géographiques montre que le recours aux SIG et à la télédétection permet d'améliorer grandement les données actuellement à la disposition des hydrologues et des hydrogéologues (*cf.*, Ch 4). Néanmoins l'utilisation des SIG et surtout de la télédétection en hydrogéologie des milieux semi-arides reste un fait très rare. Dans le Bassin du Lac Tchad ces outils n'ont jamais été employés pour l'étude de l'aquifère quaternaire.

Aussi a-t-il été décidé d'examiner l'utilisation des SIG et de la télédétection pour cartographier les zones de recharge et de prélèvement de l'aquifère quaternaire. Une telle application en milieux semi-arides et sur des matériaux meubles représente, à notre connaissance, une première. Les résultats sont très positifs et révèlent des découvertes.

Au dessus des dépressions piézométriques la topographie apparaît si plate que l'on n'observe pas de ruissellement et de concentration des eaux de pluies dans des mares (*cf.*, Ch 6.3). Ainsi l'infiltration des précipitations ne pas peut être de type indirect, mais se fait essentiellement sous forme diffuse (recharge directe). Or, en zones semi-arides la recharge de type indirecte est reconnue comme étant généralement plus importante que la recharge directe (Favreau, 2000 b; Leduc and Desconnets, 1994 b; Leduc et al., 2001; Lerner et al., 1990; Simmers and Hendrickx., 1997). Toujours dans les régions de dépressions, les données thermiques du satellite Météosat ont montré pour la première fois qu'en fin de saison des pluies l'eau ne s'infiltre pas mais reste à la surface du sol où elle est soumise à une forte évapotranspiration (*cf.*, Ch 6.3.4). Par ailleurs, on relève dans le paysage la présence d'arbres phréatophytes (Gaston, 1996) dont le système racinaire extensif peut atteindre la nappe à plusieurs dizaines de mètres sous le sol. En terme de bilan, d'une part la très faible infiltration des eaux de pluie, et d'autre part l'évapotranspiration pouvant affecter la nappe même à grande profondeur se traduit par un déficit en eau. Si bien que les dépressions piézométriques peuvent être interprétées comme des zones de prélèvements naturels. Ces informations sont les premières observations à supporter clairement le schéma théorique émis par Aranyossy et Ndiaye (1993). Selon ce schéma certaines dépressions piézométriques du Sahel ont lieu dans des régions de très faible recharge par les précipitations, où le déficit en eau ainsi généré par l'évapotranspiration n'est pas compensée par de faibles apports latéraux.

En contraste, il n'est pas observé de dépression piézométrique là où la topographie permet une importante concentration des eaux de pluie dans les bas-fonds et donc une recharge indirecte de la nappe (*cf.*, Ch 6.3).

De manière frappante il n'y a pas de végétation arborée au dessus des dômes piézométriques du Harr et du Kanem. Par conséquent l'évapotranspiration est faible dans ces zones. On obtient par là une explication clef de la présence des dômes piezometriques dans ces deux régions (*cf.*, Ch 6.2.3).

Ailleurs dans les champs de dunes, une multitude de petites zones dispersées dans le paysage apparaît sur les images satellitaires comme les seules zones où la végétation reste active durant la saison sèche; ce sont les oasis. Seul l'aquifère quaternaire peut permettre d'alimenter cette végétation tout au long de l'année. Ces oasis correspondent donc à des zones de prélèvements naturels dans la nappe (*cf.*, Ch 6.3.5).

Dans l'ensemble ces travaux montrent que l'aquifère superficiel du quaternaire est très dépendant des caractéristiques de surface. La télédétection et les SIG s'avèrent des outils très pertinents et efficaces pour la cartographie des zones de recharge et de prélèvement.

Un autre volet de cette thèse est le développement d'un modèle d'écoulement souterrain pour l'aquifère quaternaire. Cette seconde phase est une suite logique car un modèle constitue un outil idéal pour comprendre et gérer l'aquifère. Mais surtout, grâce au SIG, le modèle fait une utilisation originale et avant-gardiste des données de terrain et de la télédétection. Ce qui plus largement, démontre l'intêret d'une utlisation optimale de ces données lors de modélisation hydrogéologiques en milieux semi-arides. Dans le cas du bassin du lac Tchad cette approche nous a permis de modéliser l'aquifère quaternaire dans son ensemble (500,000 km^2), mais aussi de simuler les changements majeurs survenus entre 1960 et 2000 dont les variations hydroclimatiques. C'est, à notre connaissance, la première fois au Sahel que la modélisation d'un large aquifère superficiel est réalisée de manière si compréhensive.

La calibration du modèle en régime permanent montre qu'il n'existe qu'un jeu limité de possibilités pour la distribution et la valeur des zones de recharge et de prélèvement. Cette distribution est similaire à celle obtenue à partir du SIG et de la télédétection, et fournit donc une validation indépendante des résultats et de la méthode. A partir de là, il est devenu possible d'utiliser le SIG et la télédétection pour mieux délimiter les zones de recharge et de prélèvements. Ceci constitue encore une nouvelle application en matière de modélisation hydrogéologique dans les milieux semi-arides.

Le modèle montre que l'hydrodynamique de l'aquifère se caractérise par de faibles écoulements. Ceci est d'ailleurs confirmé par les faibles gradients hydrauliques qui s'observent sur l'ensemble du domaine et par le fait qu'il n'existe qu'un nombre limité de sorties possibles.

En effet, le modèle indique que les débits sortant vers les Pays-Bas tchadiens ne sont pas supérieurs à 100E+06 m^3/an. Les autres zones de sortie sont les dépressions piézométriques. Le modèle indique qu'un faible prélèvement de l'ordre du mm/an, en accord avec la profondeur importante de la nappe dans ces regions, suffit à recréer les dépressions telles qu'on les observe, pourvu que des transmissivités relativement faibles limitent les échanges latéraux. Le modèle corrobore ainsi le schéma conceptuel discuté plus haut.

La recharge de l'aquifère par le Lac Tchad peut être estimée entre 40E+06 m^3/an et 100E+06 m^3/an, c'est à dire beaucoup moins que les estimations précédentes (Carmouze et al., 1983; Isiorho et al., 1996; Roche, 1980).

Une recharge régionale par les précipiations a lieu dans les champs dunaires et les zones de mares temporaires. Cette recharge néanmoins reste faible et ne dépasse pas les quelques mm/an.

La modélisation a été étendue en transitoire pour simuler l'évolution de la nappe depuis 1960 jusqu'en 2000. Grâce au SIG et aux archives satellitaires, il a été possible de reconstituer et d'introduire dans le modèle les variations du Lac Tchad pour l'ensemble de la période (*cf.*, Ch 9.3). Un emploi aussi intensif de données satellitaires représente sans doute une première en modélisation hydrogéologique. Ce travail illustre la valeur des archives satéllitaires pour relater les changements de l'environnement. Il apparaît désormais clair qu'elles sont d'un grand intérêt pour la construction des modèles hydrogéologiques de long terme.

Une nouvelle analyse des chroniques piézométriques est proposée sur l'ensemble de l'aquifère en ne conservant que les données de qualité. Elle montre régionalement entre les années 1960 et 1990 une légère baisse de la nappe à l'exception des environs du Lac Tchad où la baisse est plus prononcée.

En accord avec les données de terrain, le modèle en transitoire montre que le retrait du Lac Tchad engendre une baisse importante des niveaux de la nappe, mais que cette baisse est limitée à la bordure du lac "normal" (*cf.*, Ch 9.6.1).

L'impact de l'augmentation des prélèvements anthropiques est fort dans les zones densément peuplées: Maiduguri, N'Djamena, et zone interfluviale du Chari-Logone ("zone de concentration"). De même, dans la région de Bol, le modèle indique que les forts prélèvements pour l'irrigation ont abaissé le niveau de la nappe. Sur le reste du domaine, c'est à dire la quasi totalité de l'aquifère quaternaire, l'augmentation des prélèvements n'a pas causé de baisse significative de la nappe (cf., Ch 9.6.2).

Dans les régions de recharge par les précipitations, champ de dunes et zone de recharge indirecte, une diminution de la recharge de 50% engendre une baisse de la nappe comparable à celle observée (*cf.*, 9.6.3).

C'est à notre connaissance la première fois au Sahel qu'un large aquifère est modelisé de manière aussi approfondie. Cette étude montre clairement la valeure des données satellitaires et de l'utilisation des SIG en hydrogéologie des milieux semi-arides. Les succès rencontrés dans le bassin du Lac Tchad nous laissent penser que dans d'autres régions semi-arides du monde, une telle approche peut s'avérer d'une grande assistance pour la compréhension et la gestion des ressources en eaux.

Abstract

This project investigates applications of GIS and remote sensing to advance the hydrological understanding and improve the management of the water resources in large semi-arid regions. In the Lake Chad Basin, Africa, it is demonstrated how remotely sensed data can contribute significantly to a groundwater problem, something which historically has not often been achieved, particularly in semi-arid areas.

In semi-arid areas, water is scarce and groundwater is often the only perennial resource available for the population. In the central part of Lake Chad Basin, this study focuses on the Quaternary aquifer which covers a vast surface area of 500,000 km^2 and provide most of the water used by human activities (Eberschweiler, 1993; FAO-Schroeter and Gear, 1973; UNESCO-PNUD-CBLT, 1972). So far, there are significant differences in the estimations of recharge and discharge phenomena of the Quaternary aquifer. Another scientific issue is the presence across the Quaternary aquifer of large piezometric depressions (Eberschweiler, 1992; FAO-Schroeter and Gear, 1973; Greigert, 1979; Schneider, 1969; Schneider and Wolff, 1992; UNESCO-PNUD-CBLT, 1972). Although, various theories about their formation and their mechanism have be raised (Aranyossy and Ndiaye, 1993; Dieng and Ledoux, 1987; Dieng et al., 1990; Durand, 1995), up to now little or no evidence has been gathered to confirm a particular explanation.

An analysis of the basin's data shows that the use of GIS and appropriate remotely sensed data can greatly enhance the information currently available to hydrologists and hydrogeologists.

The use of GIS and remote sensing to map groundwater recharge and discharge areas constitutes, in this kind of environment, a novel application. In the centre of the Lake Chad Basin, this approach has highlighted our knowledge of recharge and discharge processes, and it has enabled mapping major recharge and discharge areas. Among the outcomes, this approach has compiled, for the first time, evidence that the piezometric depressions correspond to very low infiltration areas. The fact that the rainfall recharge is considerably limited leads us to believe that evapotranspiration processes dominate the vertical exchanges, and that the piezometric depressions correspond to discharge areas. In the dunefields, a multitude of small discharge areas are revealed by vegetation indices, which show that the vegetation remains very active during the dry season. Such areas correspond to active oases, and were mapped in the Manga and at the border of the Harr and Kanem regions. Surprisingly, there are neither active oases, nor any tree layers, over the piezometric domes. One can deduce that the transpiration processes are lower than in the rest of the dunefield, and thus that the net recharge of the aquifer might be higher. Overall, throughout the Quaternary aquifer, surface characteristics (topography, soil permeability and vegetation) appear to have a strong influence on recharge and discharge processes.

A groundwater model of the whole of the Quaternary aquifer was developed to explore novel applications of GIS and remote sensing in groundwater modelling. The model has allowed new

knowledge of the aquifer system to be gained and has offered a first quantification of the groundwater reserves.

The model's calibration in steady-state was first conducted independently of applications of GIS and remote sensing to map groundwater recharge and discharge areas. Outcomes clearly back up the information revealed with GIS and remote sensing. It was then possible to use remote sensing and GIS to improve the calibration of the model with a finer definition of recharge and discharge areas.

The steady-state model has given information on the value and the distribution of long-term regional recharge and discharge. Rainfall recharge takes place in the dunefields, but appears to be small (less than 1 mm/yr in the Manga and less than 5 mm/yr in the centre of the Harr and Kanem). The model shows the necessity of representing the piezometric depressions as discharge areas. A good representation is obtained for a discharge rate below 3 mm/yr. The contribution from Lake Chad is very different from previous estimations and is thought to be less than 100E+06 m^3/yr (Carmouze, 1983; Isiorho, 1996; Roche, 1980).

The model was then extended to a transient simulation from 1960 to 2000. Satellite archived data and GIS have allowed a comprehensive reconstruction of the fluctuations of the extent of Lake Chad. These data were implemented into the groundwater model in order to assess the impact of this major environmental change on the aquifer. This novel application, which makes an intensive use of remote sensing and GIS in the model, demonstrates the value of archive satellite data for long-term groundwater modelling.

The model shows that the impact of the shrinkage of Lake Chad on the aquifer is limited in space to the Lake's region. It also reveals that the aquifer's reserves are threatened by the increase of the population in densely populated areas (Maiduguri, N'Djamena and "zone de concentration"). The drop of the water table in the dunefields could be related to a decrease of the rainfall recharge by more than 50%.

Overall, the water budget of the aquifer is characterised by the endorheism of the system, with most of the outflows assured internally. Also, with regard to water resources management, the Quaternary aquifer offers a paradox: it is characterised by vast reserves, but a small renewable resource (recharge).

It is, to the best of our knowledge, the first time that a large superficial aquifer of the Sahel has been modelled so thoroughly and understood as a whole. This study clearly illustrates the value of GIS and remotely sensed data in the hydrogeology of semi-arid areas. Successful applications of the Lake Chad Basin leads us to believe that in other semi-arid regions of the world, remote sensing and GIS could bring valuable assistance to hydrologists and hydrogeologists.

Chapter 1

INTRODUCTION

1.1 ISSUES AND OBJECTIVES

In semi-arid regions, sustainable management of the water resources is generally regarded as a crucial requirement in response to the limited water resources of these regions and the prospect of water shortages. Attaining this sustainable management is often difficult because of a fragile and rapidly changing environment, as well as an insufficient knowledge of hydrological processes.

Environments strongly affected by aridity (hyper-arid to semi-arid) account for 32 % of the World and 57% of Africa (Figure 0-1). Semi-arid areas are characterised by very high evapotranspiration rates and low seasonal precipitation. Surface-water features are generally temporary and therefore groundwater is often the only perennial resource available for the population. In this context, it is an essential task for hydrogeologists to estimate recharge of aquifers. Unfortunately, it is also recognised as a challenging issue: in semi-arid regions, recharge processes are complex and varied, and methods developed for temperate climate are not appropriate (Allison et al., 1994; Lerner et al., 1990; Simmers and Hendrickx., 1997). In arid and semi-arid parts of Africa, a major concern is the 'dramatic' hydroclimatic change that has particularly affected the Sahel since the middle of the 1960's. A large decrease in rainfall and river discharge has led to severe droughts in the Sudano-sahelian zone (Mahe and Olivry, 1995; UNEP, 1992). Still in the Sahel band, another example of an unsolved question is the origin of enigmatic piezometric depressions (also referred as hollow aquifers) that affect superficial aquifers (Figure 0-2). The first descriptions of these piezometric anomalies were given by Archambault (1960) and Degallier (1954). Since then, they are often considered as "the major enigma in Sahelian hydrogeology" (Aranyossy and Ndiaye, 1993) and explanation of their origin is still under much debate (Aranyossy and Ndiaye, 1993; Dieng and Ledoux, 1987; Dieng et al., 1990). It must be acknowledged that when, in addition to these difficulties, water resources managers have to study a very large basin (such as the Lake Chad Basin), the task becomes very daunting.

The overall scope of the work presented in this PhD thesis is to investigate the benefits of using GIS and remote sensing for water resources management in large semi-arid regions, and to apply these tools for the specific case of the Lake Chad Basin (see Figure 1-3). The characteristics of semi-arid regions – such as vastness, hostile conditions, lack of infrastructure, remoteness, etc – often restrict the scope and scale with which systematic studies are carried out. In many of these regions, this has certainly contributed to limit our understanding of the hydrological and hydrogeological processes. It is, therefore, of critical importance that, for the development of these regions, a more systematic and integrated approach is adopted. As such, advances in recent technologies, like remote sensing and GIS, offer a solution to improve the acquisition, processing, management and interpretation of data from various sources at various scales.

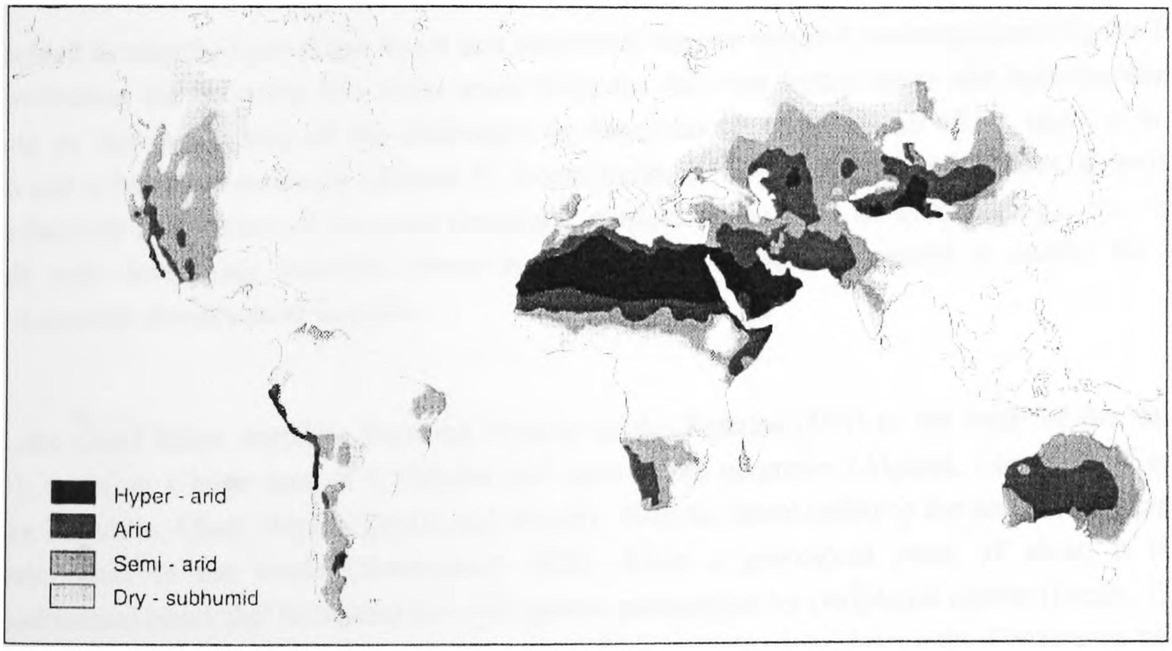


Figure 1-1: Location of semi-arid areas in the World (UNEP, 1992).

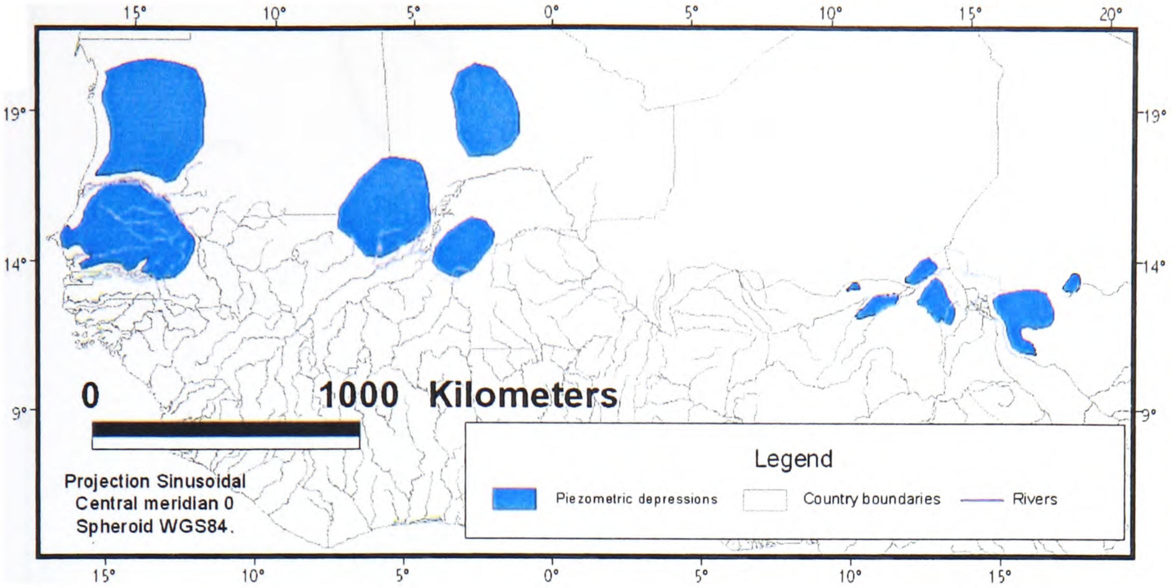


Figure 1-2: Location of the major piezometric depressions in Sahel (modified from Aranyossy, 1993).

1.1.1 THE LAKE CHAD BASIN CASE STUDY

We decided to take the Lake Chad Basin as a case study for our research investigations (Figure 1-3). Our motivation for choosing this basin arose from the fact that hydrologists and hydrogeologists working on this region face all the challenges we have just mentioned. Half of the basin is in the Sahara and it has been seriously affected by recent hydroclimatic changes. Besides that, there have been relatively few studies of its water resources, particularly so with its hydrogeology. The basin extends over developing countries where more scientific efforts are needed to enable the best socio-economic development possible.

The Lake Chad Basin stretches from the vicinity of the Equator (5°N) to the heart of the Sahara (27°N), covering a huge area of 2,500,000 km^2 over seven countries (Algeria, Cameroon, Central African Republic, Chad, Niger, Nigeria and Sudan). With no direct outlet to the sea, it is the largest endoreic basin in the world (Herdendorf, 1982). From a geological point of view, it is an intracontinental basin that is located in a rift system surrounded by peripheral uplifts (Burke, 1976). The central part of the basin began to fill with sedimentary deposits during the Cretaceous period (Cratchley, 1984; Genik, 1992). Within the basin, there are three climatic zones with differing hydrology, namely: Saharian, Sahelian and Sudanian. Groundwater is the only water resource in the arid northern part. At the latitude of Lake Chad (between 14°N and 10°N) the climate is Sahelian, with a monsoon season from March-April to October-November and a dry season for the rest of the year (Beauvilain, 1996). In this zone, most of the surface water features are temporary. In the south, the climate is Sudanian (tropical humid) with two rainy seasons, and two main perennial rivers – the Chari and the Logone.

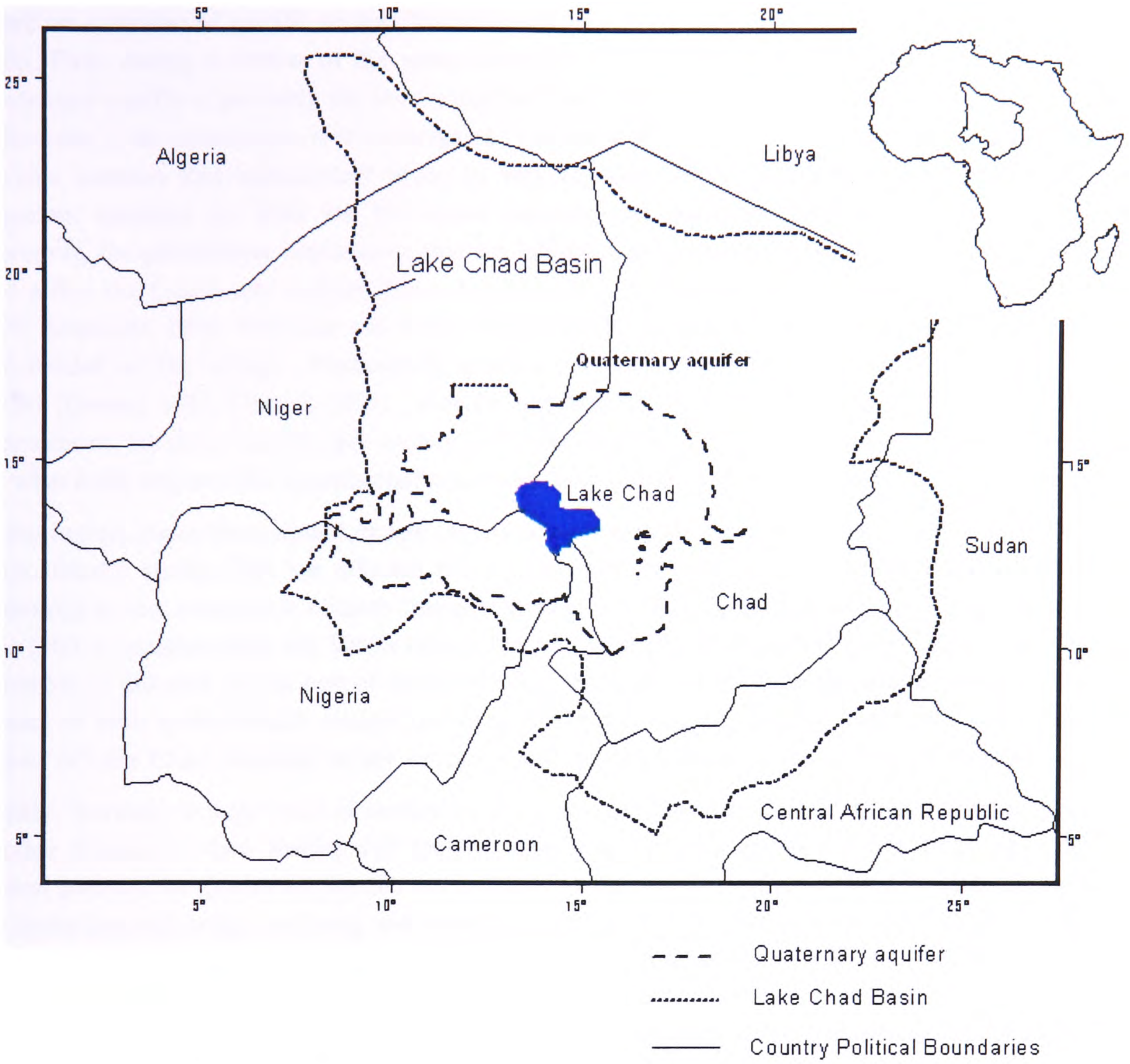


Figure 1-3: Location of the Lake Chad Basin in Africa.

Bearing in mind the basin as a whole, our research work focuses on the central part in the Sahel. This region is characterised by a large fresh water lake – Lake Chad – which lies just at the border of the Sahara and is shared by four countries (Cameroon, Chad, Niger and Nigeria). The main rivers of the basin discharge into the lake, with the Chari/Logone rivers contributing the most, whilst the El'Beid and the Komadugu Yobe only bring in relatively small inputs (Roche, 1980). In this central part of the basin, most of the water used for human activities is abstracted from the Quaternary aquifer. This aquifer is a continuous water table contained in superficial deposits that are composed of aeolian and fluvio-lacustrine sediments. It forms an extensive reserve covering the whole centre of the basin and offers a relatively easy access to water (Eberschweiler, 1993 b; FAO-Schroeter and Gear, 1973; UNESCO-PNUD-CBLT, 1972).

There are a number of specific reasons that led us to concentrate our efforts on the central part of the basin. First, during a review of the water resources in the basin, we noticed that although the Quaternary aquifer is probably the most essential water resource of the basin, there are significant differences in the estimations of its recharge and discharge phenomena (see Ch 3). An important and obvious question that immediately arises is, why are there these discrepancies? An even more important question, is, what are the actual recharge and discharge processes of the aquifer? Moreover, the piezometric depressions that are observed in superficial aquifers of the Sahel band also affect the Quaternary aquifer (Eberschweiler, 1992; FAO-Schroeter and Gear, 1973; Greigert, 1979; Schneider, 1969; Schneider and Wolff, 1992; UNESCO-PNUD-CBLT, 1972). More research is also needed on this subject . Explanations given for the depressions of the Quaternary aquifer are varied (Durand, 1982; Durand, 1995; Schneider and Wolff, 1992). The literature so far formulates suppositions, but does not offer any evidence. We are therefore left with fundamental questions such as: what is the origin of the depressions? what does their current dynamics consist of?

In this region, major issue cannot escape anyone concerned with water resources. It is the `dramatic′ hydroclimatic change that has affected the region since the 1960's. In fact, the basin's surface hydrology is very sensitive to climate change (Olivry et al., 1996). According to Lemoalle (1996) and Coe (2001) droughts since the 1960's caused the lake to shrink from approximately 22,600 km^2 to about 5% of this size. To the best of our knowledge, there has not yet been any attempt to assess the impact of such hydroclimatic change on the groundwater. Urgent questions such as "what is the impact of Lake Chad shrinkage on the surrounding Quaternary aquifer?" have yet to be addressed.

Finally, working on large areas is certainly a common problem in the GIS community, but it takes another dimension when dealing with regions such as the Lake Chad Basin. Even restricted to the central part and the Quaternary aquifer we are still talking of an area of about 500,000 km^2. There is no doubt that collecting, analysing and managing data at such a scale represents a difficulty. Even with the use of remote sensing, which is acknowledged as a powerful tool for data collection over large areas, the scale here is still phenomenal. For example, to cover the basin with Landsat MSS data would require more than a hundred scenes and 25 are needed for the Quaternary aquifer alone. In addition, the economic situation of the countries in the basin offers limited resources for surveying and systematic data acquisition. This, together with the difficulties of accessing many areas of the basin, makes data collection a real challenge. The consequence of all these factors is a scarcity in geographical information. Hydrologists and hydrogeologists often need to look at the basin or at the aquifers as a whole entity. However, at the same time they need accurate information (high-resolution data). For instance, they need to be able to define ponding areas or oases. Most of the published maps covering the entire basin or the aquifer are generally too sketchy and are unable to offer the accurate information required. Besides, only a limited number of scientific studies have been carried out on the basin. Therefore, the cartographic works available are limited (see Ch. 3). The scale of the Lake Chad Basin is such that it extends over seven countries and the Quaternary aquifer over four. Each of these countries has various institutions involved in water resources management. The situation is therefore that hydrologists have to manage transboundary resources, which implies greater management difficulties and requires close collaboration with exchange of information and harmonised policies. This shows that for such environments, working with geographical information is still a real challenge and that GIS has a key role to play here.

1.1.2 REMOTE SENSING AND GIS CONTRIBUTION

The motivation for this thesis arose from our beliefs that further research on applying GIS and remote sensing can enhance the current knowledge and management of the water resources in the central part of the basin. So far in the basin, remote sensing has been successfully applied to monitor the extent of Lake Chad (e.g., Lemoalle, 1979 a; Olivry et al., 1996). However, it appears that hydrologists and hydrogeologists studying the Lake Chad Basin do not use all the possibilities offered by remote sensing, and this remark can probably be extended to other similar regions. For example, in groundwater hydrology of semi-arid areas, remote sensing has mainly been used for the detection of faults and lineaments affecting fractured rocks, as they often indicate more permeable zones because of the high degree of fracturation (Edet et al., 1998; Magowe and Carr, 1999; Sabins, 1997). To the best of our knowledge, remote sensing and GIS have never been used to map recharge and discharge areas under such conditions, i.e. semi-arid areas/unconsolidated sediments (Meijerink, 1996). Additionally, approaches combining the use of GIS and remote sensing with hydrological modelling have never been applied to the Lake Chad Basin.

1.1.3 SPECIFIC OBJECTIVES FOR THE THESIS

Having raised all the challenges and reviewed the unexplored areas for which GIS and remote sensing can make a contribution, our specific objectives for the thesis are to:

- Exploit multi-source and multi-scale remotely-sensed and ground-based data in a GIS in order to enhance the current level of understanding of the superficial aquifer in the central part of the Lake Chad Basin;

- Search for patterns in the surface characteristics over the piezometric depressions that could explain the origin of the depressions;

- Evaluate the application of remote sensing and GIS to map groundwater recharge and discharge areas;

- Demonstrate novel applications of remote sensing and GIS for the hydrogeological modelling of the Quaternary aquifer, with specific regard to the assessment of hydroclimatic change (particularly Lake Chad's shrinkage) on the aquifer;

- Offer a 'bird's eye view' of the centre of the basin. This is an opportunity to understand the basin's dynamics from a global and local perspective. The model developed is expect to allow modelling of the Quaternary aquifer (500,000 km^2) as a whole, to take into account surface characteristics and to represent hydroclimatic change affecting the surface. It is anticipated that this approach will throw new light on our knowledge of the basin;

- Provide the first steps towards an integrated system for the water resources management in the central part of the basin.

In addition to these scientific interests, it is important in our view that this research work leads to valuable and practical applications that contribute to the development of the countries sharing the water resources of the Lake Chad Basin.

1.2 MULTI-DISCIPLINARY APPROACH AND PARTNERSHIP

Our main contribution consists of bringing new information with the use of under exploited remote sensing data. We have decided to focus on affordable and readily accessible data to offer simple and operational applications with the intention to disseminate the results of our research work to relevant groups. The main reason for the under use of remote sensing in the basin so far, is probably that the cost of the data and of their processing used to be prohibitive. This has changed as more sensors continue to be launched, computer power and software capacity keep increasing and international efforts are made by the satellite operators to release geo-data to the scientific community.

These new data are integrated together with archived field data and published maps in order to offer an integrated representation of the basin dynamics and the most comprehensive database possible. The relevant way to handle all these data sets is to use a Geographical Information System (GIS). Indeed, GIS is a powerful tool for data capture, storage, manipulation, analysis and communication. It also supports multi-source and multi-scale data. GIS acts as a pre- and post-processor for the groundwater model and in that sense it can be seen as the first step towards an integrated system to support water resources management of the basin.

The approach employed makes use of two disciplines – hydrogeology, and GIS and remote sensing. The strength of our project lies in this multi-disciplinary approach which has been possible thanks to the collaboration of scientists with distinct expertise. Two European Universities are involved in the supervision of the present PhD: the University of Glamorgan (UK) and Poitiers University (Fr). This is formalised as a European co-supervision agreement for the PhD. The University of Glamorgan in the UK originated and led the program with its expertise in GIS and remote sensing. Meanwhile, the Hydrogeology Department from Poitiers Univeristy in France brought an essential contribution in hydrogeology and groundwater modelling. Following the move of one of the supervisors from Glamorgan, the collaboration now also involves Cardiff University as an additional centre of expertise.

Other collaborations and expertise were gathered for this project. The French Research Institute for Development (IRD) has been involved since the beginning of the project. It has greatly enhanced the project by bringing field knowledge and scientific expertise, and by allowing us to use their infrastructure in Niger.

We cannot forget the warm welcome our project has received from local and regional institutions. During the project, we have developed many links with African Institutions and particularly with the Lake Chad Basin Commission, which has an essential role as a regional institution in the management of the basin's water resources. Exchanges with all these African institutions have been particularly fruitful. We have been given access to numerous archived field data and, above all, we have benefited from their field knowledge. The richness of this thesis lies not only in the variety of data employed and in the originality of the approach, but also in the sharing of expertise and ideas with all our partners.

We wish to emphasise that field knowledge has been a constant concern throughout the project. In this respect, we had the chance to carry out two field missions in the central part of the basin. Both of them had the same goals: to develop collaboration with the basin's institutions, to retrieve archived information and to collect new field data. The first field mission took place in Niger for five weeks in June and July 1999. It was co-financed by the University of Glamorgan and the IRD. This allowed us to visit Niger's institutions in charge of or linked with water resources management. We also conducted a field mission throughout the whole Manga region to collect field data and water samples. This included surveying in the Kadzell, the Sahara (Termit Massif) and Lake Chad (which was back in Niger – see Ch. 9). The second visit to the basin was in February 2000 to Chad. It was co-financed by the University of Glamorgan and a travel grant from the Royal Academy of Engineering. During this field mission, we developed co-operation with local and regional institutions. It was also an opportunity for field visits to Lake Chad, the Chari River and Chari-Baguirmi plain.

1.3 STRUCTURE OF THE THESIS

The thesis is divided into three major parts. The first part examines the current management of the basin's water resource with a special emphasis on how GIS and remote sensing could be beneficial. It therefore seems natural to start with a chapter that presents the major characteristics of the basin with a special emphasis on its water resources. It does not contain any original material, but is simply aimed at introducing the reader to the water resources of the Lake Chad Basin. We then move on to a critical review of recharge and discharge estimations for the main water resource in the central part of the basin, i.e. the Quaternary aquifer. Although this chapter does not bring any new information either, it has the merit of being the first synthesis on the subject. We have no doubt regarding the importance of this, given the value of this aquifer for the socio-economic development of the region. It also raises the specific issues that need to be tackled, including significant differences in the estimation of recharge and discharge, but also an assessment of hydroclimatic change impact (especially Lake Chad's shrinkage) on the aquifer. The last chapter of this part is dedicated to the data challenge. It gives an assessment of the data sets available to hydrologists and hydrogeologists up to now. Then, it illustrates how GIS and remote sensing can significantly improve the situation and help to tackle the major issues raised above.

The second part investigates the use of GIS and remote sensing to map recharge and discharge areas of superficial aquifers in semi-arid regions. Chapter 5 reviews the literature on the subject, which leads to the development of a methodology for the Quaternary aquifer. In the next chapter we apply these techniques, for the first time, to map recharge and discharge areas of the Quaternary aquifer. Results are `astonishingly′ interesting and emphasise that remote sensing and GIS should become essential tools for hydrogeologists working in such environments. This chapter also answers the following question: Are there any surface characteristics linked to the presence of the piezometric anomalies in the Quaternary aquifer of the basin, i.e. the piezometric depressions and domes?

The third and final part of the thesis is entitled groundwater modelling with GIS and remote sensing. Chapter 7 analyses the characteristics of the Quaternary aquifer and proposes the development of an adequate groundwater model. The next chapter is dedicated to running the model in steady flow. It aims to understand and estimate the flows within the aquifer and the exchanges with the surrounding environment. It gives the location and the values of recharge and discharge areas. This allows a comparison with the results obtained in the second part with remote sensing and GIS. The last chapter of this part is devoted to running the groundwater model in transient mode. It reveals how we have been able to assess the impact on the aquifer of hydroclimatic change and of Lake Chad's shrinkage for the first time thanks to GIS and remote sensing.

This last part is therefore rich in new information. It gives a new estimation of the exchanges between Lake Chad and the Quaternary aquifer, and between the rivers and the aquifer. It also offers estimation of rainfall recharge, of discharge areas, and of the impact of Lake Chad's shrinkage.

This part gives us a better understanding of the Quaternary aquifer of the Lake Chad Basin as a whole. In this respect, beyond the value of each specific estimation, we identify and explain the hydrological processes for a large superficial aquifer of the Sahel.

PART I

Water Resources Management of Semi-Arid Regions: the need for GIS

In semi arid regions, such as the central part of the Lake Chad Basin, water is scarce. Yet, one is astonished by the diversity, the complexity and sometimes the elusiveness of the hydrological and hydrogeological processes. Far from solving all these enigma, this first part intends to set the thesis in this framework.

This part also offers a critical assessment of the successes, but also of the difficulties, currently encountered in the water resources management of the Lake Chad Basin. It proposes to tackle the following questions:

What are the urgent issues that need to be addressed in terms of water resources management?

Are there difficulties in defining and quantifying recharge and discharge processes?

What are the benefits hydrologists and hydrogeologists could expect in using GIS and remote sensing? Nowadays is this technology readily accessible?

Chapter 2

THE WATER RESOURCES OF THE LAKE CHAD BASIN

2.1 INTRODUCTION

Due to arid conditions, water is a scarce resource in most of the Lake Chad Basin. The majority of the basin's population is rural with extensive livestock farming and rainfed cropping. These factors, together with the recent droughts that have affected the Sahelian region, make it essential to be able to accurately assess and efficiently manage the water resources of the basin.

The objective of this chapter is to provide a concise background on the geography of the basin and on its water resources. It is proposed to describe, within their socio-economic context, the major issues regarding the water resources of the basin. Specific areas for which remote sensing and GIS can make a significant contribution are then identified. Given the time and resources attributed for this thesis, we specify which of them we regard as priorities and propose to investigate. This chapter is important since it justifies the choices we made regarding the subject of this PhD and places them, as well as the entire thesis, in a more general context.

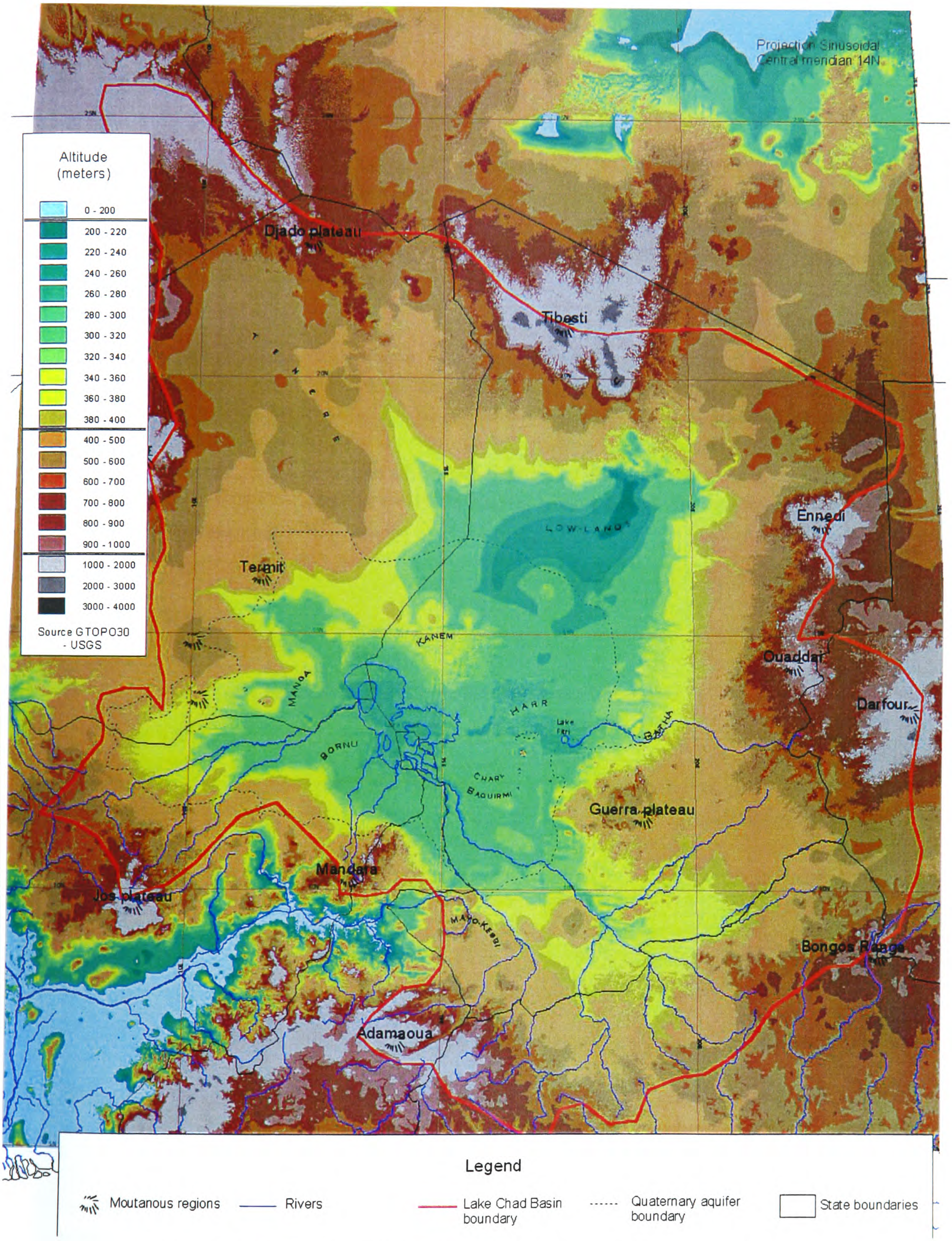


Figure 2-1: Topography of the basin and other elements of its geography.

2.2 GEOGRAPHY OF THE BASIN

The Lake Chad Basin lies in the centre of the African Continent, between 5°N - 25.7°N and 7°E - 27°E (Figure 2-1). It is a rich and beautiful environment. It extends through the Sahara in the north, the Sahel in the centre and the tropics in the south. The edges of the basin are surrounded by mountain ranges. Yet, the central part is very flat, and about 30% of the basin's surface area is between 200 and 400m above sea level.

The population of the conventional basin, which occupies the centre, is estimated to be about 10 million inhabitants. It is largely rural with activities ranging from cropping in the south, to livestock breeding in the north. Thus, it is not surprising that water occupies a central place in the societies of the basin (Jungraithmayr et al., 1997). However, water supplies need to be improved. It is reported, for example, that a large part of the population is without access to safe water: 46% in Cameroon; 32% in Chad; 39% in Niger; 51% in Nigeria (source UNDP for the period 1990-1998, see at http://www.undp.org/hdro/).

2.3 CLIMATE

2.3.1 MECHANICS OF THE CLIMATE IN THE LAKE CHAD BASIN

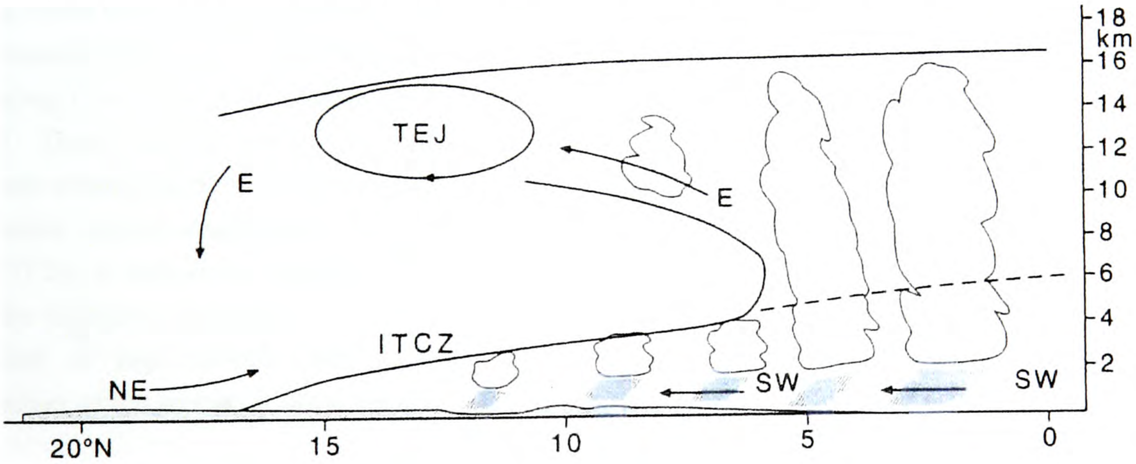


Figure 2-2: Typical meridional cross-section and climate mechanisms over West Africa during August (in McGregor, 1998).

This paragraph gives a brief background in tropical meteorology and recaps the mechanisms of the climate in the Lake Chad Basin. Heat transfers take place in the atmosphere between the warm inter-tropical regions and the colder high latitudes. This transfer is made through the North and South Hadley cells. Air masses flow in these cells according to a meridian circulation centred on the Meteorological Equator (ME), which is generally located to the north of the geographical equator

(Figure 2-2). The hot and light air of the Meteorological Equator rises and flows towards the poles. It progressively loses its heat and increases in density, so that, around the latitude of 30 degree, it goes down again. Most of it then returns to the Equator at a low altitude to complete the cell. Those air masses going back to the Equator are called trade winds and are initially dry. Nevertheless, on their way back to the equator, their humidity can increase considerably as they flow over the oceans. Their direction is deviated to the west by the Coriolis force. These airflows converge at the Intertropical Convergence Zone (ITCZ) where they rise, creating clouds and precipitation. In the tropics, this ITCZ is the major mechanism forming rainfall (in McGregor, 1998).

Low-pressure masses characterise the junction of the ascending Hadley cells flow at the ME. On the other hand, high-pressure masses (anticyclones) are found at the meeting of the descending flows. In our area of interest, these anticyclones are known as the Saint Helen anticyclone in the southern hemisphere and the Lybian anticyclone in the north.

The climate of the Lake Chad Basin is shaped by the relative strength of these anticyclones and the trade winds blowing from them towards the meteorological equator (Leroux, 1983). The Harmattan is the continental trade wind coming from the Lybian anticyclone (north of the ME) and oriented to the south-west. It brings dry and hot air and often carries dust. On the contrary, a wet oceanic trade wind known as the Monsoon comes from the Saint Helen anticyclone (south of the ME). Originally oriented to the north-west, it is deviated to the south-east once it has passed the geographical equator. It carries all the potential rainfall for the region.

The confluence of these trade winds takes place on the Meteorological Equator, which in section has the shape of an inclined plan (Figure 2-2). The northern part of the ME is also called the Inter Tropical Front (ITF). The monsoon brings potential rains to the ITF. However, the dry and hot air of the Harmattan blows upon the monsoon, which prevents the humidity of the monsoon rising by evaporating it or cutting the clouds. Brief and violent rains may nevertheless occur occasionally in the ITF. These rainfall events are called squall lines. They are generated by the intrusion of westwards stream inside the monsoon that lifts up the humid air in a mobile front of cumulo-nimbus along which rainfall and storms are generated. South of the ITF is the Inter Tropical Convergence Zone (ITCZ). It represents the central part of the ME. It is the place where the northern trade wind meets the southern trade wind in altitude. Both carry the humidity of the monsoon. This leads to production of high clouds and generates intensive rainfall. Behind the ITCZ, the normal stratification of the monsoon does not allow the formation of rains.

The whole system is mainly generated by the solar radiation (excluding Jet). Hence, it follows the sun's annual migration with a delay and smaller spatial amplitude. Since it is the only main rain producing system, this variation is highly significant. In the summer the ME goes to the north and reaches the centre of the basin where it brings rain. In January and February it has a southern position, and most of the basin doesn't receive any rain (Figure 2-3).

To conclude, one must remember that the climate of the Lake Chad Basin is guided by the movement of the ITCZ. It is characterised by seasonal patterns and a northward decreasing gradient of the rainfall. Additionally, due to the convective character of the ITCZ, rainfall events are often intense and of short duration.

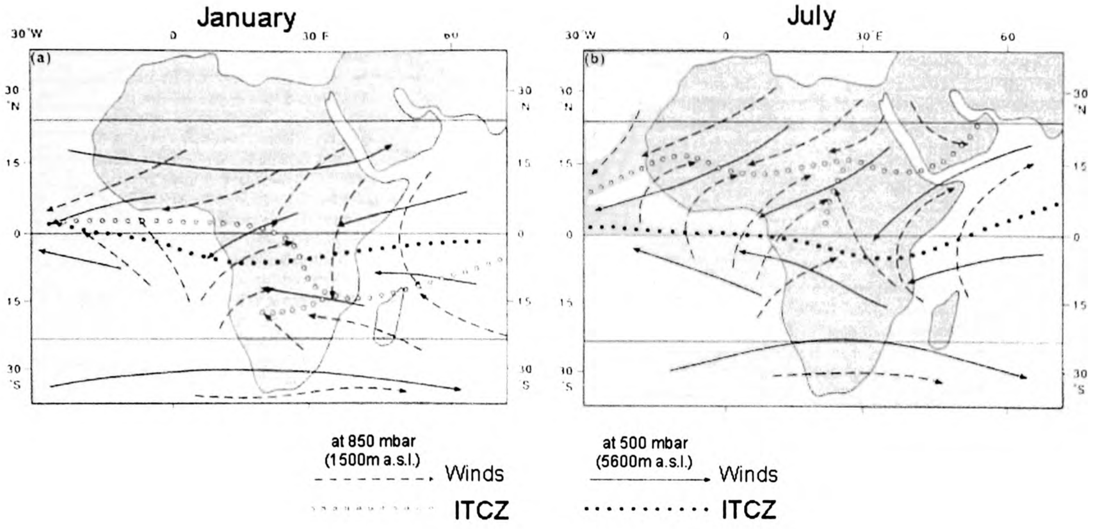


Figure 2-3: The position of the ITCZ and the circulation of winds over Africa during January and July at 1500m and 5800m (in McGregor, 1998).

2.3.2 CLIMATIC DOMAINS IN THE BASIN

From north to south, one can distinguish three main climatic zones within the basin (Figure 2-4). This general schema can change close to small relief and the massifs at the edge of the basin.

The Saharan domain

This covers all the northern part of the basin. The continental trade wind (the Harmattan) is continually present, whereas the monsoon and the ITCZ (or ME) never reach this domain. The climate is characterised by a high daily variation of the temperature, very low rainfall (for example, the average annual rainfall at Bilma is 18 mm/yr), and a very low relative humidity.

The Sahel domain

This covers the central part of the Lake Chad Basin (from 15°N to 10°N). It is characterised by a short rainy season, which occurs once per year during the boreal summer (May to October). The rainfall events, brought by the monsoon, correspond to the squall lines of the ITF. For the rest of the year, roughly 8 months, the climate is very dry and dominated by the winds of the Harmattan. This area is rarely under the central structure of the ME where the rainfalls are the most important.

The south Sudan domain

To the south of the basin, the rainy season starts with the arrival of the ITF and its squall lines. It is followed by the central part of the ME that stays from July to September bringing with it heavy rains. The end of the rainy seasons is characterised by the retreat of the ME and a second passage of the ITF. Later comes a dry period of three to four months dominated by the Harmattan.

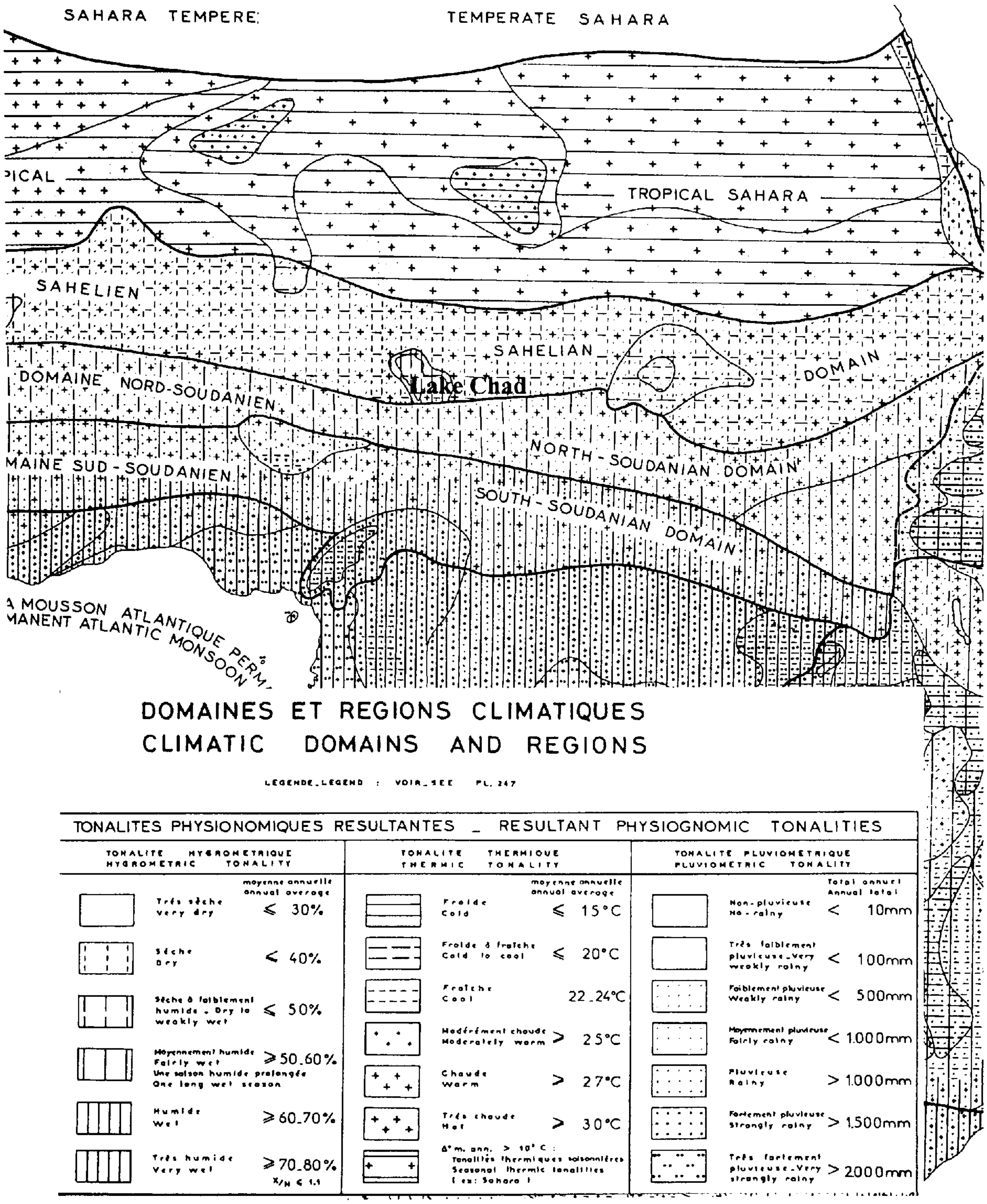
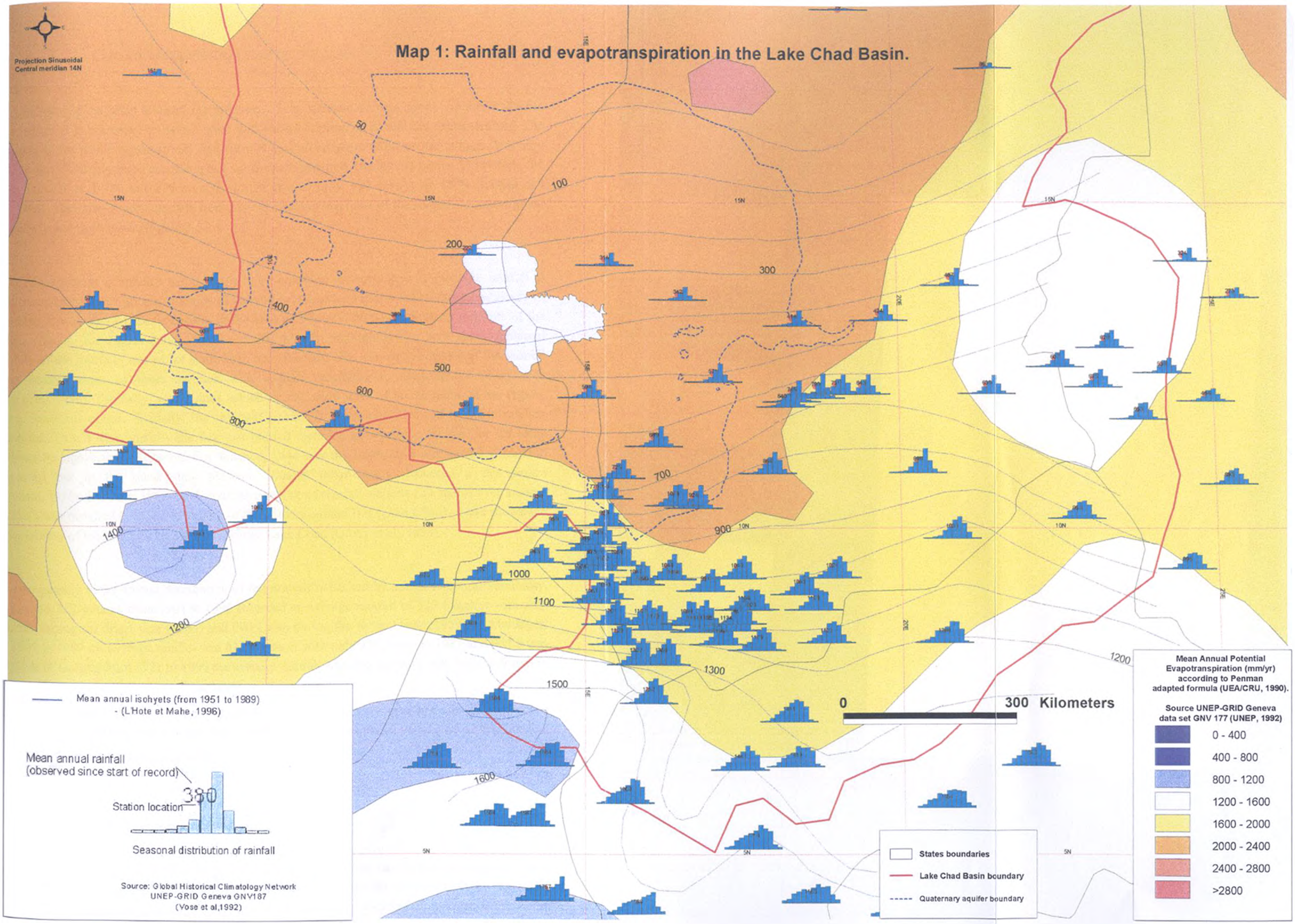


Figure 2-4: Climatic domains in the Lake Chad Basin (from Leroux, 1983) - Note that the latest data used are from 1970.

The permanent South Atlantic monsoon domain

To the extreme south of the basin, one can notice the influence of another climate: the permanent south Atlantic domain. It doesn't have a real dry season, but two heavy rainy seasons separated by two low rainy spells. These two strong rainy seasons correspond to the passages of the central part of the ME (characteristic bimodal of the rainfall) - once when the ME goes to the north at the beginning of the boreal summer and once when it comes back.



Map 1: Rainfall and evapotranspiration in the Lake Chad Basin.

2.3.3 CLIMATE IN THE CENTRAL PART OF THE BASIN

Rainfall

The central part of the basin is under the influence of the sahelian climate. Since the thesis focuses on this region, it is necessary to have a more detailed description of its climate characteristics. The topography of the whole region is very flat; there is thus no orogenic effect on the climate. It is only guided by the ITCZ migration according to a south-north gradient. During the period 1951-1989, the average rainfall at 10°N was 800 mm/yr, whilst it was only 100 mm/yr at 15°N (L'Hôte and Mahé, 1996). The rainy season extends from May to October but most of the rainfall is concentrated between July and September (Figure 2-5).

Behind this apparent simplicity lies a much more complex meteorology. In fact, the rainfall is characterised by a very high spatio-temporal variability. Elsewhere in the Sahel, this particularity of the climate is well known. For example, in the area of Niamey, often taken as an example of the Sahelian climate, the Hapex-Sahel experiment has clearly highlighted the high spatio-temporal variability of the rainfall (*Journal of hydrology*, vol 188-189). The convective nature of the rainfall implies heavy storms of short duration with a high variability in their spatial distribution (Amani et al., 1996). Typically, squall lines, which are the main form of precipitation in the region, are very localised events. Spatially, the seasonal rainfall is hence characterised by large random fluctuations. This is illustrated by the fact that rainfall recorded at two close stations for the same period can be significantly different. For instance, 1944 was the height of a wet period at Mokolo (Cameroon) but in the mean time Maroua, situated 60km away, recorded a dry period (Beauvilain, 1996). Between 1962-1964, a dense network of rainfall stations (20 stations for an area of 31 km^2) was installed to study the region of the polders around Bol (Lake Chad). It has shown the high variability of the rainfall at local scale nearby Lake Chad (Olivry et al., 1996).

The heterogeneity in the spatial distribution of the rainfall is backed by a high temporal variability. For example, N'Djamena from 1904 to 1990 recorded an average rainfall of 575.4 mm/yr with only 226.1 mm during the driest year (1984) and 990.1 mm during the wettest year (1959); at Maiduguri from 1909 to 1989 the average rainfall was 621.9 mm/yr with only 239.2 mm in 1982 and 963.5 mm in 1939; at N'Guigmi from 1921 to 1990 the average rainfall was 206.5 mm/yr with only 40.9 mm in 1928 and 472.2 mm in 1961 (Beauvilain, 1996).

In the Sahel, it seems that each type of rainfall storms is stationary in space and in time at the interannual scale: i.e. they conserve the same magnitude. The interannual variability of the Sahelian rainfall appears hence to result only from fluctuations in the number of rainfall events (D'Amato and Lebel, 1998; Lebel and Le Barbe, 1996).

Inter-annual evolution during the 20th century

It is sometimes difficult to extract general variation of the climate given the high variability: for the same station two extremes and opposite years can follow each other (Beauvilain, 1996). Tools such as running mean can, however, reveal general trends. Above all, rainfall must be analysed regionally bearing in mind that a dry spell regionally may be for a specific location an average spell. As an example, the 1940's is generally a dry period over the basin, but this is not true at Bebedja, Sarh, Bongor and N'Djamena where 1938-1947 was a wet spell (Beauvilain, 1996).

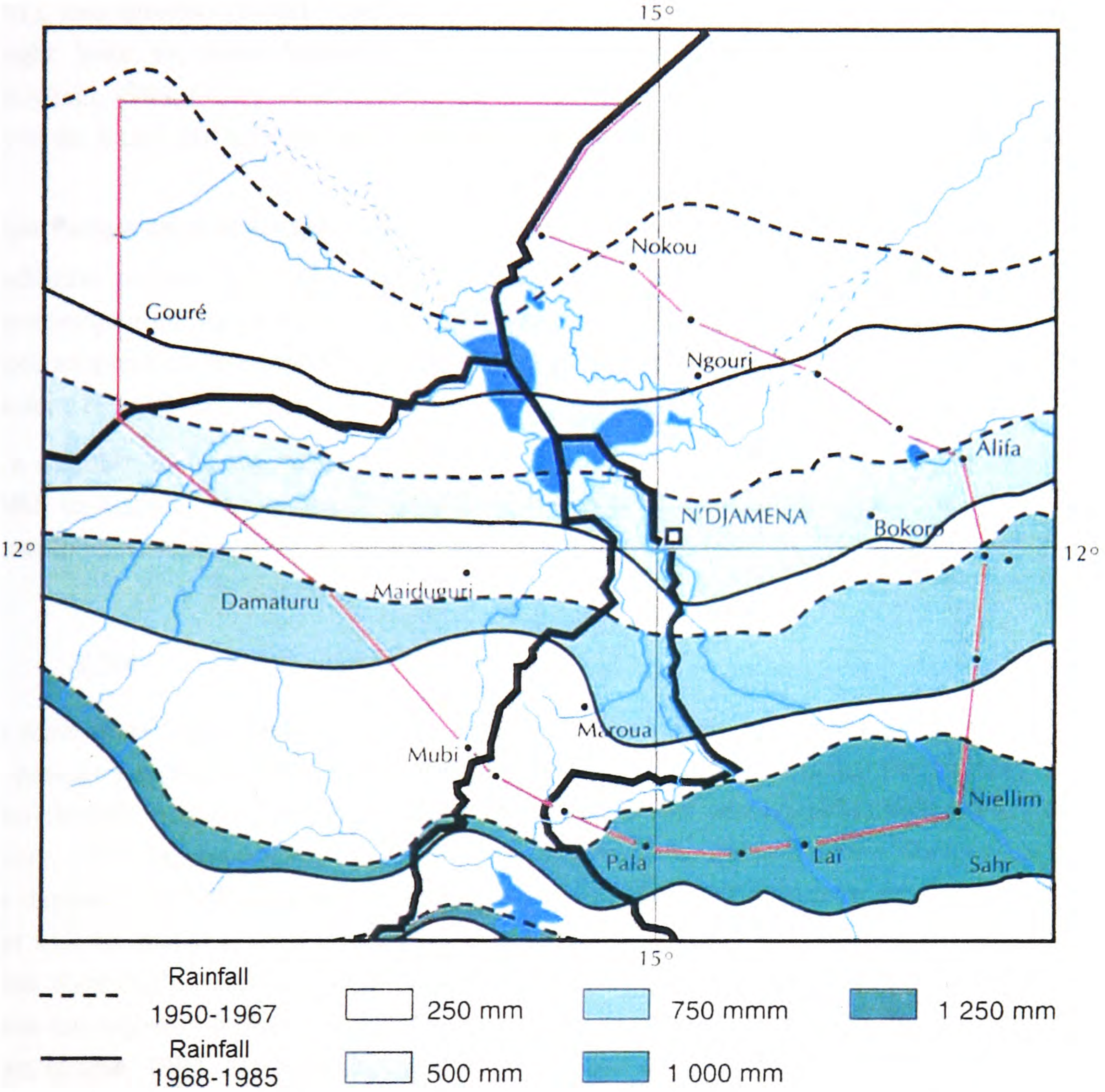


Figure 2-6: Change in the rainfall (Morel 1992, in Livestock Atlas CIRAD-CTA, 1996).

During the 20th Century, the Sahel has been affected by three major dry spells: 1910-1916, 1941-1945 and 1968-1986 (Rognon, 1991). Data for the period 1950-89 confirms the important deficit in precipitation since the 1970's. The magnitude of this drought is high in the whole Sahel and Sudan zones, but decreases towards the equator (Olivry, 1995; Mahe 1993, 1995).

The climate of the central part of the Lake Chad Basin was also strongly affected by these variations (see Appendix 2-1). A severe drought occurred in 1913-1915. The 1930's appear as an average period. The 1940's correspond to a dry period. A very wet period started from 1952 to 1966. The last dry spell of the 20th Century was also the strongest. It started in the middle of the 1960's and reached its peak in the 1980's (Beauvilain, 1996). In the basin, the second half of the Century is hence characterised by a severe drop of the rainfall (Figure 2-6). Such a `dramatic´ drought had a strong impact on the environment and on the socio-economy of the basin (Beauvilain, 1996).

Recent data show an improvement of the situation. From 1990 to 1994, the rainfall has relatively increased. For instance, the drought seems to be finished at Garoua and Poli since 1990, Maroua (1991), and Mokolo (1992). The situation is also better at N'Djamena and Bongor. However, the drought lasts in some locations. It seems to increase at N'Gaoundere, Sarh and Bebedja (Beauvilain, 1996; Olivry et al., 1996). Olivry (1996) describes important rainfall during 1994 not only in the basin, but also generally in west and central Africa.

Evapotranspiration and water deficit

In addition to low and highly variable rainfall, the centre of the basin is characterised by high evapotranspiration rates. For the period 1951-1980, the region recorded an average potential evapotranspiration between 2000 and 2400 mm/yr, according to Penman modified - GRID Geneva data set 177 - (UNEP, 1992).

On a monthly scale, the balance between rainfall and evapotranspiration only shows an excess of rainfall in August. All the rest of the year is dominated by evapotranspiration processes. Therefore, the central part of the basin is characterised by a strong water deficit. It is a semi-arid area.

2.3.4 ISSUES TO TACKLE

The main issue regarding the climate of the Lake Chad Basin is its interannual variability. As with the present day meteorology, the climate of the past has shown many fluctuations. Some major paleo-climatic periods have been identified (Maley, 1973; Maley, 1981; Schneider, 1994; Servant-Vildary, 1973; Servant-Vildary, 1978), but the chapter of the Paleo-climatic fluctuations is still open. The decline in rainfall observed since the middle of the 1960's leads to the inevitable question on what will be the long-term trend. Is this drought part of an anthropogenic phenomenon (such as global warming or deforestation), or only one of the many natural fluctuations the climate of the region has known? It seems that we still have no answer to this crucial question (Hulme et al, *in press*; Hulme, 1992; McCarthy et al, 2001; McGregor and Nieuwolt, 1998; Olivry et al, 1996). The latest information available indicates that 1999 was very humid and 2000 humid (see Ch. 9). Whatever, it is clear that in the planning policies, climate (rainfall) has to be taken as a variable and not as a constant.

Another problem is the data acquisition with regards to the spatio-temporal variability of the rainfall. The overall number of stations is very low compared to the area and the high variability of the precipitation. This is particularly true in the Central African Republic and Nigeria. Besides the quality of the data is often poor, with many gaps and several errors occurring when reading and transferring the data (Beauvilain, 1996).

2.4 SURFACE WATER

This section presents the surface water resources of the Lake Chad Basin with, again, a particular emphasis on the central part. Map 2 regroups all the best geographical information available to date on the surface water of the basin. Since all the north part of the basin is in the Sahara, about half of it is desert with no surface water. In the remaining southern part, surface water shows a great variety of forms and are characterised by large seasonal and interannual fluctuations.

2.4.1 MAIN RIVERS

Major rivers of the basin are: the Chari, the Logone and the Komadugu Yobe. The Komadugu Yobe does not have a high discharge compared to the first two, but it has a long reach which spreads life to a large part of the basin. They all flow into Lake Chad and receive most of their water from the south part of the basin where rainfall is important.

The Chari–Logone system

The Chari and its tributary the Logone have a vast drainage network originating in the Central African Republic and in Cameroon. The rivers are characterised by a main peak flow and a low flow during the rest of the year (Billon, 1967; Billon et al., 1974; Olivry et al., 1996). Figure 2-8 shows, for instance, the seasonal fluctuation of the Chari discharge at N'Djamena with its annual peak flow.

The two rivers meet at N'Djamena. After N'Djamena the river has a deltaic nature with a large mouth at the connection with Lake Chad. In their downstream parts the rivers run through the very flat region of the central part of the Lake Chad Basin (see section 2.2). It is probably why, all along this area, the drainage network of these two rivers is particularly degraded, with many peripheral canals leaving the rivers and either returning with much less water or becoming lost completely (Billon, 1967; Billon et al., 1974; Lemoalle and Brami-Hourtal, 1996; Olivry et al., 1996). Figure 2-7 shows the mechanism of this hydrological system and its annual average water balance for the period 1956-1974. First, one notices a particularity in this system: exchanges can take place between the Lake Chad Basin and the Niger Basin. On the right bank of the Logone between Lai and Bongor, water from the Logone can flow to the Benue (Niger Basin) via the Kabia and the Mayo Kebbi. However, the amount of water exchanged remains very small and the phenomena can be considered as minor (Billon, 1967). A second phenomenon is the water losses that occur along the system. They are strong for the Logone and less pronounced for the Chari. Although it seems logical to attribute them mainly to evaporation, no study has yet estimated what the role of an eventual infiltration to the water table could be (see Ch. 3).

Map 2 and Figure 2-9 illustrate the high interannual variability of the rivers regime. They show the decline of the rivers discharge since the middle of the 1960s. After two high flow decades (1950's-1960's), we observe a long period with low flow which reaches its climax in the middle of the

1980's (see also, Olivry, 1996). It is not only the discharge of the rivers that is affected by rainfall variability; it is the entire system. Lemoalle (1996) highlights that overflow in peripheral channels and flood plains are proportionally much lower in the dry period. This is explained by the fact that during low flow the water remains in the channels and cannot get to the distributaries and the flood plains. Since the flood plains contribution is reduced, evaporation losses of the Chari/Logone system are also much lower in these dry periods. Recently, one can notice an improvement of the figures since the middle of the 1990's (Figure 2-9).

Infrastructures have been built on these rivers. A series of dikes were constructed between 1954 and 1959 on both banks between Bongor and Katoa. They prevent high flow feeding the Yaere in this part. They have had strong impact on the regime of the rivers and their flood plains and it seems that this concern has been so far insufficiently monitored and studied.

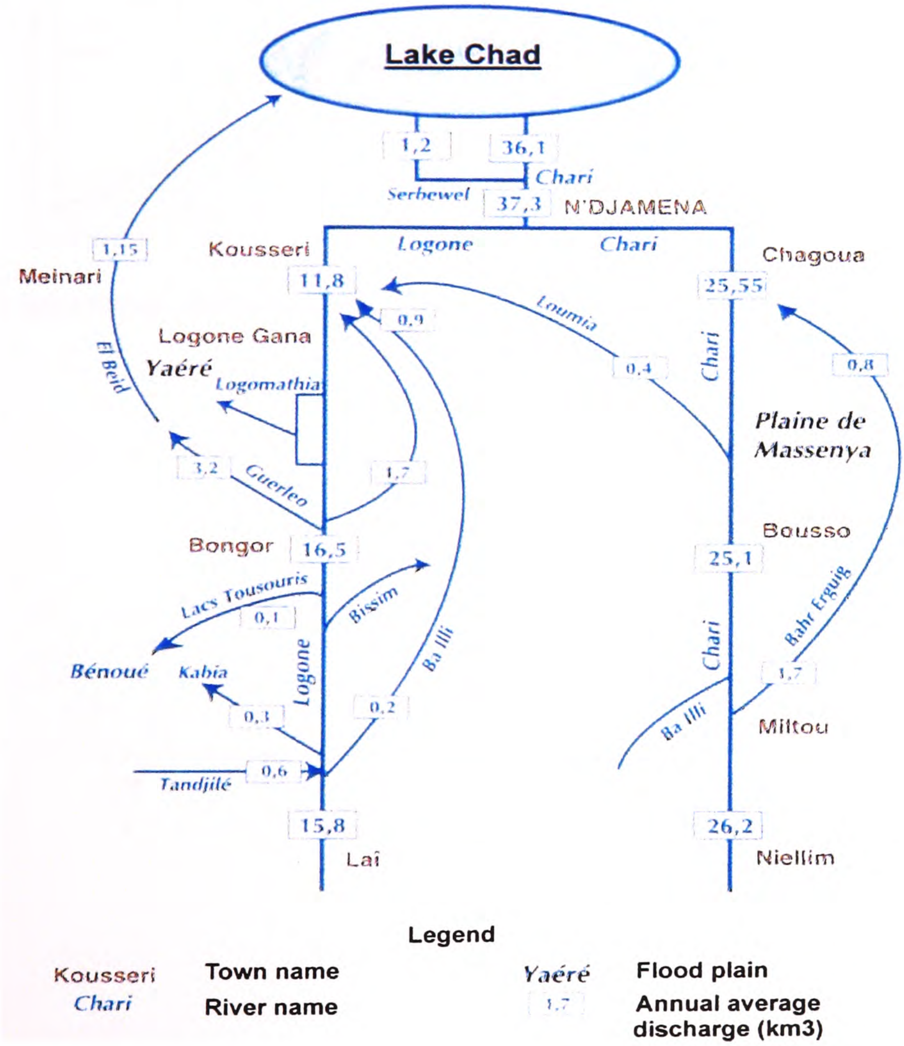


Figure 2-7: Interannual water balance of the Logone-Chari system for the period 1956-1974 (from GAC 1980, in Livestock Atlas CIRAD-CTA, 1996).

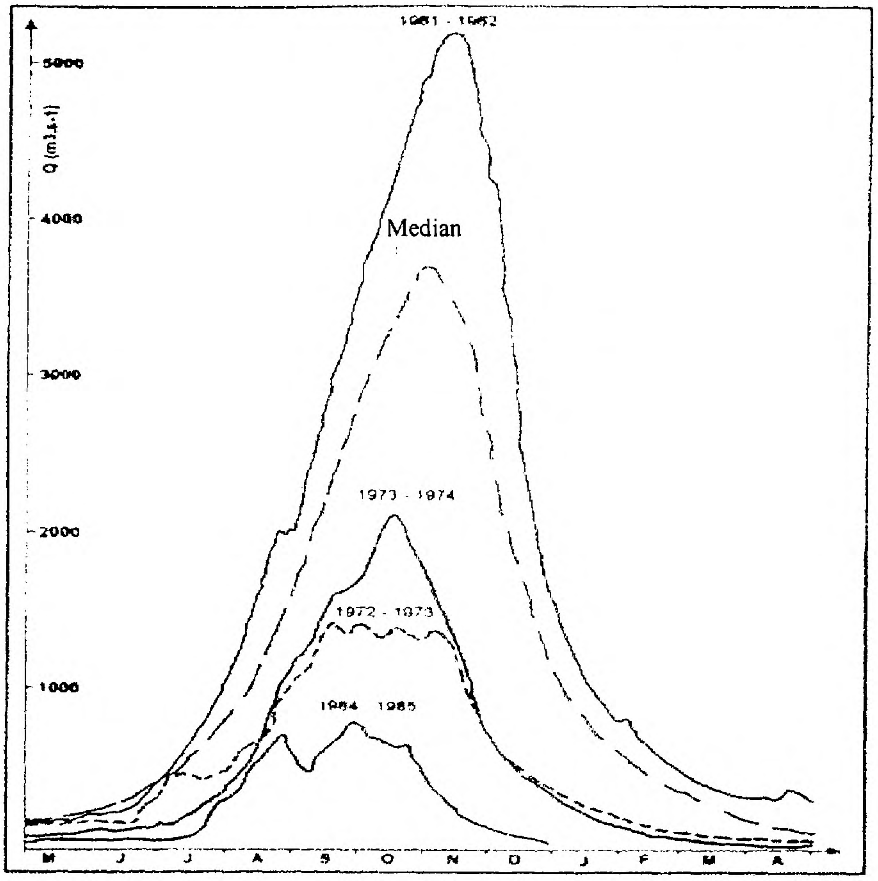


Figure 2-8: Interannual and seasonal fluctuations of the Chari discharge (from Olivry 1996).

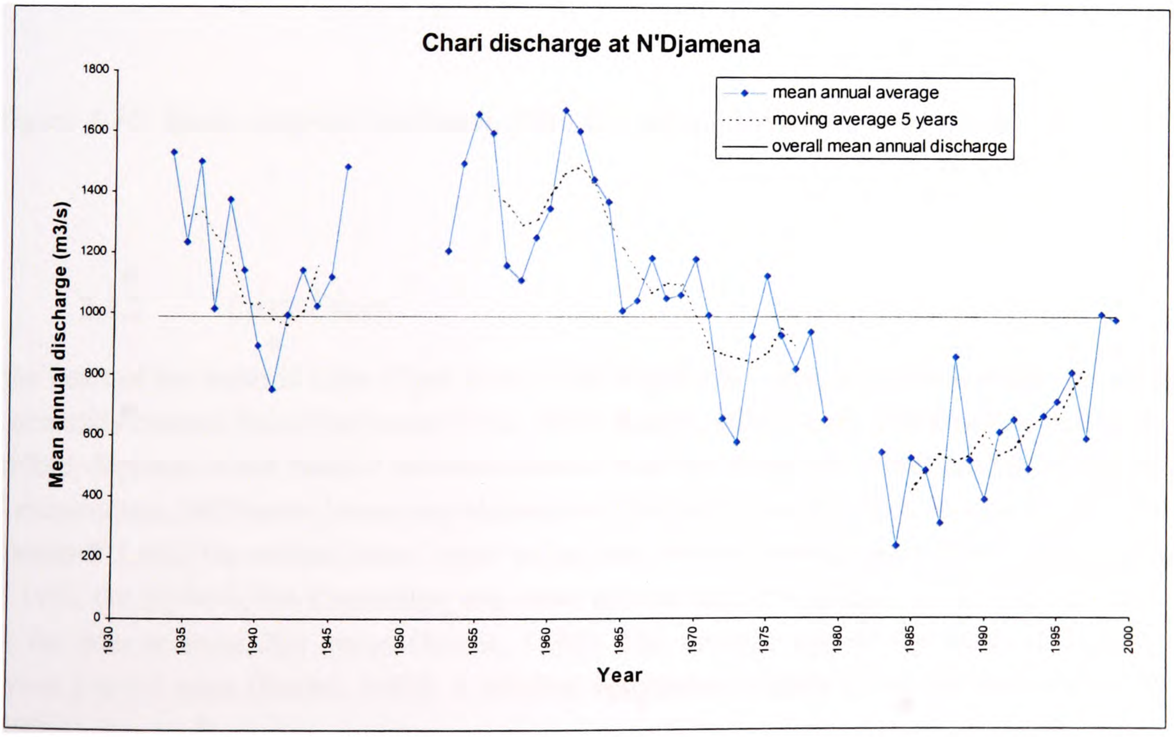


Figure 2-9: Interannual fluctuation of the Chari at N'Djamena (source data DREM).

The Komadugu Yobe

The Komadugu-Yobe flows seasonally from Nigeria and Niger to the north of Lake Chad. From Gashua to Lake Chad, Figure 2-10 shows a decrease of the river's discharge, and on its downstream part, the river only flows for a few months. Like the Chari and the Logone, its regime has been affected by the droughts (Figure 2-10). In the meantime, numerous dams have been constructed in Nigeria especially for irrigation purposes (Iwaco, 1985). To the best of our knowledge, although this situation raises concerns, there has been so far a very limited number of studies on this river.

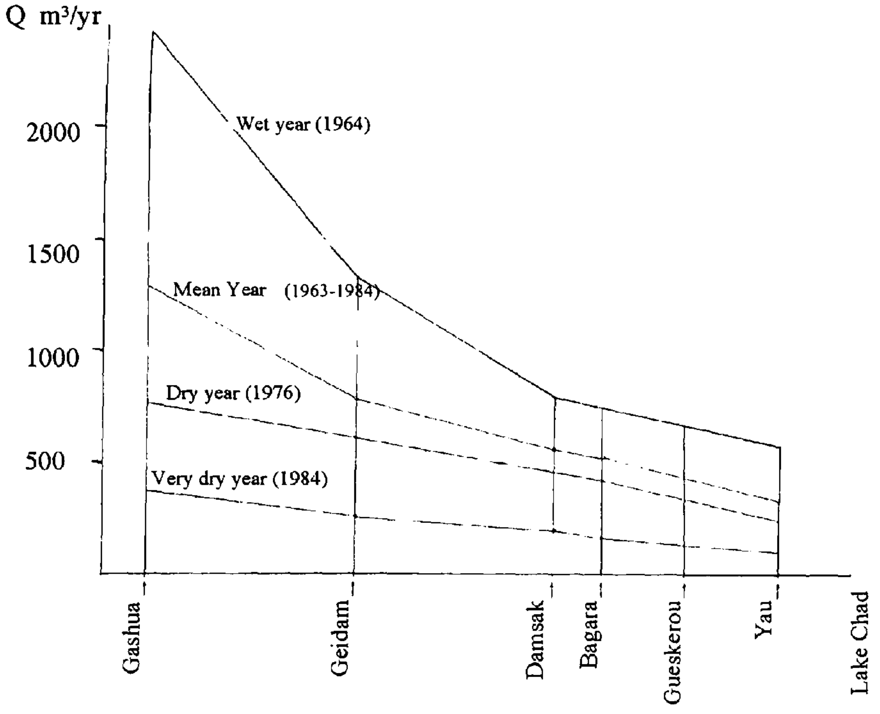


Figure 2-10: Spatio-temporal evolution of the Komadugu-Yobe Discharge (from IWACO, 1985).

2.4.2 LAKE CHAD

At the heart of the basin is Lake Chad. It is a vast inland lake containing fresh water. Its depth does not generally exceed 10 m (Carmouze et al., 1983; Roche, 1980). Lake Chad has no outlet. Its level, therefore, depends on the balance between inflows from the rivers and direct rainfall on the one hand and evaporation, infiltration losses and abstraction (irrigation) on the other. Between 1954 and 1968 ("Standard" Lake) the annual water inputs to the lake were in average as follows: the Chari 82.3%; rain 14%; the El Beid, the Komadugu and other tributaries 3.6% (Olivry et al., 1996). Evaporation over the lake is about 220 cm/yr (Roche, 1980). The average age of the water in Lake Chad is between 2 to 5.5 years (Roche, 1980). A detailed description of Lake Chad can be found in Olivry et al (1996).

Being very shallow and with no outlet, the major characteristic of Lake Chad is certainly its sensitivity to hydro-climatic changes.

Tilho (1911, 1925, 1928) introduced a classification of the lake according to its level and surface area: a "Little" Lake Chad; a "Standard" Lake Chad and a "Great" Lake Chad (Tilho, 1911; Tilho, 1925; Tilho, 1928). This description is still of use nowadays to characterise the state of Lake Chad (Lemoalle and Brami-Hourtal, 1996; Olivry et al., 1996):

- A "Standard" Lake Chad is observed at 281 m – it appears as one continuous body of water all year long with a wide archipelago band to the east;
- A "Great" Lake Chad has an average level of 284 m – it implies the disappearance of the archipelago islands and the flooding of a part of the Bahr el Ghazal (paleo-valley);
- A "Little" Lake Chad occurs for a level below 279-280m – it is characterised by the split in two major pools with large parts of the lake dry and periodically re-wetting.

Looking back in the geological time it seems that Lake Chad has been subject to important fluctuations throughout its history (Olivry et al., 1996; Schneider, 1994; Schneider and Wolff, 1992; Servant and Servant, 1970; Servant-Vildary, 1973; Servant-Vildary, 1978).

In the 20th Century, three periods of "Little" Lake Chad have occurred. The first one was reported in 1904-1917 (Tilho, 1911; Tilho, 1925; Tilho, 1928). In the early 1940's another "Little" Lake Chad appeared (oral tradition). Lately, in the middle of the 1960's, Lake Chad started to shrink and this led in 1973 to the advent of a "Little" Lake Chad. Fluctuations of the lake during this last event are depicted in Olivry 1996 and Lemoalle 1979, and can be summarised as follow:

1. From 1964 the level of Lake Chad started to decrease – in January 1963, the lake's level was at 283m with a surface area of 23,200 km^2 and a volume of 86E+09 m^3;
2. From 1968 this drop accelerated;
3. In 1973, the continuing decrease of the lake level led to the emergence of a shallow ridge: "the Great Barrier". Then the northern pool, which did not receive any more water from the main tributary of Lake Chad (the Chari), started to dry (evaporation= 2.2 m/yr) – in July 1973, Lake Chad level was at 279.8m with a surface area of 10,000 km^2 and a volume of 10E+09 m^3;
4. From 1974 to 1979 the hydroclimatic situation improved slightly or at least stabilised. However, the inflows into Lake Chad were still below average and insufficient to restore the situation. This period saw the development of aquatic vegetation in large regions of the southern pool. The vegetation also grew on the "Great Barrier" and it slowed the flow toward the northern pool. During this period, inflows through the "Great Barrier" were small and the flooding of the north pool was only partial and of brief time-span. Consequently the north pool of the lake stayed mainly dry;
5. In the 1980's, the drought worsened. Except for a humid year in 1988, which led to a short replenishment of the north pool in the beginning of 1989, the lake recorded very small areas.
6. An update with the latest information available is presented in chapter 9, and shows a recent improvement of the situation since 1995, with large re-wetting of the north pool.

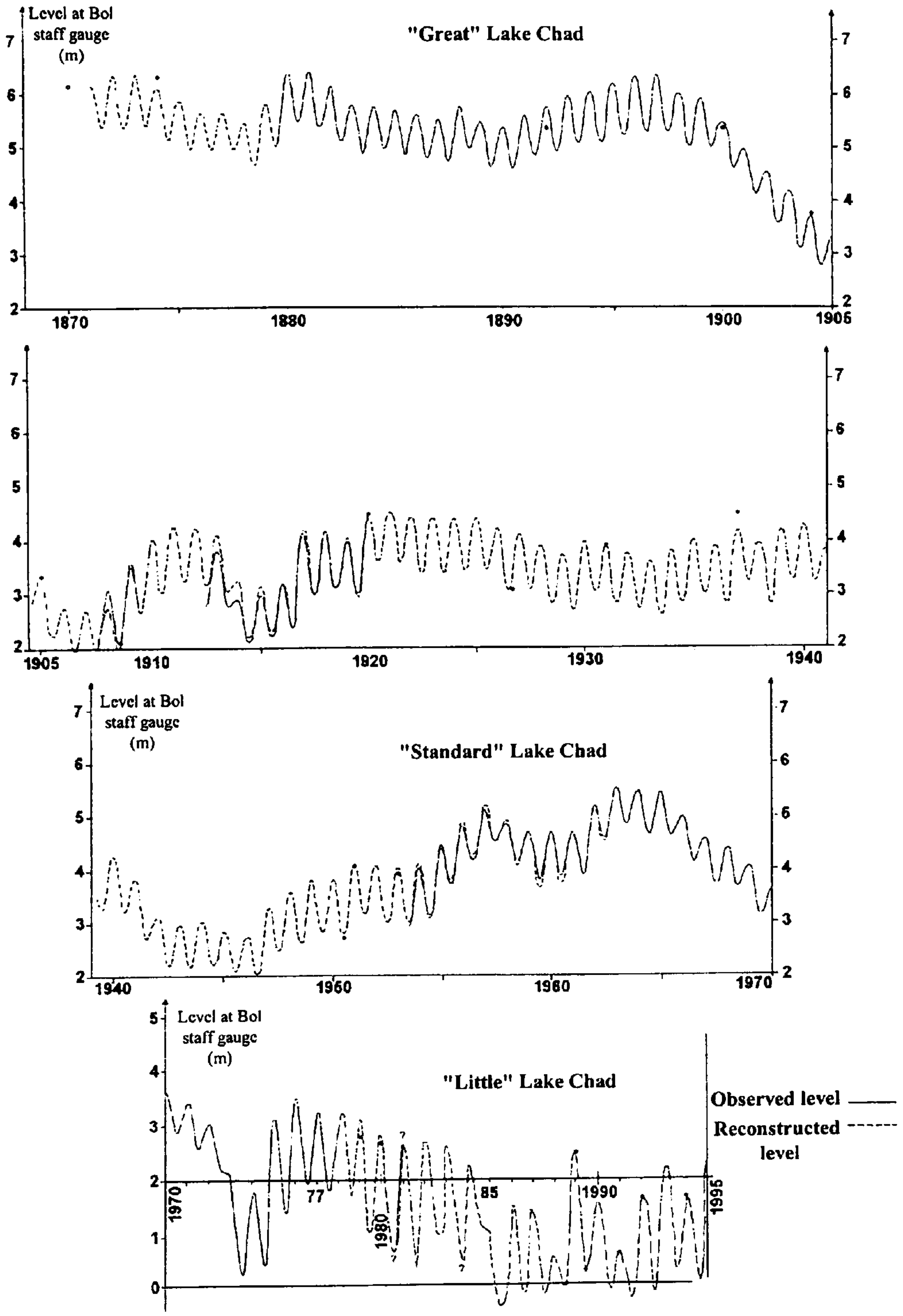


Figure 2-11: Fluctuations of Lake Chad level (from Olivry, 1996).

A high Lake Chad sustains a wealthy socio-economic environment. The lake is indeed an essential resource for agriculture, livestock farming, and above all for fishing (CIRAD-CTA, 1996; FEWS, 1997; FEWS, 1998; Hutchinson et al., 1992). About 750,000 people are living in the area of Lake Chad (FEWS, 1997; Hutchinson et al., 1992). Its fluctuations are thus a major concern. Of course, the shrinkage of Lake Chad has drawn attention, but the risk for the population of its subsequent reflooding should not be forgotten. People's dwellings follow the migration of the lake when it shrinks, so that they settle in areas susceptible to be flooded rapidly with the reappearance of better hydroclimatic conditions (Olivry et al., 1996; Olivry and Leduc, 1996). After a heavy rainy season in 1999, the annual flood of Lake Chad is reported to have left 25,000 people homeless in Nigeria (IRIN-WA, 1999a; IRIN-WA, 1999b).

There have been a number of scientific studies on Lake Chad hydrology, and it is clear that within the basin it is the most detailed feature. Field studies have brought a thorough description of the "Standard" Lake Chad (Bouchardeau, 1958; Bouchardeau and Lefevre, 1957; Carmouze et al., 1983; Chouret, 1977; Gac, 1980; Olivry et al., 1996; Roche, 1980). The fluctuations of Lake Chad level and extent have been described (Birkett, 2000; Lemoalle, 1979 a; Lemoalle, 1991; Olivry et al., 1996), modelled (Coe and Foley, 2001; Guganesharajah and Shaw, 1984; Mott MacDonald Int, 1993; Olivry et al., 1996; Vuillaume, 1981) and reconstructed (Maley, 1981; Olivry et al., 1996). Ways to monitor them with remote sensing have been put forward (Birkett, 1995; Birkett, 2000; Lemoalle, 1979 a).

However, Lake Chad is a complex, fragile and changing environment, and there is certainly still room for more research. There is also a need for an operational system to forecast Lake Chad extent (Olivry and Leduc, 1996). Finally, means to manage Lake Chad fluctuations, if ever possible, have to be examined. Projects such as water transfer from the Zaire or Ubangui basin already proposed (Bonifica-SA, 1991; LCBC, 2000; Mott MacDonald Int, 1991; Mott MacDonald Int. et al., 1992).

2.4.3 OTHER LAKES

Lake Fitri

Lake Fitri is located 240km east of Lake Chad between 12°40'N - 12°58'N and 17°20'E – 17°40'E. Very little is known about Lake Fitri. It is endoreic, shallow and contains fresh water. It is often referred as a 'miniature' Lake Chad. It is fed by the Batha, which flows only from July to October, and to a less extent by the Aboutelfan. Unfortunately, it is even more sensitive to climatic variations than Lake Chad because its catchment area is located further north. Its average surface area is of the order of 800 km^2 (for inputs of 0.7 to 2 km^3/yr) but it can vary from 1,300 km^2 (1870) to be completely dry as in 1973 (Burgis and Simoens, 1987; Lemoalle, 1979 a). The lake provides a resource for fishing for the small population living in this region.

The Kanem lakes

To the north-east of Lake Chad, between 13°30' - 14°07' N and 14°10' - 15°04'E, about a hundred temporary or permanent lakes can be found in the interdune depressions of a vast ancient erg, which now forms an undulating plateau. The lakes are very shallow: between 0.5 to 1 m for the temporary, and 1 to 2 m for the permanent. Their surface areas vary from a few hundred m^2 to 2 km^2 (Burgis and Simoens, 1987; Lemoalle, 1979 a). There is no runoff or drainage network feeding these lakes. In fact, they are said to be fed by direct rainfall and groundwater flow (Burgis and Simoens, 1987; Eberschweiler, 1990).

These lakes appear to be very sensitive to climate change. They can dry completely during droughts, or alternatively temporary lakes can become permanent during wet periods. The last period of drought to affect the basin since the middle of the 1960's seems to have reduced considerably the number of these lakes (Lemoalle and Brami-Hourtal, 1996).

The density of the human population is very low in the region (1.5 inhabitants per km^2). In the dried depressions, sodium carbonate and sodium bicarbonate, known as natron, is often exploited.

Otherwise, there is a limited use of the depression for agriculture with irrigation (Burgis and Simoens, 1987; Eberschweiler, 1990).

The Manga lakes

Very little is known about these lakes. They are not even mentioned in the study of the water resources of the region concerned by IWACO (1985). The number of permanent lakes is probably small (Carter, 1994 b; Carter, 1995). Nevertheless, this thesis highlights that the number of temporary lakes can be important after the rainy season (see, Ch 6). The local population uses the environment sustained by the lakes for agriculture (Carter, 1994 b; Carter, 1995; Mortimore, 1989).

It is clear that too little is known on these lakes. More studies and closer monitoring of these lakes are required, as they too, like Lake Chad, appear to be very sensitive to rainfall variability.

2.4.4 FLOOD PLAINS

Vast and very flat regions border the Logone, the Chari and the Komadugu rivers. They are covered by hydromorphic soils which are poorly drained (ORSTOM, 1979; UNESCO-PNUD-CBLT, 1972). The combination of direct rainfall and river over bank flooding produce seasonal inundation in these large areas (see, Map 2). In the central part of the basin the flood plains of significant size are:

1. Downstream after Bongor, the “Great Yaeres” which extends from north Cameroon to the west of the Logone (another flood plain to east of the Logone is sometimes also considered as part of the Yaere);
2. The Massenya flood plain, which is formed along both banks of the Bahr Erguig;
3. Large flood plains occur between the Chari and the Logone in the triangle formed between Lai, Bousso and N’Djamena – the Grand Courant which floods the Deressia plain – the southern part of the Ba-Illi – to the east bank of the Logone between Katoa and Logone Gana (Lemoalle and Brami-Hourtal, 1996);
4. Along the banks of the Komadugu Yobe, and particularly upstream from Gashua where the intertwined channels form an inland delta (Leveque, 1987; Toucheboeuf, 1969);
5. The region of Lake Fitri.

The best information on the location of these flood plains is given in Burgis (1987) and is reported on Map 2. However, their boundaries remain ill-defined and extremely variable from one year to another (Lemoalle and Brami-Hourtal, 1996). The extent of the floods is very sensitive to climatic fluctuation. To the best of our knowledge, there is simply no geographical information available for the flood plain between the Chari and the Logone (see also, Ch. 4).

With a relatively important and complex surface water system, flood plains have a great ecological interest and a rich biodiversity. For instance, a large part of the Yaeres forms the Waza National Park and also supports fishing activities (Carmouze et al., 1983).

The flood plains have been modified by human activities. Major structures have affected the Yaeres: a dyke has been raised along the left bank of the Logone between Yagoua and Tekele; an artificial dam (Maga dam) has been built between Guirviding and Pouss. These projects have reduced the extent of the annual flood, leading to an ecological degradation of the region. Recently, attempts to reverse the degradation were conducted (Mott MacDonald, 1999; Mott MacDonald Int, 1993). Many small dams have been constructed in the upstream part of the Komadugu, but their impact is not known (Iwaco, 1985).

2.4.5 ISSUES TO BE TACKLED

Overall, our knowledge of the basin's surface water needs to be improved.

The "Standard" Lake Chad is reasonably documented, but it is not well known if the "Little" Lake Chad, as observed from 1973, has the same characteristics. For instance, one can notice phenomena such as the increase in aquatic vegetation (Lemoalle, 1979 a; Olivry et al., 1996) and the reduction in the exchange area between Lake Chad and the surrounding phreatic aquifer.

The impact of climatic fluctuations on the one hand, and of human structures and abstractions on the other, have yet to be fully assessed and monitored. For instance, Vuillaume (1981) estimates that from 1968 to 1977 the impact of irrigation on Lake Chad has been limited (compared to climatic change) and accounts for only 5% of the decrease of the lake area. However, Coe (2001) highlights that there has been a high increase of irrigation abstractions from 1983 (11.2 km^3/yr from 1980's – instead of 2.5 km^3/yr in the 1960's and 1970's) which account for roughly 50% of the observed decrease in the lake area (in nearly equal parts with the continued decrease in precipitation). To us the problem in reaching a reliable conclusion lies in the difficulty of assessing irrigation: little is said in Coe's article about the origin and validity of irrigation data. If an increase of irrigation is probable, Coe's irrigation figures, nevertheless, exceed all other estimations (e.g, Shiklomanov, 1999). It seems to us that, given the importance of Lake Chad and the conjunction with a period of deficit rainfall, this question of irrigation impact requires more investigations.

There is clearly a need to study and monitor other lakes and the flood plains of the basin, as so far they have hardly been studied.

In the central part of the basin, the rivers have a common and interesting characteristic. From upstream to downstream they show a decrease of their discharge. Although evapotranspiration is known to be strong, the distribution between the three types of possible losses (evapotranspiration, irrigation and infiltration) is not well known.

2.5 GROUNDWATER

This chapter provides a concise hydrogeological synthesis of the basin. Hence, it starts with a background on the geology.

2.5.1 OUTLINE OF THE GEOLOGY

Burke (1976) describes the Lake Chad Basin as an intra-continental basin that owes its origin to the existence of peripheral uplifts, and is located over an intra-continental rift system. Map 3 shows the geology of the Lake Chad Basin.

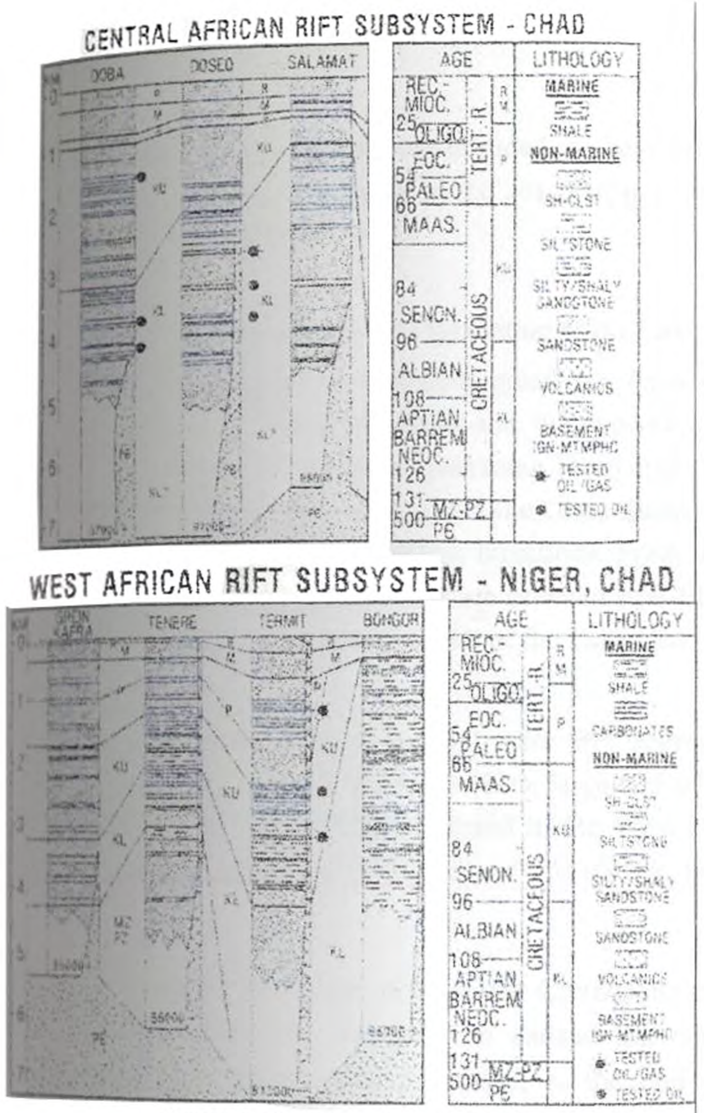
Precambrian

A Precambrian basement forms the frame of the Lake Chad Basin. It is composed of metamorphic and igneous rocks. The Panafrican orogenesis has affected this basement at the end of Proterozoic and at the beginning of Paleozoic period (750-550 million years BP). During this event, fractures were created, such as the fault of Agades or the fault of Adamaoua. These tectonic features might have been reactivated later and affect the structure of the Lake Chad Basin. Many granite plutons in the basin are also a result of the Panafrican orogenesis.

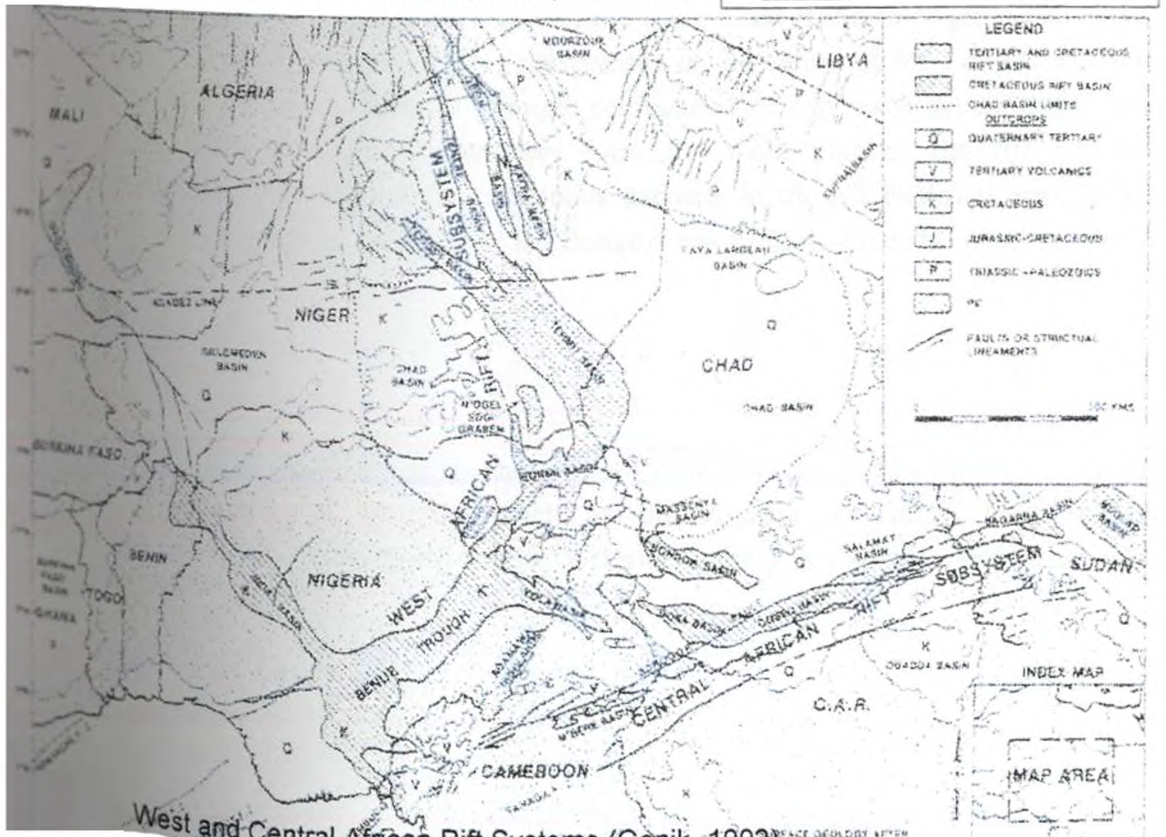
The rocks of the Precambrian basement can be seen on the edges of the Basin. They occur mainly in south Chad, the Central African Republic, the Ouaddai and the Darfour massifs, and the Bauchi plateau in Nigeria. They are also present, to a lesser degree, in the massifs of the Air and in the massifs of the Tibesti. In the central part of the basin, some rhyolites outcrop at the Hadjer and the Khamis massifs.

Paleozoic and Low Jurassic

The activity of the Hercynian orogeny in North Africa caused an uplift of the crystalline Waddai, Darfour and Tibesti massifs (Burke, 1976; Genik, 1992). During Paleozoic and Jurassic periods, we observe the beginning of the sedimentation, but it is still restricted to the northern part. Deposits can be found in the Djado massif (or Kufra and Murzuk basin) in Niger and in the Erdis basin (Tibesti) in the Waddai and Darfur massif in Chad. They consist of continental and shallow marine sediments. The sequence starts with Cambrian or Devonian sandstone, followed by a layer of clay and finishes with Mid Carboniferous sandstone (Kusnir, 1996).



Generalised stratigraphic columns,
Central African and West African Rift Subsystems (Genik, 1992).



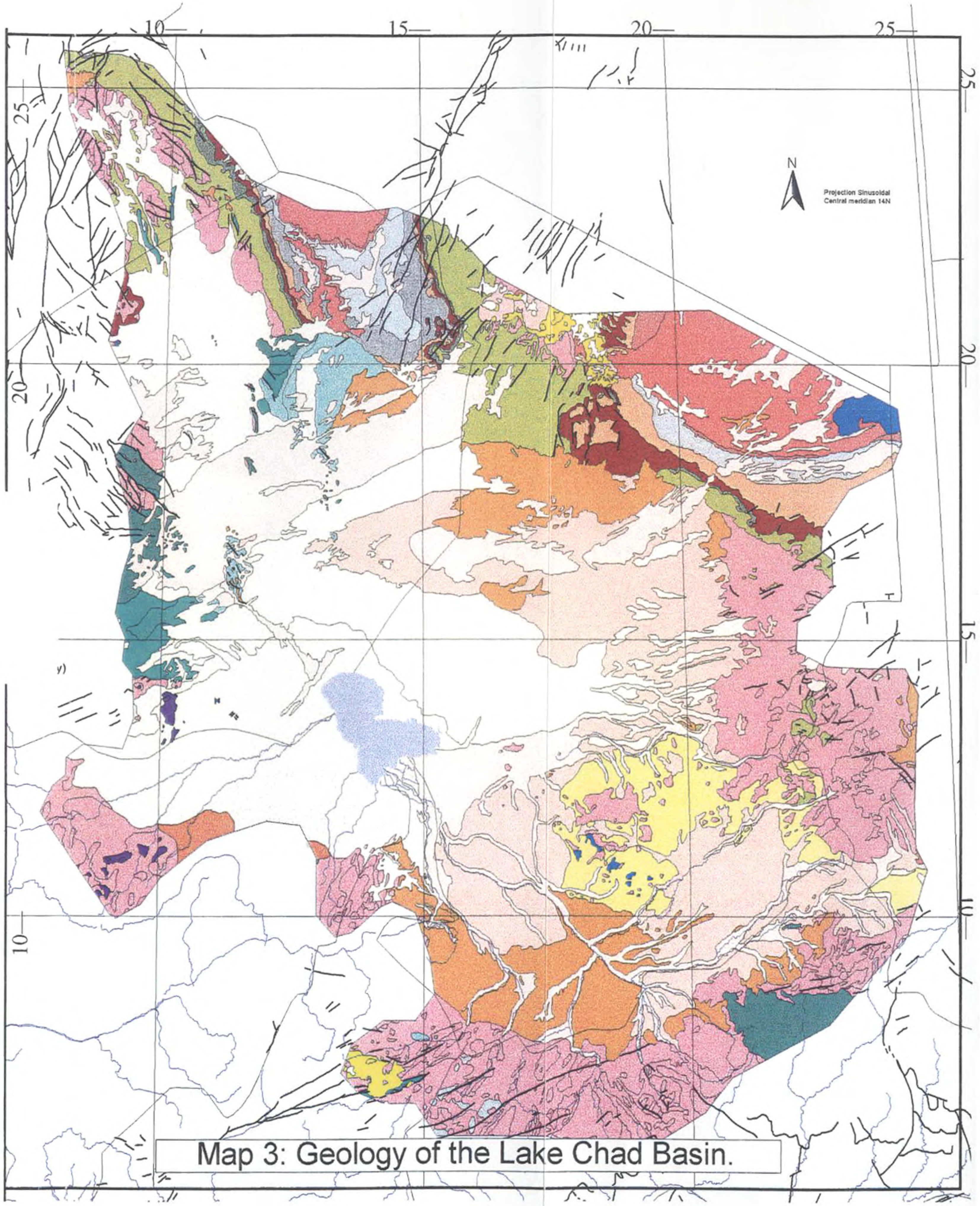
West and Central African Rift Systems (Genik, 1992)

Geology

- ☐ Quaternary
- ☐ Holocene
- ▨ Pleistocene
- ▨ Quaternary and Neogene
- ▨ Tertiary
- ▨ Pliocene-Pleistocene
- ▨ Neogene
- ▨ Paleocene
- ▨ Cretaceous-Tertiary
- ▨ Mesozoic
- ▨ Mesozoic, Jurassic or Cretaceous
- ▨ Cretaceous
- ▨ Upper Cretaceous
- ▨ Middle and upper Cretaceous
- ▨ Middle Cretaceous
- ▨ Lower and middle Cretaceous
- ▨ Lower Cretaceous
- ▨ Jurassic-Cretaceous
- ▨ Jurassic
- ▨ Permian-Trias
- ▨ Carboniferous-Cretaceous
- ▨ Carboniferous
- ▨ Upper Carboniferous
- ▨ Middle Carboniferous
- ▨ Lower Carboniferous
- ▨ Middle and upper Devonian
- ▨ Lower Devonian
- ▨ Silurian-Devonian
- ▨ Silurian
- ▨ Cambrian-Ordovician
- ▨ Lower Paleozoic
- ▨ Precambrian or Paleozoic

International Geological Map of Africa
(CGMW-UNESCO, 1987).

- Surface waters
- Faults
- State Boundaries



Map 3: Geology of the Lake Chad Basin.

During the Paleozoic, alkaline granite intruded the basement in the Air and the Damagaran/Mounio regions. In the Jurassic, it intruded in the Jos plateau (160 MY BP). This granite is alkaline and forms ring complexes (Kusnir, 1996).

Upper Jurassic and Cretaceous: The formation of the Lake Chad Basin

In the Upper Jurassic/Lower Cretaceous great rifts opened in Central Africa. They were formed during the break up of Gondwanaland and the separation of Africa from South America. They developed toward the old Panafrican structures. Deep drills and geophysical records clearly show the presence of such rift systems inside the Lake Chad Basin (Cratchley, 1960; Cratchley, 1984; Genik, 1992; Louis, 1970). These rifts have two directions. From the Tenere to Lake Chad, they are called the West African or Nigerian rifts and are oriented NW-SE. The others are called Central African rifts. They are located in the southern part of the Lake Chad Basin and are oriented WSW-ENE (see, Map 3).

During the Cretaceous, 130-75 million years BP, sedimentary basins developed in these rifts (Cratchley, 1984; Genik, 1992). They now form large and thick basins. Grein, Kafra, Tenere, Tefidet, Termit, Bongor, and Bousso basins formed in the West African rifts, whereas Doba, Doseo, and Salamat basins formed in the Central African rifts (Genik, 1992).

The filling of these rifts started in the lower Cretaceous with detritic continental deposits. In the Upper Cretaceous, a new transgression caused the deposition of marine carbonates in the western and the southern parts. However, at the end of the Cretaceous period, continental sedimentation largely dominated.

Cretaceous sediments outcrop on the edges of the Lake Chad Basin in Niger, Chad and Central African Republic. They are also largely represented in the centre of the Lake Chad Basin, but they are overlaid by a thick layer of younger sediments that can reach several hundred metres thick. Deep drills have shown that they form the main part of the rift basins filling (Genik, 1992). The thickness of the cretaceous deposits in the rift basins is several thousand metres (with a maximum thickness in Bongor basin that exceeds 4000 metres - see Genik, 1992).

Tectonic activity was important at the end of the Cretaceous and the beginning of the Tertiary. The reactivation of old structures such as the Agades or Borop faults caused the individualisation of the different rift basins. Volcanic activity is also observed to have occurred during this time.

The Tertiary

The sea left the entire basin at the beginning of the Tertiary (UNESCO-PNUD-CBLT, 1972). Afterwards, tectonic activity caused the subsidence of the centre of the Basin and an uplift of its borders (Petters, 1981; UNESCO-PNUD-CBLT, 1972). These epirogenic movements generated intensive erosion of the previous deposits, especially on the edges and a thick detritic series was deposited in the centre of the Basin. A vast continental sedimentation filled the basin with the deposit of the Continental Terminal formation (Oligocen-Miocen). On the edges of the basin, the Continental Terminal outcrops. It is formed of sandstone and clay, and usually contains a lateritic top.

During the Pliocene, which marked the end of the Tertiary in the basin, a lacustrine sedimentation extended widely over the basin. According to Pias (1970), this humid period could be the first major transgression of the paleoclimatic oscillations of Lake Chad. Pliocene sediments are made of lactustrine clay with few sandy interstratifications. They can be some hundred metres thick with diatomites marking the top of the series (FAO-Schroeter and Gear, 1973; Schneider and Wolff, 1992; UNESCO-PNUD-CBLT, 1972).

The end of the Tertiary was also characterised by the onset of an intense volcanic activity at the periphery of the basin.

The Quaternary

The Quaternary was marked by hydro-climatic oscillations that regulated the sedimentation process. During arid periods, aeolian deposits dominated whereas during humid periods the sedimentation was mainly alluvial and lacustrine. The total sedimentation of the Quaternary is important and covers most of the central part of the Lake Chad Basin (Grove and Warden, 1968; Pirard, 1967; Schneider and Wolff, 1992; Servant, 1970; Servant-Vildary, 1973).

The volcanic activity that began at the end of the Tertiary continued and became more intensive in the Quaternary. Volcanic rocks can be found in northern Cameroon, the Jos plateau, the North of Termit, in Darfur and especially in Tibesti (Kusnir, 1996).

2.5.2 MAIN AQUIFERS

The principal aquifers of the Lake Chad Basin are: the Quaternary phreatic aquifer; the Pliocene aquifer; the Continental Terminal aquifer and the Continental Hammadian aquifer (middle Cretaceous-Maastrichian). In the first descriptions of the hydrogeology of east Nigeria, the Quaternary, the Pliocene and the Continental Terminal aquifers were referred to as: the upper, the middle and the lower aquifers of the Chad formations, respectively (Barber, 1965; Carter et al., 1963; Miller et al., 1968). Although these terms are still sometimes used in recent literature (Carter, 1995; Carter and Alkali, 1996; Carter et al., 1994; Edmunds et al., 1999; Isiorho et al., 1996) we will follow the recommendations of FAO (1973) and use the terms: Quaternary, Pliocene and Continental Terminal aquifers.

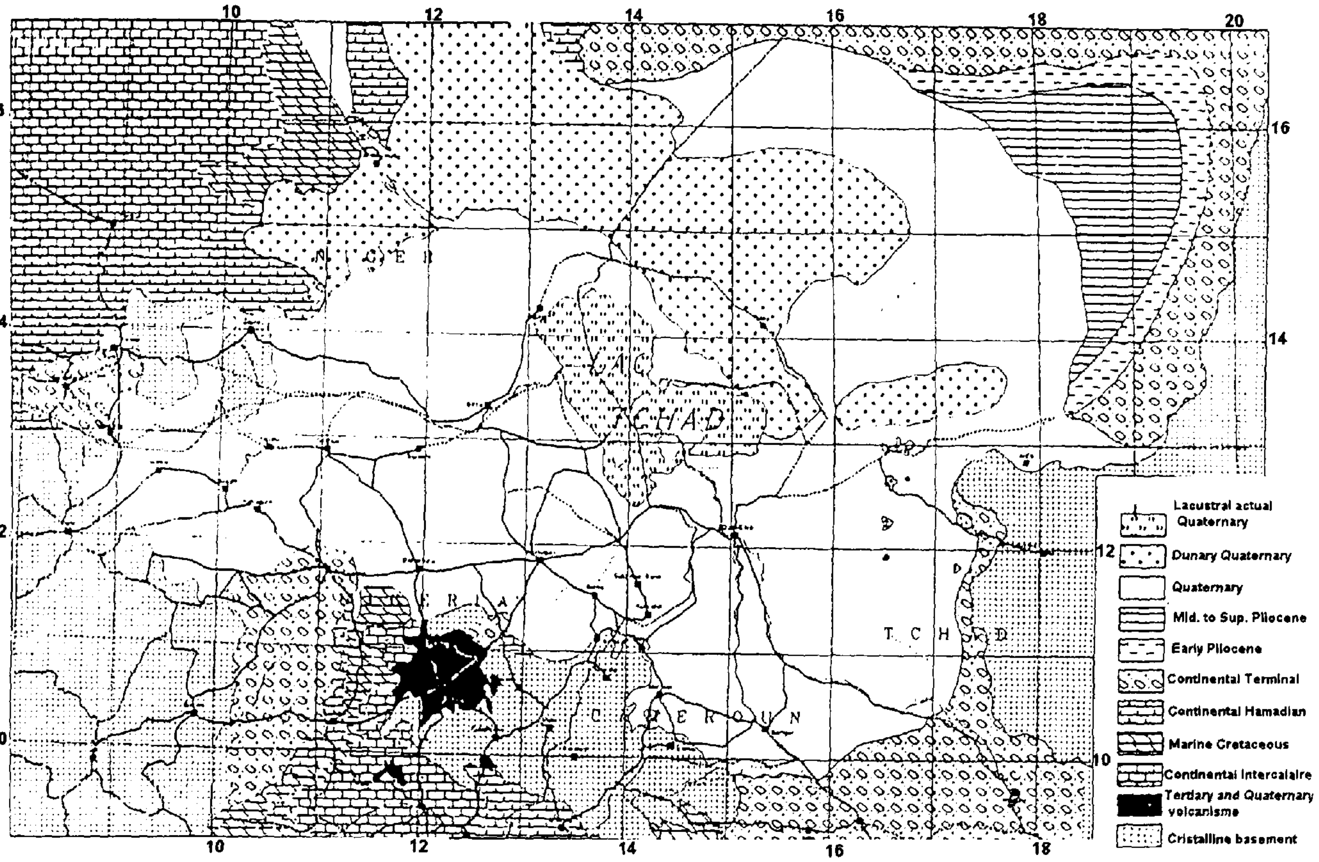


Figure 2-12: Major aquifers in the Lake Chad Basin (from Eberschweiler 1993).

2.5.3 QUATERNARY AQUIFER

The Quaternary aquifer covers a large area of about 500,000 km^2 in the centre of the Lake Chad Basin (Figure 1-). It is isolated from the underlying aquifers by a thick layer of Pliocene clay (Carter et al., 1963; Eberschweiler, 1993 b; Leduc-PNUD, 1991; Schneider and Wolff, 1992). The reservoir is made of two major types of sediments: fluvio-lactustrine deposits, which predominate in the south, and aeolian sands, which are widespread in the north. Fluvio-lacustrine sediments form the Chari-Bagiurmi plain in Chad and Kadzell in Niger. They also represent the major part of Nigeria. They are dated from the Early Pleistocene in Chad (Schneider and Wolff, 1992). The nature of this formation can be summarised as an alternation of sandy and clayey banks, whose thickness generally does not exceed 5 metres (Greigert and Pougnet, 1967a; Schneider and Wolff, 1992). The Chadian Kanem, the Manga in Niger and the north-east of Nigeria are covered by aeolian sand dunes. These aeolian sands are very homogenous and consists of a relatively uniform unit (Greigert and Pougnet, 1967a; Schneider and Wolff, 1992). They are attributed to the Late Pleistocene in Chad.

Groundwater contained in these sediments forms a phreatic and continuous water table, although there might be some local anomalies due, for example, to the intercalation of small clay layers (Eberschweiler, 1993 a; FAO-Schroeter and Gear, 1973; Greigert, 1979; Schneider and Wolff, 1992; UNESCO-PNUD-CBLT, 1972).

Figure 2-14 shows the isopiezometric lines for the whole Quaternary aquifer in the 1960's with an interval of 10 metres. It has been obtained by joining the maps published by UNESCO and by Schneider (Schneider, 1966; UNESCO-PNUD-CBLT, 1972). Schneider's map has essentially been used for the north and south-west parts of Chad. There might be several sources of error in the field measurements, due to the difficulty of obtaining a static water level and the uncertainty in the precise topography (see also, Ch. 9). Despite this possible inaccuracy, this document can certainly be considered representative of the piezometry at a regional scale: "In general, the margin of error is unlikely to be greater than 10m" (UNESCO, 1972). The Piezometry of the water table present large anomalies - domes and depressions that have been identified since the 1960's (FAO-Schroeter and Gear, 1973; Schneider, 1966; UNESCO-PNUD-CBLT, 1972):

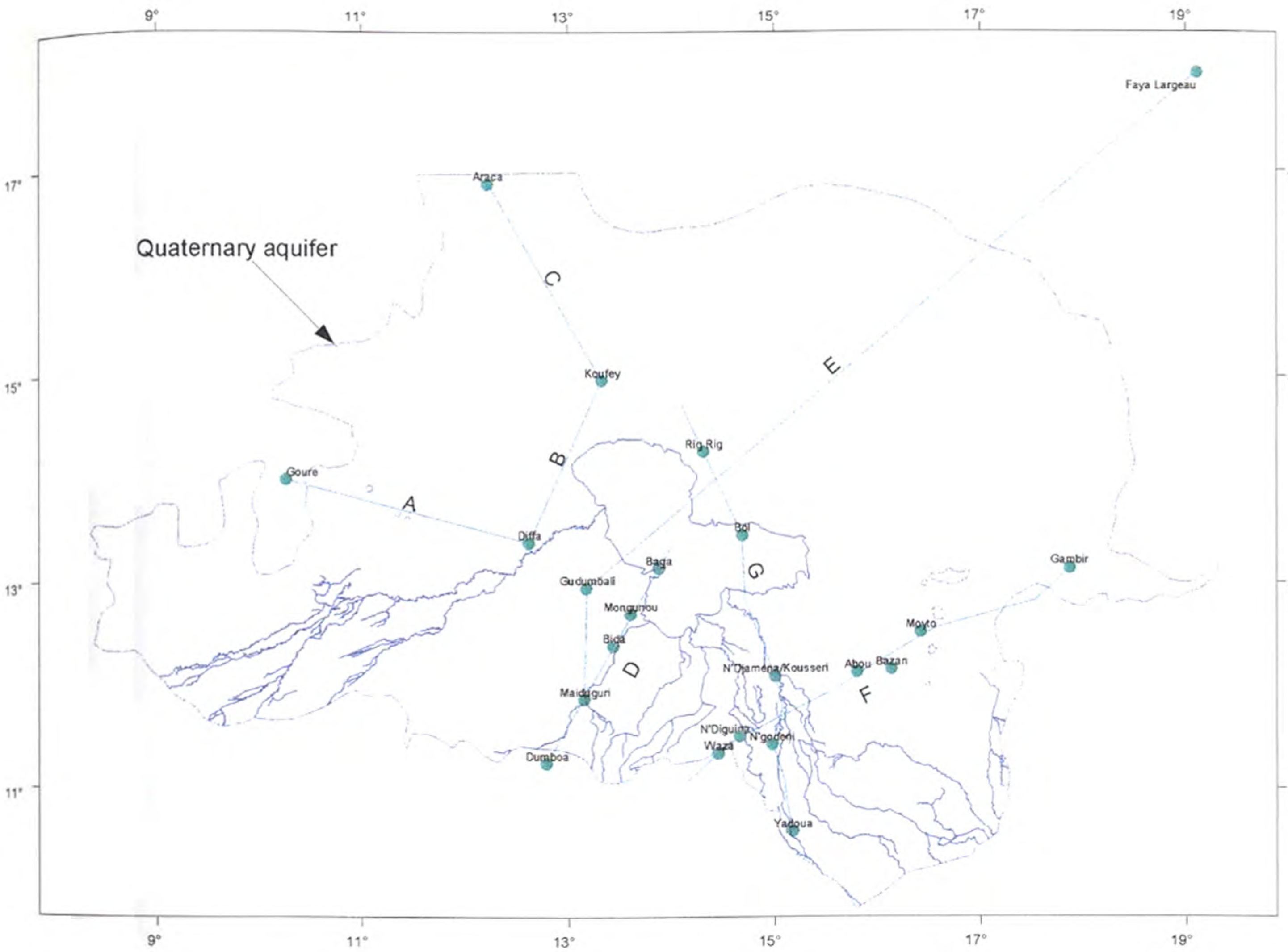
- Large piezometric domes occur in the dunefields of Kanem and Harr in Central Chad. The dome of Kanem covers approximately 17,000 km^2 and reaches 310m at Kimi Kimi (Figure 2-14). In Harr, it is about 5,500 km^2 with an altitude of 290m at Am Danobeye.

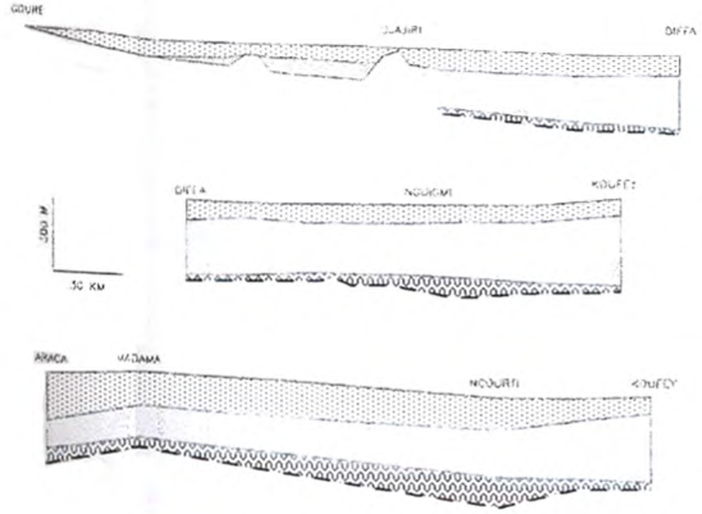
- In the southern part of the Quaternary aquifer, five deep and large depressions affect the water table (Figure 2-14). Their amplitude is about 40 metres. Major ones are found in Kadzell (Niger), Chari-Baguirmi (Chad) and Bornu (Nigeria). The Kadzell depression is about 6,000 km^2 and its piezometry varies from 280 m to 250 m. The one north of Maiduguri (Bornu depression) is about 17,000 km^2 and the water table there, falls from 280/270 m to 240 m. The largest one is the Chari Baguirmi with a surface area of 25,000 km^2 and levels varying from 270 m to 230 m. Smaller depressions are located in the Logone and between the reaches of the Komadugu and to the south of Mounio massif.
- In addition, there are some shallower depressions (about 10m deep) in the inter-fluvial zone of the Chari and the Logone, to the south-west of the Yares; in the Chari delta (between the El Beid and the Chari) (Detay, 2000) and to the south-east of the Harr (near Gambir) (Schneider, 1969).

South of Latitude 13.5°N, groundwater flows from the southern boundary of the aquifer, the rivers, the Harr dome and Lake Chad to the piezometric depressions. North of this latitude, groundwater goes from the east and west limits of the aquifer, and from the Kanem and Harr domes towards the Lowlands (north-east Chad).

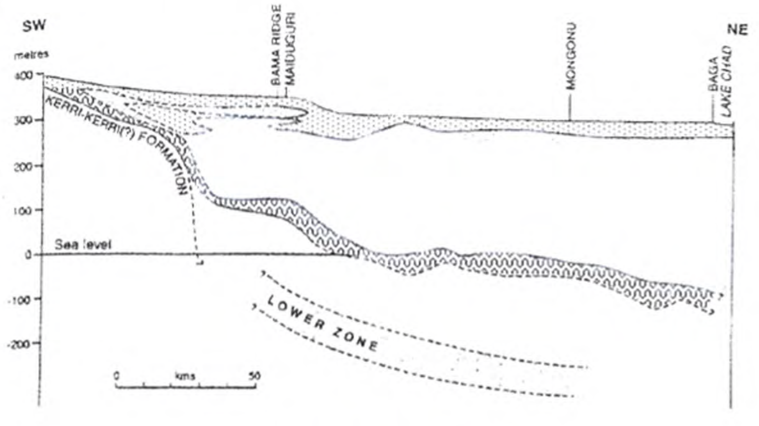
All along these flow paths, hydraulic gradients are very gentle. Maximum levels are observed in the surroundings of Mounts Koutous (390m) and Mandara (370m). Low levels of the water table are the piezometric depressions (230m in the Chari-Baguirmi) and the Lowlands area (220m). If we exclude the Koutous surroundings and south-east Nigeria, as piezometry in these areas is due mainly to local relief, then the water table varies only by about 100m throughout the whole aquifer. The little information available indicates good transmissivity and specific yield, which confirms the aquifer's capacity (see, Ch 7). Being continuous and relatively shallow, the Quaternary aquifer offers a relatively easy and permanent access to water for the population. The water is also of good quality with a bicarbonated facies and a moderate mineralisation. Locally though, near Lake Chad and in the oases, its mineralisation can be quite high. Among the aquifers of the basin, the Quaternary aquifer offers the best chemical characteristics for human consumption and irrigation (Eberschweiler, 1992; FAO-Schroeter and Gear, 1973; Schneider and Wolff, 1992).

It is estimated that about 10 million people depend on its groundwater (Eberschweiler, 1992; Kindler et al., 1990; PNUD, 1980). This aquifer is, however, a shallow groundwater system in interaction with a changing environment (climate, surface water and human abstraction) that requires monitoring and management. Unfortunately, the present knowledge of the Quaternary aquifer is limited. For example, we do not yet have a precise figure of abstractions (see Ch. 7). The major rivers and water bodies of the basin (Lake Chad included) have exchanges with the Quaternary aquifer, which have still to be quantified.



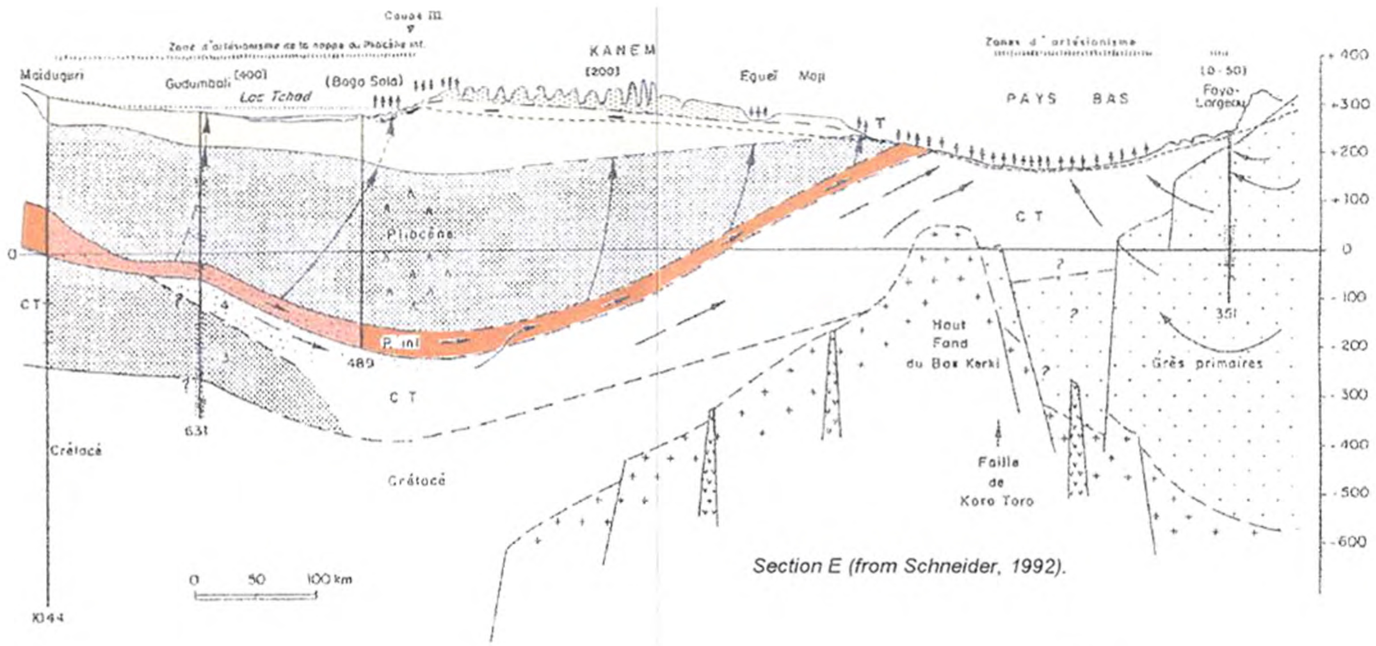


Sections A, B and C (from Leduc-PNUD 1991).



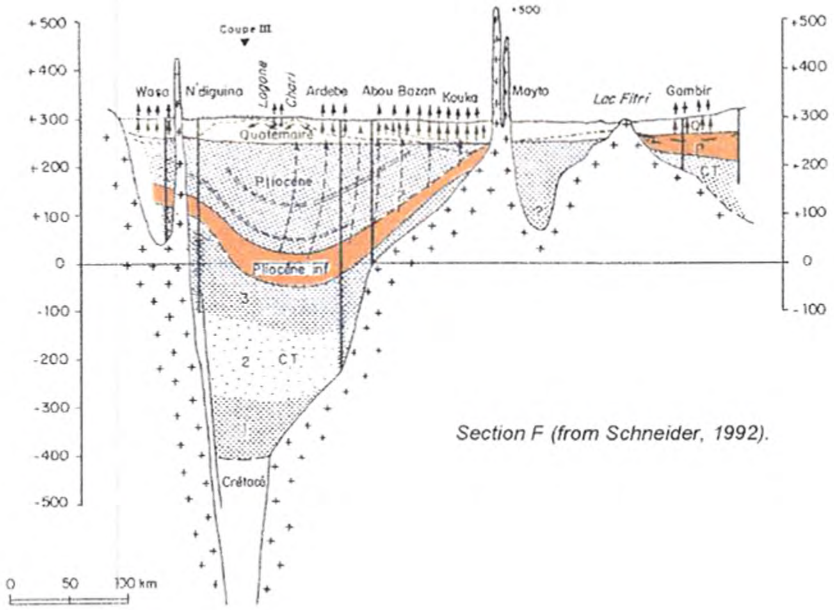
Section D (from Miller 1968).

- Quaternary aquifer
- Pliocene impermeable clay
- Pliocene aquifer

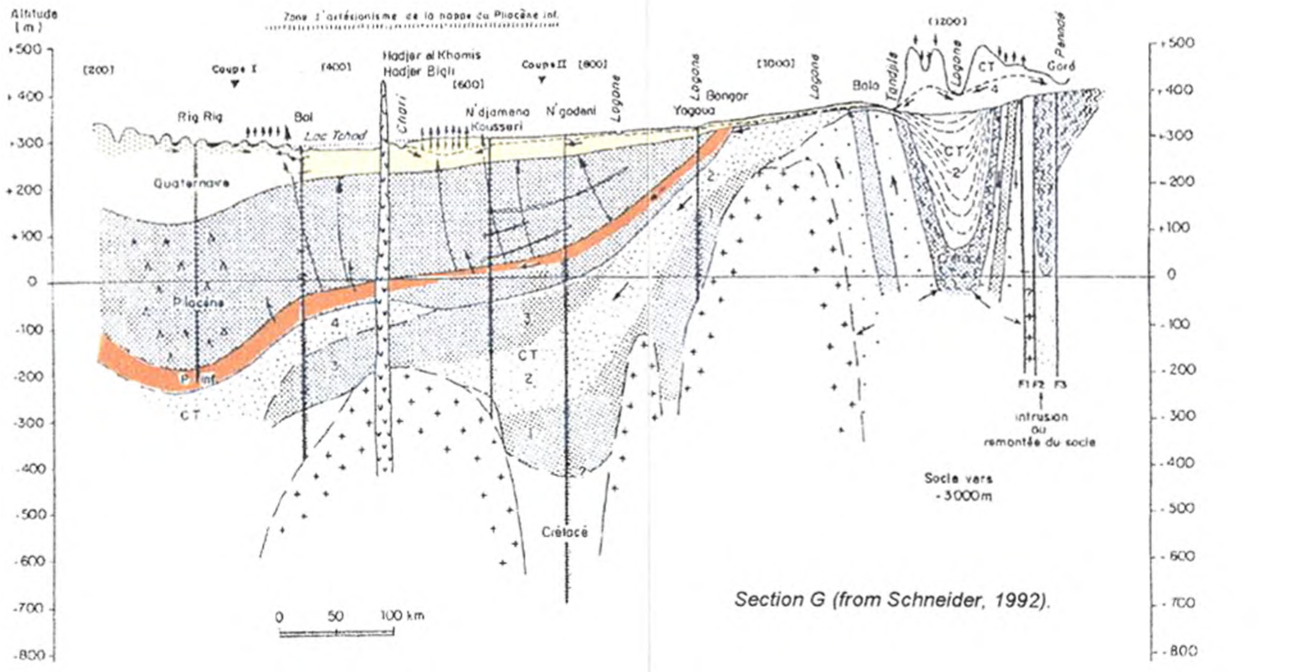


Section E (from Schneider, 1992).

- ↑↑↑ Rainfall recharge area
- ↑↑↑↑↑ Exfiltration (evapotranspiration) ai
- → Groundwater flow direction
- Quaternary aquifer
- Pliocene aquifer
- Impermeable layer (clay)
- Sand and sandstone deposits
- + + Cristaline basement
- Heavy gravimetric anomaly
- ∧ ∧ Gypsium



Section F (from Schneider, 1992).



Section G (from Schneider, 1992).

Figure 2-13: Hydrogeological sections and main aquifers in the central part of the Lake Chad Basin.

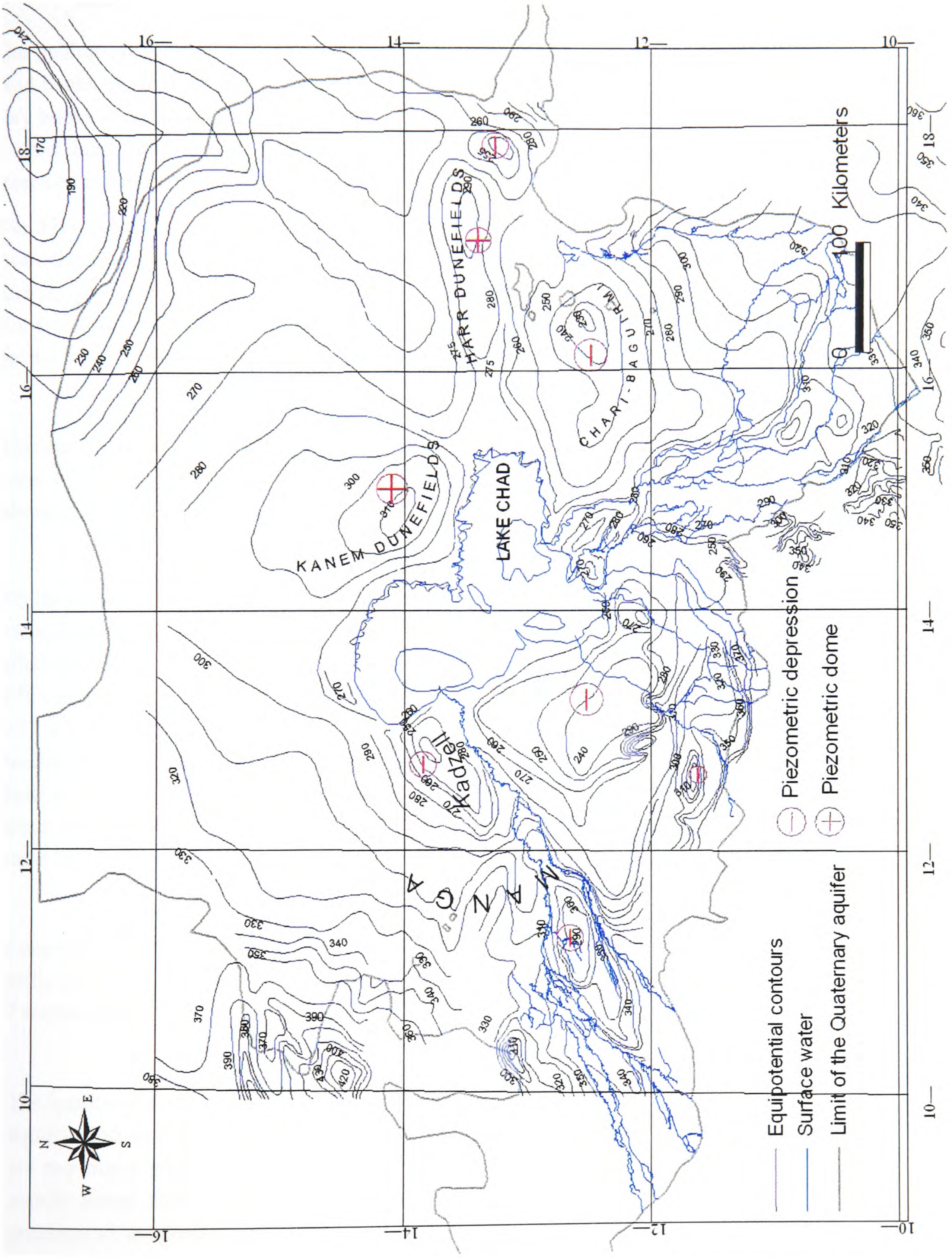


Figure 2-14: Piezometry of the Quaternary aquifer in the late 1960's (from UNESCO-PNUD 1972; Schneider 1969).

2.5.4 PLIOCENE AQUIFER

The geological formation that contains the Lower Pliocene aquifer is made of an intercalation of sand banks of small to coarse grains of quartz (gravels are sometime observed) with pure or sandy clay banks. The thickness of these banks is often about 5 to 10m, but their horizontal extension is limited due to their fluvial or deltaic deposition mode. As such, the sandy banks are hydraulically inter-connected (FAO-Schroeter and Gear, 1973; Schneider and Wolff, 1992).

The Pliocene aquifer is separated from the phreatic aquifer by a thick layer of clay deposits dated from the Pliocene-Pleistocene. To the north-east, the lower Pliocene sands may be superposed directly on those of the Miocene (Continental Terminal aquifer) to form a single aquifer. In the Kanem region (Chad), the union of the Pliocene and Continental Terminal aquifers is reported to have a thickness that may exceed 275 metres (Eberschweiler, 1993 b; Schneider and Wolff, 1992).

This aquifer flows from the south towards the Lowlands region in the north-east. It is confined (over most of its extent) and artesian in the region of Lake Chad, with pressures exceeding 20 metres above ground level.

To its southern limit, it can be considered in continuity with the Quaternary aquifer (Miller et al., 1968; Schneider and Wolff, 1992). Some authors also picture this region as its "active recharge area" (Eberschweiler, 1992; Eberschweiler, 1993 a; Eberschweiler, 1993 b). However, isotopic measurements (^{14}C) indicate ages ranging from 18.6 to 24 kA BP in Nigeria (Edmunds et al., 1999) and from 23 to >37 kA BP in Chad (Schneider and Wolff, 1992). The small hydraulic gradients and the ages increasing along the line of flow indicate very slow movements of water (Edmunds et al., 1999; FAO-Schroeter and Gear, 1973). The absence of Holocene age water confirms that effective recharge in the south has ceased since the last Glacial optimum. From the latest evidence, it is clear that the aquifer must be considered as fossil with limited reserves.

Long-term evolution shows a drop in the levels of the Pliocene aquifer from 1960's to 1990's on drills in Nigeria, Niger, Chad and Cameroon. For instance at Yasku in Nigeria the level dropped by 7 metres between 1962 and 1992 (Eberschweiler, 1992).

The quality of the water in this aquifer is poorer and more mineralised than that of the Quaternary aquifer. The waters are generally aggressive and have a mineralisation that can reach 1.0 g/l. There are two major groups: bicarbonated (calcic or sodic) or sulphate-sodic type. The second group is mainly found near the lake, where such characteristics are suspected to be inherited from the presence of evaporated deposits in the formation (Eberschweiler, 1992; FAO-Schroeter and Gear, 1973; Schneider and Wolff, 1992).

More research on the general mechanism and properties of the Pliocene aquifer is needed. However, the high level of sulphate, the presence of iron in quantity in certain wells, and a mineralisation that reaches the gram per litre renders level it of poor quality for human consumption and livestock

(FAO-Schroeter and Gear, 1973). In addition, many areas of the artesian zone have a rate of residual sodium carbonate that is too high and classify the water as unsuitable for irrigation (Eberschweiler, 1993 b; FAO-Schroeter and Gear, 1973). Given its depth, exploitation is also limited by the cost of boreholes. At the moment, it is only tapped in Niger and above all in Nigeria.

2.5.5 CONTINENTAL TERMINAL

The Continental Terminal aquifer is essentially contained in an alternation of sandstone and clay. It is about 100 to 200 m thick but can reach 600 m in the rifts such as that of Doba (Eberschweiler, 1993 b). Its extension in Niger is not well known. To the south, recharge takes place from the outcropping sandstones (Figure 2-12) and is estimated of 15 to 20 million cubic metres per year (FAO-Schroeter and Gear, 1973). It is confined in the centre of the basin. Its waters have a sodic-carbonated facies. It is in the south where it outcrops (south Chad and east Nigeria – Kerri Kerri formation) that the quality of its water is the best and offers good characteristics for human consumption and irrigation. Elsewhere, to the north and the centre of the basin, the quality of the water is poor. With too much sodium and generally a high mineralisation, it is not suitable for human consumption and irrigation (Eberschweiler, 1992; FAO-Schroeter and Gear, 1973; Schneider and Wolff, 1992). Hence it is mainly exploited where it outcrops (Figure 2-12), and in the rest of the basin it is only tapped at Maiduguri, Nigeria, and Kousseri, Cameroon.

2.5.6 THE CONTINENTAL HAMMADIEN

Lastly, the Continental Hammadien aquifer was discovered in the basin during oil exploration drillings. The very little information available on this aquifer in the conventional basin shows that water is of very poor quality (FAO-Schroeter and Gear, 1973). Given its depth and the low quality of its water, it is not tapped in the centre of the basin.

2.5.7 ISSUES TO TACKLE

The main concern regarding the groundwater resources of the basin is the Quaternary aquifer. Priority should be given to improve our general knowledge of this aquifer for its sustainable management. First because it is a vital water resource on which the population and the socio-economy of the basin depends, and second, because being a shallow aquifer system, it is vulnerable to surface events. Furthermore, the impact of recent droughts has not been studied yet, and the increase in water demand of the population might also endanger the reserves of the aquifer.

Careful management of the Pliocene aquifer is required as it holds fossil waters and its levels are reported to have decreased.

Fundamental information on the confined aquifers of the Continental Terminal and Continental Hammadian is missing (such as their precise extent or their hydrodynamic properties). Work should rather be restricted to the south, where the Continental Terminal outcrops and is exploited by the population. Nevertheless, the more humid climate of the south renders the area less vulnerable to droughts and to water shortages in general. In other words, this is probably not a priority in terms of water resources management.

2.6 USE OF REMOTE SENSING AND GIS FOR WATER RESOURCES MANAGEMENT IN THE BASIN

2.6.1 RAINFALL

Given the high spatio-temporal variability of rainfall and the gaps in field data, remote sensing appears useful to estimate precipitation. Sensors like TRMM, Meteosat and AVHRR already contribute to estimation of rainfall in Africa. More work is required, however, to achieve a higher degree of accuracy.

2.6.2 SURFACE WATER

Lemoalle (1978, 1979) was the first to report on the usefulness of remote sensing to monitor the extent of large water bodies in the Lake Chad Basin. Open waters of Lake Chad, the Yaere and Lake Fitri were detected with Landsat MSS data for several dates in the 1970's. Airborne and ground observations supported and confirmed the results from Landsat MSS data. Later, Lemoalle (1991; 1996) used Landsat and mainly Meteosat to reconstruct a long-term time series (from 1973 to 1991) and depict the interannual variations of Lake Chad's extent.

The use of NOAA/AVHRR was first investigated by Schneider (1985). Vegetation activity index (from channels 1 and 2) and thermal data were respectively proven as useful for detecting vegetation and water extent change in the region of Lake Chad.

Rosema and Fiselier (1990) used the principle of thermal inertia to detect Lake Chad and the Yaere extent with Metheosat thermal infrared images at noon and at midnight. They showed that despite the relatively low spatial resolution (5km) Meteosat data are, given the size of the area and their temporal resolution, an ideal tool for monitoring the extent of Lake Chad and the flood plains.

For the period covering 1995 to 1998, Birkett (2000) showed that AVHRR imagery (band2 - 0.9μm) can be used to detect both seasonal and interannual variations of Lake Chad's extent. The author pointed out two limitations: no detection is possible during the rainy season because of clouds (June to September); and problems might also be experienced given the relatively low sensitivity of the near infrared (NIR) histogram technique used.

Birkett (1995; 2000) demonstrates that satellite radar altimetry (TOPEX/POSEIDON) can be used to monitor interannual and seasonal variations of surface water level in the basin with a precision of 10 cm rms or better. Experiments were successfully conducted not only on Lake Chad's level (from 1992 to 1998), but also on the flood plains and on large rivers, such as the Logone and the Chari.

One should note, however, that the satellite has a repeat pass of 10 days, which limits the frequency of observation.

From this appraisal, the use of remote sensing to date in the surface hydrology of the basin has been successful and encourages more applications. Most of the works have focused on Lake Chad, but further applications could contribute, for example, to enhance our knowledge of other water bodies of the basin. In other words, there is a need to apply remote sensing and GIS to study and monitor the flood plains, small lakes and large ponds.

The use of GIS and remote sensing could be extended through application for hydrological modelling. GIS and remote sensing are powerful tools that can be used to provide and handle data for surface water models (Maidment, 1993; Singh and Fiorentino, 1996). So far, the most extensive modelling project developed to manage the basin's surface water has been HydroChad (Mott MacDonald Int, 1993). However, this model does not make the most of GIS and does not use remote sensing. Lately, Coe (2000) developed another hydrological model of the basin. The author concluded that this model could be improved with better GIS data and particularly a higher resolution digital elevation model (DEM). This model does not make any particular use of remote sensing either and uses a coarse grid of about 10km.

Finally, remote sensing could provide operational tools for near-real time monitoring of the basin's surface water. This seems feasible and would be very useful (Birkett, 2000; Olivry and Leduc, 1996).

2.6.3 GROUNDWATER

In order to characterise the Quaternary water table in the Chari-Baguirimi plain (Chad), Bonnet (1995) used a GIS to display and analyse hydrogeological data archived at the Direction de l'Hydraulique et de l'Assainissement (DHA-N'Djamena). Institutions of the basin often have databases of hydraulic works. In the best cases, these databases are integrated in a GIS.

These are to the best of our knowledge the only use so far of GIS regarding the hydrogeology of the basin. Remote sensing has simply not yet been applied to groundwater. Groundwater models have already been developed in Niger (Leblanc, 1997; Leduc-PNUD, 1991), in Nigeria (Isiorho et al., 1996) and for the whole basin (Eberschweiler, 1993 a). However, they use neither remote sensing nor GIS possibilities.

The minor use of GIS and remote sensing up to now does not reflect the real need for geographical information. There are key issues in the hydrogeology of the region for which GIS and remote sensing could be extremely useful.

For us the interactions between surface phenomena and the shallow quaternary aquifer have to be investigated. This is particularly true as the hydrological processes are not yet fully understood. Recharge and discharge phenomena as well as their spatial distribution could be revealed in spatio-temporal patterns of surface characteristics. UNESCO (1972) attempted to investigate the relationship between the surface characteristics and the Quaternary water table. However, it was one of the first hydrogeological studies of the basin, and the data available were limited. Besides, given the study period, no satellite data or GIS were used either. Although the study raised interesting questions it was not conclusive and, particularly, it could not provide any evidence of many hydrogeological interpretations.

The impact of hydroclimatic change, such as Lake Chad's shrinkage, has to be assessed. Groundwater models are a tool of choice for groundwater management. In the basin, groundwater modelling of the Quaternary aquifer should be directed towards an integrated management of the basin's resources, i.e., including representation of (i) the interaction with surface water, (ii) human demand/human structure, (iii) surface characteristic as well as their change. It is also necessary to view the basin and the aquifer as a whole. Given the scale of the aquifers spatial domain, remote sensing is needed to collect data and GIS to manage the resulting huge volume of data. They are an essential means to reach a state of the art groundwater modelling.

2.7 CONCLUSION

The Lake Chad Basin shows extremely variable hydroclimatic conditions. The central part of the basin is affected by a water deficit with high evapotranspiration rates all year long and low seasonal rainfall. Additionally, in this part of the basin, there has been during the recent decades an increasing pressure on water resources, that arises from the combined effect of the drought and the increase of water for human consumption and irrigation.

Regarding all the water resources of the basin, the use of GIS and remote sensing has been very limited, which is surprising given the scale of the basin. As for groundwater problems specifically, there have been limited applications of GIS and simply no use of remote sensing.

For us, a top priority for a sustainable management of the Basin is the Quaternary aquifer. It clearly constitutes the main water resource in the central part of the basin where there are water shortages. However, this aquifer has been little studied. Hence, given the limited time accredited for this PhD thesis, we decided to concentrate our efforts on the Quaternary aquifer. From a broader point of view, this is also a choice to investigate the use of remote sensing and GIS for original applications in hydrogeology of semi-arid regions. When this thesis was drawn up, Coe's work (2001) on the development of a surface water model was in progress. Meanwhile, first results observed on hydrogeological issues were encouraging. Being of the view that it is better to spread general efforts, this reinforced our choice to focus on the hydrogeology and the Quaternary aquifer.

In this context, our specific objectives to improve the water resources management in the basin are to:

- Exploit multi-source and multi-scale remotely-sensed and ground-based data in a GIS in order to enhance the current level of understanding of the superficial aquifer in the central part of the Lake Chad Basin;
- Analyse the surface patterns over the piezometric depressions to find if certain factors could explain the origin of the depressions;
- Evaluate the application of remote sensing and GIS to map groundwater recharge and discharge areas;
- Demonstrate novel applications of remote sensing and GIS for the hydrogeological modelling of the Quaternary aquifer, with specific regard to the assessment of hydroclimatic change (particularly Lake Chad's shrinkage) on the aquifer;
- Offer a `bird's eye view′ of the centre of the basin. This is an opportunity to understand the basin's dynamics from a global and local perspective and it is expected that this will throw new light on the knowledge of the basin. The groundwater model developed is anticipated to allow the modelling of the Quaternary aquifer (500,000 km^2) as a whole, to take into account surface characteristics and to represent hydroclimatic change affecting the surface;
- Provide the first steps towards an integrated system for the water resources management in the central part of the basin.

Chapter 3

CRITICAL APPRAISAL OF RECHARGE AND DISCHARGE PROCESSES OF THE QUATERNARY AQUIFER

3.1 INTRODUCTION

3.1.1 OBJECTIVES

We have chosen to focus on the most sensitive region of the Lake Chad Basin, i.e. the central part, and particularly on what constitutes the main water resource there, i.e. the Quaternary aquifer. In terms of water resources management, defining recharge and discharge regions of an aquifer has always been a major task for hydrogeologists. This is indeed necessary for the assessment of the water resources available.

To this day, there has not been any document identifying and estimating recharge and discharge areas for the whole of the Quaternary aquifer. Recent increases in human abstractions as well as hydro-climatic changes, make this work indispensable (see, Ch. 2). The work in this chapter aims to fill this gap. It puts forward for the first time a comprehensive review of the recharge and discharge processes that affect the whole Quaternary aquifer of the Lake Chad Basin. It addresses rainfall recharge as well as aquifer interactions with surface water. It also compares different methods for estimating recharge in such environments. Finally, it contributes to our global knowledge of semi-arid area hydrology by providing critical information over a large phreatic water table of the Sahel.

First, recharge and discharge processes are identified and described. Subsequently, the estimations of the recharge values are examined. These goals are achieved through a critical review of scientific literature as well as technical and consultant reports. Then, comments are developed on the estimations of the recharge and proposals on further work to be undertaken for a better understanding.

To complete these investigations it is convenient to divide the whole Quaternary aquifer into smaller geographical areas. Natural regions with the same characteristics such as the piezometric depressions, the piezometric domes, and the rivers have been regrouped in common sections. The other paragraphs analyse specifically the Manga, the Kanem and Lake Chad.

3.1.2 GENERAL PROBLEM

Definitions

First, the difference between recharge and infiltration must be emphasised. As hydrogeologists, what we are trying to define is the amount of water that actually reaches the water table. Infiltration can be defined as the amount of water passing through the ground surface. However, not all of this will reach the water table, particularly in semi-arid areas. In fact, a large part is retrieved by soil moisture deficit and evapotranspiration processes in the unsaturated zone. Recharge or its opposite, discharge, corresponds to the natural quantity resulting from the balance between infiltration, and evapotranspiration processes. Recharge or discharge is generally expressed in mm/yr. If the annual budget is positive and rainfall or surface water infiltration is feeding the water table then we talk about a recharge (inflow to the aquifer). If the annual balance is negative and evapotranspiration flows dominate the vertical exchanges then one calls it discharge (outflow from the aquifer).

In semi-arid areas, one can distinguish three main types of recharge (Lerner et al., 1990; Simmers and Hendrickx., 1997) such as shown in Figure 3-1:

- A direct recharge – the rainwater directly infiltrates into the deposits as falls;
- A localised recharge – where the water percolates to the ground after runoff and concentration in the absence of well-defined channels. It occurs in bare hard rocks or limestone terrain, topographic depressions, minor wadis or arroyos, and in mountain front systems;
- An indirect recharge – percolation to the water table through the beds of surface watercourses.

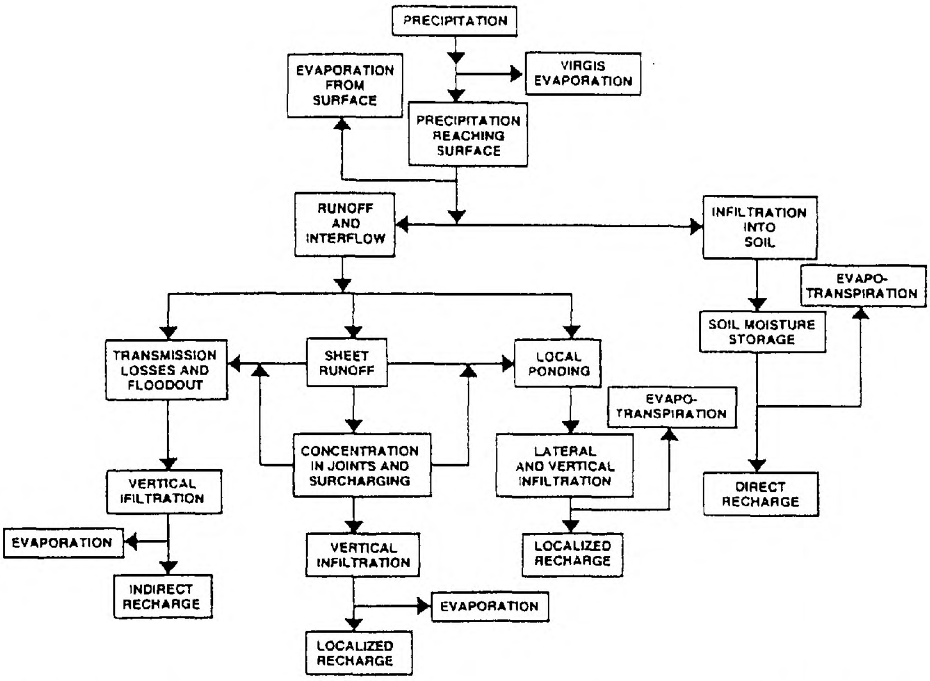


Figure 3-1: Various elements of recharge in (semi-) arid areas (Lloyd, 1986).

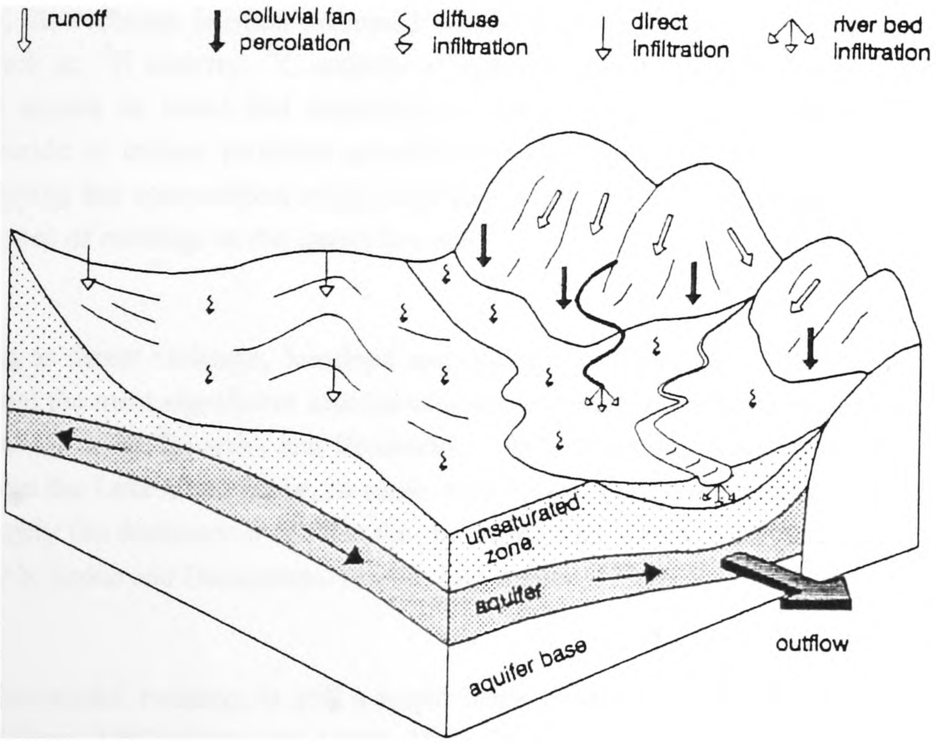


Figure 3-2: Mechanisms of the recharge in the Pitsanyane and Nnywane basins, Botswana (Gieske, 1992).

In the Lake Chad Basin, potential sources of recharge to the Quaternary aquifer are namely: direct rainfall recharge, localised rainfall recharge (through ponding in topographic depressions) and indirect recharge via the rivers (mainly from Chari, Logone and Komadougu) and Lake Chad.

When studying a large aquifer, recharge is also a matter of scale. A local recharge is the value of recharge for a restricted area. Typically, chloride profiles of the unsaturated zone will give point results and indicate a local recharge. Conversely, a regional recharge is an estimation of the average recharge over a large area. Small-scale groundwater models or statistical approaches of local recharge measurements give an estimation of regional recharge. Because we are studying the water resources available across the whole of the Quaternary aquifer, throughout this study we will be more interested in obtaining regional values.

Worldwide estimations

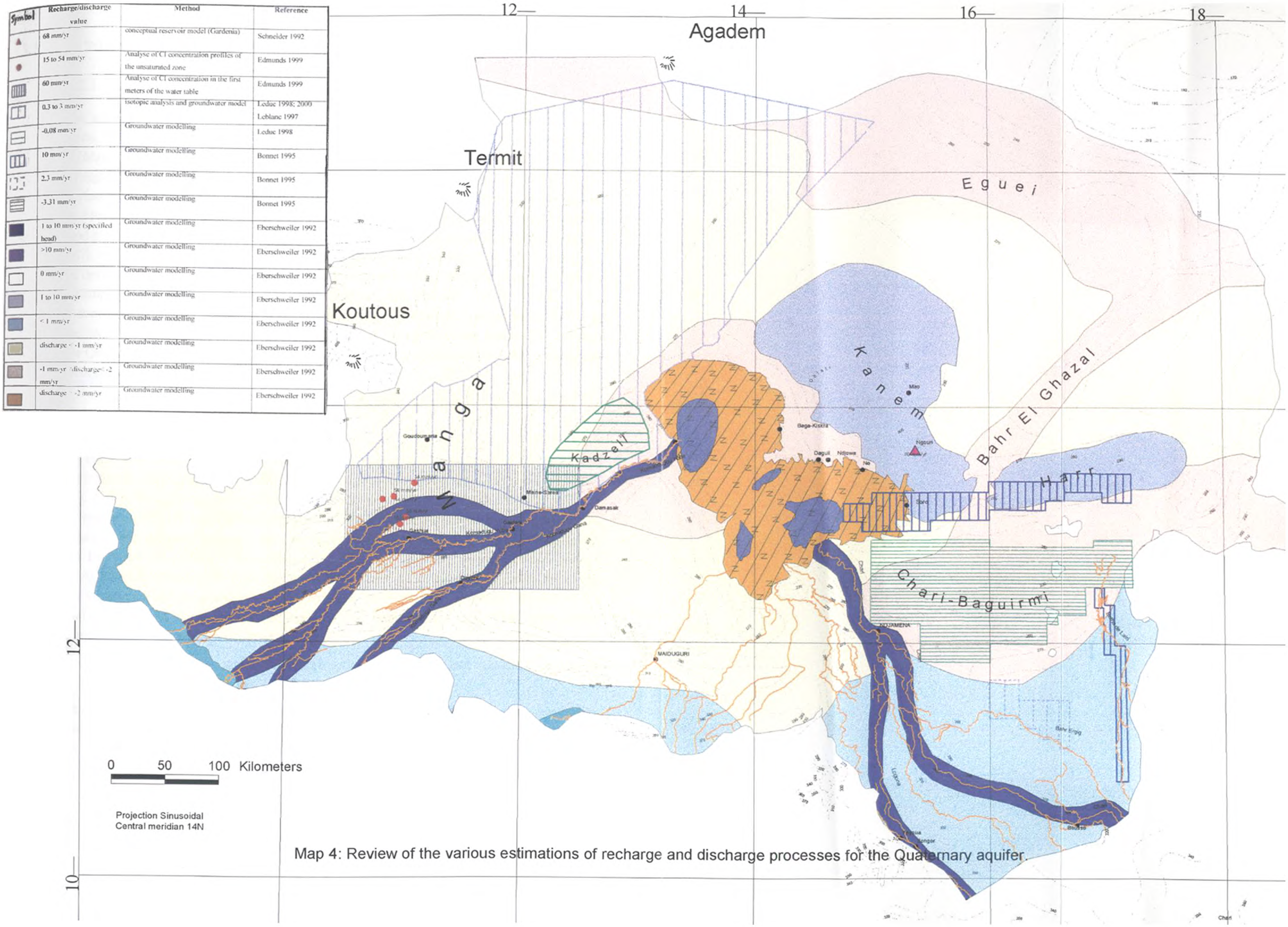
In semi-arid hydrology, estimating recharge and discharge processes is particularly difficult as the flows involved can be very small and classical methods often used for temperate climates reach their limit when used for such areas (Fontes and Edmunds, 1989; Gee and Hillel, 1988; Lerner et al., 1990; Simmers and Hendrickx., 1997). This is emphasised when the study area is in developing countries and few data are available (Fontes and Edmunds, 1989).

Methods of estimation might focus on the unsaturated zone with two common techniques both using vertical tracer profiles: the method of chloride balance or the search for the tritium peak. Alternatively, the recharge is often estimated via the saturated zone. This latest approach involves techniques such as: ^3H activity, ^{14}C activity of mineral carbon, chloride balance and groundwater modelling. It should be noted that depending on the location of the sampling, unsaturated zone methods (chloride or tritium profiles) generally quantify only a direct recharge. On the contrary methods analysing the composition of the saturated zone (^3H, ^{14}C), as well as groundwater models integrate all types of recharge in the quantification.

In comparison to direct recharge, localised and indirect recharge are often considered at least as significant if not the most significant sources of natural recharge in semi-arid regions (Gee and Hillel, 1988; Lerner et al., 1990; Simmers and Hendrickx., 1997; Stephens, 1994; Wood and Sanford, 1995). Not too far from the Lake Chad Basin, in south-west Niger near Niamey, it has been established that ponding is largely the dominant mode for the recharge of the Continental Terminal phreatic aquifer (Favreau, 2000 b; Leduc and Desconnets, 1994 b; Leduc et al., 1996).

Quantifying the rainfall recharge is still a major issue in semi-arid hydrology (Allison et al., 1994; Aranyossy and Gaye, 1992; Carter and Alkali, 1996; Fontes and Edmunds, 1989; Gee and Hillel, 1988; Leduc et al., 2000; Lerner et al., 1990; Simmers and Hendrickx., 1997). In the dunefields of Saudi Arabia, Dincer (1974) showed that even with an annual rainfall of only 80 mm/yr there can be a significant infiltration through the sand dunes (and probably recharge depending on the grain size). In the dunefields of Southern Australia (rainfall of 350 mm/yr), Allison (1983) reports a direct recharge rate of between 0.1 to 3 mm/yr using the chloride profile method (backed up by tritium profiles). In Senegal, Edmunds (1992) interprets tritium profiles of the unsaturated zone collected in Quaternary sands. Results indicate a direct rainfall recharge rate of between 4.6 mm/yr to 34.4 mm/yr (mean at 15.2 mm/yr) with an average annual rainfall at St Louis of 356mm/yr (1893-1982). Meanwhile, still in Senegal, the search of ^3H peak in the unsaturated zone led Aranyossy and Gaye (1992) to estimate the recharge to be between 20 and 30 mm/yr. In the region of Niamey, south-west Niger where rainfall is about 560 mm/yr, Bromley et al. (1997) find a long-term average direct recharge of 13 mm/yr using the chloride profile method of the unsaturated zone. Meanwhile, in the same area, Leduc and al. (1996; 1997) applied methods based on hydrodynamic observations and tritium content in the saturated zone. They obtained a rainfall recharge of 25 to 50 mm/yr including direct and localised (ponding) processes. Lately, still for the same area in Niger, Favreau (2000-b) obtained a first estimation of the long-term regional recharge with a groundwater model to about 1 mm/yr and a second estimation of between 0.6 and 5 mm/yr from ^3H and ^{14}C measurements in the saturated zone. In the Kalahari, Botswana, investigations based on hydrodynamic properties and Cl and tritium profiles of the unsaturated zone led Foster (1982) to state that: "in an area with a mean rainfall of 450 mm, direct rainfall recharge should not be presumed to be occurring where the Kalahari's sand-cover is more than 4m". However, Mazor (1982) challenges this assumption. For this later author, there is evidence of an active rainfall recharge in the Kalahari, even under thick sand cover: high tritium and ^{14}C values of the water table; rises of the water table following above average rainy years; and lack of substantial lowering of the shallow wells that have been exploited for a long time. Recently, Gieske (1994) has studied an area close to that studied by Foster. He estimates, using chloride and tritium profiles, that the direct recharge is between 9 to 22 mm/yr.

Worldwide, the estimations of rainfall recharge in semi-arid areas vary greatly according to the method used and the region studied. Therefore, one generally advises a series of techniques to be used to cross-check the results (Fontes and Edmunds, 1989; Gee and Hillel, 1988; Lerner et al., 1990; Simmers and Hendrickx., 1997).



Symbol	Recharge/discharge value	Method	Reference
▲	68 mm/yr	conceptual reservoir model (Gardenia)	Schneider 1992
●	15 to 54 mm/yr	Analyse of Cl concentration profiles of the unsaturated zone	Edmunds 1999
▥	60 mm/yr	Analyse of Cl concentration in the first meters of the water table	Edmunds 1999
◫	0.3 to 3 mm/yr	isotopic analysis and groundwater model	Leduc 1998; 2000 Leblanc 1997
⊟	-0,08 mm/yr	Groundwater modelling	Leduc 1998
▥	10 mm/yr	Groundwater modelling	Bonnet 1995
⬚	2.3 mm/yr	Groundwater modelling	Bonnet 1995
▤	-3.31 mm/yr	Groundwater modelling	Bonnet 1995
■	1 to 10 mm/yr (specified head)	Groundwater modelling	Eberschweiler 1992
■	>10 mm/yr	Groundwater modelling	Eberschweiler 1992
☐	0 mm/yr	Groundwater modelling	Eberschweiler 1992
■	1 to 10 mm/yr	Groundwater modelling	Eberschweiler 1992
■	< 1 mm/yr	Groundwater modelling	Eberschweiler 1992
■	discharge < -1 mm/yr	Groundwater modelling	Eberschweiler 1992
■	-1 mm/yr >discharge> -2 mm/yr	Groundwater modelling	Eberschweiler 1992
■	discharge > -2 mm/yr	Groundwater modelling	Eberschweiler 1992

Map 4: Review of the various estimations of recharge and discharge processes for the Quaternary aquifer.

3.2 RAINFALL RECHARGE AND DISCHARGE IN MANGA

3.2.1 INTRODUCTION

This section addresses the rainfall recharge and discharge affecting the Quaternary aquifer in the Manga region. Manga is a vast region of the Lake Chad Basin extending from north-east Nigeria to east Niger (Map 4). It is bounded to the south by the Komadugu-Yobe river and to the north by the Termit and Agadem massifs. Westward, the hills of Termit, Koutous and Mounio surround it. To the south-east, Kadzell and Lake Chad mark the end of this region. A major part of Manga is covered by dunefields. Fluvio-lacustrine sediments can also be found especially in the south, along the banks and the flood plains of the Komadugu-Yobe. There, these fluvial deposits are often covered by dunes (Pirard, 1967). At a regional scale, the topography of Manga appears to be very flat. Yet, looking at a much more detailed level, almost the whole of Manga topography is dominated by dunefields with a series of humps and depressions (Greigert, 1979; Greigert and Pougnet, 1967b; Pirard, 1967). Interdunal depressions, especially in the south, can form oases (playas) with small lakes. In a few cases, these lakes are perennial, but normally they only occur during the rainy season. The relation between the Quaternary aquifer and surface water (Lake Chad and the Komadugu-Yobe) are detailed in subsequent paragraphs.

3.2.2 QUALITATIVE ANALYSIS

Mortimore (1989) and Carter (1994b) have described the hydrological processes of the oases and dunefields system in south Manga (Nigeria). This description is mainly based on the topography (Figure 3-3). Lower topographic depressions, also called active oases, are typically flat surfaces covered by organic silt, clay and diatomite deposits. They are characterised by the presence of temporal lakes during the rainy season. The water table in these areas is very shallow with levels between 0.5-1m below the surface or sometimes confined and occasionally forming gravity springs or seepage. At a higher altitude, one finds the intermediate level depressions or "dead oases". They support less vegetation and the water table is generally 5-10 metres below ground. Finally at the highest level are the sand dunes, which are made of fine homogenous sand. They have sparse vegetation and the water table is at a depth of 12-15m.

Carter (1994b) considers that these systems are more or less independent and that the hydrological processes taking place can be described as follow (Figure 3-3):

1. Direct rainfall-recharge is assumed to take place on the sand dunes as they have high permeability (infiltration capacities), and as there is no sign of surface water runoff, and because of low vegetation density (small transpiration);
2. After direct recharge, groundwater flows from the sand dunes to the oasis depression.
3. In the oasis depression, there is evapotranspiration of all the direct rainfall recharge from the sand dunes. Carter (1994b) also proposes that all rain falling in the oasis depression during the rainy season might entirely be taken out by evapotranspiration processes and does not contribute to the recharge of the aquifer.

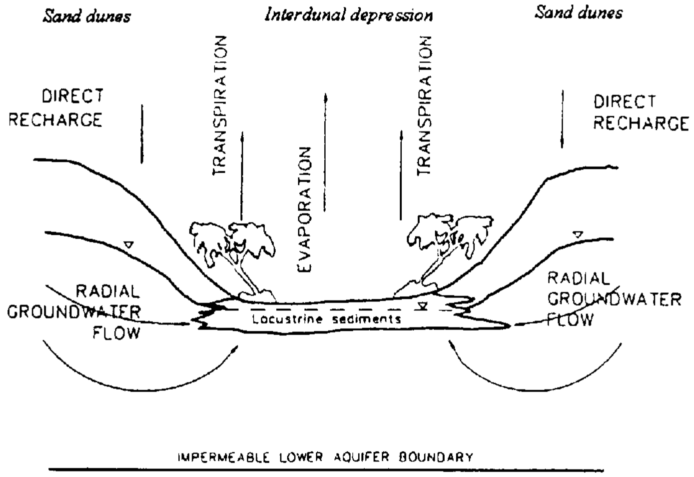


Figure 3-3: Conceptual model of oasis hydrology in Manga (from Carter, 1994b).

In south-east Niger, Leduc (1998) suggested a different description of rainfall recharge processes. He indicates that between Goure and Goudoumaria localised rainfall recharge could take place after concentration of rainwater (runoff) in the topographic depressions.

Another characteristic of these systems is the very high spatial variability (within a few hundred metres) of the groundwater hydrochemistry: "groundwater quality, in terms of electrical conductivity, shows a very marked change between the dunefields and the oases. Conductivity of well waters in the upland and on the edges of the active oases are typically around 100-500 µs/cm, while in the interior of the oases values range from 6000 to 61000 µs/cm" (Carter, 1994 b). Leduc (1998) also reports the high spatial variability of the water table chemistry in Niger. This points to strong evapotranspiration processes in the active oases.

Carter (1994) infers that the high recharge rate takes place due to the important infiltration capacity of sand dunes in south Manga and the sparse vegetation that cover them. Evidence of recharge in the Niger part is further supported by increases in the water table levels (0.5 to 1m) during the rainy season as observed in the Maine-Soroa and Goudoumaria areas (Greigert, 1979; Leduc et al., 1998). In Nigeria, nearby Kaska, Carter (1996) also reports seasonal variations of about 0.16 m each year. In this latter area, Carter (1996) describes that after wet years the water table can rise significantly, for example, rising by 0.65 m between 1994 and 1996 (Carter and Alkali, 1996).

3.2.3 QUANTITATIVE ANALYSIS

Eberschweiler (1993) developed a groundwater model of the whole Quaternary aquifer, and found that there is no regional recharge in Manga. In fact, according to this model, the region would be affected by small discharge losses (through evapotranspiration) of less than 1mm/yr. In a technical report (Iwaco, 1985) it is assumed that all rainfall infiltration evapotranspirates without recharging the aquifer. In this document, it is assumed that regional rainfall recharge in south Manga is "nil".

Nevertheless, this is only a hypothesis rather than the result of a field study. No proof or calculation is given in the report.

Based on preliminary field work in 1992, Carter (1994b) proposes an estimation of direct rainfall recharge in the sand dunes of the Kajemarum oasis in south Manga (Nigeria). As described in the previous paragraph, it is considered that a sand dune and oasis complex is an independent and steady-state hydrological system in which all local rainfall recharge on sand dunes flows to the centre of the oasis where it evapotranspirates entirely. Carter estimated, independently, the three following terms of the hydrological system:

- Recharge on the sand dune was estimated at 60 mm/yr from results of a water balance obtained "elsewhere" in the Sahel by Kowal (1978). Applied to the surface area of Kajemarum sand dunes a total rainfall recharge of 4503 m^3/day was calculated;
- Flow towards the oasis was considered analogous with flow to a well and estimated using a steady-state equation for an unconfined aquifer (Todd, 1980). With a saturated aquifer thickness at the oasis margin of 20m, an hydraulic conductivity of 7 m/d and a head difference of 4m, then the flow towards the oasis is of 4416 m^3/day;
- Evapotranspiration in the oasis during the dry season has been estimated at 5 mm/d and the evaporation on bare soil at 1.3 mm/d. Using aerial photographs, these rates have been applied to the corresponding land cover of the oasis interdunal depression. The annual outflow through evaporation processes is then of 4665 m^3/d.

Edmunds (1999) studied the same area as Carter (Map 5). He used chloride unsaturated zone profiles of interstitial water to calculate a direct recharge. The direct recharge is calculated using the formula:

$$Rd=P*Cp/Cs \quad \text{(Equation 1)}$$

where P is the regional rainfall, Cp is the spatially average rainfall chloride concentration and Cs is the mean unsaturated zone Cl concentration. The regional rainfall (P) is estimated at 434 mm/yr from the Gashua rainfall station records between 1960-1990 (Hess et al, 1995). Cp is approximately 1.43 as mentioned above. In total, five chloride profiles were made during the study period (1992-1993) and their approximate locations are shown on Map 4. Three of these were collected in the Manga Grasslands, and show a local recharge rate of between 33.9 mm/yr and 54 mm/yr with a mean of 44 mm/yr. The two other sites, outside the dunefields, indicate a recharge rate of 14.9 and 53 mm/yr.

The same author used the concentration of chloride in the wells to quantify a value for "long-term (30 years) regional recharge". The method supposes that the water table concentration, which is taken from the top (1-2 m) of the aquifer, represents atmospheric inputs and can then be used to calculate a "regional recharge". For this purpose, chloride concentration of groundwater was measured in 340 wells at the study time (1992-1994). Well depth is generally limited and the approximation that they tap the 1-2 first metre of the Quaternary aquifer seems reasonable. The samples with NO3-N> 15 mg/l were excluded as they can be considered contaminated by pollution. The average Cl concentration for the whole study area is then 10.3 mg/l. Applying the same conservation formula (Equation 1) as for the unsaturated zone profile and with the same parameters (regional rainfall of 434 mm/yr and a spatially average chloride concentration in the rainfall of 1.43 mg/l) gives a "long-term regional recharge" of 60.2 mm/yr.

In Niger, a groundwater model has been developed in order to assess the regional recharge of the aquifer (Leblanc, 1997; Leduc et al., 1998; Leduc-PNUD, 1991). Although limited data are available, the authors were still able to assess the regional recharge. In fact the model appears to be very sensitive to the recharge and only allows a very limited range of values for it. It matches the observed piezometry and field measurements for a regional recharge rate of the order of a mm/yr.

Leduc (2000) also applied another approach to the same area using tritium and radiogenic Carbon. The samples were interpreted statistically to give a value of regional recharge. During previous studies between 1967 and 1970 (FAO-Schroeter and Gear, 1973; UNESCO-PNUD-CBLT, 1972), 15 tritium samples were gathered in Niger and 21 in Chad at the same latitude. In Niger, sample values vary from 0.4 T.U. to 256 T.U. with a median at 5.2 T.U. In Chad, they vary from 0.5 to 143 T.U. Without the doubtful highest values, the total median is 3.5 T.U. "This means that in 1967, after a decade of high and heavily tritiated rainfall, most of the Quaternary aquifer had only very little modern water" (Leduc et al., 2000). Applying a simple model of perfect mixing (Leduc et al., 1996), the author obtained a median renewal rate of 0.1%. Assuming that the Quaternary aquifer has a saturated thickness of 35m and a specific yield of 10%, then the groundwater regional recharge is about 3.5 mm/yr.

The article also analyses five ^{14}C samples in Niger and five in Chad (at the same latitude) which were collected during field missions between 1967 and 1970. They vary from 89 to 146 pmc with a median of 96. In addition, nine recent measurements were taken in 1996. Their values vary from 11 to 98 pmc with a median of 68. Highest values (> 120 pmc) and Fly Camp samples (10.8 pmc) were excluded from the calculations as they represented suspicious values. The data were analysed using, as for the tritium interpretation, a perfect-mixing model. Results indicate a median renewal rate of 0.05% and a mean of 0.17%. The regional recharge is then 2 mm/yr, if we assume the same features for the aquifer as above (Leduc et al., 2000; Sabljak, 1998).

3.2.4 DISCUSSION

According to Eberschweiler (1993), the whole Manga is dominated by discharge processes. Yet, a series of facts tend to show that in Manga there is a rainfall recharge of the Quaternary aquifer: good hydraulic conductivity of the materials, seasonal fluctuations of the water table, results from isotopes of the aquifer and chloride of the unsaturated zone and of the water table. Thus, most of the authors identify a recharge in Manga. Two distinct groups of estimations, nevertheless, emerge from this review:

- A low recharge is supported by Leduc (1998; 2000) on the basis of groundwater modelling and radioactive and stable isotopes interpretation;
- A high recharge of 60 mm/yr is proposed by Carter (1994b) and Edmunds (1999) who used, respectively, water balance and chloride techniques.

In Nigeria, the rainfall is higher than in Niger so that a higher recharge is expected anyway. However, Carter's and Edmunds' study area is bordering Leduc's (Map 4). Therefore, a difference can be expected, but certainly not that significant. Even reduced to its south part, results in Leduc's study area still tend to indicate a low recharge rate.

The first element of explanation is that the authors are not always estimating the same quantity under the term recharge. The Manga dunefields are presumed to be a combination of numerous recharge areas (sand dunes) with many discharge zones (oases). Regional groundwater models like the ones developed by Eberschweiler (1993) or Leduc (1991) calculate a spatially average term that represents the net difference between local recharge and discharge processes. In a region like south Manga where discharge processes are assumed to be important it can make a difference. The temptation to average local direct recharge value (as those obtained by Edmunds) in order to propose a regional recharge would not include discharge processes. Similarly, hydrochemical methods of the saturated zone, used by Edmunds and Leduc to calculate a regional recharge, are unable to take into account discharge areas. In fact, with these two methods a local discharge area will contribute to the regional recharge as only being a low value (there cannot be a negative value with the techniques employed). Therefore, it is necessary to distinguish the regional recharge values obtained by statistical analysis of hydrochemical measurements in the unsaturated (profiles) or in the saturated zone (radioactive isotopes and well chloride concentration) that do not take into account small discharge areas, from the recharge given by regional groundwater models that do.

A high recharge?

To Carter the fact that all his different calculations reach the same estimation supports the assumption that the local rainfall on the sand dunes is of the order of 60 mm/yr.

However, a first criticism of Carter's work is the lack of information regarding the accuracy of the results. The first method to calculate the recharge is simply based on an estimation made "elsewhere" by Kowal (1978) using a simple water balance for mid-Sahel. However, such a method is not recommended for the calculation of recharge in semi-arid regions (Allison et al., 1994; Gee and Hillel, 1988). A groundwater flow equation is applied to estimate the quantity of water flowing from the sand dunes toward the lower depression. The hydraulic conductivity of the aquifer, which is involved in the equation, was derived from aeolian sand texture together with falling head permeameter tests, and was estimated by the author to be between 2 m/d and 7 m/d. The highest value (7 m/d) is the one taken in the calculation. What if 2 m/d or the mean value were taken instead of 7 m/d? Also, permeabilities might have been deduced from subsurface measurements, but drilling logs in south Niger and north-east Nigeria show that finer material (clay) is common towards the bottom of the Quaternary aquifer (Barber, 1965; Greigert, 1979; Greigert and Pougnet, 1967a). The third calculation estimates the evapotranspiration in the oasis during the dry season, assuming again that it is equal to the sum of recharge. Little is said on how evaporation and transpiration rates have been obtained. Are the evapotranspiration rates given by the Penman-Montheith formula applied at Nguru station (FAO 1980) as mentioned in the article? In which case, what is the suitability of this formula to calculate the evapotranspiration for the vegetation of an oasis? Finally, another problem is the initial hypothesis of Carter's approach. It considers an oasis/sand dunes system as a closed system, i.e., where all direct recharge of the neighbouring sand dunes evaporatranspirates in the oasis. Adopting this hypothesis, to find the same recharge rate for each oasis/sand dunes system would imply that the ratio between the surface area of the sand dunes and the surface area of the oasis is the same everywhere. However, it is very unlikely that all these oasis systems have the same configuration, and as the author said: "The Kadjamerom lower depression is exceptional in its size". So what about if the sand dunes/oasis ratio is different for other systems? In fact, a smaller oasis compared to the dunes surface area would imply a smaller recharge rate.

Edmunds (1999) also points out a "high recharge" of the Quaternary aquifer in NE Nigeria (south Manga). From the unsaturated zone chloride profiles, he suggests that in the Manga dunefields ("Manga Grasslands") the average recharge is 44 mm/yr. To him, this estimation represents a minimum. In fact, the chloride profile data are long-term estimates spanning up to 21 years (Edmunds et al., 1999). As such, the value obtained is related to the drought affecting the Sahel since the end of the 60's. Therefore, a recharge at least "30% higher might be expected under the wetter climatic period which characterise the long-term" (Edmunds et al., 1999). Alternatively, for the same author the higher recharge (60 mm/yr) obtained from the concentration of chloride in the wells indicates that at the regional scale other sources of recharge (probably ponding and surface runoff) significantly complement the direct recharge.

To support Edmund's results it must be recognised that the same Cl techniques (especially unsaturated zone profiles) are used widely elsewhere in the world and over a number of years now (Allison and Hughes, 1978; Edmunds et al., 1988). It has been used in Senegal (Edmunds et al., 1988), Niger (Bromley et al., 1997), Botswana (Foster et al., 1982; Gieske et al., 1995), Australia (Allison and Hughes, 1978), and in North America (Stone and McGurk, 1985). Also, Edmunds obtains the same results as Carter over the same area.

However, one can notice significant limitations to the method. It assumes that rainfall is the sole source of chloride entering the groundwater. First, the subsequent assumption is that rainfall data includes both dry and wet deposition, i.e. that dust passing through the region is in steady-state with as much being removed as deposited. Also, it presumes that no salinity is taking place at the surface and that chloride remains inert during all of the recharge (Edmunds et al., 1999). Yet, there could be another source of chloride for the aquifer, namely Lake Chad. The low salinity of Lake Chad has long been recognised. Among the processes contributing to the low salinity of the lake, is the fact that a significant portion of the minerals could be swept away by the wind (during many of the drying spells that characterise the lake).

The second concern is about the accuracy of the results in the study area. The mean value of chloride concentration of the rainfall is reported at 1.43 mg/l. It has been obtained from data of both Kaska and Garin Alkali stations that were collected between 1992 and 1997. No detailed information is given in the article on the way the data were collected, and whether or not they had been gathered during this period for each rainfall event. The article also points out the temporal variability of rainfall chemistry. Only between 1992 and 1994, at Kaska in the driest year (1993 with 320 mm rainfall) the weighted mean Cl is 1.28 mg/l while during the wettest year (1994 with 705 mm rainfall) it is 0.61 mg/l (Edmunds et al., 1999). In the Sahel, Taupin (1993) has shown the "small-scale spatial variability of the annual rainfall is unexpectedly large", which highlights the difficulty of rainfall sampling.

Lastly, chloride profiles are point measurements. Nevertheless, Edmunds (1999) use them propose an average recharge for the south Manga dunefields. Unfortunately, exact locations of unsaturated zone profiles are not given, nor are the measurements placed in their geographical environment. Yet, Carter (1994b) and Mortimore (1989) have shown the high spatial variability of this environment. There is also a high spatial variability observed in groundwater chemistry. Carter (1994b) reports that within several hundred metres typical groundwater conductivity might vary from 100 µs in the sand dunes up to 61000 µs in the centre of oases. Moreover, hydrological processes are totally different: rainfall recharge is expected on sand dunes while evapotranspiration is presumed in oases. We can also expect this high spatial variability to be present in the unsaturated zone. It is therefore difficult to generalise point measurements to such a vast and complex region.

The recharge rates suggested by Carter (1994b) and Edmunds (1999) are very high. There is no doubt that such rates imply recent water to be found and dominate in the aquifer. Then how can we explain a recharge of 40-60 mm/yr if radioactive (especially ^{14}C) and stable isotopes of the saturated zone are showing old waters? Some ^{14}C measurements presented by Leduc (2000) are located relatively close to Carter and Edmunds' study area but still show relatively old waters.

If a high recharge is assumed for the region then this leads to an another problem. Even if recharge takes place only on sand dunes, as Carter (1994b) comments, this represents an enormous inflow to the aquifer. Where does this water go? Are there any outflow features (discharge) able to absorb all this water? Inside Manga, there might be a major discharge feature, i.e., evapotranspiration dominated areas (oases). For example, Carter assumed that at Kadjemarum the oasis is so vast that it can absorb all local recharge on sand dunes. However, the Kadjemarum oasis is an exception by its size (Carter, 1994 b) and it is very unlikely that the others have a sufficient area to absorb all high recharge on sand dunes. The piezometry in Manga shows that to the east the aquifer is fed by the relief (Mounio, Koutous, Termit), to the south it is recharged by the Komadugu-Yobe, to the north an inflow arrives between Termit and Agadem, in south-east Lake Chad is reported to be at a higher altitude than the water table. Then the only outflows (discharge) from the Manga to other hydrogeological regions are in the north-east, towards Chad, and to the south-east, in the piezometric depression of Kadzell. However, piezometric gradients are so small that only a limited amount of water can leave Manga through these outflows. Sensitivity tests on a groundwater flow model developed for the Niger area have shown that it would be impossible to reproduce the water table with a high value of recharge (Leblanc, 1997; Leduc et al., 1998).

A small recharge?

Northwards of Carter's and Edmunds' study area, Leduc (2000) derived from radioactive isotopes (^{3}H and ^{14}C respectively) renewal rates of the aquifer of 0.10% and 0.05%. He concludes that a low regional recharge rate of about 2 or 3 mm/yr is taking place. To him these results are compatible with the stable isotopes contents (^{2}H, ^{18}O), which shows a mixing of old and recent waters. Results are also confirmed by a regional groundwater model, which indicates a global recharge of about a mm/yr.

Can we doubt about the ability of chemical signatures in the saturated zone to estimate recharge rates in the region? In fact, if low recharge rates are assumed, then there is the possibility of mixing/dilution of small amounts of modern water with paleowaters. Also, ^3H samples were collected in 1967. One can therefore question if the tritium signal from atmospheric nuclear tests had reached the water table at that time, as in fact, the unsaturated zone may store water for several decades before it actually reaches the water table. The water table depth is often important in the Manga region (Leduc-PNUD, 1991). Aranyossy (1992) conducted unsaturated zone tritium measurements in a similar environment of Northern Senegal (Quaternary sand deposits with a semi-arid climate). He finds out that in 1989-90 the thermonuclear tritium peak was still in the unsaturated zone, only 12 to 20 metres below ground level. However, Leduc assumes that in Manga the recharge is mainly taking place with a localised type, in which case the water infiltrates rapidly into the ground.

To conclude, in the dunefields, this section has raised the need to distinguish regional recharge calculated from hydrochemical methods and regional recharge calculated by groundwater models. In fact, unlike other methods, regional groundwater models will take fully into account the evapotranspiration areas in the interdunal depressions (oases). They will give at a regional scale the balance between these small evapotranspiration areas and the recharge zones.

The comments made during the discussion lead us to think that a high rainfall recharge rate is unlikely to take place in south Manga. Also a small recharge appears to be more related with the lack of response of the water table to the droughts of the 1970's and 1980's (Leduc et al., 1998). If the recharge was very high, there is no doubt that the drought that started to affect the whole Sahel since the late 1960's would have led to an important drop of the water table levels. Leduc (1998) and Sabljak (1998) have analysed long-term fluctuation of the water table in Niger. Records show that there is no sign of an important decrease.

3.3 RAINFALL RECHARGE AND DISCHARGE IN THE HARR AND THE KANEM DUNEFIELDS

3.3.1 INTRODUCTION

Kanem and Harr are located in west central Chad between 13°N - 16°N and 14°E - 17°30'E. They are covered by vast dunefields. In these regions, the water table forms two large piezometric domes. In north Kanem, these deposits are in continuity with the dunes of the Manga region in Niger. During the rainy season intermittent lakes appear in the interdunal depressions (some of them are perennial, see section 2.4.3). Together with Lake Chad these small lakes represent the only surface water of the region (no river). Fine lacustrine sediments often cover the interdunal depressions. Here, unlike in Manga, the authors make the distinction between the small water tables occurring in the interdunal deposits and the general Quaternary aquifer contained in the aeolian sand. In fact, this does not necessarily mean that there is a real difference between Manga and Chadian Oases. Water tables of the interdunal regions are characterised by seasonal fluctuations and a high piezometric and chemical variability (Eberschweiler, 1990; Schneider and Wolff, 1992). The relation between the Quaternary aquifer and Lake Chad in west Kanem is analysed in a following section.

3.3.2 QUALITATIVE ANALYSIS

Rainfall recharge

The aeolian sands of the dunes are fine and very homogenous. They have a high permeability that facilitates rainfall infiltration (Schneider and Wolff, 1992). As in Manga, it is therefore expected that rainfall infiltrates through these deposits. Eberschweiler (1990) states that a part of the heaviest rainfall infiltrates through the sand dunes and directly recharges the general Quaternary water table. The topography is also reported to facilitate localised recharge by concentrating runoff of heavy rainfall. Rainwater has been reported to flow down the slopes of the sand dunes and concentrate in the interdunal depressions (Eberschweiler, 1990). In 1992 at Kaai, J. Lemoalle (pers. Communication) noticed runoff landforms on the slope of dunes after heavy rain.

Seasonal fluctuations of the water table showing a maximum after the rainy season and a minimum at the end of the dry season have been observed at several locations and especially where the water table is close to the surface. This has been interpreted as an evidence of rainfall recharge of the Quaternary aquifer (Eberschweiler, 1990; Schneider and Wolff, 1992).

In addition, the fact that the Quaternary aquifer shows two large piezometric domes centred on the Kanem (Chiati/Kimi-Kimi) and the Harr regions is often interpreted as a proof that, these areas correspond to rainfall recharge zones (Bichara et al., 1989; Eberschweiler, 1990; Eberschweiler, 1993 a; Schneider, 1966; Schneider and Wolff, 1992).

Isotopic measurements were conducted by UNESCO, FAO and ORSTOM in the late 1960's (FAO-Schroeter and Gear, 1973; Faure et al., 1970; UNESCO-PNUD-CBLT, 1972). Most of the isotopic measurements have been interpreted qualitatively to obtain information on the rainfall recharge. Fontes (1969) and Faure (1970) propose an interpretation of isotopic data in west Kanem nearby the north part of Lake Chad. The Lake Chad Basin is favourable for the use of isotopic methods (Fontes 1970). In east Kanem towards Lake Chad, the mean ^{18}O isotopic composition of the rain was recorded between -6 to -7 ‰. Conversely, due to evaporation processes the lake waters appear enriched in heavy isotopes and may, at the extreme end of the lake's branches, reach a ^{18}O and a ^{2}H of, respectively, +20 ‰ and +100‰. Records show that except at the immediate vicinity of Lake Chad, shallow groundwater of the Quaternary aquifer has a $\delta^{18}O$ between -3.5 and -6.5. These values are closed to the rain signature. Thus, the authors conclude that in east Kanem the Quaternary aquifer is directly recharged by rainfall (Faure et al., 1970; Fontes et al., 1969; Fontes et al., 1970b).

Results from radioactive isotope measurements are, however, less convincing. For this region, ^{14}C values show apparent ages varying from modern to ages over 4000 years BP (Faure et al., 1970; Schneider and Wolff, 1992). In fact, several of the ^{14}C and ^{3}H isotopic measurements collected in the late 1960's (FAO-Schroeter and Gear, 1973; UNESCO-PNUD-CBLT, 1972) have values of over 100 pmc and 10 T.U, respectively. which indicate recent waters. For example, in Chiati (centre of the Kanem piezometric dome) and to the south of Eguei (to the north of Kanem) values are generally around (or over) 90 pmc and reflect contemporary rainfall recharge. Fontes (1970) analysed the value of ^{18}O and ^{2}H in Liwa's inter-dune depression (north-east to Lake Chad). There, data showed that salt brine collected in the centre of the depression and groundwater of the general Quaternary aquifer belong to the same family (they have the same origin, i.e.: they have the same ratio of $^{18}O/^{2}H$ and the are on the same line). He concludes that there is a contemporary recharge of the Quaternary water table by rainfall. However, small values of ^{14}C (less than 60pmc) have been measured around N'Gouri. They give apparent ages of about 4000 yr BP. This latter result is in complete disagreement with the seasonal variations of the water table observed in this area (Eberschweiler, 1990; Faure et al., 1970; Schneider and Wolff, 1992).

Discharge

Like in Manga, active oases have dense vegetation and the water table is close to the surface (high evapotranspiration). They are thus assumed to correspond to discharge areas (Eberschweiler, 1990). Such discharge phenomena are suspected to be at the origin of a slight piezometric depression, observed in the 1960's at the surroundings of the lake (Eberschweiler, 1990; Schneider, 1966).

3.3.3 QUANTITATIVE ANALYSIS

Several estimations of the recharge of the Quaternary aquifer have been put forward for these regions. Level variations at Ngouri's well have been simulated using a conceptual tank model called Gardenia. From rain and evaporation data, which are the inputs, the model represents hydrological processes by a series of reservoirs that drop from one into another (Milville, 1991b; Roche and Tierry, 1984). A high specific yield of 24% was assumed for the aquifer. The calibration of this model, from 1963 to 1965 on the levels of N'Gouri's well, indicates that the local rainfall recharge is of 68 mm/yr (Schneider and Wolff, 1992).

Bonnet (1995) has developed a groundwater flow model of a part of the Quaternary aquifer, which includes the Harr area. This model was calibrated on the piezometry observed in 1963 and 1994. After testing several values, a regional recharge of 10 mm/yr was proposed in the Harr region (Bonnet and Meurville, 1995). The groundwater model of the Quaternary aquifer proposed by Eberschweiler (1993) indicates a regional recharge of between 1 and 10 mm/yr for both the Harr and the Kanem regions.

3.3.4 DISCUSSION

Piezometric measurements (seasonal variations and domes) indicate a rainfall recharge of the Quaternary aquifer. The aeolian sands that characterise this region are probably a determining factor of this recharge. They are very homogenous and highly permeable thus allowing high infiltration during rain events (Schneider and Wolff, 1992).

Like in Manga, recharge values from groundwater models represent a spatially average budget between recharge and discharge phenomena. If discharge is assumed in active oases then it will be integrated to the value given from the regional groundwater models.

Does a conceptual model like Gardenia really represent the hydrological phenomena of the region? Probably not, although it has already been applied in a semi-arid zone and gives a good simulation of the observed measurements (Martin and Tierry, 1986; Milville, 1991a). Furthermore, the model only gives a local recharge as a point measurement would. There is no detail on the environment, the location and the characteristics of the well modelled. Piezometric measurements reported by Schneider (1992) and Eberschweiler (1990) show however, that N'Gouri's well has maximum piezometric fluctuations compared to other wells of the region. Results of this modelling should thus be taken with caution as it certainly exceeds the value of the regional recharge.

Isotopic analyses in the region are contradictory (Schneider and Wolff, 1992). Firstly, seasonal variations of the water table show a present recharge by rain in the N'Gouri area. Meanwhile, ^{14}C analyses give an apparent age of the groundwater of about 4400 years BP. Moreover, tritium values in the Chiati region are less than 1T.U. and indicate old water with a lack of recharge, while ^{14}C values in the same region are very high and shows contemporary water. Faure (1970) was of the view that the wide range of isotopic values obtained show that the Quaternary water table is the result of the mixing of old and recent waters. Also, regarding the use of ^{3}H samples, one could wonder if the thermonuclear peak had the time to reach the water table. Later, we will see that the topography of this region is fairly flat and might not be favourable to localised recharge (see section 6.3.2). If direct recharge is the dominant process, the unsaturated zone might store rainwater for decades before it reaches the water table (especially where it is thick) (Aranyossy and Gaye, 1992). In this case, low values of ^{3}H obtained in the late 1960's do not mean that there is no rainfall recharge.

3.4 RIVERS-QUATERNARY AQUIFER INTERACTION

The major rivers of the Lake Chad Basin are the Chari, the Logone and the Komadugu-Yobe. All are tributaries of Lake Chad (see section 2.4.1). Defining and quantifying the relationship between the Quaternary aquifer and these rivers is of major importance. The rivers' surroundings are dense population areas and the demand for water supply is high. There are also many irrigation fields along the banks of the rivers.

3.4.1 THE CHARI – LOGONE RIVERS AND THEIR FLOOD PLAINS

Qualitative analysis

In principle, surface water may recharge the Quaternary water table in two ways: by channel seepage or by flood plain infiltration. Little is said in the literature about the relationship between the

Quaternary aquifer and the flood plains. It is difficult to conduct piezometric measurements while the flood plains are inundated. Also, no piezometric data prove that there is a recharge of the water table by the flood plain. Soil maps (ORSTOM, 1979; UNESCO-PNUD-CBLT, 1972) reveal the clay nature of the sediments at the surface of the flood plains. The soil type is often indicated as hydromorphic with a very low infiltrability. Study of the "Great Yaere" by Naah (1989) suggests that, after the floodwaters have spread to their full extent infiltration, losses are extremely low - "The soils of the flood plains are fine alluvial deposits which seal after initial wetting" (Naah, 1989). In a consultant report, Mott MacDonald (1994) suggested that infiltration of surface water from the flood plains to the water table is insignificant.

On the other hand, piezometric maps draw contours that clearly indicate a recharge from the river beds (Bonnet and Meurville, 1995; Schneider and Wolff, 1992). Moreover, seasonal fluctuations of the water table following the rivers' discharges have been recorded in the vicinity of the rivers (Bonnet and Schneider, 1968; Bonnet and Schneider, 1969). At N'Djamena, the relation between the Chari river and the Quaternary water table has been studied with measurements made between 1963 and 1968 by the BRGM. Water table levels were measured at least once per month in two wells located respectively at 400 and 850 m from the Chari bank. Records show that the river is always connected to the water table and in a higher position. In the proximity of the river, the water table levels follow closely the variations of the Chari. In 1966, for an annual flood of about 6 m, the water table rose by more than 2 m and approximately 1 m at 400 m and 850 m away from the bank, respectively. A third piezometer located at 3400 m from the bank only recorded seasonal fluctuations of 10 cm maximum (Bonnet and Schneider, 1968; Bonnet and Schneider, 1969; Schneider and Wolff, 1992). The Chari is thus feeding the water table, but records suggest that the influence of the river is very limited spatially.

Quantitative analysis

The groundwater model of the Chari-Baguirmi region developed by Bonnet (1995) proposes an estimation of the recharge from the channel of the Chari. Two simulations were made in steady-state for 1963 and 1994. The river is represented as a specific head, imposed directly to the aquifer. Its levels are given from main gauging stations and a linear interpolation is applied between them. The model indicates that, from Bousso to Lake Chad, between 26E+06 m^3/yr (in 1963) to 32E+06 m^3/yr (in 1994) infiltrates the bed of the Chari to recharge the water table on the right bank of the river. In fact, values vary between the given range according to the withdrawals to supply N'Djamena. These abstractions have increased from 1.5E+06 m^3/yr in 1963 to 8E+06 m^3/yr in 1994. The consultant concludes that the recharge from the Chari is limited. In the model, this is due to low permeabilities of the aquifer along the river, which are necessary to reproduce the piezometry (Bonnet; 1995).

In the same consultancy report, recharge to the right bank of the Bahr Erguig (Massenya flood plain) and from the Batha de Lairi is estimated at 6E+06 m^3/yr and 7E+06 m^3/yr respectively. However, mechanisms of the recharge are not detailed in the report and there is little literature to discuss this matter. The only indication of recharge are the piezometric domes that appear on hydrological maps in these areas (Schneider, 1966).

Discussion

Recharge from the channels of the Chari and the Logone is confirmed, but there is only a rough approximation of the quantities of water at issue. The first estimations available only concern the Chari. They indicate that the recharge is limited. In fact, the model developed by Bonnet 1995 show low permeabilities along the river, which limit the seepage. A moderate recharge is partly confirmed by the piezometric measurements conducted at N'Djamena between 1963 and 1968 which, together with a moderate transmissivity, show that the influence of the river is spatially limited. Another result of this groundwater model is that "85% of the water table abstractions to supply N'Djamena come from the Chari" (Bonnet and Meurville, 1995). This is important information and it would be wise to undertake a more detailed study on this issue. N'Djamena's needs for domestic water are increasing and at the same time the rivers are subject to climatic variations. A transient groundwater model is needed in order to study these important changes.

The lack of knowledge is even more important regarding the role of the flood plains. Recharge from the "Great Yaere" and the flood plain between the Chari and the Logone is so far considered negligible. However, this is more an assumption than the result of a field study. The Massenya flood plain and the Batha de Lairi are thought to recharge the aquifer (Bonnet and Meurville, 1995; Schneider, 1966), but the literature is so sketchy that there is a real need for a basic description of hydrological phenomena. For instance, the occurrence of Massenya flood area is not systematic every year but depends on the magnitude of the Chari flood discharge. Then what could be the impact of the decrease of the Chari discharge since the 1970's? Are the old channels of these rivers contributing to localised recharge? These are further questions that need to be addressed.

Considering the high population and the numerous irrigation fields in the vicinity of these two rivers and their flood plains, understanding and quantifying the hydrology and hydrogeology of this area must be considered as a priority. UNESCO is carrying out an ongoing field study, from which results are not available yet, in the area of the Chari and Logone. It could bring the first detailed elements of analysis and quantification.

3.4.2 THE KOMADUGU-YOBE

Qualitative ananlysis

IWACO (1985) conducted a study on the water resource of the Komadugu-Yobe basin. The study was restricted to the downstream part of the basin (from Gashua and Dapchi to Lake Chad). A map of the water table as well as an analysis of the rivers discharge give evidence that the Komadugu-Yobe feeds the Quaternary water table (Iwaco, 1985; Leduc et al., 1998):

- The river is higher than the water table;
- The water table forms a piezometric dome along the river;
- From upstream to downstream, the Komadugu shows an important reduction of its discharge (especially from Gashua and Dapchi to Lake Chad) (see Figure 2-10).

In Niger, fluctuations of the water table were measured monthly from 1994 to 1996 (inclusive) at Gueskerou and Bagara (nearby Diffa). Records show that in the vicinity of the Komadugu-Yobe the water table levels vary according to the discharge of the river (Leduc et al., 1998; Sabljak, 1998). At Bagara, which is located on the bank of the river, the water table also has an isotopic signature (^{2}H; ^{18}O) close to the river's one (Sabljak, 1998).

In the west of Gashua, Alkali (1995) installed 20 piezometers to study the response of the aquifer to river rise and recession. Data were collected from the floods of 1992 to June 1993. They also indicate the contribution of the river to the water table through channel infiltration. They reveal a rapid and important response of the aquifer to the river's rise. In Alkali's study area, drill logs and electrical resistivity measurements together with this rapid response led him to assume that locally the aquifer may be confined.

The same study discusses the issue of the recharge through the flood plains. Alkali (1995) points out the importance of the clay deposits that cover the surface of all his study area. In addition, most of the water table increase (at least 75%) takes place before significant surface flooding in mid-September. This evidence leads Alkali (1995) to conclude that there is no significant recharge of the aquifer through the flood plain.

Quantitative analysis

IWACO (1985) proposes a first estimation of the recharge through channel seepage. For this purpose, the hydraulic gradient of the water table along the banks of the river was extracted from a piezometric map drawn in 1985 (Iwaco, 1985). Then Darcy's Law was applied with a transmissivity fixed at 100 m^{2}/day to quantify groundwater flow from the river. The report suggests that between Gashua and Geidam the supply from the river to the north and south banks is 4.5E+06 m^{3}/yr and 2.7E+06 m^{3}/yr respectively. Then between Geidam and Damasak it indicates that 1.7E+06 m^{3}/yr leaves the river to the left side and 2.5E+06 m^{3}/yr to the right. Finally, between Damasak and Bosso the recharge is of 2E+06 m^{3}/yr to the north and of 3.5E+06 m^{3}/yr to the south.

Leduc (1991) has applied the same method from Geidam to the Lake but using a map of the water table drawn in 1991 and a transmissivity of 860 m^{2}/d. He obtains a value of infiltration to the north of 12.5E+06 m^{3}/yr.

Discussion

In the downstream part of the Komadugu-Yobe initial work has identified the relationship between the river and the Quaternary aquifer. Evidence indicates that the river recharges the aquifer through channel seepage. The contribution of the flood plains, upstream of Gashua, is conversely thought to be very small. First quantifications of the recharge by river seepage used rough methods and estimation of errors should have been applied. Further studies including field measurements and modelling are required for a better quantification of the recharge from the river. In the first place, pumping tests should help to assess the aquifer properties in the vicinity of the river. A transient groundwater model of the water table could give a better estimation of the recharge.

3.5 LAKE CHAD - QUATERNARY AQUIFER INTERACTION

3.5.1 QUALITATIVE ANALYSIS

Piezometry

Several hydrogeological maps of the lake's surroundings have been drawn (Dieleman and Deridder, 1964; Greigert, 1979; Isiorho et al., 1996; Leduc-PNUD, 1991; UNESCO-PNUD-CBLT, 1972). UNESCO's map shows the Quaternary aquifer over the four states whereas the other maps are more local. Maps reveal that, along its periphery, Lake Chad is generally at a higher level than the water table. Hydraulic gradients are thus oriented from the lake towards the piezometric depressions (Bornu, Chari-Baguirmi and Kadzell depressions). In the 1960's, Schneider (1968) described a slight piezometric channel, about 5 to 7 metres under the average level of the lake, to the north-west. It separated the lake from the large piezometric dome of Kimi-Kimi where the water table reaches an elevation of about 310m above mean sea level. To the extreme north nevertheless, the water table seems to be in a higher position than Lake Chad's level.

It is considered that infiltration can take place not only from the shoreline but also from the bottom of the lake (Carmouze et al., 1983; Dieleman and Deridder, 1964; Isiorho et al., 1996; Roche, 1980). This is confirmed by the nature of the deposits on the lake's bottom (Dupont, 1970; Isiorho et al., 1996). Isiorho (1996) also reports that, using minipiezometers within the south-east region of the lake, he observed that Lake Chad is at a higher level than the water table. Nevertheless, hydraulic gradients are small and suggest low flows.

In 1969, quarterly piezometric measurements were collected in the surroundings of Lake Chad at Ndjowa, Daguil, and Baga Kiskra. They showed that in the immediate vicinity of the lake the water table was sensitive to the lake's seasonal variation, but that this influence tends to reduce rapidly when moving away from the lake. Records also indicate that even for a seasonal fluctuation of the lake of about a metre, the piezometry was always oriented from the lake toward the water table (Roche, 1980). Other piezometric data indicate that the Quaternary aquifer seems to be sensitive to inter-annual fluctuations of the lake. At No (Kanem/Chad), under the dunes of Tao, the water table dropped by 45 cm to 55 cm between 1970 and 1972 while the lake level fell by 70 cm (Roche, 1980). In Niger, Leduc et al. (1998) notices an important drop (about 7m) in the water table from the 1970's to the 1990's. The authors connect this drop with the disappearance of the northern part of the lake since 1973.

Hydrochemistry

The spatio-temporal evolution of the mineralisation in Lake Chad shows the existence of a salt regulation system, which explains why even under semi-arid conditions Lake Chad is still a fresh water lake. Three main phenomena were identified in the regulation of the salinity of the lake. First, a quantity of ions is selectively captured in sedimentation processes and interaction with mineral and biological materials. Second, elements also leave the lake through infiltration from the lakebed and shoreline to the water table (Roche, 1980). Thus, seepage from the lake is often said to contribute to the low salinity of its water (Carmouze et al., 1983; Isiorho et al., 1996; Roche, 1980). Lastly, in interdunes of the east shoreline of Lake Chad, Fontes (1976) reports that minerals can also leave the lake via a succession of processes. The salt may be brought in interdunal depressions by the Lake's water and later be swept away by rainfall.

Isotopic data

Isotopic samples of rainfall, rivers, Lake Chad and the aquifers were collected during the end of the 1960's (FAO-Schroeter and Gear, 1973; Fontes, 1976; UNESCO-PNUD-CBLT, 1972). Measurements show that the rainfall has a $\delta^{18}O$ vs SMOW around -5‰. At their entrance in the lake, surface water brought by the rivers has a mean $\delta^{18}O$ of -3‰, but inside the lake, as the water moves towards the shorelines, it evaporates and values of $\delta^{18}O$ are between +5‰ to +17‰ (Fontes, 1976; Roche, 1980).

In the east and south surroundings of the lake, isotopic data have revealed some hydrological processes regarding the recharge of the Quaternary water table. In the proximity of the shoreline, the first metres of the water table have a value of $\delta^{18}O$ that is generally rich and close to the lake values. It decreases rapidly when moving away from the lake and converges on the rain value ($\delta^{18}O$ between -4‰ and -5‰). Hence, there is a recharge from the lake, but it is not so important and becomes rapidly insignificant and replaced by rainfall recharge (Fontes, 1976; Fontes et al., 1970a; Roche, 1980).

Vertical profiles of $\delta^{18}O$ at No and Soro (Kanem/Chad) show an increase of value from the top to the bottom. This indicates that in the surroundings of Lake Chad the upper part of the Quaternary water table contains water with a rain origin, while in the lower part, the high values of $\delta^{18}O$ reveal waters from lactusrine origin. For Roche (1980), this groundwater from lacustrine origin is probably inherited from recent geological history and could have infiltrated during a major extent of Lake Chad (6000 BP).

3.5.2 QUANTITATIVE ANALYSIS

Salt and water budget

Roche (1980) made an estimation of the seepage from the Lake into the aquifer. He used a salt annual budget based on the principle that the annual quantity of ions entering in the lake is equal to the quantity of ions leaving the lake. For this purpose, measurements of conductivity throughout the lake were collected from 1962 to 1970. Results indicate that, depending on whether the infiltration takes place only from the shoreline or also from the bed of the lake, the seepage represents respectively 4.2% (only shoreline) or 7.2% (shoreline and bed) of the lake inflows (rivers and rain). At study time, this corresponds to a volume of water that infiltrates from Lake Chad of between 2.1E+09 m^3/yr and 3.6E+09 m^3/yr.

Carmouze (1983) considers that the sodium in the lake is only eliminated by infiltration. He thus applied a sodium budget and an estimation of the lake water volume to calculate the percentage of water removed through seepage. Applying this method from 1954 to 1972 ("Standard" Lake Chad), he estimates that the amount of water that infiltrates to the aquifer is between 5% and 8% of the annual inputs to the lake.

Seepage measurements

Isiorho (1996) proposes another estimation of the infiltration from the lake to the water table based on seepage field measurements (Isiorho and Matisoff, 1990; Lee, 1977; Lee and Chery, 1978). Data were collected with a seepage meter in July-August 1985 and July 1991 at eight locations in the south and south-west of the lake. They indicate a mean seepage velocity of 7.1E-03 m/d and a median of 1.3E-03 m/d. Thus, Isiorho estimates that for a surface area of the lake of 2.1E+10 m^2 (situation of the lake between 1954-1968 (Roche, 1980)) the total volume of water that infiltrates towards the water table is about 10E+9 m^3/yr (21% of the 48E+09 m^3/yr annual water input between 1954-1968).

Groundwater modelling

Isiohro (1996) has also developed a groundwater model of the lake's south-west region in order to quantify the seepage. The model was calibrated in steady-state on the piezometry observed in the late 1960's (Miller et al., 1968). In the simulated area, the model gives a value of the lake seepage to the aquifer of 9.5E+08 m^3/yr. The author then applied this value to the whole extension of the lake when it was 21,000 km^2 in area ("Standard" Lake Chad). The total amount of water infiltrating from the lake to the aquifer is thus estimated as 15E+09 m^3/yr. This volume equates to 32% of the annual water input to the lake at that time (1954-1968).

The configuration of Lake Chad has changed, and a more recent representation of the lake has been put forward by Eberschweiler (1993) in his model of the whole Quaternary aquifer. The author estimates that about 10 mm/yr infiltrates from the areas that are still flooded regularly, while the areas where the lake has disappeared are now affected by an evapotranspiration of 1 to 10 mm/yr.

3.5.3 DISCUSSION

All the authors agree that infiltration from the lake does take place. Piezometric and isotopic data indicate that the along the shoreline the lake can recharge the aquifer. It is highly probable that there is also a generalised infiltration from the bed of the lake (Isiorho et al., 1996; Roche, 1980). However, the value of the seepage is much debated.

Fontes (1976) concludes that the lake does not significantly recharge the aquifer and "does not contribute to the aquifer's reserve". On the other hand, salt budgets led Roche (1980) and Carmouze (1983) to state that, for a "Standard" Lake, the infiltration represented between 4% to 8% of the annual water input to the Lake. Finally, Isiohro states that the lake's recharge to the aquifer represents between 21% (seepage measurements) to 30% (modelling) of the total annual water input to the lake. Several arguments suggest that the values proposed by Isiohro (1996) are excessive. First, the general piezometry of the Quaternary aquifer is chracterised by small hydraulic gradients, which indicate that the flows are relatively small. Second, data obtained by seepage measurements vary within a wide range of values from 0.02E-03 m/d and 1.17 m/d. This shows that there is a high spatial variability. Thus, generalising the values obtained from the 8 measurements to the rest of the lake appears doubtful. Moreover, the model developed by the same author has many constant heads, especially on the inland boundary. It is probable that these constant heads allow a more important volume to flow in the model. Isiohro (1996) indicates that in his study area (south-west of Lake Chad), the hydraulic gradient of the water table is higher than in any other areas around the lake. It is therefore logical to expect an over-estimation of the value of seepage while extending the result obtained in this area to the rest of the lake. Finally, isotopic measurements show that seepage to the water table only affects a very limited area surrounding the lake, and thus indicate a very moderate recharge from the Lake.

Roche (1980) and Fontes (1976) draw attention to another factor limiting the recharge from the lake. In the vicinity of the lake, the water table is very close to the surface and evaporation processes are probably very active. Therefore, an important part of the water that infiltrates from the shorelines is subject to evapotranspiration (Fontes, 1976; Roche, 1980). Similarly, Eberschweiler (1990) considers that areas where the lake has now disappeared are subject to evaporation.

Lake Chad is a complex and sensitive environment, but it is also a resource that supports a mass of people, such as a fisherman community. It is of critical importance that caution is adopted in estimating the water quantities available. Particular scientific efforts should be undertaken to understand hydrological processes at issue and to assess the water resources available. It is recommended that continuous long-term monitoring, using multiple techniques, should be undertaken in order to follow the lake through its different stages.

Early conclusions must, if possible, be avoided. Isiohro (1996) suggests that about 10E+09 m^3/yr to 15E+09 m^3/yr infiltrates from the lake to the aquifer. These estimations are made from measurements in a permeable area and at a period corresponding to a particularly high lake (surface of the lake at 21,000 km^2). Therefore, he should not conclude that "a large amount of water is still available and could be used for the development of new irrigation projects".

3.6 PIEZOMETRIC DEPRESSIONS

3.6.1 BACKGROUND

The Quaternary aquifer, like other aquifers of West and Central Africa, is characterised by large piezometric depressions, also referred to as "hollow aquifers". First descriptions of these piezometric anomalies were made by Archambault (1960) and Degallier (1954). Since then, they are often considered as, "certainly the major enigma in Sahelian hydrogeology " (Aranyossy and Ndiaye, 1993) and an explanation of their origin is still much debated (Aranyossy and Ndiaye, 1993; Dieng and Ledoux, 1987; Dieng et al., 1990). The piezometric depressions are located all along the Sahelian band in West and Central Africa. Major ones are (Figure 1-2):

- Ferlo in Senegal (Degallier, 1954)
- Gondo, Nara and Azaouad in Mali (Aranyossy et al., 1989b; Aranyossy and Ndiaye, 1993)
- Trarza in Mauritania (Depagne 1966)

To this list must be added the depressions of the Lake Chad Basin (see also, section 2.5.3):

- Chari Baguirmi in Chad (Chouret et al., 1977; Schneider, 1966)
- Kadzell in Niger
- Bornu in Nigeria
- Interfluvial zone of the Komadugu

Several theories have been put forward to explain these anomalies:

1. **Overexploitation of the aquifer by human abstractions:** In general, this idea is not satisfactory, as the depressions are located in very low populated areas. Hence, human abstractions are very small and could not generate such deep depressions. For this reason, Dieng (1987, 1990) and Aranyossy (1989, 1993) have respectively rejected this explanation in Senegal and Mali.
2. **Geological subsidence or uplift:** Neotectonics has been suggested as an explanation (Risier and Petit-Marie, 1986, Durand 1982, Muller 1997). However, Dieng (1987) argues that this is more of a local phenomenon and it cannot provide a general explanation for the depressions that affect a large part of the African continent. Moreover, neotectonics in this part of the world cannot be considered active enough to create such deep depressions (Aranyossy and Ndiaye, 1993).
3. **Sea level change:** Dieng (1987, 1990) suggests that oscillations of the sea level following the last glaciation of the Holocene could be an explanation for the coastal aquifers. During the last marine regression of the Quaternary (125000 to 18000 years BP) water levels on the West African coast fell about 100 metres below the present level (Debrias et al, 1986). Low levels of the sea, and consequently of the rivers, over such a long period might have lowered the piezometry of the surrounding aquifers. Besides, the arid climate of this period might have accentuated the processes. On the contrary, the transgression that followed (18000 – 8000 years BP) was too short, so that far from the coast and the rivers, the piezometry remained depressed. To test this hypothesis Dieng (1987, 1990) developed a groundwater model of the Ferlo region in Senegal. The model was designed in transient to assess the impact on the aquifer of the variation of sea and rivers levels from 18000 BP to actual. In this case, the water table height changes but so slowly that it cannot be noticed on human scale (Dieng and Ledoux, 1987; Dieng et al., 1990). Results of the modelling show that such a hypothesis allows the reproduction of the piezometry currently observed in the Ferlo depression. This indicates that coastal piezometric depressions can be the results of sea level and climatic variations since the last glaciation of the Holocene. This hypothesis provides a satisfactory explanation for coastal aquifers but it cannot explain the depressions far away from the sea (Dieng and Ledoux, 1987; Dieng et al., 1990).
4. **Excess losses by evapotranspiration (discharge):** Another explanation of the depressions, and probably the favourite one among the authors, assumes excess losses by evapotranspiration in an area of negligible recharge. If, in addition, low hydraulic conductivity of the aquifer does not allow a sufficient lateral flow from the recharge zones on the limits of the depression, then even a small vertical water deficit could create, in the long-term, such depressions. Aranyossy (1991) checked this hypothesis with a simple analytical model and with a transient numerical model simulating in 1D the evolution of an unconfined aquifer between two constant head boundaries

during 8000 yr under such conditions. Results indicate that from a state of total replenishment of the aquifer at the last pluvial Holocene period for the Sahelian region, even a very small water deficit between infiltration and evapotranspiration, can generate deep depressions as observed today.

Regarding the depressions of the Lake Chad Basin, the following consideration can be made. The main depressions of Kadzell, Yaere and Chari Baguirmi occur in very low populated areas. Estimations of the water quantities withdrawn, especially before the construction of the first cemented wells and bore holes since the middle of the 20th century, do not indicate a sufficient discharge to create such depressions. The idea of leakage to a deeper aquifer must also be rejected. In fact, the Quaternary aquifer is separated from the underlying aquifer by a thick impermeable layer of clay that prevents any exchange between the two. Moreover, piezometric levels in the underlying aquifer (Pliocene) are generally higher than the Quaternary aquifer levels. In Kadzell, for instance, the Pliocene is artesian while the Quaternary water table is 40m below the ground. All the depressions are located more than 800km away from the Atlantic Ocean. Hence, sea level change must be discarded as the origin of the Lake Chad Basin depressions (Aranyossy and Ndiaye, 1993; Dieng and Ledoux, 1987; Dieng et al., 1990). On the other hand, the assumption generally adopted for the Lake Chad Basin is that the depressions are caused by evapotranspiration losses exceeding the small rainwater recharge (Eberschweiler, 1993 a; Greigert, 1979; Leblanc, 1997; Leduc et al., 1998; Schneider and Wolff, 1992). Yet, to this day, this remains an assumption as little evidence has been collected.

This has left the door open for authors to formulate different theories. Durand (1982), considers that there is a contradiction in admitting that the depressions are caused by excess evapotranspiration, because at the same time the piezometric domes of Harr and Kanem, which are located to the north in more arid areas, are not affected by this very strong evapotranspiration processes. Durand (1982) also affirms that such dropdown of the water table in the depressions (up to 60m in the centre of the Chari-Baguirmi) is too important to have been generated by evapotranspiration processes. Durand (1982) and before him Muller (1977) have thus considered that neotectonics could be the origin of the depressions. Muller (1977) suggests that isostatic anomalies might be correlated with piezometric anomalies. Durand (1982) gathered evidence that neotectonics is currently active in the Lake Chad Basin. The deep structures of the Lake Chad Basin, analysed by Louis (1970), are thought to still govern the present geomorphology. Therefore, for Durand (1982) neotectonics can be at the origin of both piezometric depressions and piezometric domes. However, one could argue that the assumption that the piezometric depressions are correlated to isostatic anomalies is not obvious. And even if they are currently active, would tectonic movements be fast enough to affect the shape of the water table?

Finally, with neither detail nor justification, Iwaco (1985) merely states that the depressions of the Quaternary aquifer are "paleo-features that are slowly refilling".

So far, only two of the Lake Chad Basin depressions have been subject to preliminary investigations. In the remaining sections of this chapter, the results of these works are summarised.

3.6.2 THE CHARI- BAGUIRMI PIEZOMETRIC DEPRESSION

The Chari-Baguirmi region has the largest and deepest piezometric depression of the Lake Chad Basin. The centre of the depression is located in the Kouka area where the depth of the water table reaches 60 m below ground. Quaternary deposits of the region are made of fluvio-lacusrine sediments from the Early Pleistocene. They are composed of interbeds of clay and sandbanks, whose thickness generally do not exceed 5m. The topography throughout the whole area is very flat.

Measurements gathered by the BRGM (French Geological Survey) between 1963 and 1967 show a lack of seasonal variations in piezoemetric levels (Schneider and Wolff, 1992). On the other hand, a slow and regular drop of the water table is observed. For instance, since the beginning of measurements in the middle of the 1960's the water table has fallen by 8 cm/yr in the vicinity of Massaguet (Schneider and Wolff, 1992).

As in Kadzell, Niger, various authors explain the existence of such a piezometric depression by natural discharge processes (Bonnet and Meurville, 1995; Eberschweiler, 1993 a; Schneider and Wolff, 1992). Of course, considering the fact that the water table is deep the flows involved are very small. However, a small negative budget repeated over a very long period can explain the creation of this large depression (Bonnet and Meurville, 1995; Schneider and Wolff, 1992). Bonnet (1995) suggests that the discharge flow might be greater in the north because dry conditions and clay deposits are more important than in the south.

Eberschweiler's model of the aquifer in 1992 suggests a discharge between 1 and 2 mm/yr. The groundwater model of the Chari-Baguirmi region developed by Bonnet (1995) also gives an estimation of the discharge. Several values were tested during the calibration of this hydrodynamic model. Finally, the model reproduces correctly the piezometry in 1964 and 1994 for a discharge of about 3mm/yr (Bonnet and Meurville, 1995).

3.6.3 THE KADZELL DEPRESSION

Kadzell is another region of the Lake Chad Basin where a major piezometric depression is observed. It is about 100km long and 50km wide for a depth reaching 40 metres (Figure 2-14). The ground of this area is characterised by clay deposits and a very flat topography. Frequent measurements of the water table levels were collected by the DDH-Diffa (Diffa Department Hydraulics Agency) between 1990 and 1997. They do not show any seasonal variation. The groundwater model of Manga developed by Leduc (1991; 1998) includes the Kadzell area. It indicates a value of discharge in the depression of 0.08m/yr (Leblanc, 1997; Leduc et al., 1998; Leduc-PNUD, 1991). Another estimation is given by Eberschweiler's model representing the whole Quaternary aquifer in 1992. It gives a discharge of between 1 and 2 mm/yr.

Discussion

A discharge rate of 3 mm/yr proposed by Bonnet (1995) for the Chari-Baguirmi depression is very high compared to the 0.08 mm/yr obtained by Leduc (1998) with the same method in the Kadzell. Studies conducted in other Sahelian zones show that the evaporation is unlikely to be more than 2 mm/yr at a depth exceeding 10m (Aranyossy et al., 1991; Coudrain-Ribstein et al., 1998). We could therefore keep the value proposed by Bonnet (1995) as a maximum value possible for the discharge in the piezometric depressions of the basin.

3.7 CONCLUSION

Map 4 summarises all the estimations of recharge and discharge proposed in the literature and technical reports. Major disagreements have appeared in the review. In Manga, Eberschweiler (1993) suggests a discharge, while Edmunds (1999) proposes a regional recharge of about 60 mm/yr. Regarding Lake Chad, Isiorho (1996) indicates that, between 21% to 30% of the water inputs to a "Standard" Lake infiltrates to the water table. Yet, Carmouze (1983) and Roche (1980) stress that this volume is only about 4% to 8%. All the authors state that the rivers of the basin do feed the aquifer, but few quantifications of recharge rates from the rivers are available. The piezometric depressions are often recognised as regions affected by evapotranspiration processes, whose value is assessed to vary between -0.08 mm/yr (in Kadzell) to -3 mm/yr (in Chari-Baguirmi). However, a hypothesis has been proposed that both piezometric depressions and domes are due to neotectonics movements. Across most of the aquifer, the gentle hydraulic gradients of the water table suggest that lateral flows within the aquifer are very small. A consequence is that the role played by vertical processes is amplified. So even a very small discharge can generate large depressions and only a small recharge is consistent with this relatively flat piezometry. Typically, groundwater models developed so far illustrate this by being unable to reproduce the water table when the value of the recharge is too high (60 mm/yr for example) (Eberschweiler, 1993 a; Eberschweiler, 1993 b; Leblanc, 1997; Leduc et al., 1998; Leduc-PNUD, 1991).

To conclude, more studies are urgently needed to provide a better understanding and assessment of the recharge and discharge processes. At a regional scale, a long-term scheme would be particularly relevant to monitor the evolution of the water resources. Data should be regular and of quality, and various methods (including modelling and isotopic approaches) are recommended for the analysis. Local studies, on the other hand, are an opportunity to understand in more detail hydrological processes.

Chapter 4

THE DATA CHALLENGE

4.1 INTRODUCTION

There are many challenges regarding the data of the basin. In fact, hydrologists studying the Lake Chad Basin are confronted with major difficulties such as its vast expanse, the remoteness of large regions and the little means for field data collection. A major expectation of this research project is to find and propose ways of overcoming these problems. This would surely be a significant contribution and would allow more applications to pursue. This chapter aims to enhance current geographical data sets available for water resources management with the use of unexploited data sets (remote sensing data) and the application of a powerful tool for data analysis and management (GIS). The research work presented in this chapter has been submitted for publication (Leblanc et al, *submitted*)

An assessment of the elementary hydrological data sets available in the basin (rainfall records, river discharge, water table levels) has been conducted in the framework of a Water Assessment exercise by the UNDP, the World Bank, the African Bank for the Development and the French Office of Foreign Affaires (Mott MacDonald Int. et al., 1992). Reports are available for each country and the whole of West and Central Africa. It offers a comprehensive appraisal which follows the guidelines of a UNESCO handbook for assessing at national scale water resources data collection (Godwin et al., 1990). Overall, the report highlights a dire situation: "the data collected are insufficient and the situation is under threat to worsen… The main reason seems to be the lack of funding to cover these activities" (Mott MacDonald Int. et al., 1992).

Besides these fundamental data sets there is also, regarding water resources, a real need for data characterising the surface and its temporal and spatial change (see Ch. 2). Up to now, this type of data appears to have been neglected, but it is certainly a matter for which remote sensing can bring new information. Hence, our first contribution will be to seek relevant satellite data describing surface characteristics and superficial processes in order to improve the current data sets available to hydrologists. GIS supports integration, management, analysis and modelling of spatial data from mutliple sources and at multiple scales. Our second contribution thus consists of using GIS to make optimum use of such data.

In this chapter, it is first proposed to review the challenges occurring from the collection to the interpretation and management of the data. Then, the geographical data available, i.e. published maps, will be examined. Subsequently, we will explore the relevant satellite data accessible and will highlight its contribution to the already available data sets. Then we will review the advantages of using a GIS.

4.2 THE DATA CHALLENGES

4.2.1 SCALE

The Lake Chad Basin is about 2,500,000 km^2. Even restricted to the Quaternary aquifer we are still talking of an area of 500,000 km^2. There is no doubt that collecting, analysing and managing data at such a scale is a challenge.

With little means for surveying and the difficulties of access to many areas, the large extent of the area to monitor is a real problem for data collection. Transportation infrastructures are limited to a small number of roads and access is generally difficult throughout most of the basin (see Photo 1). Even with remote sensing the scale is still a challenge, though it is acknowledged for its ability to collect continuous data over a large area. For example to cover the basin with Landsat MSS data would require about 100 scenes (25 scenes are needed for the Quaternary aquifer).

The large extent of the region also implies difficulties for data management: the Lake Chad Basin extends over seven countries and the Quaternary aquifer over four. It is necessary to manage the hydrological systems as a whole, but in the case of the Lake Chad Basin, this implies managing transboundary water resources. Each of the countries concerned has various institutions involved in the water resources management (Table 4-1). There is a need for data exchange and the adoption of harmonised policies. In this context, it is essential to have regional institutions such as the Lake Chad Basin Commission.

Photo 1: Mission Niger, June 1999.

4.2.2 SCARCITY

In addition to the collection and management difficulties, the scale of the basin raises another challenge. Hydrologists and hydrogeologists often need to look at the basin or at the aquifers as a whole entity to understand and quantify associated processes in their complexity and to avoid arbitrary cuts of the study area. However, at the same time they need good high-resolution data that could be used to define local features such as ponding areas or oases. However, only a limited number of scientific studies have been carried out on the basin (see Ch 1). Therefore, cartographic works available are limited and maps are generally too sketchy to offer the level of detail required.

4.2.3 DATA RELIABILITY

Data reliability is probably one of the most difficult criteria to assess about data quality. As has been said, field data in the Lake Chad Basin are collected by different institutions, and a large proportion of the data have been collected during special field missions. Such work is often carried out by various consultancies. This lack of consistency make the data quality difficult to assess especially if it is not specifically mentioned in the reports.

In some cases, the uncertainty of the field data is evident; for instance, not so long ago, barometric measurements were a common way to obtain altitude. One must expect an uncertainty of about 10 metres in the determined altitude values. But in many cases, the reliability of a data set is difficult to establish.

4.2.4 MULTI-SOURCES AND MULTI-SCALE DATA

The available data are of various types: point measurements, published maps, digital elevation models, and satellite data. They also come from various sources such as: several institutions, and various consultant reports (see Table 4-1). There is often a need to harmonise and integrate them in the same management system. For example, maps were often produced at different scales and satellite data have different resolutions depending on the sensor used. Once all these data are gathered, we have a large volume of information to manipulate, store and analyse.

4.3 ASSESSMENT OF THE GEOGRAPHICAL DATA SETS CURRENTLY AVAILABLE

4.3.1 INTRODUCTION

This section assesses the geographical data sets currently available and used for water resources management in the Lake Chad Basin. An analysis is carried out to assess the quality of essential data sets such as the maps showing the geology, geomorphology and topography of the basin. The priority is to look for maps covering all the Quaternary aquifer. Meanwhile, to assess the quality of these regional maps we also examine the work that has been done in each country. Lists of the maps available in the basin are given in technical reports (Mott MacDonald Int. et al., 1992; Solages, 1986; UNESCO-PNUD-CBLT, 1972). In addition, libraries of various institutions in the member states of the basin have been visited (LCBC; CNAR; DHA; DH-Niger) as well as those of the BGS (UK), BRGM and the IRD (Fr).

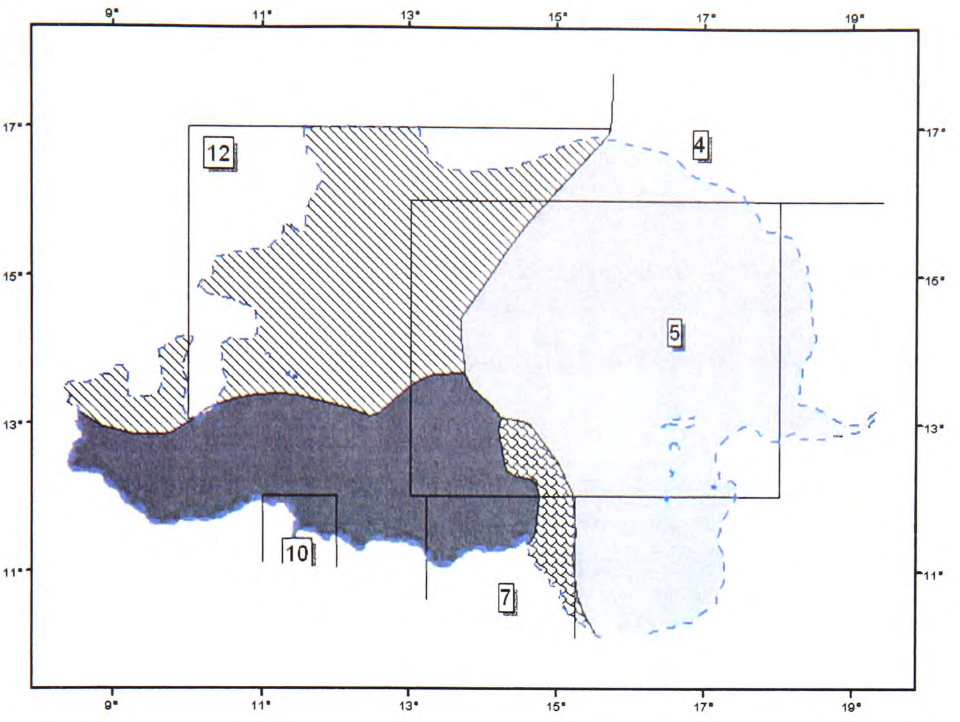
Regional Institutions		The Lake Chad Basin Commission; BP 727 N'Djamena; Chad Centre Regional AGRHYMET; BP 11011 Niamey; Niger
National Institutions	Chad	DREM (Direction des Ressources en Eau et de la Meteorologie), N'Djamena, Chad DHA (Direction de l'Hydraulique et de l'Assainissement), N'Djamena, Chad CNAR (Centre National d'Appui a la Recherche), N'Djamena, Chad DRGM (Direction des Ressources Geologiques et Minieres), N'Djamena, Chad DREM (Direction des Ressources en Eau et de la Meteorologie), N'Djamena, Chad
	Cameroon	Centre des Recherches Hydrologiques, Yaounde, Cameroun
	Niger	Direction des Ressources en Eau, Niamey, Niger Direction Departementale de l'Hydraulique de Diffa, Diffa, Niger
	Nigeria	Nigeria Geological Survey, Lagos, Nigeria
European Institutions		IRD (Institut de Recherche pour le Developpement), Montpellier, France BRGM (Bureau des Ressources Geologiques et Minieres), Orleans, France BGS (British Geological Survey), UK CEH (Centre of Ecology and Hydrology), Wallingford, UK

Table 4-1: List of institutions holding data or involved in the water resources of the Lake Chad Basin.

4.3.2 THE GEOLOGY

Figure 4-1 shows the list of all the geological maps available that cover all or part of the Quaternary aquifer. Examination of these maps indicates that little cartographic work has been undertaken. The most recent and comprehensive maps of the geology were made in the 1950's-1970's. Since then no major cartographic work has been undertaken and many areas have been mapped only once. Consequently, description of the geology is rather sketchy. In the same way, all the maps have a small-scale that does not show much detail. In Cameroon and Niger it is possible to find maps at 1:500,000 otherwise the most detailed maps are at 1:1,000,000. On top of this, very large areas are reported homogeneous on some of these maps. How true can this be? For example, in Chad the Plateaus of Harr and Kanem are not differentiated from the rest of the Harr and Kanem region. In these regions oases are not reported either (see Figure 4-4). In Niger, a large region of about 20,000 km^2 has the designation "unexplored". None of these maps shows a sign of neotectonics. However, signs of neotectonics have recently been reported in Kadzell and in the south banks of Lake Chad (Durand, 1982; Durand, 1995; Maurin, 2000). Others noticed that the Dillia valley and the Bahr el Ghazal valleys follow tectonic directions and that Lake Chad itself is at the intersection of African rifts (Burke, 1976; Cratchley, 1984; Genik, 1992; Matheis, 1976).

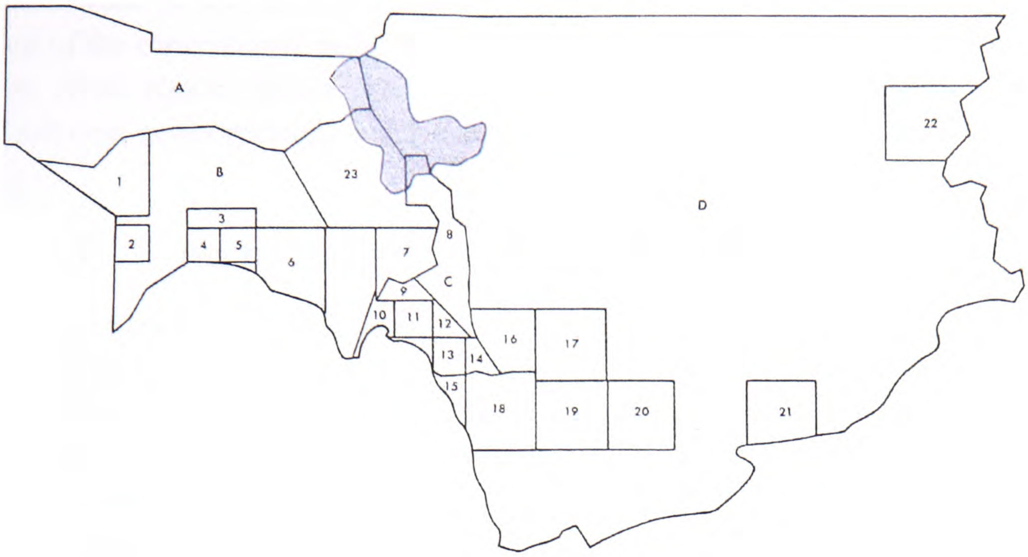
At a regional scale, there are only two geological maps covering the whole of the Quaternary aquifer. One is the geological map of the world, but this is too general to be useful in terms of water resources management. The second was drawn by UNESCO (1972) who collected all the geological maps into one single map covering most of the Lake Chad Basin. Efforts were made to harmonise the data and link up the different units on their boundaries. This is the best document to describe the geology of the entire basin and of the whole Quaternary aquifer. One regrets, however, that this map does not have a comprehensive legend or leaflet. In addition the quality of the information it contains is only equal to the geological maps available in each country of the basin from which it has been drawn and which we have just analysed.



Basin and all Quaternary aquifers	– – –	Geological map of the Lake Chad Basin. 1:1,000,000. UNESCO. In: Study of water resources in the Lake Chad Basin 1966-1970. UNESCO, Paris. TR/ UNESCO/ UNDP/REG 71. 1972.
	– – –	International Geological Map of Africa. Sheet n2. 1:5,000,000. Choubert,G. Faure-Muret, A. Commission for the Gegological Map of the World. UNESCO: Paris. 1987.
Chad	▭	Carte geologique de la Republique du Tchad. 1:1,500,000. Par J.P. Wolf. BRGM, 1964.
	4	Carte geologique provisoire du Borkou - Ennedi - Tibesti. 1:1,000,000. Wacrenier, P., Hudeley, H. et Vincent, P. Direction des Mines et de la Geologie de L'A.E.F., 1958.
	5	Carte geologique de reconnaissance de l'A.E.F: Feuille ND.30: Fort-Lamy. 1:1,000,000. Par Barbeau, J. Direction des Mines et de la Geologie de l'A.E.F., 1956. Notice (35p.).
Cameroon	▨	Carte Geologique de la Republique Unie du Cameroun 1979. 1:1,000,000. Direction des Mines et de la Geologie. Yaounde (Mise a jour des cartes de 1943 et 1956)
	7	Carte Geologique de reconnaissance du Cameroun. 1:500,000; Feuille de Maroua (feuille NC – 33 NO. – E. 62), par Y. Peronne et J.C. Dumort. Yaounde: Direction des Mines et de la Geologie du Cameroun, 1966.
Nigeria	■	Geological map of Nigeria. 1984. 1:2,000,000; compil. By the Geological Survey Department, Nigeria, 1985. 1 sheet in colour. (update of 1974, 1964, 1954 maps).
	■	Geological map of Nigeria showing sedimentary formations. 1:2,000,000. Compil. By Desauvagie, T.F.J. (1972). Modified to include data from Desauvagie, T.F.J. (1974). I:n Whiteman, A. - Nigeria: Its eptroleum geology, resources and potential. London: Graham and Trotman, 1982.
	10	Maps of the Geology of Nigeria: 1:250,000 Geological Series. Map of Pokiskum n25. Carter, J.D. et al.. Geological Survey of Nigeria: Lagos. In: The geology of parts of Adamawa, Bauchi and Bornu Provinces in north-eastern Nigeria. Bull. n30.,1963.
Niger	░	Republique du Niger. Carte Geologique. 1:2,000,000; coord. J.Greigert et R.Pougnet (Interpretation aout 1965. Paris: BRGM, 1966. 1 feuille et notice (62p.) 1967.
	12	Carte de reconnaissance geologique du Manga. (Niger sud-oriental). 1:500,000; par F.Pirard. Dressee en 1962. Paris: BRGM (pour la Direction des Mines et de la Geologie du Niger)); 1967. 1 feuille et notice (35p).

Figure 4-1:List of all the geological maps available covering the Quaternary aquifer

4.3.3 THE PEDOLOGY



1 - Cartes à petite échelle
1 - Maps of small scale

A - Carte pédologique de reconnaissance de la République du Niger au 1/500 000. Feuille de Zinder. BOCQUIER et GAVAUD. 1964.
B - Pedological sketch map 1/500 000 (unpublished). KLINKERBERG.1968
- 1/500 000 (compilation). Land Systems. N-E Nigeria project. BAWDEN, CARROLL, TULEY. 1968.
C - Carte pédologique du Cameroun Oriental au 1/1 000 000. SEGALEN,MARTIN, SIEFFERMAN, VALLERIE. 1965.
D - Carte pédologique du Tchad au 1/1 000 000. PIAS. 1968.

2 - Cartes au 1/200 000 et à échelle plus grande
2 - Maps of 1/200 000 and larger scale

1 et 2 - PULLAN. 1962
3 - HIGGINS. 1967
4 et 5 - HOPE. 1963
6 - KLINKENBERG. 1961
7 - PULLAN. 1968
8 - PIAS. 1962
9 - MARTIN. 1961
10 - SEGALEN, VALLERIE. 1963
11 - SEGALEN. 1962
12 - BARBERY. 1968
13 - SIEFFERMAN. 1963
14 - SIEFFERMAN, VALLERIE. 1963
15 - MARTIN. 1963
16 - CLAVAUD. 1966
17 - VIZIER, FROMAGET. 1966
18 - CHEVERRY, FROMAGET. 1968
19 - VIZIER. 1967
20 - AUDRY, POISOT. 1966
21 - BOCQUIER. 1964
22 - BOCQUIER. 1968

3 - Travaux utilisés indirectement
3 - Indirectly used works

23 - HIGGINS, RAMSAY, PULLAN, DE LEEUW
Divers travaux de / *Various works of* GUICHARD, LEPOUTRE, SOBERON, TOMLINSON

Figure 4-2: List of the maps of the pedology covering the Quarternary aquifer (in UNESCO 1972).

As for the geology, most of the latest cartographic works on the pedology were made in the 1950's-1970's. In its study the UNESCO (1972) also gathered the various published maps on the pedology throughout the basin. The collection of these works led to a map that covers most of the Quaternary aquifer (see Figure 4-3). Later, ORSTOM (1979) repeated this work and produced a relatively more detailed map with a comprehensive legend (scale at 1:1,000,000). After these works there has been, to the best of our knowledge, only one map of the pedology published - in the region of Bogo-Pouss in Cameroon.

Overall, the pedology appears to have been described in much more detail than the Geology or geomorphology (see after).

4.3.4 THE VEGETATION

In the framework of the Livestock Atlas of the Lake Chad Basin, Gaston (1996) mapped the vegetation of the conventional basin. It is, as far as we know, the most complete document on the vegetation of the region. Herein vegetation is described together with factors interacting with it: rainfall, soil type, geomorphology and human use.

4.3.5 THE TOPOGRAPHY

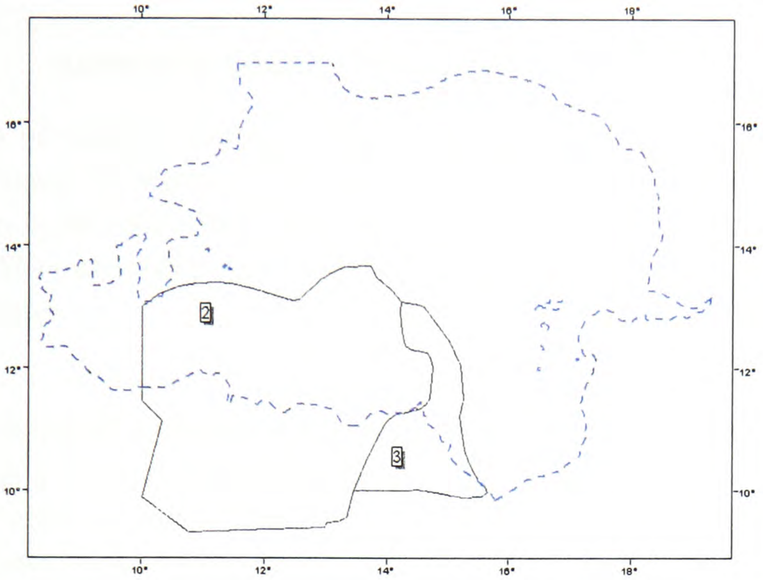
Large-scale (1:50,000) topographic maps are only available for Lake Chad itself and Cameroon. Apart from these areas the best data sets on the topography consists of a series of topographic maps at 1:200,000 (and 1:250,000 for Nigeria). They cover the whole Quaternary aquifer. Most of them were surveyed in the 1950's - 1960's and since then there has not been any other survey. The main problem is the scarcity of the information. Field point measurements are often separated by distances of more than 10km. Hence, there are often no contours on the topographic maps. From a regional perspective the topography of the centre of the basin is very flat and varies smoothly. However, locally it can be affected by important variations such as dunefields consisting of an alternation of humps and depressions. For hydrologists it is important to know precisely the local variability of the topography as it can, for instance, facilitate ponding and hence induce concentrated recharge. There are also difficulties establishing the altitudes of drainage networks. There are many large flood plains in this region. However, the lack of sufficient data does not allow hydrologists to develop a 3D model of the flood plains (Mott MacDonald Int, 1993).

Currently GTOPO30 is the only Digital Elevation Model available for the central part of the basin. It is a global digital elevation model with a horizontal grid spacing of 30 arc second (approximately 1km). It is distributed free of charge by the USGS (USGS, 1998). In the Lake Chad Basin GTOPO30 is derived from the Digital Chart of the World (Danko, 1992; ESRI, 1993) and the Digital Terrain Elevation Data set (DTED) of the United States of America National Imagery and Mapping Agency (NIMA). As far as we can trace, it as been derived from the national topographic maps described above, for which we have shown that there are insufficient field measurements. Hence, the information contained in GTOPO30 is not accurate and can lead to major errors. Additionally, the 1km resolution grid is by far too coarse to detect any variations in the local topography that could influence aquifer recharge processes. For instance, GTOPO30 cannot be used to detect ponding, dune slopes, or indeed any other local features of hydrological significance.

4.3.6 THE GEOMORPHOLOGY

Looking at the countries individually, only Nigeria and Cameroon have a map to describe the geomorphology of the region. In the other countries of the Quaternary aquifer (Niger and Chad), there is simply no map of the geomorphology. However, UNESCO published a map covering the whole southern part of the basin at 1:5,000,000. To the best of our knowledge, these three maps are the only documents reporting the geomorphology within the central part of the basin. Examination of the maps, and especially the one covering the whole basin, reveals that they are too sketchy. Here again the geomorphology of the central part of the basin has only been mapped once (see Figure

4-3). As for the geology, large areas are described as homogenous whilst they are not so: within dunefields no distinction is made between the plateaus, ergs and oases.



– – –	Geomorphological map of the Lake Chad Basin. 1:1,000,000. UNESCO. In: Study of water resources in the Lake Chad Basin 1966-1970. UNESCO, Paris. TR/ UNESCO/ UNDP/REG 71. 1972.
2	In Nigeria see Tuley (P) Ed. The Land Resources of North East Nigeria. Surbiton: land Resources Division, 1972, 55 vol. (Land Resources Study N9). 4 volume.
3	Maurin S. 2000. Geomorphologie de la province de l'extreme Nord Cameroon. Atlas de la province extreme nord du Cameroun. MINREST; IRD, Yaoundé (CMR); Paris (FR).

Figure 4-3: List of the maps of the Geomorphology available.

4.3.7 SURFACE WATER BODIES

The Atlas of African wetlands and shallow lakes is probably the only attempt to map the water bodies of the Lake Chad Basin (Burgis and Simoens, 1987). However, this mapping faces major problems: the boundaries of many water bodies are ill-defined and changing according to hydroclimatic conditions (Lemoalle and Brami-Hourtal, 1996). Small lakes in Manga have not yet been mapped.

Hence, to this day, there is no fine geographic information available on the location and the extent of the surface water bodies in the basin (see also, Ch. 2).

4.4 INTRODUCING REMOTE SENSING DATA SETS: BENEFITS AND EXPECTATIONS

4.4.1 ADVANTAGES OF REMOTE SENSING

"The public use of satellite data to manage water resources is still in its infancy, and more application techniques are urgently in need of development" (Shih, 1996). Regarding the hydrology and hydrogeology of the Lake Chad Basin, the capabilities of remotely sensed data might have been underestimated. The main reason for this is probably that the cost of the data and of their processing used to be prohibitive.

As previously mentioned, available conventional data sets are insufficient for hydrological studies and hence there is a need for high-resolution spatio-temporal data covering very large areas. Such data should be able to reflect the surface characteristics in their complexities and provide information on seasonal and inter-annual changes. Remote sensing appears to be a solution to providing such data owing to its synoptic capability, and its spectral, spatial and temporal resolutions. In addition, remote sensing acquires spatially continuous data, unlike fieldwork, where discrete measurements are collected.

There is a wide range of remote sensing sensors (airborne and spaceborne) with applications in hydrological studies (for example Lidar, RADARSAT, ERS-1/2, Ikonos, IRIS, SPOT, AVHRR, LANDSAT, MODIS). These sensors provide earth observation data at various spectral, temporal and spatial scales. Ideally, remote sensing data for hydrological studies should be of (i) high spatial resolution able to detect small features like ponds; (ii) high spectral resolution to reflect the complexity of the ground; and (iii) high temporal resolution to follow fast changing hydrological phenomena such as floods.

Unfortunately at the moment, there is no satellite able to deliver this, though efforts are made to go in this direction. Hence, the solution is to use a mix of sensors, each having their own advantages and limits. Working in developing countries and large areas also requires appropriate remote sensing, i.e. low cost and accessible data. This is becoming achievable as more sensors of low cost data continue to be launched, computer power keeps increasing and international efforts are made by the satellite operators to release data. Nowadays, it is possible to purchase, or sometimes download for no charge, very recent data. This section presents some relevant examples and illustrates the benefits remote sensing and GIS add to the conventional data sets of the basin.

4.4.2 LANDSAT DATA

Recently, NASA has made available, for no charge, orthorectified mosaics of Landsat TM data covering Africa. The mosaics are made from contrast adjusted colour composite of TM bands 7, 4 and 2. Other TM bands are not provided in the data set. However, the data are of high spatial resolution (28.5m by 28.5m). Hence, as it is, this data set is still very attractive and promising. The scenes were taken around 1990 and have been selected as close to the local peak growing season as possible. To cover the whole Quaternary aquifer, four mosaics have been downloaded from NASA's Web site: http://zulu.ssc.nasa.gov/mrsid/.

In addition to the above data set a series of Landsat MSS scenes of the Lake Chad Basin were acquired by the University of Glamorgan. Landsat MSS (Multispectral Scanner) data have 4 bands in the visible and near infrared. The spatial resolution is 56 m by 79 m and one scene covers approximately 185 x 170km. MSS data can be purchased at EROS Data Centre. Their cost is relatively affordable (250 USD) if the image is more than 10-years old. The idea when purchasing the MSS data was to have a high-resolution image over the Quaternary aquifer during the dry season. Choosing this particular period makes it possible to avoid cloud and vegetation interference and to focus on the geology, the geomorphology and the pedology of the region. Ten scenes acquired between January 1973 and February 1975 were merged to form one mosaic covering most of the Quaternary aquifer. This resulted in two complementary high-spatial resolution data sets - one during the dry season in the early to middle 1970's, and one during the rainy season in the early 1990's.

The first benefit of these two data sets is that they constitute the best geographical information available. They are a more accurate and up to date representation of the land surface than existing maps (i.e., 1:200,000 to 1:250,000 and 1:1,000,000). They are likely to become the medium-scale geodetic reference archive for the basin. In fact, Landsat TM images are orthorectified using techniques which provide a good positional accuracy. It is then possible to co-register Landsat MSS scenes with the Landsat TM data. The good georeferencing with the high-spatial resolution of these MSS and TM mosaics turn them into the most accurate geographic maps available in the Lake Chad Basin.

A second advantage is that MSS and TM data have a wide range of applications in geosciences. With these images it is possible to detect small geomorphological and geological features. This is a significant improvement and complements the geological and geomorphological maps of the basin. For example, Figure 4-4C shows a comparison of MSS data with the geological map (Figure 4-4A) and the geomorphological map (Figure 4-4B) in the Harr region (Chad). All the oases, which were not reported on the maps, appear on the MSS image. They have deposits that are different from the sandy surrounding dunes but similar to the clayey alluvial plain of the Chari-Baguirmi (Figure 4-4C). The centre of the Harr, which appears different from the rest of the dunefields, can be interpreted as a plateau. The Bahr El Ghazal valley and the drainage network passing through the dunefields associated with it, can be mapped with great precision from the imagery. On the TM image (Figure 4-4D), some ponding can be observed in the Bahr El Ghazal valley. This is certainly known locally, but to the best of our knowledge has never been reported in the literature describing the hydrology of the basin.

4.4.3 MODIS

In 2000, NASA launched a very promising sensor called Moderate Resolution Imaging Spectroradiometer (MODIS), to be part of the NASA's Earth Observation System to monitor the environment and global climate change. MODIS has a very good spectral resolution (36 bands with 7 particularly useful for land studies), a good temporal resolution (a view of the entire basin surface every 1 to 2 days) and fairly good spatial resolution (up to 250m). From the raw data, the MODIS data team processes a series of derived products (see the MODIS Web site at http://modis.gsfc.nasa.gov/). The list of products available is important and opens a wide range of applications. NASA makes data freely available to the research community. Consequently, this makes land surface change affordable even for large areas.

From the list of products offered, 8-day and 16-day composite images appear particularly convenient for studying hydrological phenomena around the rainy season. Images, over the given interval are merged to create a single cloud free image with minimal atmospheric and sun-surface-sensor effect. The MODIS land team processes a Land 8-day Surface Reflectance Composite at 500m resolution, corrected for atmospheric effects, polarization and bidirectional effects. The product has seven bands, ranging from the visible to the reflected infrared (Band 1: 620-670nm; Band 2: 841-876nm; Band 3: 459-479nm; Band 4: 545-565nm; Band 5: 1230-1250nm; Band 6: 1628-1652nm; Band 7: 2105-2155nm). The near-infrared wavelength (0.7 to 1.1 nm - Band 2 of MODIS) is particularly useful for hydrology as it is sensitive to water (Sabins, 1997).

Other interesting products include 16-day composite of Vegetation Indices (MOD13) with 500m resolution. It includes a type of normalized difference vegetation index (NDVI), referred to as the "continuity index" to the existing NOAA-AVHRR derived NDVI (Huete et al., 1999), which is particularly useful. Vegetation Indices are robust spectral measures of the amount of vegetation present on the ground in a particular pixel. They typically involve transformations of two or more bands designed to enhance the vegetation signal and allow for precise inter-comparisons of spatial and temporal variations in terrestrial photosynthetic activity. In the Sahel, vegetation blooms when there is water and dies rapidly when the soil dries. Therefore, vegetation health indices such as NDVI are a very good indicator of water. Thus, it can be used to show seasonal variations in vegetation and indirectly changes in soil moisture.

4.4.4 METEOROLOGICAL SATELLITES

Since 1977, the geostationary satellites Meteosat have delivered images covering all Africa and Europe with two channels (visible and near-infraread). The spatial resolution is of 4 km at nadir and one image is taken every half an hour. Views of recent Meteosat images are available at: http://www.nottingham.ac.uk/meteosat/. Archived data and more details on Meteosat can be obtained from http://www.eumetsat.de/.

Additionally, NOAA has launched several polar orbiting satellites. The mission started with TIROS-N in 1978 and was later replaced by the AVHRR instrument. AVHRR has a spatial resolution of 1.1 km (LAC format) and 5 channels (2 visibles, one IR, and 2 thermal IR). It covers the basin at least once every day. AVHRR archived data can be obtained at: http://www.saa.noaa.gov/ .

There are several reasons to find meteorological satellites useful though they have a poor spatial and spectral resolution. Firstly, Meteosat and AVHRR have a long history. It is possible for example, to use them to obtain the long-term history of the fluctuations of the extent of large water bodies such as Lake Chad (Olivry et al., 1996). Secondly, because they have a coarse resolution they do not produce large files even for large regions and are easier to handle. Thirdly, during the rainy season some areas might be under cloud most of the time so that even composite images from MODIS, for exemple, will not detect the land reflectance. However, because of its high-temporal resolution (1 image every half an hour), this is very unlikely to happen with Meteosat. Meteosat composite products of Africa are processed on a regular basis at the CMS of Lannion, France, in the framework of the "Veille Climatique Satellitaire" program, a collaboration between the IRD (formerly ORSTOM) and Météo-France. These data are available to the scientific community on request. Finally, at the moment MODIS data are not available in near real time, but AVHRR and especially Meteosat data are.

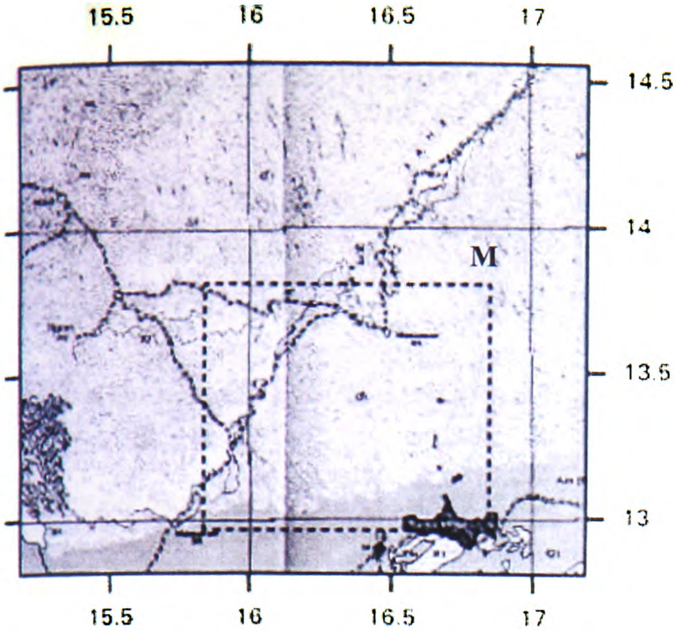


Fig. 4-4A: Map of the geology in Chad (Wolf 1964).

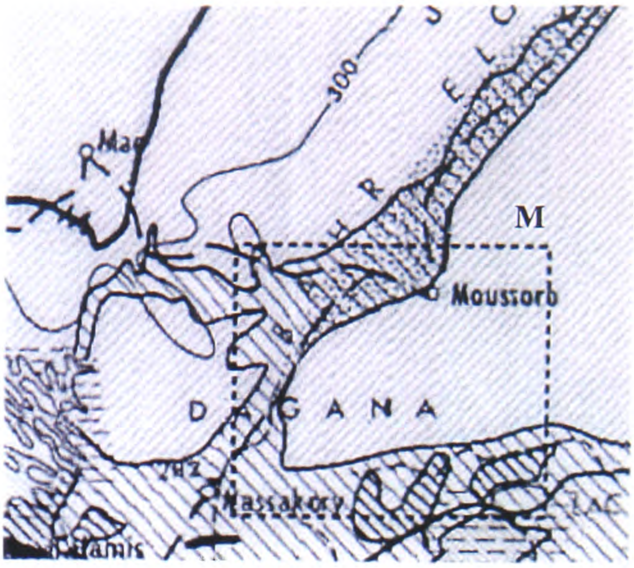


Fig. 4-4B: Map of the geomorphology in the Lake Chad Basin(UNESCO 1972).

Projection UTM
zone 33 North.

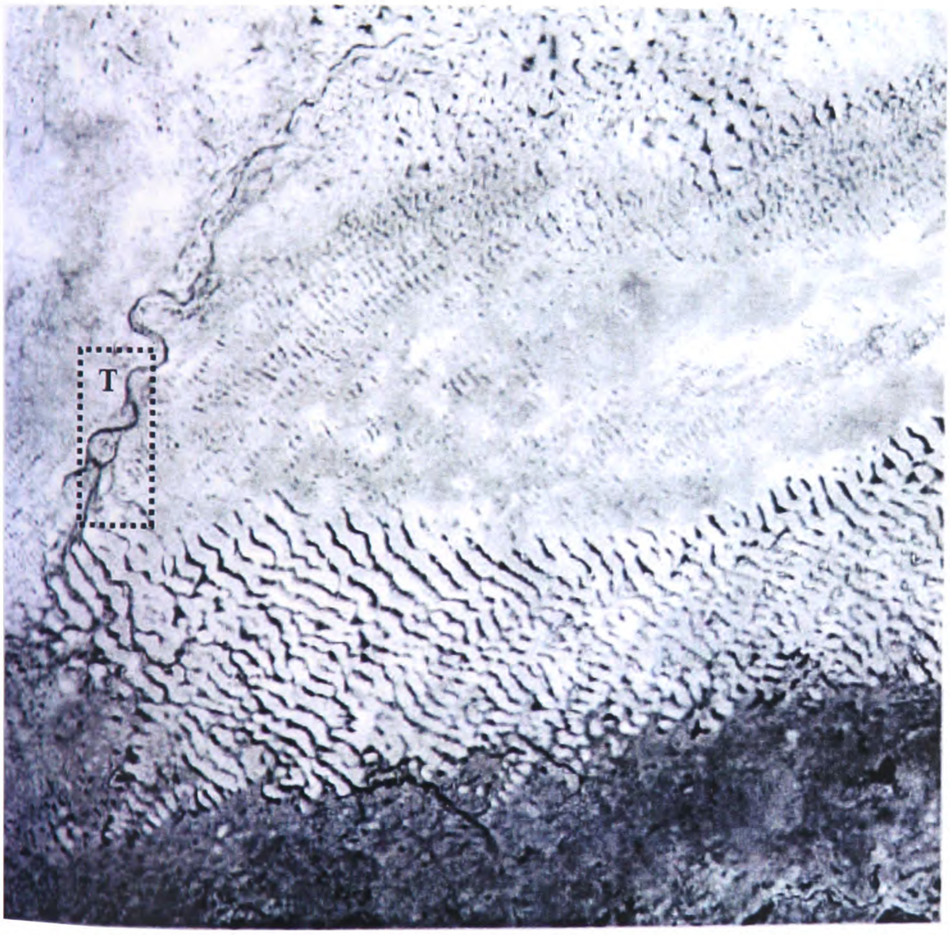


Fig. 4-4C: Landsat MSS first principal component of area M in Figures 4A and 4B. The image was taken in Jan. 1973 (dry season) and shows: a) the Harr plateau; b) oases in dunefields; c) the paleo-valley of Bahr El Ghazal; d) the alluvial plain of the Chari-Baguirmi.

Fig. 4-4D: Detail of Landsat TM mosaics (Source NASA) during the rainy season corresponding to the area T of Figure 4C.

Figure 4-4: Comparison of the geological and pedological maps with Landsat MSS and TM data.

4.5 GIS, THE DATA MODEL

This section looks at how GIS can globally contribute to improve water resources management in the Lake Chad Basin by providing an optimum use of geographical data.

All the data gathered are of various types: point measurements, published maps, digital elevation model, and satellite data. They also come from various sources such as: several institutions, and various consultant reports. There is often a need to harmonise and integrate them in the same management system. For example, maps were often produced at different scales; satellite data have different resolutions depending on the sensor used. Once all these data have been gathered, we have a large volume of information to deal with, that may only be manipulated and processed using a computer. The relevant way to handle these data sets is to use a Geographical Information System. Indeed, GIS supports integration, management, analysis and modelling of geographical data from multiple sources and at multiple scales. Once captured, point measurements (e.g., well measurements, level fluctuation of a river), scanned maps, digital elevation model and satellite data are stored as points, lines, polygons, grids, images. The software chosen are ArcInfo7® and ArcView3.2®, which are both developed by ESRI.

For the project, published maps were scanned and reprojected in a common system (Sinusoidal-14). In the meantime, archived field data were collected, integrated in specific databases and incorporated in the GIS.

The choice of a projection is an important and early decision which will support subsequent phases of GIS application (ESRI, 1994). This is particularly true when working at small-scale. The Lake Chad Basin represents a large area and its representation on a flat surface, if not optimum, might cause distortions. The projection has to be established considering the geographic features of the basin and the specific requirements for the hydrological modelling. The selection of a particular projection is always a compromise between conserving shapes, areas, distances or directions. The area lies in the tropics and its shape is roughly circular. For the project it is essential to have a projection that maintains the areas and distances. As an example, an error in the areas could introduce a bias in the volumes exchanged in the hydrologeological model. Lambert Azimuthal Equal area and Sinusoidal are two projections matching these criteria and commonly used. The common projection chosen for the project is Sinusoidal with a central meridian at 14°E. Sinusoidal was simply more widely available in the various software used than that of Lambert Equal Area. To choose a central meridian at 14°E enabled the line of zero distortion (standard line) to be located in a centre of basin, which limits more the distortion (ESRI, 1994; Mailing, 1992; Pearson. and Frederick., 1990; Synder, 1983; Yang et al., 1999).

The GIS also brings the groundwater model and geographical information together, thus extending the modelling possibilities. GIS is well acknowledged as a powerful tool to provide and manage input data for hydrological models (Singh and Fiorentino, 1996). There is a high interoperability between our GIS software (Arcinfo® and Arcview®) on the one hand and our groundwater modelling software (GMS®) on the other. Direct Export and import of geographical information is, for example, supported between the GIS and the modelling package.

By bringing such a variety of data together, GIS allows an integrated interpretation of the hydrological processes in the basin. It is thus expected that the analysis and interpretation of various data together will throw new light on our current understanding of the basin's hydrological processes. This should allow, for the first time, inspection of a large aquifer of the Sahel with `a bird's eye view′ and giving a comprehensive vision of the hydrological system.

4.6 CONCLUSION

An overview of the collection, interpretation and management of geographical data in the Lake Chad Basin reveals great difficulties. Such problems are certainly common to the GIS community but they take on another dimension when dealing with areas like the Lake Chad Basin. This shows that working with geographical information is still a real challenge and that GIS and remote sensing have a key role to play.

The conventional data sets of the Lake Chad Basin currently available do not appear to reflect the complexity of the ground. Many maps are from the 1950's-1970's. It is to be acknowledged that the maps of the basin represent real progress and magnificent work, especially given the restricting field work conditions. Nevertheless, we must not forget that the latest cartographic work was often the first undertaken on the topic in the region. This, together with the scale of the basin, raises the question of whether every significant feature has been mapped. The maps of the geology and of the geomorphology, for instance, are too sketchy. With their scales ranging from 1:1,000,000 to 1:5,000,000 they do not give much detail: there are no signs of lineament or neotectonic activity. Some very large areas might not be as homogeneous as described. The scarcity of the data and the need for better maps is obvious regarding the topography. Also, there is a need for updated information. Another limitation of the conventional data set (published maps) is that they are not appropriate for change detection.

Fortunately, it is concluded that satellite data significantly complement and supplement these existing data by providing more spatio-temporally accurate and up to date information, which even enables us to comprehend certain hitherto unexplained hydrological processes. The examples of satellite images given in this chapter are all based on affordable and readily accessible data. With the exception of MSS images, all the data presented in this chapter are distributed free to the research and scientific community, most downloadable via Internet. This then breaks down the barriers previously hindering hydrologists and hydrogeologists working in large and inaccessible areas (such as the Lake Chad Basin) from using satellite data.

There are still, however, some difficulties. The topography, though an essential characteristic of the terrain, has not yet been properly mapped. Radar data (such as SAR) and interferometry techniques seem promising to build Digital Elevation Model, but their cost in the case of large areas and developing countries is still prohibitive.

PART I I

Using Remote Sensing and GIS to Map Recharge and Discharge Areas of Superficial Aquifers in Semi-Arid Regions

The first part of the thesis has raised the importance of, and also the difficulties associated with, defining groundwater recharge and discharge areas in environments such as the central part of the Lake Chad Basin. One must acknowledge that hydrological processes of semi-arid regions of the world are still largely debated (Gee and Hillel, 1988; Lerner et al., 1990). There are significant differences between estimates of rainfall recharge concerning the Quaternary aquifer, which is the main water resource of the Lake Chad Basin (see chapter 2). Another issue is the presence of piezometric depressions. Aranyossy (1993) describes these as "the greatest mystery of Sahelian hydrology". This part of the thesis contributes by bringing new tools, namely GIS and remote sensing, to this overall problem. Our objective is to investigate the use of GIS and remote sensing for mapping groundwater recharge and discharge areas of semi-arid regions, using the Quaternary aquifer of the Lake Chad Basin as an example. It is expected that this section will offer answers to the following questions:
In semi-arid areas, are there any surface patterns that could play a significant role in aquifer recharge and discharge processes? Can we identify and map them?
If such factors exist, can they help us to understand the observed piezometric anomalies in the basin?

Chapter 5

REVIEW AND METHODOLOGY

5.1 INTRODUCTION

Remote sensing has never been applied to hydrogeological problems in the central part of the Lake Chad Basin (see section 2.6.3). Worldwide, GIS and remote sensing have often been used to map recharge and discharge areas in temperate regions, but the situation appears to be different for semi-arid areas.

The aim of this chapter is to search for analogous studies and to identify specific tools that would be relevant for the Lake Chad Basin. We start by reviewing the worldwide application of GIS and remote sensing to this issue in semi-arid regions. Subsequently, a methodology to apply for the Quaternary aquifer of the Lake Chad Basin is developed.

5.2 LITERATURE REVIEW

5.2.1 WORLDWIDE REVIEW ON THE USE OF REMOTE SENSING IN HYDROGEOLOGY OF SEMI-ARID AREAS

So far, in groundwater hydrology of semi-arid areas, remote sensing has mainly been used for the detection of faults and lineaments affecting fractured rocks, as they often indicate more permeable zones because of the high degree of fracturation (Edet et al., 1998; Magowe and Carr, 1999; Sabins, 1997). As far as we know there has not been any attempt yet to use satellite data to map groundwater recharge and discharge areas of unconsolidated aquifers in semi-arid areas. Meijerink (1996) also noticed this in his review of the use of remote sensing for hydrogeology.

However, it is possible to find some applications which are fairly close to what we require: i.e. the same goal but under different conditions or same conditions but with only partially related goals.

There have been applications of GIS and remote sensing to map recharge and discharge areas under different hydroclimatological conditions or under the same climate but in hard rock terrain. Salama et al (1994) used satellite imagery in the semi-arid western part of Australia (Salt River Basin-crystalline basement) to map groundwater recharge and discharge areas. Landsat TM images and aerial photos were used to search for geomorphic features (such as sand plains, laterite crust and hard rock outcrop); hydrogeomorphic features (such as streams, lake, playa, paleochannels, paleodeltas) and structural features (lineaments). Once detected, these elements have allowed the definition of groundwater recharge and discharge areas. In this study the authors point out the "importance of integrating the different layers of data" (Salama et al., 1994). Bobba et al (1992) used satellite data to detect groundwater recharge and discharge areas in southern Ontario, Canada. Landsat data were used to distinguish recharge and discharge areas. Landsat thermal data proved valuable in spring to detect discharge areas (as the water table comes close to the surface it generates thermal anomalies). India probably offers one of the best examples of operational use of GIS and remote sensing in groundwater management (Corbley, 1994; Krishnamurthy et al., 1996).

There have been some applications of remote sensing in similar conditions (semi-arid areas and unconsolidated material) with closely related goals. Belhadj-Aissa et al (1995) confirmed that classical image processing techniques are very helpful in finding hydrogeological features of arid areas. In the region studied, Principal Component Analysis, directional filters, indices, or simply true-colour compositions have been very efficient in the search for lineaments, geomorphologic features, drainage network and active vegetation areas. Escadafal (1989; 1993; 1996; 1998) studied the application of remote sensing to define soil infiltrability in Tunisia (arid climate). Field measurements were carried out to obtain soil infiltrability and spectral properties of areas with different characteristics. Degraded surfaces, with low infiltration capacity, often show pale and dull colours. Therefore, colour indices (such as SPOT band ratio) can be used to detect and map soil infiltrability. Thermal imagery of meteorological satellite, like the infrared band of METEOSAT, has been used in semi-arid regions to map soil moisture change (Lahuec and Guillot, 1994; Randriamanga et al., 1993). Dutartre et al. (1993) used radar and SPOT data for hydrogeological prospecting over the Kutum area. Satellite imagery was used to detect subsurface water resources locally concentrated in the alluvial deposits and the aeolian material accumulated in wadis flood plains. El-Baz (1993) used radar imagery to discover potential aquifers in the Arabian Desert at a junction of paleo-rivers, which are now covered by dunefields.

The successful techniques employed in these studies are a guideline in our study.

5.2.2 PREVIOUS WORKS THAT HIGHLIGHTS POSSIBLE LINKS BETWEEN PIEZOMETRIC ANOMALIES AND THE SURFACE CHARACTERISTICS.

In the Lake Chad Basin, only a few authors have worked on the importance of surface characteristics in groundwater recharge and discharge processes. Eberschweiler (1993) used a soil-based map to define recharge and discharge areas for a groundwater model. Unfortunately, very little explanation or justification is given in the report. The most comprehensive study so far, has been developed in a technical report of UNESCO (1972). This document highlights, for the first time, possible links between the piezometric anomalies of the Quaternary aquifer and the surface characteristics. It was noticed that there is a contrast between the north, made of permeable superficial formations and the south, made of impermeable soils. It was then pointed out that the piezometric domes are located in the permeable areas of the north, whereas the depressions are located in the south. Another surface particularity was noticed. It is the occurrence of Acacia or other phreatophytes, known to have extensive roots systems, above the depressions. However, at the time of the study, limits in information collection and mapping capacities have prevented further investigations.

On the rest of West and Central Africa, possible links between terrain characteristic and piezometric depression have, to the best of our knowledge, never been investigated (see also, Ch. 1 and Ch.3).

5.3 METHODOLOGY ADOPTED FOR THE LAKE CHAD BASIN

From the literature review, it becomes clear that little research has been carried out on the subject. In other words, to the best of our knowledge, remote sensing and GIS have never been used to map recharge and discharge areas under such conditions (semi-arid areas/unconsolidated sediments). However, related applications let us believe that it is feasible. It is enough to encourage us to carry on and expect that this original approach will throw new lights on the hydrology and hydrogeology of the Lake Chad Basin.

5.3.1 PUBLISHED MAPS

The method used to search for surface patterns is based on the complementary use of GIS and remote sensing. GIS is employed to integrate published maps. Indeed, work in the 1950's and 1960's led to the production of a series of geological and pedological maps covering the basin (see section 4.3). They will be integrated into the GIS as reference data sets for the geology and the pedology. In the same way, published resources on the topography will be incorporated in the GIS. There is no map of the depth to the water table for the Quaternary aquifer. Therefore, archived data from the basin's institutions will be used to draw one.

5.3.2 SATELLITE DATA

In environments such as the Lake Chad Basin, satellite data are a valuable source of information (see Ch. 4). They allow us to investigate issues that are not considered in the few published maps available. It is proposed to analyse two high-spatial resolution mosaics of Landsat images, one in the dry season and the other during the rainy season. In addition, low-spatial resolution satellite data (METEOSAT, MODIS, and AVHRR) pass over the same area very often. This type of satellite data is ideal to follow closely changes in the region during a hydrological cycle and especially the rainy season.

Ponding

In semi-arid areas, we distinguish two main types of rainwater recharge according to whether or not ponding occurs (see Ch.3):

* Direct (or diffuse) recharge occurs when rainwater penetrates the ground as soon as it falls on the surface;

* Localised (or concentrated) recharge when rainwater concentrates in ponds after runoff and then infiltrates.

Ponding occurs in topographical depressions and small ephemeral channels (wadis). In semi-arid environments ponding has been found to engender a higher recharge rate of the aquifer (Favreau and Leduc, 2001 a; Leduc et al., 2001; Leduc et al., 1996; Lerner et al., 1990; Simmers and Hendrickx., 1997). In the Lake Chad Basin, the relation between ponding and the recharge of the quaternary aquifer is simply not documented. Inside the basin and even more so in the Quaternary aquifer, ponds have never been mapped. It is, however, essential to know where ponding occurs and in what proportion. First, it is proposed to use high-spatial resolution satellite data to detect directly all the ponds at the end of the rainy season across the Quaternary aquifer. Second, it is intended in addition to map the areas that are *potentially* favourable for ponding. In fact, given the cost of high spatial resolution data, it is not yet possible to offer a systematic detection of all the ponds: some ponds may occur very briefly and not every year, others might be too small to be detected. To compensate for this, it is proposed this time not to try directly mapping the ponds, but to analyse the topography and to map where it is favourable to ponding and where it is not. Typically, high variation of the local topography facilitates ponding, while flat areas with no local topographic variation are unable to generate runoff and ponding.

Surface water bodies

Temporal rivers and flood plains are potentially regions of important flow exchanges with the aquifer. However, in the basin, little geographical information is available (see Ch. 4). Therefore, there may exist temporal rivers or flood plains related to the aquifer that have been ignored because they are too small, they occur too briefly, or they simply haven't been reported. In order to obtain a thorough mapping of recharge and discharge areas, it seems essential to check if such features have been omitted.

Soil moisture change

In semi-arid areas, the study of soil moisture at the end of the rainy season could be used to indicate regions of poor infiltrability. In fact, such regions retain water at the surface and thus may be detectable with satellite images. It is possible to use thermal imagery to obtain semi-quantitative information on soil moisture. The temperature of the ground and, particularly, its thermal inertia are related to its moisture content. Typically, a soil thermal inertia increases as its water content (soil moisture) increases. Thermal inertia can be measured from remote sensing and then used as an indirect determination of soil moisture (e.g., Engman and Gurney, 1990; Sabins, 1997). However, such methods are restricted to areas of low vegetation cover, which is the case for the central part of the Lake Chad Basin.

Vegetation activity

In semi-arid areas, the vegetation is very sensitive to water. It blooms when there is water and dies rapidly when the soil dries. Therefore, indices of vegetation activity, such as NDVI, can be used to obtain, indirectly, information on water resources.

5.4 CONCLUSION

From the literature review, it appears clear that applications of remote sensing in hydrogeology of semi-arid areas have been limited. Up to now, no research work has investigated the possibility of using GIS and remote sensing to map groundwater recharge and discharge areas under such conditions: semi-arid area and unconsolidated material.

As far as we could investigate, closely related studies indicate that our proposal is feasible and worthwhile. The method we propose to follow consists of determining if there are patterns in the characteristics of the terrain, e.g. topography, soil type and vegetation, that are related to the water table features: piezometric domes and piezometric depressions. To achieve this, published maps (piezometry, geology, and soil type) are integrated into a GIS together with the satellite images.

From a scientific point of view, the advantage of using our methods for the Lake Chad Basin is that it has at least five large and deep piezometric depressions. This gives support for our results through a statistical validation of our observations and interpretations. Later in the thesis, the independent development of a groundwater model should, further, validate or revoke the results.

Chapter 6

MAPPING RECHARGE AND DISCHARGE AREAS OF THE QUATERNARY AQUIFER

6.1 INTRODUCTION

Following the guidelines established in the previous chapter, we are now ready to investigate the Quaternary aquifer. The objective is to find out if there are any surface patterns that would characterise groundwater recharge and discharge areas.

Thanks to the published maps, the importance of both geological and the pedological characteristics will be analysed. Archive data should allow us to draw a map of the depth to the water table. Satellite imagery will be used to map and interpret ponding, surface water bodies, soil moisture change and vegetation activity.

6.2 ANALYSIS OF PUBLISHED MAPS

6.2.1 GEOLOGY

The joint examination of the geological map with the piezometric map (Figure 6-2 and Figure 6-3) reveals a possible link between the distribution of geological material and the location of the piezometric anomalies. There are two main types of Quaternary sediments: fluvio-lacustrine deposits and aeolian sediments. Fluvio-lacustrine deposits consist of an alternation of sandy and clayey banks, whose thickness generally does not exceed 5 metres (Greigert and Pougnet, 1967a; Schneider and Wolff, 1992). On the other hand, aeolian sediments are made of homogenous sands (Schneider and Wolff, 1992). A lower hydraulic conductivity is expected for the fluvio-lacustrine material. It emerges that the piezometric depressions are generally located in the fluvio-lacustrine sediments, whereas the domes are covered by aeolian sand (Figure 6-2). In Niger, going eastwards on the same latitude, i.e. equivalent rainfall, one passes from the erg of the Manga, with no piezometric anomaly, to the fluvio-lacustrine sediments of the Kadzell, where the water table is affected by a large depression. The extent of the depression appears restricted to these fluvio-lacustrine sediments. Similarly, in Chad, when passing from the erg of the Harr to the juxtaposed fluvio-lacustrine deposits in the Sinetay region, there is a change from a piezometric dome to a depression. Still in Chad, north to south, though following an increase of the rainfall, one passes from the piezometric domes in the ergs of Harr and Kanem to a large piezometric depression in the fluvio-lactustrine deposits the Chari-Baguirmi.

However, according to the map of the geology, not all the piezometric depressions are located in fluvio-lacustrine sediments. In Nigeria, both the Borno and the interfluvial depression of the Komadugu Yobe are mentioned on the map as "ergs of dunes". South of Mounio the small depression is located in "piemonts flats" reported as alluvial sands (Pirard, 1967; UNESCO-PNUD-CBLT, 1972).

Therefore, what appeared at first as a relationship between the geology and the location of the piezometric depressions is in fact not so straightforward.

6.2.2 PEDOLOGY

It is often the first centimetres of the ground that have a strong impact on runoff and rainwater infiltration. That is why it is interesting to have a look at the pedology alongside the examination of the geological maps. Additionally, soil type can influence various factors and reveal, for instance, patterns in the vegetation distribution. A review of the material available (see Ch. 4) indicates that maps showing the pedology of the central part of the basin are proposed in ORSTOM (1979) and in UNESCO (1972) (Figure 6-4 and Figure 6-5).

UNESCO (1972) had the suspicion that soil properties and especially its infiltration capacities play an important part in regional hydrology and might explain the piezometric anomalies of the Quaternary aquifer. The analysis of the distribution of the soils shows that the alluvial plains of the south are dominated by the presence of hydromorphic soils. This type of soil develops in the presence of excess water. They are generally found where drainage is poor, e.g. alluvial flats, and are classified as intrazonal. Reduction is more dominant than oxidation, resulting in a soil with blue/grey coloration, which can be detected with remote sensing. These soils are also characterised by a very low permeability, and they are seasonally waterlogged by rainwater during the rainy season (Naah, 1989; ORSTOM, 1979; UNESCO-PNUD-CBLT, 1972). The piezometric depressions of the Kadzell and of the Chari-Baguirmi are covered by these hydromorphic soils. In the same way, the Yaere and interfluvial zones of the Chari-Logone are covered by vertisols, which are even more impermeable. Therefore, in these regions, the infiltration of the rainwater during the rainy season or of floodwater is considerably limited by the soil characteristics. Thus, it is sensible to associate these areas with a very small recharge to the aquifer.

However, the same exceptions, which we have noticed during the analysis of the geological map appear. The depressions of Borno in Nigeria, of the interfluvial zone of the Komadugu Yobe and of south Mounio are not covered by hydromorphic or other impermeable soils. Indeed, brown soils on sand dunes are reported (J-on the map, Figure 6-4) to cover the interfluvial region of the Komadugu. There are hydromorphic soils on the south and north part of the Bornu depression, but the centre is covered by brown soil weakly developed on sand (H-on the map, Figure 6-4). The depression southward of Mounio is described as covered by brown soils on sand.

Thus, it is difficult to give a firm conclusion. Certainly, the presence of impermeable soil over the Chari-Baguirmi and Kadzell is more than a coincidence. However, the examination of the map of the soil does not allow the extraction of a governing factor common to the depressions.

From here, one could say that each depression might have its own system with different characteristics. The soil type might not be the only important parameter to define the recharge of the aquifer. It might also be a combination of terrain features. Alternatively, the problem might be inherent to the map. Firstly, the scale does not offer a good spatial accuracy and little cartographic work has been done especially northwards (see Ch. 4). Secondly, it might also be too simplistic to extract the infiltration capacity directly from the map of the pedology. The pedology has been mapped by various pedologists whose priority was not necessarily to describe the soil infiltrability. Finally, given the classification rules, a soil type describes an entire toposequence. Often, it is only the first few centimetres that have a very strong impact on runoff and infiltrability. Therefore, it is hard to tell whether such soil maps with their classifications always give a good indication of surface water infiltrability (rainfall and floodwater).

Depression	**Soil type**	**Permeability range**
Chari-Baguirmi	Hydromorphic soils: leached alkali soils (Wp); leached and weakly leached ferruginous soils on siliceous sands and clayed sands (O); hydromorphic soils with surface of pseudo-gley or pseudo-gley (Zb).	impervious (ORSTOM)
Kadzell	Hydromorphic soils: hydromorphic soils with surface of pseudo-gley or pseudo-gley (Zb); and (Hd).	impervious (ORSTOM)
Borno	Hydromorphic soils in the south and north (Zb) and (Hd) and Brown soils on siliceous sand (Hc)	impervious (ORSTOM) pervious
Yaere	Vertisols on clays	"very" impervious
Interfluvial zone of Komadugu	Brown soils on sand dunes (J)	pervious
South Mounio	Brown soils on siliceous sand (Hc)	pervious
East Harr: Sinetay	Brown soils on siliceous sand (Hc) Hydromorphic soils (Wb)	pervious impervious (ORSTOM)
`Interfluvial zone between the Chari and the Logone	Vertisol soils (F)	impervious

Table 6-1: Principal types of soil over the piezometric depressions (ORSTOM; UNESCO,1972)

6.2.3 VEGETATION

The vegetation of the central part of the basin is described in Gaston (1996) and is presented in Figure 6-6. Of course, the main component in the distribution of the vegetation is a decrease of the density to the north, according to the decrease in rainfall. However, apart from this general trend, some particular patterns appear with probable implication on the hydrological system.

It seems that the tree layer has a particular importance. One can notice the general presence in the landscape of deep rooting trees, also called phreatophytes, with species like Acacia raddiana and Acacia senegal. These trees are known for having extensive roots system, which can reach more than 30m under the ground and skim off small quantities of recharging water as it reaches the water table.

Unfortunately, there is little literature to describe precisely the density of trees in the landscape and how each species specifically acts on the hydrological system. Consequently, our analysis is only restricted to major and clear patterns. Yet, just by separating regions with a tree layer from those without, a `surprising´ pattern appears. Only two regions have *no* woody layer and it is a large part of the sandy plateaus of Kanem and Harr, where the piezometric domes are located. There the vegetation used to be characterised by the abundance of perennial grass, which, since the drought, have progressively been replaced by an annual grass layer (Gaston, 1996).

On the other hand, Kadzell is described as having a "dense woody layer" made of: Balanites aegyptiaca, Acaccia senegal, Acacia raddiana, Boscia senegalensis and Salvadora persica. The density of trees in Kadzell appears more important than in the neighbouring Manga. More generally, on the vertisols, the tree layer is also reported to be particularly well developed (Gaston, 1996).

The active oases of the dunefields (wadis), whose soil is typically clayey and where the water table is very shallow, have much denser vegetation than the rest of the dunefields. These active oases are found:

- In Kanem and particularly along the north and east shoreline of Lake Chad;
- At the border of the Harr (especially the southern border);
- In south Manga (not reported on Gaston's map).

6.2.4 WATER TABLE DEPTH

Archived data from national hydrological services, the Lake Chad Basin Commission and the UNESCO 1968-70 field measurements were gathered in the same database. The inverse distance weight function (7 neighbours) has been used to interpolate the well's data across the whole of the aquifer. The result is presented on Figure 6-1. Although it is a statistical approach, the number of measurements is reasonable enough to obtain a reliable map of the water table depth. The map is particularly reliable over the piezometric depressions where the topography is very flat. In the dunefields, because of the succession of domes and humps, sparce point measurements are unable to reflect thoroughly the depth to the water table. One notes that the traditional wells are generally located in the inter-dunal depressions.

Elsewhere in the Sahel, Favreau (2000) identified a small piezometric depression to the east of Niamey that is generated by strong evapotranspiration processes. Evapotranspiration largely dominate the vertical exchanges because in this area the water table is shallow. In the Lake Chad Basin, there are insufficient data to characterise the Bornu piezometric depression, but an analysis is possible for the rest of the aquifer. To the east of Lake Chad, in what is sometimes considered as a slight piezometric depression, the water table is very shallow (Schneider and Wolff, 1992). However, for the rest of the Quaternary aquifer, all the depressions appear to be deep. The depth in the centre of the depressions of the Chari-Baguirmi, the Kadzell and the interfluvial zone of the Komadugu exceeds 40m. An important result revealed by Figure 6-1 is that even toward the edges of the depressions, the depth remains significant (more than 20m on average). Therefore, in the case of the Lake Chad Basin, the map of the depth to the water table indicates that an eventual shallowness of the water table, which would have implied strong evapotranspiration processes, is not the reason for the presence of the major depressions.

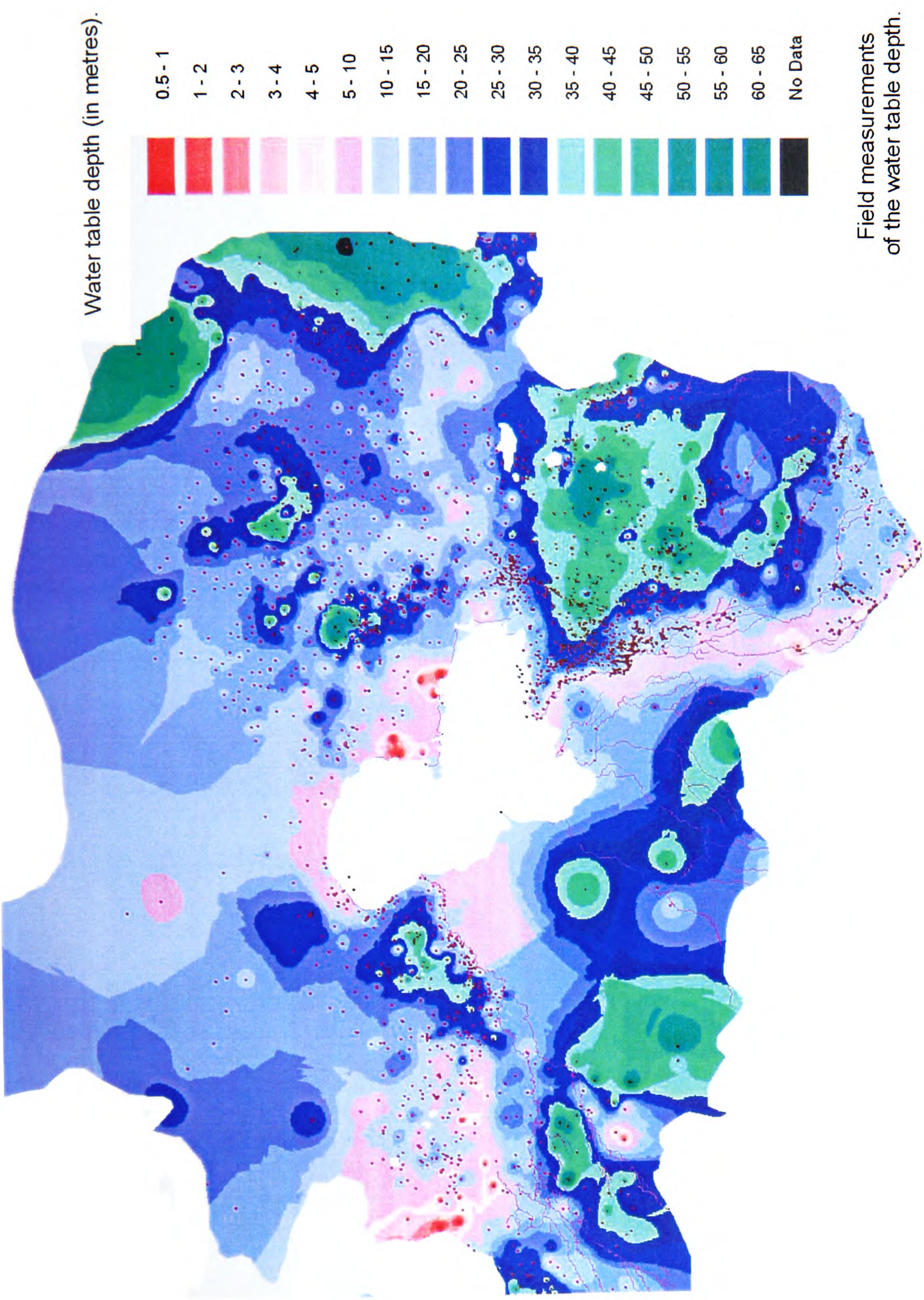


Figure 6-1: Map of the depth to the Quaternary water table.

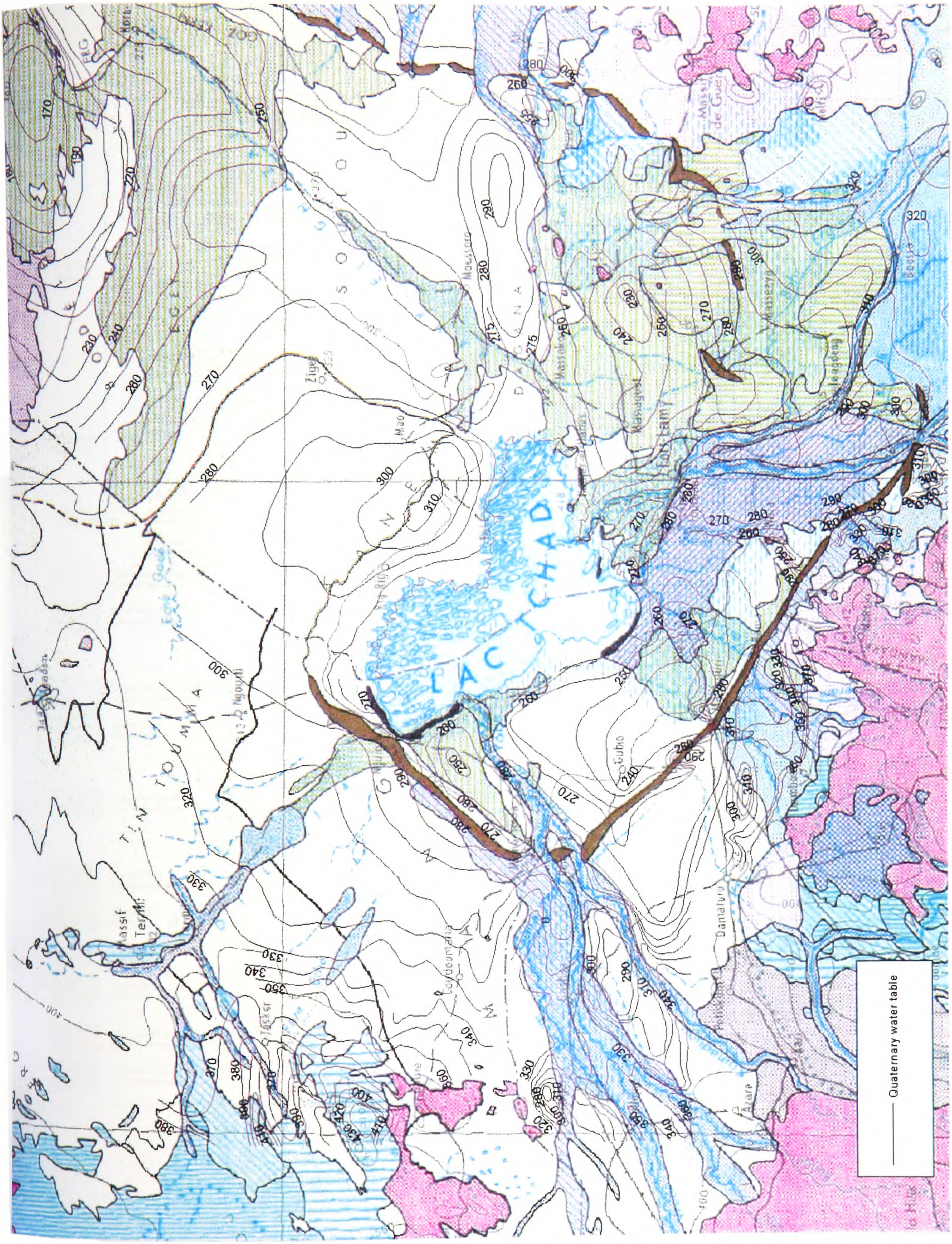


Figure 6-2: Map showing the geology (from UNESCO 1972) and the piezometry of the Quaternary aquifer.

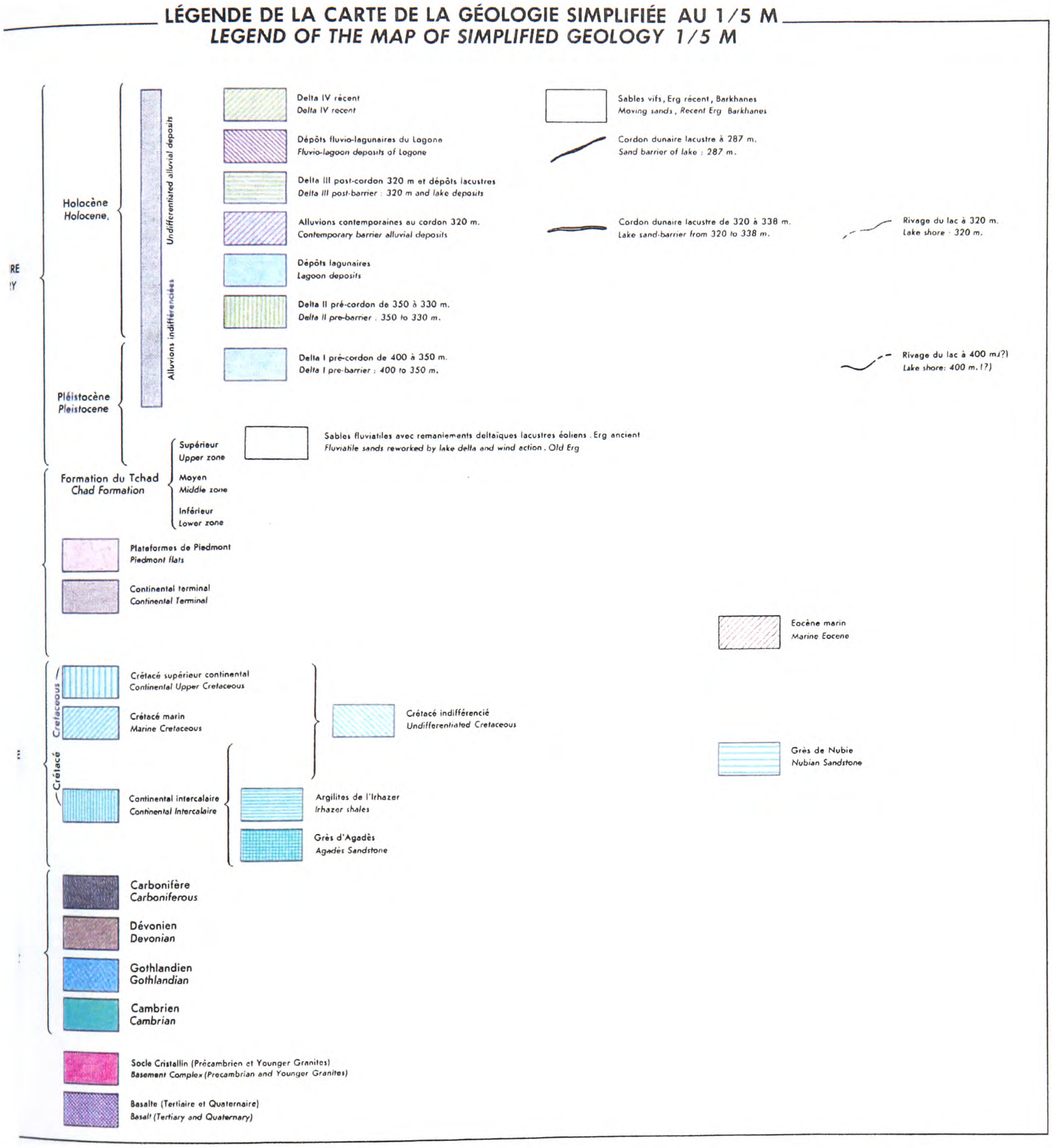


Figure 6-3: Legend of the map of simplified geology (UNESCO 1972).

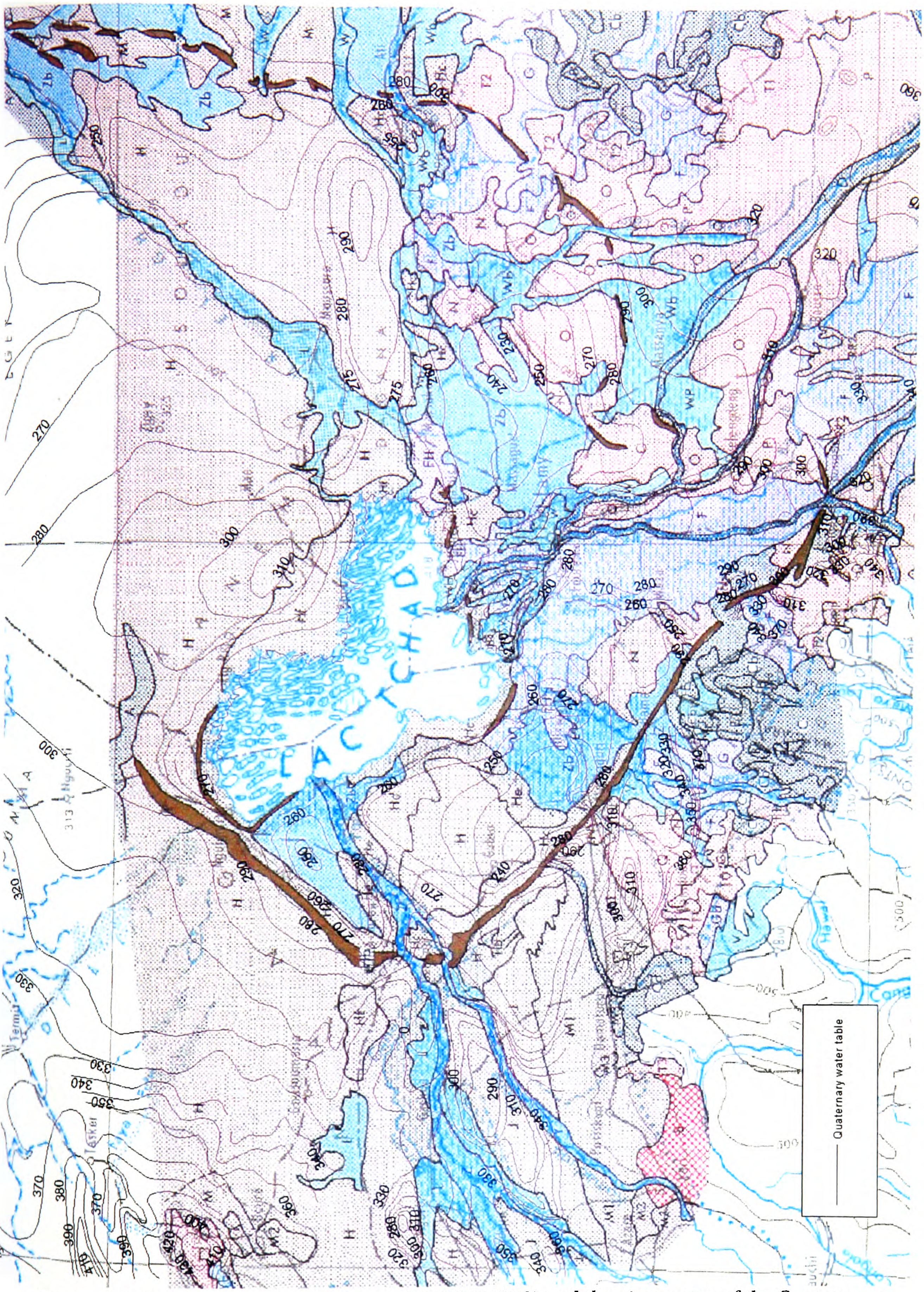
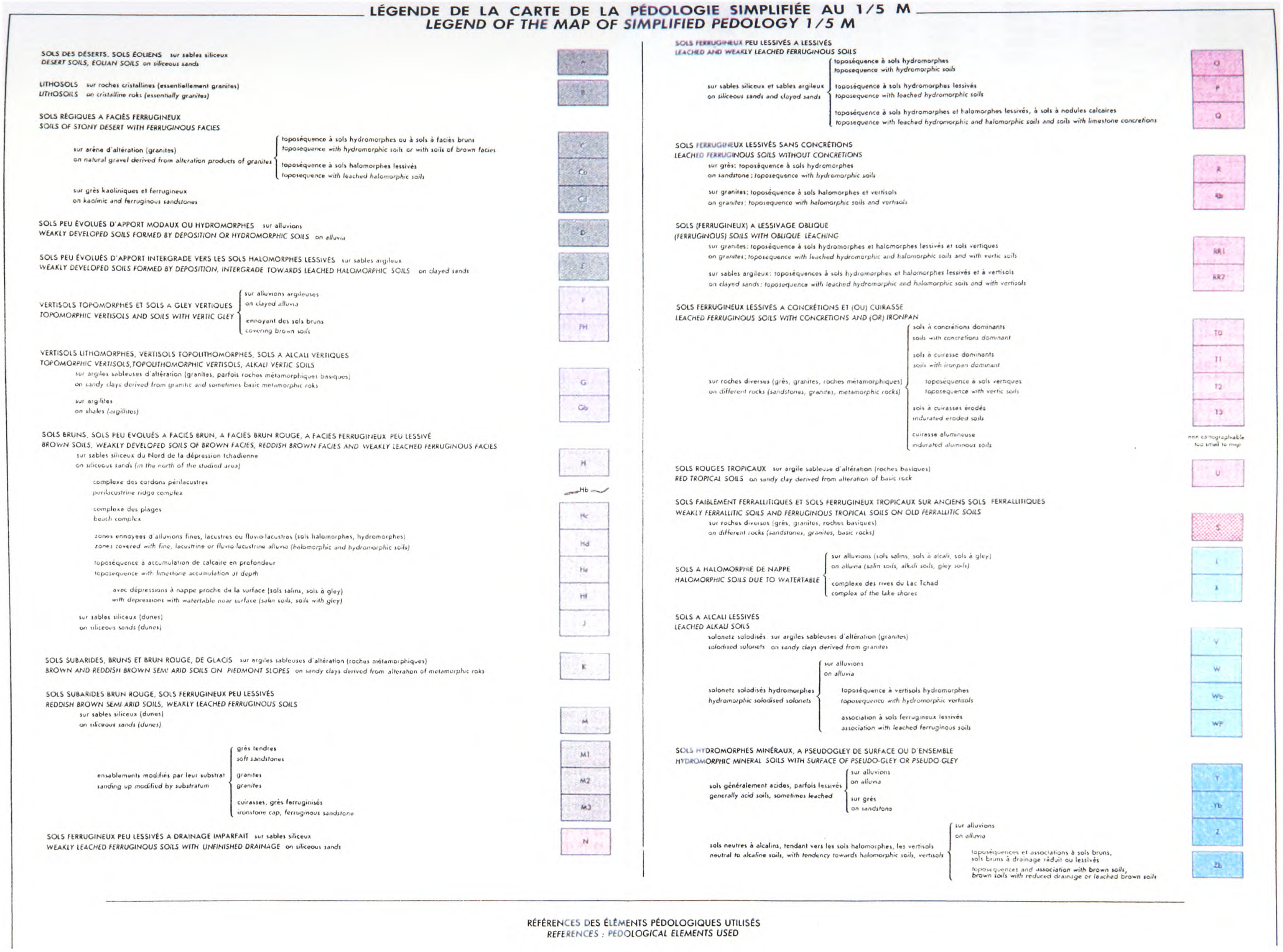


Figure 6-4: Map showing the pedology (UNESCO 1972) and the piezometry of the Quaternary aquifer.



LÉGENDE DE LA CARTE DE LA PÉDOLOGIE SIMPLIFIÉE AU 1/5 M
LEGEND OF THE MAP OF SIMPLIFIED PEDOLOGY 1/5 M

SOLS DES DÉSERTS, SOLS ÉOLIENS sur sables siliceux
DESERT SOILS, EOLIAN SOILS on siliceous sands — A

LITHOSOLS sur roches cristallines (essentiellement granites)
LITHOSOILS on cristalline roks (essentially granites) — B

SOLS RÉGIQUES A FACIÈS FERRUGINEUX
SOILS OF STONY DESERT WITH FERRUGINOUS FACIES

- sur arène d'altération (granites)
  on natural gravel derived from alteration products of granites
  - toposéquence à sols hydromorphes ou à sols à faciès bruns
    toposequence with hydromorphic soils or with soils of brown facies — C
  - toposéquence à sols halomorphes lessivés
    toposequence with leached halomorphic soils — Cb
- sur grès kaoliniques et ferrugineux
  on kaolinic and ferruginous sandstones — Cd

SOLS PEU ÉVOLUÉS D'APPORT MODAUX OU HYDROMORPHES sur alluvions
WEAKLY DEVELOPED SOILS FORMED BY DEPOSITION OR HYDROMORPHIC SOILS on alluvia — D

SOLS PEU ÉVOLUÉS D'APPORT INTERGRADE VERS LES SOLS HALOMORPHES LESSIVÉS sur sables argileux
WEAKLY DEVELOPED SOILS FORMED BY DEPOSITION, INTERGRADE TOWARDS LEACHED HALOMORPHIC SOILS on clayed sands — E

VERTISOLS TOPOMORPHES ET SOLS A GLEY VERTIQUES
TOPOMORPHIC VERTISOLS AND SOILS WITH VERTIC GLEY

- sur alluvions argileuses
  on clayed alluvia — F
- ennoyant des sols bruns
  covering brown soils — FH

VERTISOLS LITHOMORPHES, VERTISOLS TOPOLITHOMORPHES, SOLS A ALCALI VERTIQUES
TOPOMORPHIC VERTISOLS,TOPOLITHOMORPHIC VERTISOLS, ALKALI VERTIC SOILS

- sur argiles sableuses d'altération (granites, parfois roches métamorphiques basiques)
  on sandy clays derived from granitic and sometimes basic metamorphic roks — G
- sur argilites
  on shales (argillites) — Gb

SOLS BRUNS, SOLS PEU EVOLUÉS A FACIÈS BRUN, A FACIÈS BRUN ROUGE, A FACIÈS FERRUGINEUX PEU LESSIVÉ
BROWN SOILS, WEAKLY DEVELOPED SOILS OF BROWN FACIES, REDDISH BROWN FACIES AND WEAKLY LEACHED FERRUGINOUS FACIES

- sur sables siliceux du Nord de la dépression tchadienne
  on siliceous sands (in the north of the studied area) — H
  - complexe des cordons périlacustres
    perilacustrine ridge complex — Hb
  - complexe des plages
    beach complex — Hc
  - zones ennoyées d'alluvions fines, lacustres ou fluvio-lacustres (sols halomorphes, hydromorphes)
    zones covered with fine, lacustrine or fluvio-lacustrine alluvia (halomorphic and hydromorphic soils) — Hd
  - toposéquence à accumulation de calcaire en profondeur
    toposequence with limestone accumulation at depth — He
    - avec dépressions à nappe proche de la surface (sols salins, sols à gley)
      with depressions with watertable near surface (salin soils, soils with gley) — Hf
- sur sables siliceux (dunes)
  on siliceous sands (dunes) — J

SOLS SUBARIDES, BRUNS ET BRUN ROUGE, DE GLACIS sur argiles sableuses d'altération (roches métamorphiques)
BROWN AND REDDISH BROWN SEMI ARID SOILS ON PIEDMONT SLOPES on sandy clays derived from alteration of metamorphic roks — K

SOLS SUBARIDES BRUN ROUGE, SOLS FERRUGINEUX PEU LESSIVÉS
REDDISH BROWN SEMI-ARID SOILS, WEAKLY LEACHED FERRUGINOUS SOILS

- sur sables siliceux (dunes)
  on siliceous sands (dunes) — M
- ensablements modifiés par leur substrat
  sanding up modified by substratum
  - grès tendres
    soft sandstones — M1
  - granites
    granites — M2
  - cuirasses, grès ferruginisés
    ironstone cap, ferruginous sandstone — M3

SOLS FERRUGINEUX PEU LESSIVÉS A DRAINAGE IMPARFAIT sur sables siliceux
WEAKLY LEACHED FERRUGINOUS SOILS WITH UNFINISHED DRAINAGE on siliceous sands — N

SOLS FERRUGINEUX PEU LESSIVÉS A LESSIVÉS
LEACHED AND WEAKLY LEACHED FERRUGINOUS SOILS

- sur sables siliceux et sables argileux
  on siliceous sands and clayed sands
  - toposéquence à sols hydromorphes
    toposequence with hydromorphic soils — O
  - toposéquence à sols hydromorphes lessivés
    toposequence with leached hydromorphic soils — P
  - toposéquence à sols hydromorphes et halomorphes lessivés, à sols à nodules calcaires
    toposequence with leached hydromorphic and halomorphic soils and soils with limestone concretions — Q

SOLS FERRUGINEUX LESSIVÉS SANS CONCRÉTIONS
LEACHED FERRUGINOUS SOILS WITHOUT CONCRETIONS

- sur grès: toposéquence à sols hydromorphes
  on sandstone: toposequence with hydromorphic soils — R
- sur granites: toposéquence à sols halomorphes et vertisols
  on granites: toposequence with halomorphic soils and vertisols — Rb

SOLS (FERRUGINEUX) A LESSIVAGE OBLIQUE
(FERRUGINOUS) SOILS WITH OBLIQUE LEACHING

- sur granites: toposéquence à sols hydromorphes et halomorphes lessivés et sols vertiques
  on granites: toposequence with leached hydromorphic and halomorphic soils and with vertic soils — RR1
- sur sables argileux: toposéquences à sols hydromorphes et halomorphes lessivés et à vertisols
  on clayed sands: toposequence with leached hydromorphic and halomorphic soils and with vertisols — RR2

SOLS FERRUGINEUX LESSIVÉS A CONCRÉTIONS ET (OU) CUIRASSE
LEACHED FERRUGINOUS SOILS WITH CONCRETIONS AND (OR) IRONPAN

- sur roches diverses (grès, granites, roches métamorphiques)
  on different rocks (sandstones, granites, metamorphic rocks)
  - sols à concrétions dominants
    soils with concretions dominant — T0
  - sols à cuirasse dominants
    soils with ironpan dominant — T1
    - toposéquence à sols vertiques
      toposequence with vertic soils — T2
  - sols à cuirasses érodés
    indurated eroded soils — T3
  - cuirasse alumineuse
    indurated aluminous soils — non cartographiable *too small to map*

SOLS ROUGES TROPICAUX sur argile sableuse d'altération (roches basiques)
RED TROPICAL SOILS on sandy clay derived from alteration of basic rock — U

SOLS FAIBLEMENT FERRALLITIQUES ET SOLS FERRUGINEUX TROPICAUX SUR ANCIENS SOLS FERRALLITIQUES
WEAKLY FERRALLITIC SOILS AND FERRUGINOUS TROPICAL SOILS ON OLD FERRALLITIC SOILS

- sur roches diverses (grès, granites, roches basiques)
  on different rocks (sandstones, granites, basic rocks) — S

SOLS A HALOMORPHIE DE NAPPE
HALOMORPHIC SOILS DUE TO WATERTABLE

- sur alluvions (sols salins, sols à alcali, sols à gley)
  on alluvia (salin soils, alkali soils, gley soils) — L
- complexe des rives du Lac Tchad
  complex of the lake shores — X

SOLS A ALCALI LESSIVÉS
LEACHED ALKALI SOILS

- solonetz solodisés sur argiles sableuses d'altération (granites)
  solodised solonets on sandy clays derived from granites — V
- solonetz solodisés hydromorphes
  hydromorphic solodised solonets
  - sur alluvions
    on alluvia — W
    - toposéquence à vertisols hydromorphes
      toposequence with hydromorphic vertisols — Wb
    - association à sols ferrugineux lessivés
      association with leached ferruginous soils — WP

SOLS HYDROMORPHES MINÉRAUX, A PSEUDOGLEY DE SURFACE OU D'ENSEMBLE
HYDROMORPHIC MINERAL SOILS WITH SURFACE OF PSEUDO-GLEY OR PSEUDO GLEY

- sols généralement acides, parfois lessivés
  generally acid soils, sometimes leached
  - sur alluvions
    on alluvia — Y
  - sur grès
    on sandstone — Yb
- sols neutres à alcalins, tendant vers les sols halomorphes, les vertisols
  neutral to alcaline soils, with tendency towards halomorphic soils, vertisols
  - sur alluvions
    on alluvia — Z
    - toposéquences et associations à sols bruns, sols bruns à drainage réduit ou lessivés
      toposequences and association with brown soils, brown soils with reduced drainage or leached brown soils — Zb

RÉFÉRENCES DES ÉLÉMENTS PÉDOLOGIQUES UTILISÉS
REFERENCES : PEDOLOGICAL ELEMENTS USED

Figure 6-5: Legend of the map of simplified pedology (UNESCO 1972).

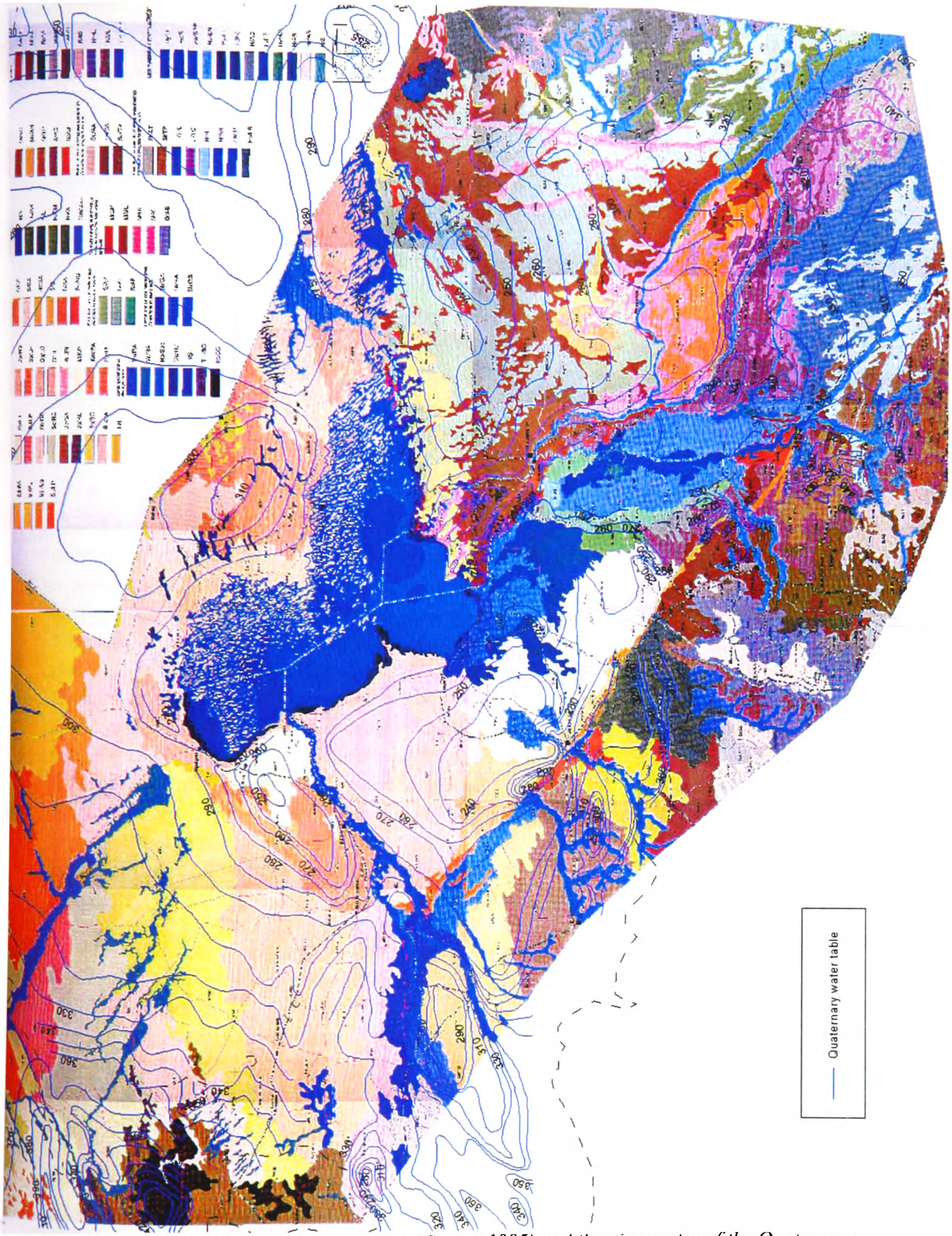


Figure 6-6: Map showing the vegetation (Gaston 1995) and the piezometry of the Quaternary aquifer.

6.3 SATELLITE IMAGERY

From an analysis of the published maps, it is already possible to sketch out some important interpretations. However, chapter 4 shows incompleteness of the geographical information contained in published maps. At this stage there is only one way for us to go further. It is to utilise remote sensing data.

In the chapter 5, we identified a set of relevant applications of remote sensing to map recharge and discharge zones: identification and mapping of ponding areas; study of soil moisture distribution at the end of the rainy season; study of the vegetation activity and search for unreported surface water bodies.

6.3.1 DIRECT DETECTION OF PONDS

The Mosaic of TM data from NASA (see section 4.4.2) is an ideal data set to map the ponds that occurred at the end of rainy season (October) in 1986. In fact, thanks to TM data spatial resolution, it is possible to detect small water bodies (such as ponds). Detecting ponds is not only a matter of finding small open-water bodies, but it must also include water covered by aquatic vegetation. Therefore, in addition to water, very active vegetation in topographic depression and flood plain areas will be mapped. In the TM mosaic from NASA, only bands 7, 4 and 2 are available. It is, however, sufficient as the features we are searching for have, in these bands, distinctive spectral signatures from the rest of the landscape: open water has an average reflectance in band 2 and a very low reflectance in band 4 and 7; aquatic vegetation and very active vegetation have a low reflectance in band 7 and 2 and very high reflectance in band 4. Ponds also have a particular appearance with a sharp boundary, a homogenous texture and a specific location in the landscape (topographic depression and drainage network channels). First, a supervised classification was run on the TM mosaic to detect all water bodies. Later, the entire TM mosaic was visually investigated and the results of the classification systematically checked.

The interpretation in terms of recharge is proposed by overlaying the map of the ponds with the map of the piezometry of the Quaternary aquifer. The distribution of the ponds is analysed in order to search for spatial patterns related with hydrogeological features and major hydrogeological regions.

Results

All the ponds detected in 1986 at the end of the rainy season are presented in Map 5. Major patterns are revealed in the spatial distribution of the ponds. Firstly, it is observed that there is almost no ponding over the piezometric depressions:

- Almost no pond over the depressions of the Kadzell, the interfluvial zone of the Komadugu Yobe/Gana and to the south of Mounio;
- Very few ponds above the depressions of east Harr and Bornu;

- Few ponds above the Chari-Baguirmi depression.

Secondly, one notices that if in a similar environment (i.e. fluvio-lacustrine deposits) dense ponding occurs, then there is no piezometric depression. This is observable in Chad, where going south from the centre of the Chari Baguirmi depression, one observes in the region of Massenya a sharp increase of ponding (see Map 5). This is followed on the aquifer by an immediate rise of the levels: the water table is not depressed any more. Going south again from this region of ponding around Massenya, one will find another zone with no ponding. In this region (between Massenya, Mogrum and Bousso) the water table drops and is once again depressed. Likewise, going north-east from the centre of the Chari-Baguirmi depression, the number of ponds becomes important in the north of the Batha de Lairi. This is again accompanied on the aquifer by a rise of the piezometry and the end of the depression. It must be noted that the Massenya region is also sometimes flooded. Ponding probably occurs every year, but it is not the case for flooding (probably no flood from the mid. 1970's to 1994).

What these images demonstrate is the fundamental difference between direct (or diffuse) recharge and localised recharge. In the case of direct recharge, water is more likely to be evapotranspirated before it can reach the water table and recharge the aquifer. On the other hand, we have a much more effective recharge (indirect/concentrated recharge) when rainwater concentrates in ponds after runoff. This is particularly so because the surface area of water affected by evapotranspiration is considerably reduced. Also, the time for rainwater to reach the water table probably diminishes (modification of the flow in the unsaturated zone).

In terms of recharge in the Quaternary aquifer of the Lake Chad Basin ponding does matter. The depressions occur where the recharge is the smallest: i.e. where there is no ponding and no localised recharge.

In the dunefield regions ponds are found in south Manga, south Harr, south Kanem. There, some authors report that the ponds are generated by groundwater (Carter, 1995; Carter and Alkali, 1996; Eberschweiler, 1990). One of the limits of the current approach is that it does not allow the distinction between ponds generated by runoff of rainwater (acting as recharge area) and ponds generated by outflow from the aquifer (acting as discharge area). Later in our investigation, we will see that it is possible to differentiate these two kinds of ponds (see section 6.3.5).

A surprising result in the dunefields region is that there is no ponding in the central part of Kanem and Harr (piezometric domes).

6.3.2 INDICES OF VARIATIONS IN THE LOCAL TOPOGRAPHY: AREAS FAVOURABLE TO PONDING

Methodology

By detecting areas where the local topography is rough and facilitates ponding, we aim to reduce the lack of sufficient resources for a systematic detection of ponds (see section 5.3.2). Yet, this task is not without difficulty. In fact, currently the best digital data set on the topography of the centre of the Lake Chad Basin is GTOPO30, but its resolution is 1km. Therefore, it can only give an indication on regional trends of the topography (see section 4.3.5). To study local features of the topography, we need a data set with a much higher spatial resolution than GTOPO30. It would have been appealing to use radar data to build a Digital Elevation Model of the region, using for example interferometry technique with SAR data (30 m in areal resolution). However, the region we have to cover is so large that the cost of purchasing the data and acquiring ground control points is prohibitive.

The solution we have adopted is to use qualitatively, high-resolution MSS and TM data which are much more affordable. Of course, these kind of data do not allow us to calculate any elevation value. However, the central part of the basin is, at a regional scale, very flat and made of unconsolidated material. It is thus presumed that geological and geomorphologic features, such as basement outcrops, sand dunes, drainage networks, paleo-channels, oases, and others features of the landscape can introduce variations in the local topography. These elements can be detected by remote sensing and later interpreted in terms of local topography variation. Figure 6-7 shows some examples of topographic indices on the Landsat MSS mosaic:

A: Dunefields of the Harr - zone with high local topographic variation

E: Dunefields of south Manga - zone with high local topographic variation

D: Temporary channel and flood plain of Massenya - zone with high local topographic variation

C: Plateau of the Harr - zone with little variation

B: Chari-Baguirmi alluvial plain - very flat area

F: Kadzell alluvial plain - very flat area

The method uses both Landsat MSS data and TM data mosaic as they have different resolutions and are taken, respectively, during the dry and the rainy seasons (Figure 6-9 and Figure 6-10). To aid interpretation the Landsat mosaics were overlaid with the drainage network layer of the Digital Chat of the World, and analysed with the topography maps at 1:200,000 (1:250,000 in Nigeria).

Results

Using this technique, a map of the local topographic variations has been produced for the Quaternary aquifer (Figure 6-8). The piezometric depressions of the Kadzell, the Chari-Baguirmi and the interfluvial zone of the Chari-Logone are distinctively located in very flat areas. It must be noted that although the region to the south of Mounio, the Borno region and the interfluvial zone of the Komadugu Yobe were described in the UNESCO maps (1972) as sand dunefields. However, the Landsat MSS image (Figure 6-10) shows that in fact these regions have different characteristics than other dunefields (see neighbouring Manga for example). In fact, the local topography of these two regions seems to be flat.

Surprisingly, the centres of the piezometric domes (Harr and Kanem) appear relatively flat areas and do not seem to be propitious to ponding. The rest of the dunefields though, is characterised by high local topographic variations.

Additionally, this map shows an area (the south of the Batha de Lairi) where no ponds have been detected in 1986 with the TM data, yet the topography seems favourable for ponding.

Results obtained here corroborate the interpretation deduced from the direct detection of ponds observed after the end of the rainy season in 1986 (Map 5). It strengthens our observation that there is no ponding over the piezometric depressions, but that in these regions rainwater tries systematically to penetrate into the ground as diffuse recharge (direct recharge). Results also confirm that the local topography, via ponding, plays an essential role in the recharge processes.

The approach here has the advantage of suppressing the time dimension, which weakens the direct detection ponds. Map 5 indicates there was no pond over a region at a certain time, whilst Figure 6-8 shows it is very unlikely to ever observe ponding in this region. Unfortunately, the method employed has limitations. It does not offer any quantitative values but depends on visual interpretation, which might be subjective. In the case of the Bornu depression, it seems impossible with MSS or TM data to affirm to what degree the local topography is flat.

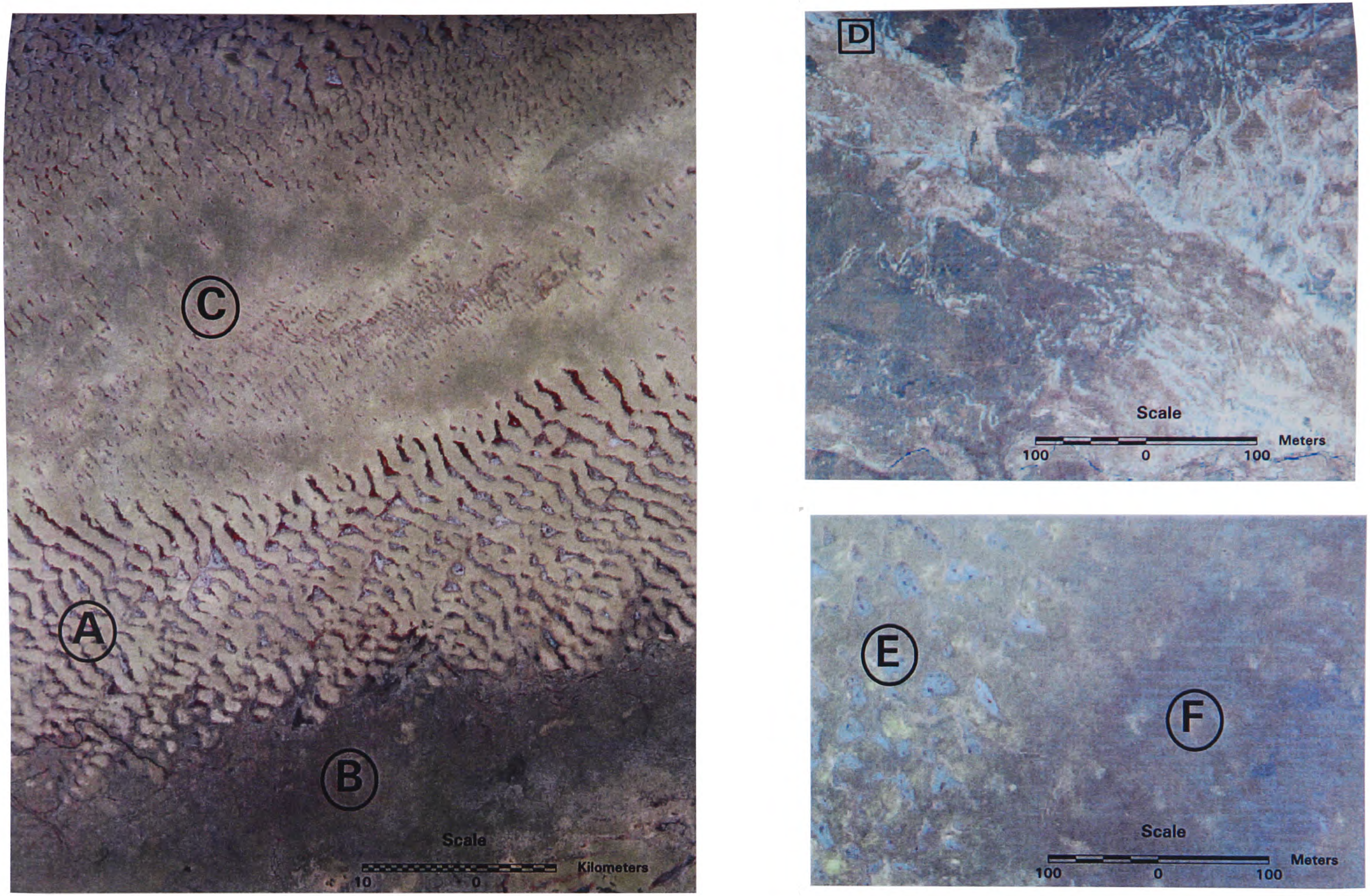


Figure 6-7: Examples of local topographic variations as observed with Landsat MSS data - dry season.

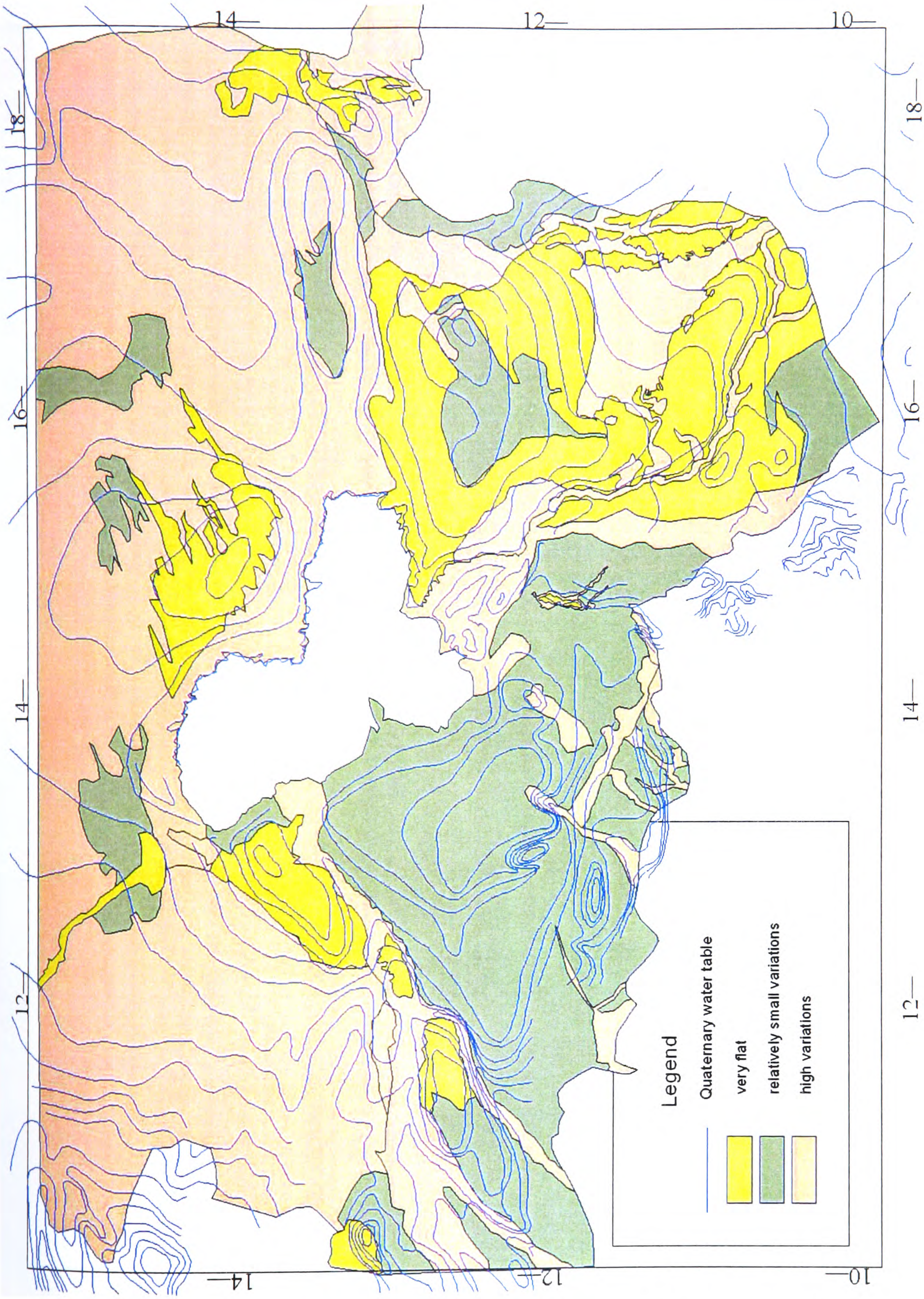


Figure 6-8: Map of the local topographic variations over the Quaternary aquifer.

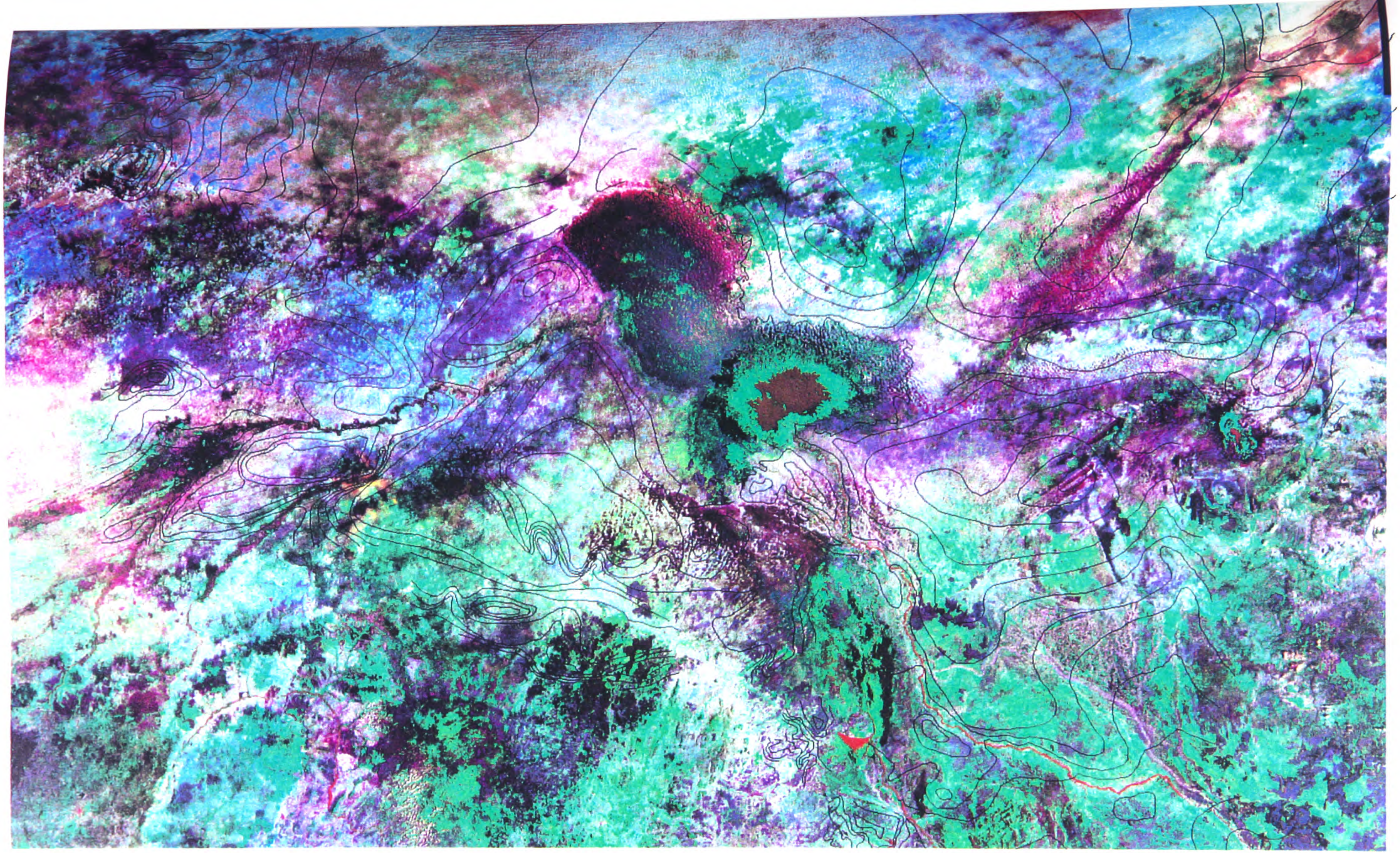


Fig.69: Mosaic of Landsat TM data during the rainy season.

color composition:

band 2-Red; band 4-Green; band 7-Blue.

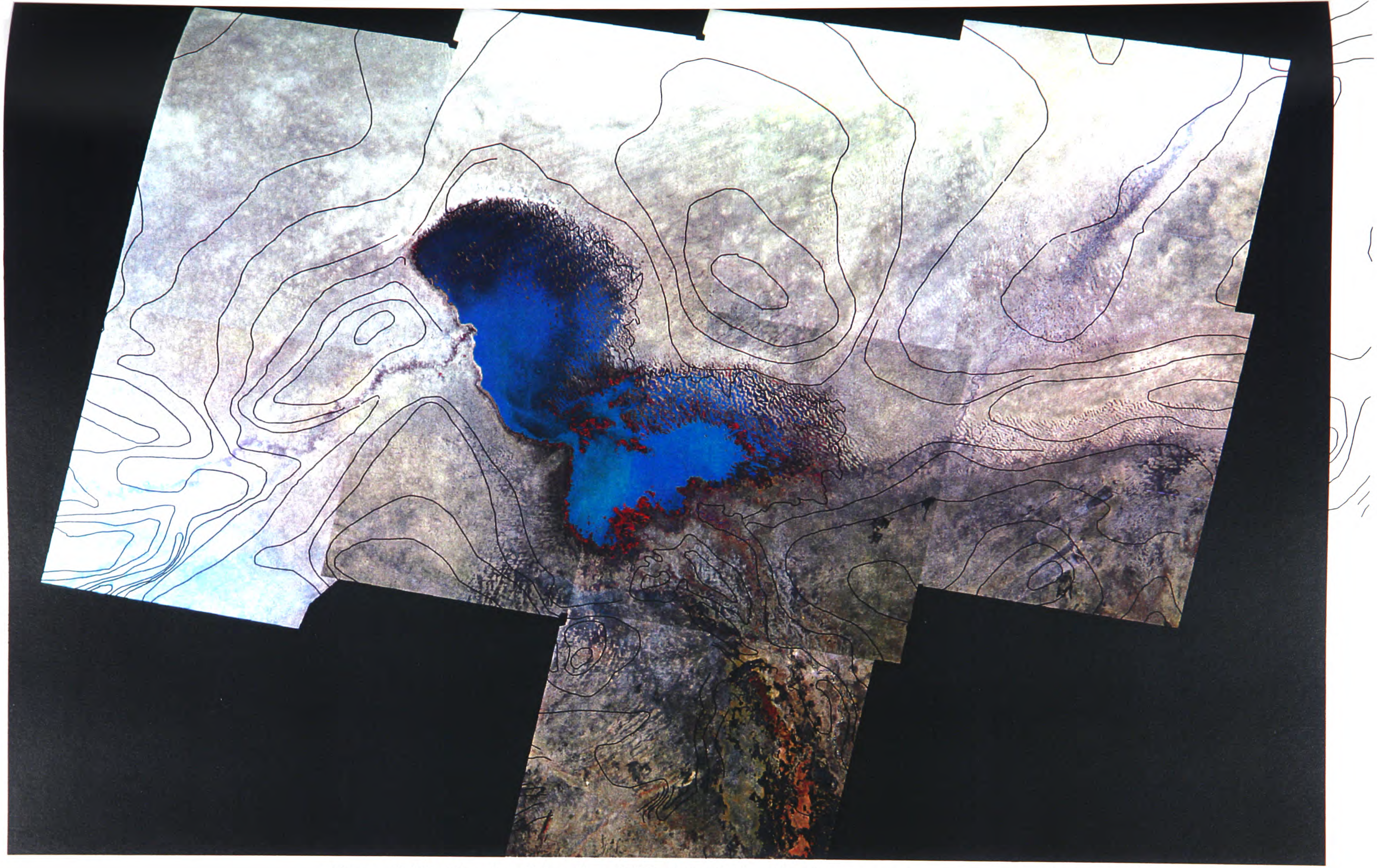


Figure 6-10: Mosaic of Landsat MSS data during the dry season.

6.3.3 LARGE SURFACE WATER BODIES

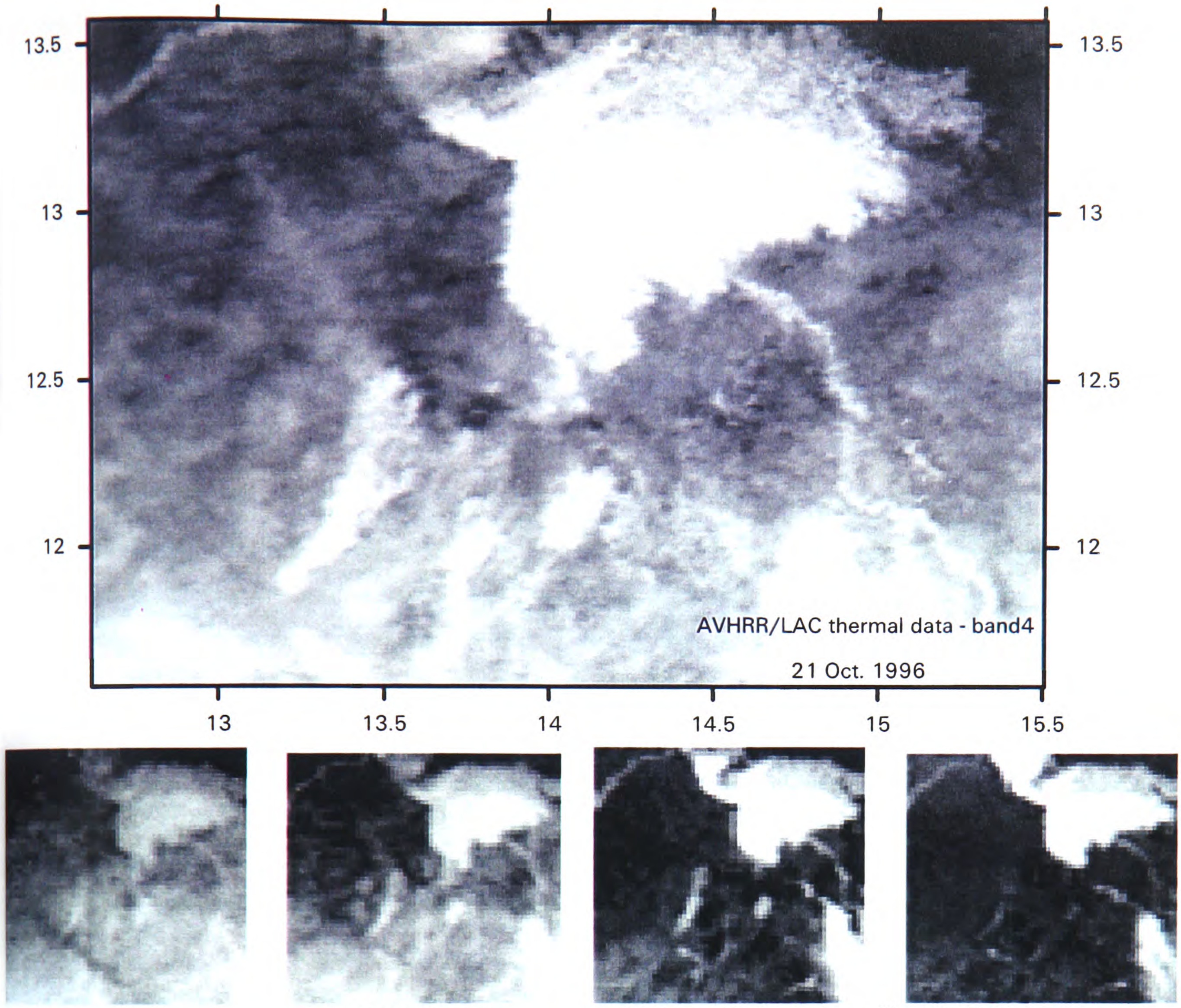
Methodology

AVHRR/LAC and Meteosat thermal data are most appropriate to detect temporal rivers and flood plains (see section 4.4). Indeed, they offer daily coverage of the aquifer and water bodies are highly detectable around noon due to their high thermal inertia (see section 5.3.2). Each water body detected is overlaid with the map of the piezometry to check for its influence on the water table. For practical reasons, we have limited our investigations to all the data available over the period extending from 1995 to 2000 with AVHRR/LAC and Meteosat data, and from 1999 to 2000 with MODIS data.

Results

Two flood plains, previously unreported, have been found in Nigeria and may have a direct relationship with the Quaternary aquifer. These areas are of significant size and, of course, they are known locally by the population. However, to the best of our knowledge, they have never been mentioned in documents on the hydrology of the basin nor in inventories of wetlands (see section 2.4.4 and Map 2).

What AVHRR/LAC and Meteosat thermal data show is the occurrence of two surface water bodies between September and December in north east Nigeria (Figure 6-11). The eastern one is located on the banks of the Yedseram, whilst the western one occurs along the Ngadda river. Examination of Landsat TM data confirms that they correspond to flood plains on the downstream part of the rivers (Figure 6-11C). Discussion with hydrologists working in the basin confirmed this information and highlight the fact that several dams and channels have been constructed on these rivers, which may interfere during some years on the flood extent. When overlaying the satellite images with the map of the piezometry of the Quaternary aquifer, it appears that the location of a rise of the water table concurs with the two flood plains. That is, these two flood plains match the location of piezometric domes and might be interpreted as recharge areas.



Meteosat Tmax

Septembre 1996

Meteosat Tmax

October 1996

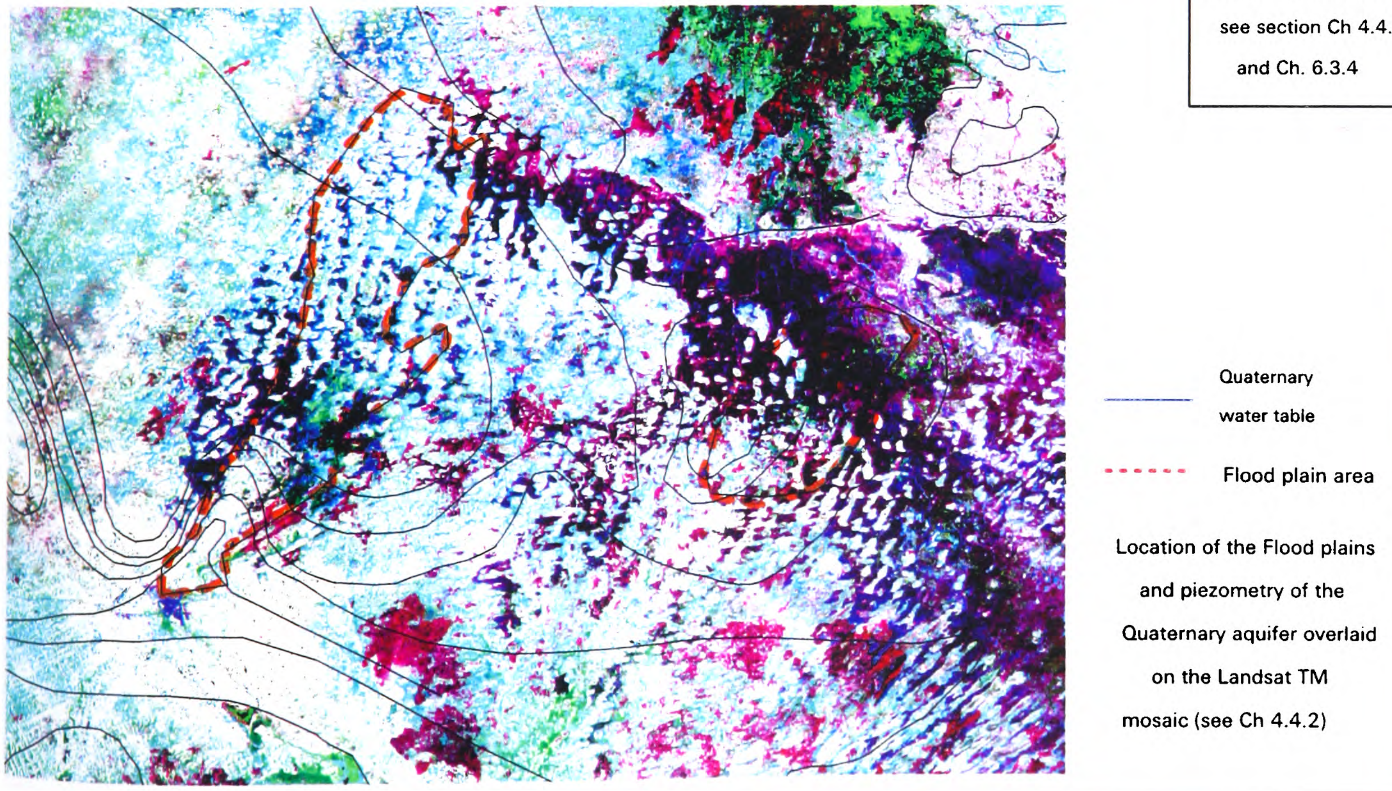
Meteosat Tmax

November 1996

Meteosat Tmax

December 1996

For a description of Meteosat Tmax data set see section Ch 4.4.4 and Ch. 6.3.4



Location of the Flood plains and piezometry of the Quaternary aquifer overlaid on the Landsat TM mosaic (see Ch 4.4.2)

Figure 6-11: Detection of two unreported flood plains in Nigeria.

6.3.4 SOIL MOISTURE CHANGE - METEOSAT TMAX

Methodology

Our aim here is to follow the spatial distribution of the soil moisture in the basin at the end of the rainy season. Ultimately, it is expected that we will obtain information on rainwater infiltrability. To obtain qualitative information on the soil moisture we used maximal value composite of thermal infrared data from Meteosat (Tmax data). The following paragraphs discuss the methodology adopted and the physical principle involved.

Tmax data set

Every 30 minutes, Meteosat records brightness temperature with its thermal infrared channel (10.5μm and 12.5μm) for the whole of Africa and a large part of the world.

Meteosat Tmax archive data were provided by the Centre de Météorologie Spatiale, Lannion (France), where they are produced in the framework of the "Veille Climatique Satellitaire" program with the collaboration of the IRD and Météo-France (see section 4.4). Meteosat Tmax are obtained by first processing the Maximal Value Composite (MVC) of all calibrated brightness temperatures obtained in 1-day with the sensor's infrared channel. A 10-day composite image is later processed as the mean of the MVC obtained over two spans of 5 days. The method has the advantage of suppressing the clouds, whilst maintaining a relatively good memory of surface events (Lahuec and Guillot, 1994). One must note, however, that the approach is limited to a semi-quantitative interpretation, given the fact that the brightness temperatures do not have atmospheric correction applied to them nor calibration to ground measured temperatures.

Retrieval of *surface* temperature

Surface temperature and surface energy budget

Most of the Earth's energy comes from solar radiation, and solar radiation is by far the most important energy source for controlling temperature conditions on the surface and near it. Three mechanisms may be involved in the transfer of heat energy: *conduction* which transfers heat through a material by molecular contact; *convection* which transfers heat through the displacement of heated matter; and *radiation* which transfers heat in the form of electromagnetic waves. A thermal sensor detects radiant energy from a target surface, heated through radiation (solar insolation and sky radiance), convection (atmospheric circulation) and conduction (through the ground).

The surface energy balance is the resultant of radiative components such as incoming and outgoing short-wave and long-wave radiation, and also non-radiative components such as sensible heat, latent heat and the change in energy stored in water or substrate on land. The pattern of temperatures are a function of net short-wave radiation, net long-wave radiation, sensible heat flux, latent heat flux and change in heat storage (Byrne et al., 1979).

All objects,at temperature above absolute zero, radiates energy at thermal wavelenghts (3 to 15 μm) during day and night. For any material, certain internal properties play important roles in governing its temperature (Sabins, 1997)

- Thermal Capacity (C): the ability of a material to store heat (in $cal.g^{-1}.{}^{\circ}C^{-1}$);

- Thermal Conductivity (K): the rate at which heat passes through a specific thickness of a substance, (in cal.cm^{-1}.sec^{-1}.°C^{-1}).
- Thermal Inertia (P): a measure of the thermal response of a material to temperature changes; defined as $P = (KC\rho)^{1/2} = C\rho (K)^{1/2}$. (in cal.cm^{-2}.sec$^{-1/2}$.°C^{-1})

Typical values of these parameters are shown in the table below.

{PRIVATE}	Thermal conductivity (K) (in cal.cm^{-1}.sec^{-1}.°C^{-1})	Thermal capacity (C) (in cal.g^{-1}.°C^{-1})	Density g.cm^{-3}	Thermal inertia (P) (in cal.cm^{-2}.sec$^{-1/2}$.°C^{-1})
Water	0.0014	1	1	0.038
Sandy Soil	0.0014	0.24	1.82	0.024
Basalt	0.005	0.2	2.8	0.053
Stainless Steel	0.03	0.12	7.83	0.168

Table 6.2: Thermal properties of some material. In Sabins, 1999.

Brightness temperature and Land surface temperature

In remote sensing, land surface temperature (LST) is generally defined as the skin temperature of the ground. For bare soil surface, LST is the soil surface temperature. For dense vegetated ground, LST can be viewed as the canopy surface temperature of the vegetation. In sparsely vegetated ground, it is the average temperature of the vegetation canopy, vegetation body and soil surface under the vegetation. Considering the spatial resolution of satellite remotely sensed data, the LST in remote sensing can be defined as the average surface temperature of the ground within the pixel mixed with different fractions of surface types. Brightness temperature is the land surface temperature obtained on the satellite level by thermal infrared sensors.

The transmission of the emitted spectral radiance from the surface through the atmosphere to the sensor is affected by a number of factors which make the retrieval of ground surface temperature from the remotely sensed data more complicated. In the thermal wavelength, the atmosphere usally has three very important effects on the spectral radiation transmission: absorption, upward atmospheric radiance and bi-directional reflection of the downward atmospheric radiance. At the same time, different viewing angles of the sensors and the characteristics of the ground objects also have significant effects on the observed radiance from space (e.g., Lillesand and Kiefer, 2000; Sabins , 1997)

For a given net solar insolation, the temperature at the surface of the earth will depend on a series of factors:

- Cloud-cover;
- Dependency of thermal response on composition, density and texture of the materials;
- Emissivities of the surface materials;
- Topographic irregularities including elevation and slope angle;
- Soil-moisture content and evaporative cooling effects near the surface;
- Vegetation canopy characteristics, including height, leaf geometry, and plants' shadows;

- Leaf temperatures as a function of evapotranspiration and plant stress;
- Near surface (1 to 3 metres) air temperature; relative humidity; and wind effects;
- Temperature history.

Relationship between surface temperature and soil moisture

Soil moisture is generally difficult to quantify/measure. It is important to discuss the relationship between land surface temperature and soil moisture. Why is it that surface temperature can give a fairly good indication on the distribution of soil moisture?

As a generalisation, land heats and cools faster than water, and to a greater degree. Why is that so?

- Water has a higher thermal capacity than land;
- Water is a much better transmitter of heat (thermal conductivity) than land. Insolation penetrates deeper into water than an equivalent thickness of land. The absorbed energy is distributed over a substantial volume of water.
- Heat may be distributed in water through mixing
- Water bodies and soil moisture have supply of water for evaporation. An effect of evaporation is the cooling of the surface affected.

For the reasons above the surface temperature of the ground and particularly its thermal inertia are related to moisture content. Typically, as the moisture content of a soil increases so does its thermal (see Appendix 6-2).

With regard to vegetation, Byrne et al. (1979) highlight that "plant canopy surface temperature is a function of energy balance, which is dominated by the availability of water to the surface" (Byrne et al., 1979). Also, in the cenral part of the Lake Chad Basin semi-arid conditions limit the development of the tree layers.

As reported earlier, remotely sensed data of surface temperature could be a measure of several factors outlined earlier (such as plant canopy, surface emissivities, surface cooling, soil moisture, and more). Vegetation effects and surface cooling by evaporation, evolve with soil moisture and have a similar impact on land surface temperature. As for the other factors, using our understanding of the basin, the effects of soil moisture variations are expected to be more dominant than any variations from over parameters.

Therefore, around the end of the rainy season, in environmental conditions such as the central part of the Lake Chad Basin, and in the absence of cloud cover or aerosols, soil moiture is the most likely parameter to influence the maximum radiant surface temperature of the day (Guillot et al, 1987; Lahuec and Guillot, 1994).

Advantages of using Tmax data

In semi-arid regions of Africa, Tmax data have already been successfully used to monitor soil moisture (Lahuec and Guillot, 1994; see also the "veille climatique" bulletin). There are very good reason for using Tmax data to follow qualitatively soil moisture change in the central part of the basin:

- Given the extent of the Quaternary aquifer, Meteosat images have the relevant swath width (see section 5.3.2);
- A long archive of Tmax has been recorded (from 1986 to present);
- The high temporal resolution - 1 image every 30 min (covering the whole of the Lake Chad Basin) - allows for effective cloud removal. Meteosat has, for instance, a much higher temporal resolution than AVHRR in comparison ;
- Tmax uses all the images available, given the high temporal resolution of Meteosat, this increase considerably the chances to get closer to real maximal values and measure around the same time of the day (Guillot et al, 1987 ; Lahuec et al. , 1994);
- Futhermore, if we measure the radiant temperature of a surface at the time of the day when it is at its maximum – which is what Tmax data do. Then we are also measuring when its thermal inertia has the maximum influence on the temperature of the ground being sensed (see Appendix 6-2);
- Data are readily available and easy to use.

Limits of the Tmax data set

One of the main limit of the approach employed is the difficulty to measure a land surface temperature and to relate it to a soil moisture (as explain above). There are also some limitations that are inherent to the processing of the Maximal Value Composites. No matter how could the temporal resolution of meteosat is, there is still a chance that an area will always remain under cloud cover during the compositing period. Finally, the brightness temperatures have not been corrected for atmospheric distortions.

Therefore, it is necessary to exercise caution in the interpretation of the images and to do only a qualitative analysis. Ideally the approach employed should be cross-checked with a different method.

Results

Each Tmax image was examined individually to search for spatial patterns in the distribution of Tmax. Results obtained from the 10-day composite are compared with results of the 1-month composites. It emerges that the 1-month and 10-day composites show the same phenomena. However, the 1-month composites are better for detecting major phenomena, as features are seen to show up more clearly on these images. On the other hand, as one would expect, the 10-day composites are more relevant for closely monitoring the temporal variation and detection of ephemeral phenomena. For example, in the first 10 days of September 1997 an area to the south of Mounio was observed to have much lower temperatures compared to surrounding regions. On the subsequent 10-day composite, this feature was not detected any more. Nevertheless, few of these short-term events have been detected, i.e. most of the information of the 10-day composites is also reflected in the 1-month composite where it appears more clearly.

The analysis of all the Tmax (1-month and 10-day composite) reveals some interesting phenomena occurring at the end of the rainy season, i.e. August and September. What makes these particularly remarkable is that the features' locations match certain hydrogeological regions and that the boundaries between the zones is characterised by a sharp variation in the temperature.

In August and September 1994, the Kadzell appeared clearly cooler than the rest of the Manga (Figure 6-13); meanwhile, the Harr appeared distinctly hotter than the Chari-Baguirmi region. The same phenomena are reproduced in August and September 1999 (Figure 6-12).

To a lesser degree, similar signatures are observed in 1995 and 1998. Indeed, in August and September 1988 (Figure 6-14) there was a break in the distribution of the Tmax when passing from the Chari-Baguirmi to the Harr, which was noticeably warmer. In August 1995 (Figure 6-14), the Kadzell seemed cooler than the rest of the Manga, but the temperature differential signature was weak. At the same time south to Mounio, there was a cool area. In 1995, from August to the end of September, the Harr stayed much warmer than the Chari-Baguirmi. In August 1998 (Figure 6-14), the Kadzell and south of Mounio were cooler than the Manga and the surroundings. Also, in 1998 the Harr again differed particularly from the Chari-Baguirmi, having a net increase in the temperature. Given this evidence, it appears that at the end of the rainy season the Kadzell is cooler than rest of Manga. This seems also to be the case for a small area south of Mounio. These regions can be interpreted as wetter than the surroundings. In direct contrast, the Harr is clearly hotter, and thus presumably drier, than the Chari-Baguirmi.

However, these phenomena have only been observed over a limited number of years, i.e.: 1988, 1995, 1998 and above all in 1994 and 1999. The phenomena do not appear systematically every year: there is nothing to report in 1990, 1992 and 1993. Additionally, there are two years (1986 and 1989) when the Kadzell depression seemed warmer than the rest of the Manga. Another piezometric depression (Bornu) appeared several times to be warmer than its surrounding regions (in 1986, 1988, 1989 and 1991. This contradicts our first interpretation by showing that depressions at the end of the rainy season are not necessarily wetter than other areas.

It is only when doing an inter-annual comparison of the images and placing them in the long-term meteorological context that an explanation can be deduced. In fact, within our study period, i.e. from 1986 to 1999, 1994 and 1999 are by far the two wettest years. This is confirmed by records at rainfall stations and inter-annual comparison of the Tmax (Appendix 6-1). Hydrogeological patterns appearing in the distribution of soil moisture are only detected in very humid years (such as 1994 and 1999). This might be related to the sensitivity of the sensor, which was not designed to study soil moisture, or to the phenomena which might actually only occur after heavy rainfall events.

Whatever the explanation, it is clear that after strong rains the regions of the depressions (Kadzell, the Chari-Baguirmi and probably south of Mounio) appear much cooler than dunefield areas (Manga and the Harr dome). Above the depressions rainwater accumulates at the surface and does not infiltrate deep into the ground, whereas in dunefield areas (Harr and Manga) the rainwater does infiltrate, which explains the observation of a warmer ground. These results are very interesting and enhance our knowledge of semi-arid hydrogeology. This is indeed the first time that phenomena like these have been observed and understood so clearly in their hydrological and hydrogeological contexts. Our understanding of the piezometric depressions is reinforced: it appears that rainwater does not infiltrate over the piezometric depressions but stays on the surface, unlike in recharge areas (Manga, and Harr dunefields).

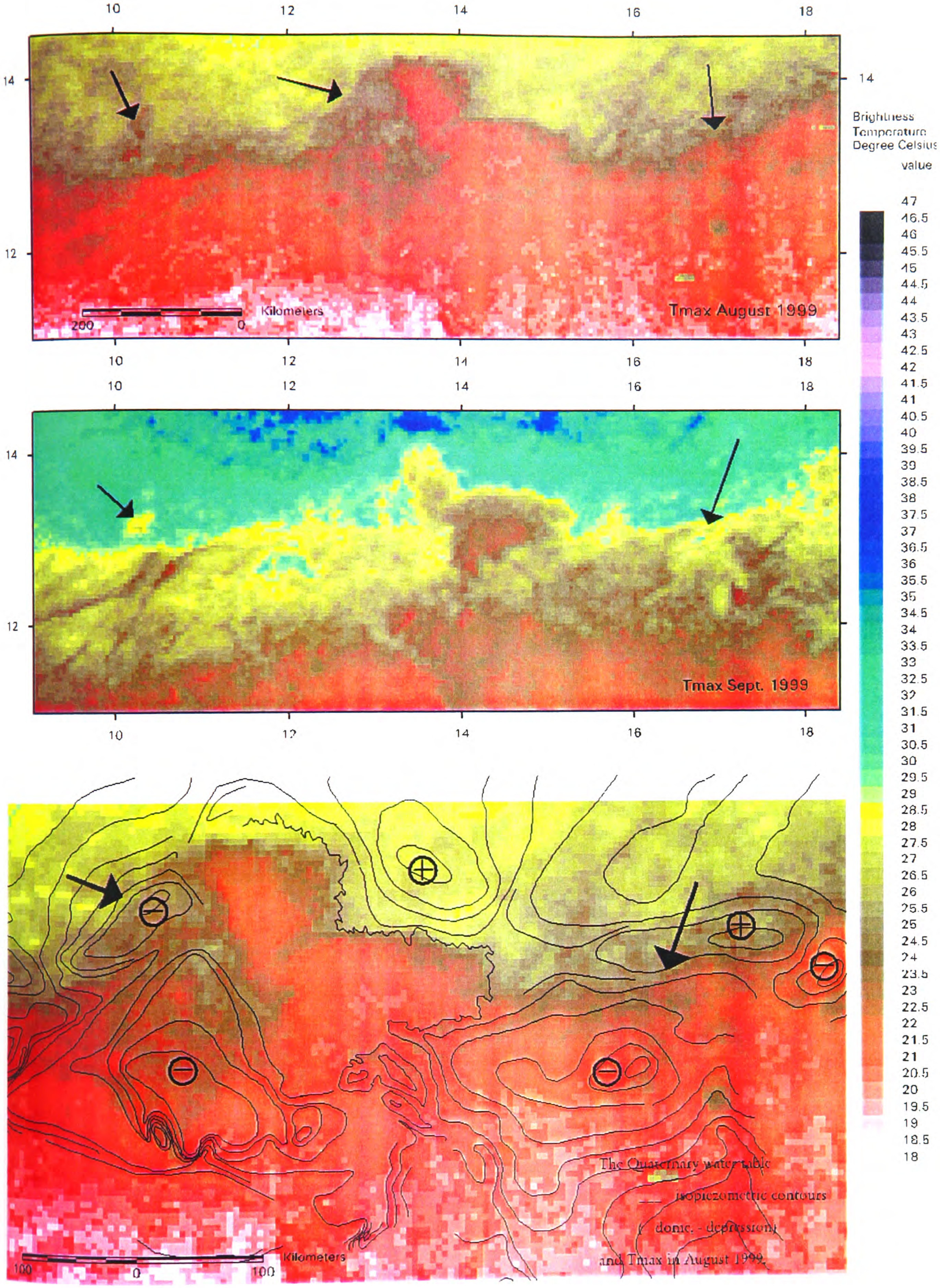


Figure 6-12: Meteosat thermal data and soil moisture distribution at the end of the rainy season in 1999.

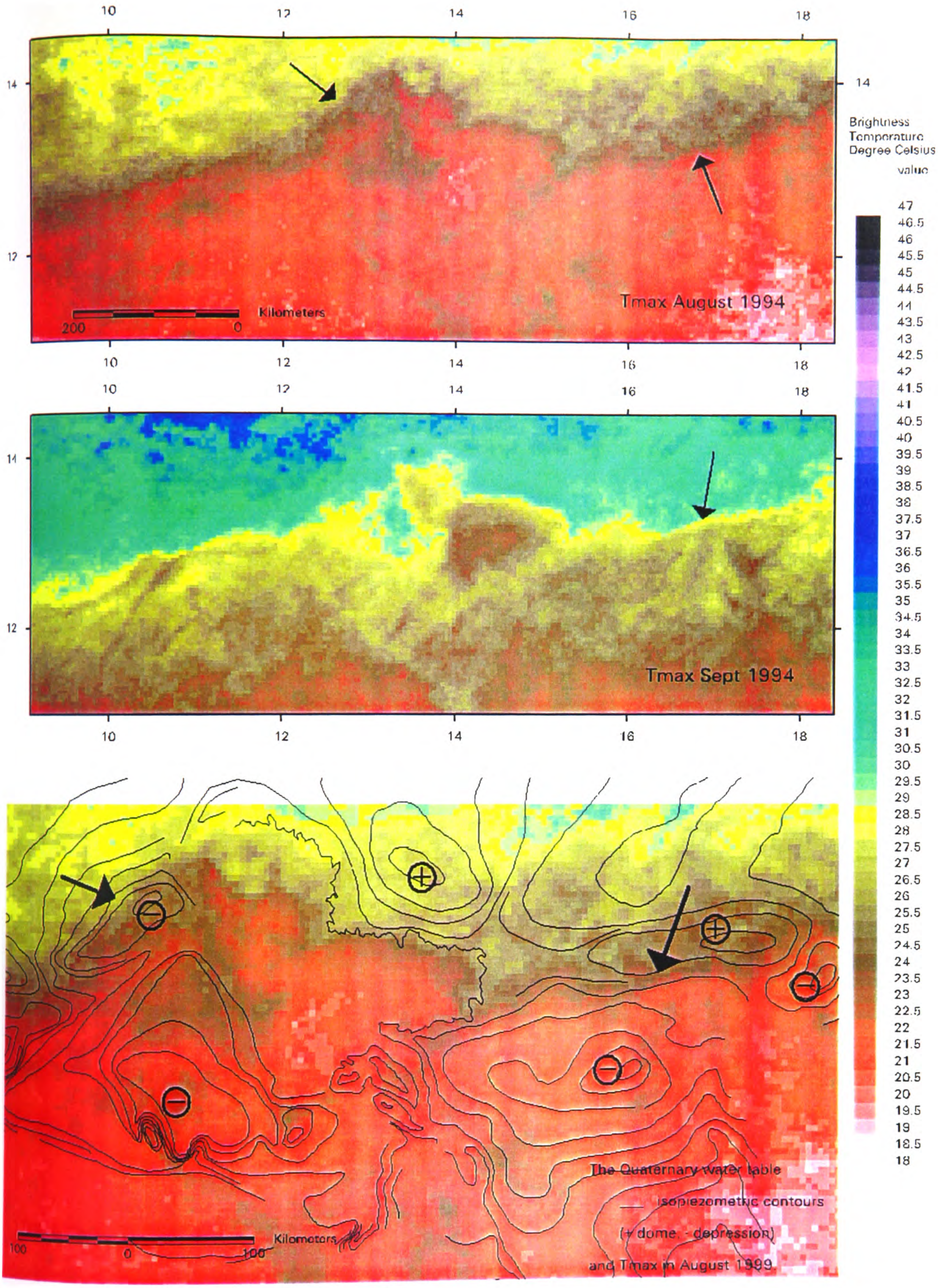


Figure 6-13: Meteosat thermal data and soil moisture distribution at the end of the rainy season in 1994.

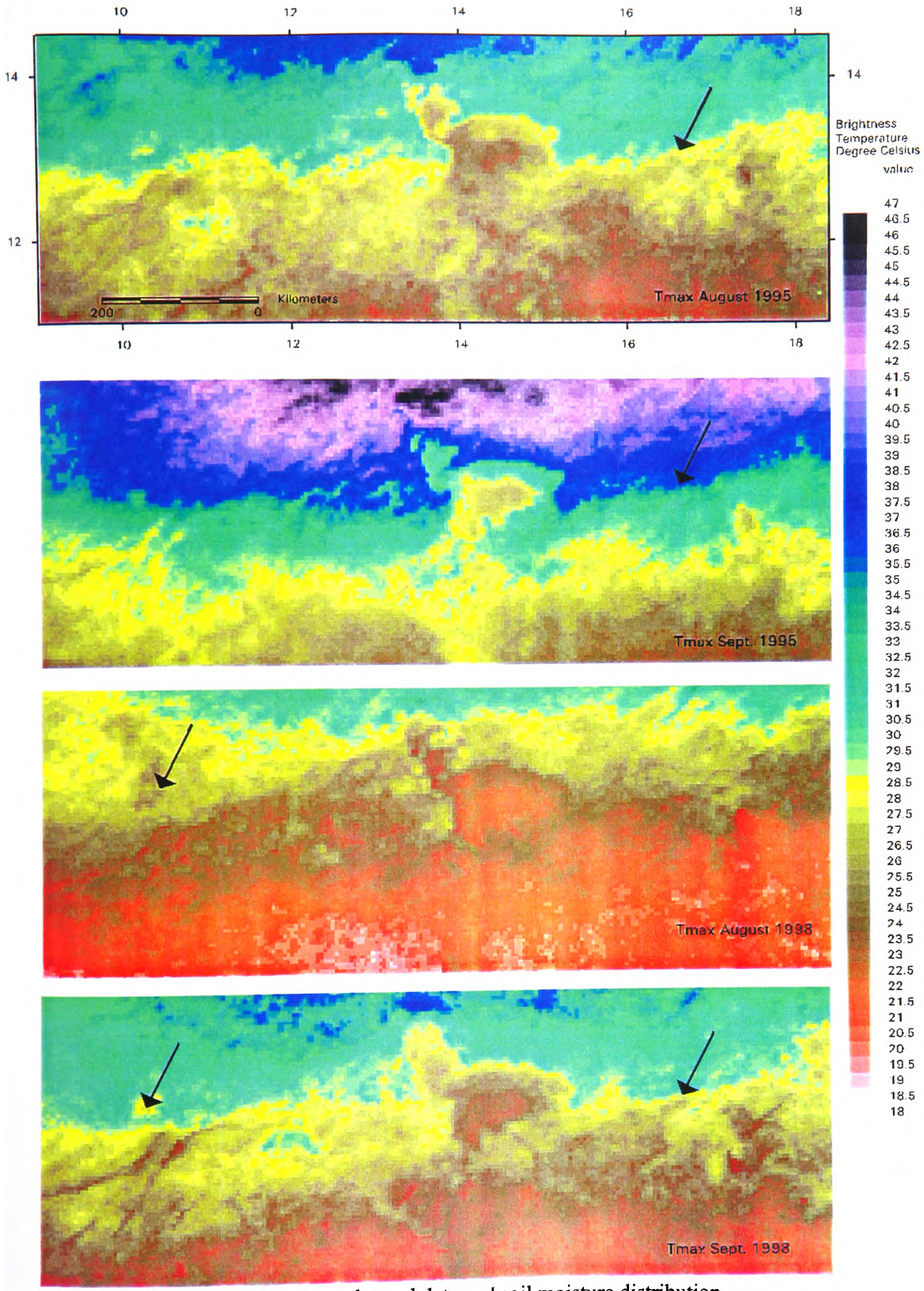


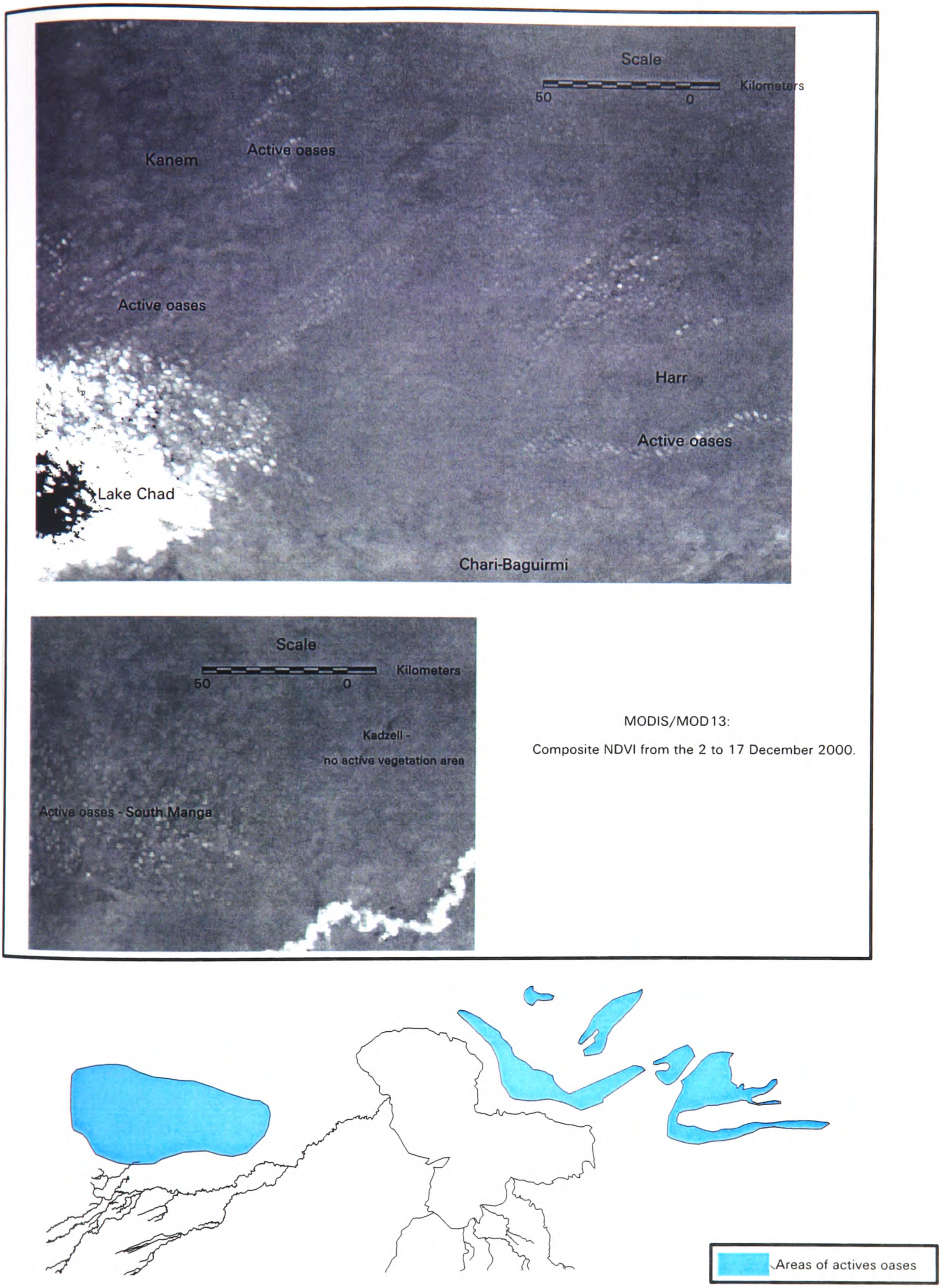
Figure 6-14: Meteosat thermal data and soil moisture distribution at the end of the rainy season in 1995 and 1998

6.3.5 VEGETATION ACTIVITY

In semi-arid areas, the vegetation is very sensitive to water. It blooms when there is water and dies rapidly when the soil dries. Therefore, vegetation activity indices, such as NDVI, can be used to indirectly obtain information on water resources. We chose to use NASA Earth Observatory System's new satellite, MODIS, as it offers a suitable spatio-temporal resolution (see section 4.4.3). The Vegetation Index from MODIS-MOD13A1 data set is a 16-day MVC image. Images are merged to create a single cloud free image with minimal atmospheric and sun-surface-sensor effect, which appear particularly convenient for studying hydrological phenomena even around the rainy season (Huete et al., 1999).

In Figure 6-15, the MODIS images show the activity of the vegetation in the dunefields of the Manga, the Harr and the Kanem. They were taken 3 months after the end of the rainy season. At this time of the year, one does not expect to see very active vegetation especially north to the 13th parallel. Indeed, over most of the region the vegetation is not active. However, locally some very high values of NDVI appear scattered in the dunefields (Figure 6-16 A and B). Such pixels come out in south Manga, and at the periphery of Kanem and Harr. They are absent in Kadzell, but also in the centre of Harr and Kanem. At time of observation, it had not rained for a long time in these regions. Thus, there can be only one source of water able to generate such active vegetation: i.e. the Quaternary aquifer.

In fact, these small areas are active oases. What these images prove is that these active oases correspond to groundwater discharge areas, where groundwater is leaving the aquifer during the dry season via evapotranspiration processes. This result corroborates the schema of a typical oasis proposed by Carter (1994 b, 1996) and Eberschweiler (1991) where during the rainy season groundwater infiltrates into the sand dunes and later feeds the oases. The location of these oases has been mapped for the dry season of 2000-2001 (Figure 6-16 C). In such region, the rainfall recharge from the rainy season is partly consumed by these oases (discharge areas) during the rest of the year. Therefore, the regional recharge of these areas is expected to be relatively small.



MODIS/MOD13:

Composite NDVI from the 2 to 17 December 2000.

Figure 6-16: Mapping active oases (discharge areas) with vegetation activity index from MODIS during the dry season in 2000.

6.4 CONCLUSION AND DISCUSSION.

Are there any surface patterns that characterised and explain the piezometric depressions?

The depth to the water table remains important throughout the major depressions of the basin (no information for the Bornu depression). Thus a hypothetical shallowness of the water table, which would have implied strong evapotranspiration processes, is not observed and cannot be the cause of the depressions.

The analysis of the geological and pedological maps points out a contrast between aeolian sediments in the north and fluvio-lactustrine deposits in the south. The former material is thought to have a higher permeability, and thus a higher infiltration capacity, than the latter. The depressions of the Kadzell, the Chari-Baguirmi, the east Harr, the interfluvial zone of the Chari-Logone and the mouth of the Chari are all in fluvio-lacustrine sediments and are overlaid by impermeable soils. However, in Nigeria the depressions of Borno, to the south of Mounio and one of the interfluvial zone of the Komadugu contradict this schema. In fact, they are reported on the maps as ergs of dunes with permeable soil. The problem might be inherent to the maps which are not accurate enough to reflect the complexity of the terrain and which were not drawn originally for the purposes we want to use them for. Finally, the soil type and its permeability might not be the only important parameter to define the recharge to the aquifer. It might also be a combination of terrain features (such as vegetation and topography).

The satellite MSS and TM mosaics contradict the information of the published maps about the depressions of the interfluvial zone of the Komadugu and to the south of Mounio. These areas seem to be flat. On top of this, the deposits of these regions appear to have spectral signatures that are closer to the ones of the Kadzell and Chari-Baguirmi and very distinct to other dunefields regions. It is, therefore, very important and necessary that this information be checked on the ground.

High-resolution satellite (Landsat TM) images reveal that at the end of the rainy season there are no ponds or very few over all the piezometric depressions. This indicates that in these regions there is no localised (concentrated) recharge but a diffuse infiltration of rainwater, which is less effective (particularly as the surface available for evapotranspiration processes is in this case very important). The explanation of these phenomena lies in the terrain characteristics. Over the depressions, MSS and TM mosaics show that no geomorphological feature perturbs what appears to be a very flat topography.

This information is backed by Meteosat thermal data that shows for the first time that rainwater over the piezometric depressions has difficulties infiltrating into the ground and therefore stagnates at the surface.

Therefore, in the regions of the depressions all the conditions are met for a very small rainfall recharge - so small that evapotranspiration processes might be higher, thus making the piezometric depression regions discharge areas. The map of the vegetation by Gaston (1996) reinforces this interpretation and reveals that deep rooting trees are widespread throughout most of the region.

These are the first observations proving that the piezometric depressions corespond to discharge areas with evapotranspiration processes dominating vertical exchanges.

Active oases are discharge areas

Other discharge areas of the Quaternary aquifer are the active oases located in the topographic depressions of the dunefields (south Manga, south Harr and south Kanem). Satellite images have clearly demonstrated that in these areas groundwater leaves the aquifer during the dry season via evapotranspiration processes.

Are there any surface patterns that characterise and explain the piezometric domes?

The piezometric domes of Kanem and Harr are covered by aeolian sands, which have a high permeability. Thus, rainfall infiltrability is probably high in these regions. This is confirmed with Meteosat thermal data that shows that in the humid years rainwater infiltrates much more in the Harr region than in the Chari-Baguirmi (Figure 6-12; Figure 6-13 and Figure 6-14). The centres of the two regions appear flat and no ponding has been detected. Therefore, unlike other parts of the dunefields, they do not have small discharge areas via active oases (note that the oases are located at the periphery of the domes, see Figure 6-15). Moreover both areas are reported as having no tree layer (Gaston, 1996). Therefore, evapotranspiration is probably limited and cannot reach important depths below the ground. High infiltrability of the soil and low evapotranspiration rates lead us to interpret these regions as preferential recharge zones. This, therefore, can explain why the water table has maintained high levels in both regions.

Dense ponding areas are recharge areas

In the fluvio-lacustrine deposits, regions of dense rainwater ponding and localised rainfall recharge correspond to recharge areas. Such regions are found to the north of the Bahr Erguig and on both banks of the Batha de Lairi. There, the water table is not depressed, but rises clearly from the bordering depression of the Chari-Baguirmi.

Two unreported flood plains were identified in Nigeria and may correspond to recharge areas

A search has revealed two large unreported flood plains that may correspond to recharge areas. Once again, this shows how hydrogeologists working in such regions should not limit their investigations to published maps but should use remote sensing to acquire additional geographical information.

PART III

Groundwater Modelling with GIS and Remote Sensing

Groundwater modelling meets the need for quantification and understanding of flows. It is also one of the most valuable tools for water resources management.

The third part of the thesis aims to develop a regional groundwater model of the whole of the quaternary aquifer. We will explore novel applications of GIS and remote sensing in order to go beyound the current limits of groundwater modelling. In terms of water resources, outcomes are expected to answer important questions such as:

Does the groundwater model indicate the same recharge and discharge areas as were mapped using GIS and remote sensing (part II)?

What is the renewable resource of the Quaternary aquifer?

Since the 1960's, what has been the impact on the aquifer of the severe hydro-climatic changes?

Is the Quaternary aquifer threatened by overexploitation?

Chapter 7

DEVELOPMENT OF A GROUNDWATER MODEL OF THE QUATERNARY AQUIFER

7.1 INTRODUCTION

The objective here is to develop a regional groundwater flow model that will offer the best simulation possible of the whole Quaternary aquifer in both steady and transient states.

A groundwater model has already been developed for the whole aquifer (Eberschweiler, 1992). Yet, there are still many hydrological processes to comprehend and quantify, and many management issues to tackle (see Ch. 1 and Ch. 2). Also, the following reasons indicate that we can offer a superior model to that of Eberschweiler's:

- Concerns have arisen about the calibration methodology of Eberschweiler's model. It employed "an automatic procedure" to work out the values of recharge and discharge. No detail is given in the text about this method so that it is difficult to assess the reliability of its outcomes;
- The interpretation of the calibration outcomes and the use of the model were limited;
- GIS and remote sensing were not used with this model;
- Eberschweiler's model has never been implemented in any institutions of the Lake Chad Basin and is not available to the scientific community.

This chapter is specifically dedicated to the development of the model that we are now proposing. It complements the concise description of the quaternary aquifer presented in chapter 1. First, the nature and the distribution of the Quaternary deposits are described in more detail. Later on, all the available data of pumping tests are used to provide the best description possible of the hydrodynamic properties of the aquifer. A section is then dedicated to a comprehensive assessment of the amount of water exchanged between the Qauternary aquifer and the surrounding aquifers and that abstracted through human activities. Finally, a conceptual model, which accounts for the representation of relevant interactions with external features, is proposed.

In general, the quantity of hydrogeological data available is limited. So throughout the modelling process an emphasis will be placed on the limitations posed by the scarcity of data.

7.2 CHARACTERISTICS OF THE QUATERNARY AQUIFER

7.2.1 NATURE OF THE DEPOSITS

Quaternary sediments cover most of the central part of the basin. They can be divided in two major categories: fluvio-lactustrine deposits which predominate in the south and aeolian (wind-blown) sands which are widespread in the north (see Map 3). Hydrogeological sections published separately for various part of the aquifer have been compiled in a single document as shown in Figure 2-13.

The fluvio-lacustrine sediments are dated from the Early Pleistocene (Schneider and Wolff, 1992). They form the Chari-Baguirmi plain in Chad and Kadzell in Niger. They also dominate in the Nigeria part of the Quaternary aquifer. The nature of this formation can be summarised as a series of sandy and clayey beds whose thickness does not generally exceed 5 metres (Greigert and Pougnet, 1967a; Schneider and Wolff, 1992).

Kanem in Chad, Manga in Niger and north Nigeria are covered by aeolian sand dunes. These deposits are attributed to the Late Pleistocene (Schneider and Wolff, 1992). Aeolian sands are very homogenous and represent a relatively uniform unit.

The differences between the two major types of deposits should certainly affect the hydrogeological properties of the Quaternary aquifer. For example, one can expect a higher hydraulic conductivity for the aeolian sands than for the fluvio-lacustrine sediments.

7.2.2 HYDRODYNAMIC PARAMETERS: TRANSMISSIVITY AND SPECIFIC YIELD

So far, only a few pumping tests have been carried out in parts of the Quaternary aquifer. The conditions of these tests are very variable and it is difficult to establish the reliability of the data.

Having said that, 111 results of pumping tests have been gathered from various hydrological services and are presented in Map 6. The data set shows that values of transmissivity vary by 3 orders of magnitude with a maximum of 7E-02 m^2/s at Mao (Chad) and a minimum of 6.3E-05 m^2/s at Maiduguri (Nigeria). Overall, the average value is of 8E-3 m^2/s and testify to the good aquifer properties of the Quaternary deposits.

However, it must be noted that tests were limited to few parts of the basin: the south of Diffa Department in Niger; Maiduguri in Nigeria and to the north-west of the Chari-Baguirmi Department in Chad. Because of this, we cannot truly analyse the spatial distribution of transmissivity. Therefore, to supplement this information, specific capacities of wells, which were obtained from multiple-step drawdown tests, are also shown on Map 6. In many areas of Chad and Niger, they are the only information available. Although they do not give a value of transmissivity, they are a good indicator - with high values typically reflecting good transmissivities.

7.2.3 ESTIMATION OF HUMAN ABSTRACTIONS

It is essential to have the best estimation possible of the abstractions by human activities in the Quaternary aquifer. One of the major issues for managers is to know what this quantity represents compared with the renewable resource (recharge) of the aquifer. For a sustainable management, it is in fact essential to assess the impact of these abstractions on the water table. There are three major categories of withdrawals from the aquifer by human activities: irrigation, livestock breeding and human consumption. It is beyond the scope of our research program to carry out an extensive assessment of the quantities of water withdrawn from the Quaternary aquifer. Therefore, estimations are essentially based on previous inventories.

Domestic consumption and breeding

Methods of Estimations

Classically, the method for estimating domestic abstractions is based on a primary assessment of the population. A quantification of abstractions is then obtained by multiplying this number with the average water consumption per inhabitant, which depends on whether people live in rural or urban areas. In the same way, having accounted for the number of animals, the withdrawals for breeding are given by applying a rate for each category of animal (Table 7-1).

Animal category	Equivalent in Livestock Unit
Camels and Horses	1 L.U.
Cattle (buffaloes, cows, bulls)	0.8 L.U.
Donkeys	0.5 L.U.
Sheep and goats	0.16 L.U.

Table 7-1: Equivalent in Livestock Unit (L.U.) according to animal species – source FAO.

Another approach consists of first defining the number of well tapping the aquifer. The estimation of abstraction is then obtained by applying an average extraction rate per day per well (Bonnet and

Meurville, 1995). This method, therefore, includes both domestic and breeding abstractions. The difficulty in applying it to the Lake Chad Basin is that traditional wells are a common abstraction means. In fact, this type of hydraulic work is generally temporary and so most inventories do not consider it. In the 1960's, traditional wells were certainly the main abstraction means in the basin (FAO-Schroeter and Gear, 1973). Nowadays, they tend to be replaced by modern abstraction means (cemented well, bore hole), but they may still be a significant means of abstraction.

Review of the estimations

Schroeter-FAO (1973) estimated the overall water consumption in the conventional basin at the end of the 1960's. Although, it is an administrative boundary, the limits of the conventional basin match approximately the area of the Quaternary aquifer. The north east of the aquifer is not included but this area is desert and the withdrawals are rather small. The census data in the four countries of the conventional basin give an overall abstraction of 130E+06 m^3/yr (Table 7-2). However, Schroeter-FAO (1973) considers that this as an overestimation as the following facts have to be taken into account:

- In the Sahara, 1 livestock Unit does not receive 40 litres of water daily but rather 15 litres;
- Depending on the location, a part of these abstractions can come from surface water (especially in Cameroon and to a lesser degree in Nigeria and Chad). The present estimation includes without any differentiation both abstractions from the water table and from surface water.

Therefore, a figure of 70E+06 m^3/yr is "closer to the reality" (FAO-Schroeter and Gear, 1973).

	Country	Number of inhabitants	Rate*	Abstractions (m^3/yr)
Human	Cameroon	1.05E+06	20 l/d/pers.	7.66E+06 m^3/yr
	Niger	0.20E+06		0.15E+06 m^3/yr
	Nigeria	3.05E+06		22.26E+06 m^3/yr
	Chad	1.15E+06		8.40E+06 m^3/yr
Total Requirements of the population: 28.5 E06 m^3/yr				
	Country	Number of Livestock Unit	Rate	Abstractions (m^3/yr)
Animal	Cameroon	1.13E+06 L.U	40 l/d/L.U.	16.5E+06 m^3/yr
	Niger	1.16E+06 L.U		17E+06m^3/yr
	Nigeria	2.10E+06 L.U		31E+06m^3/yr
	Chad	2.25E+06 L.U		33E+06m^3/yr
Total Requirements of the livestock: 98E+06 m^3/yr.				
Overall water consumption: 130E+06 m^3/yr.				

Table 7-2: Overall water consumption in the conventional basin in the 1960's (from Schroeter, 1973)

* in the 1960's, the population was almost entirely rural.

Leduc-PNUD (1991) proposed an estimation of abstractions for the Department of Diffa-Niger in 1990. This area corresponds approximately to the Niger part of the Quaternary aquifer. Using census data, he assessed that domestic and breeding abstractions represent, respectively, about 1.4E+06m^3/yr and 6E+06m^3/yr (Table 7-3).

		Number of unit	Rate	Abstractions (m^3/yr)
Human	Rural population	150 000	15 l/day/pers.	0.8E+06
	Town : Maine-Soroa ; N'Guigmi ; Diffa	30 000		0.6E+06
Animal		590 000 L.U.	40 l/day/L.U.	6E+06 (accounting for the fact that they also use surface water – 30%)

Table 7-3: Estimation of the abstractions in 1990 for Diffa department-Niger (from Leduc, 1991).

The major improvement with Eberschweiler's work (1992; 1993 a) is that it gathers information from technical reports and institutions throughout the whole Quaternary aquifer. These data were brought together according to administrative and geographic areas, which gives a fairly good image of the spatial distribution of abstractions. An analysis of the variations of the abstractions from 1970 to 1990 is also proposed. After estimating the amount of water abstracted from surface water and other aquifers, the author assessed the overall quantity withdrawn from the Quaternary water table for domestic consumption and breeding to be 80.4E+06 m^3/yr in 1970 and 107.7E+06 m^3/yr in 1990.

		Rate	Abstractions (m^3/yr) in 1970	Abstractions (m^3/yr) in 1990
Human	Rural population	36.5 l/day/pers.	63.4E+06	79.7E+06
	Town population	75 l/day/pers.		
Animal		25 l/day/L.U.	17.0E+06	28E+06
Overall water consumption:			80.4E+06	107.7E+06

Table 7-4: Estimation of abstractions (breeding and domestic consumption) in the Quaternary aquifer for 1970 and 1990 (from Eberschweiler, 1992).

Finally, it is possible to assess abstractions in Chad using the database on hydraulic works maintained by the DHA. At the end of the 1990's, the number of works tapping the Quaternary aquifer (depth<80m) in Chad was about 2250. Applying an average abstraction of 5 m^3/day per work, the abstraction capacity is approximately 4E+06 m^3/yr. This does not include N'Djamena where abstractions by the STEE are reported as: 8.2E+06 m^3/yr. The total abstractions in Chad can hence be estimated as 12.2E+06 m^3/yr (Bonnet, 1995).

Discussion

The estimation of the abstractions with the number of works tapping the aquifer does not seem to be a reliable method as it is difficult to assess the number of traditional wells. A comparison with other methods in Chad (Schroeter – Eberschweiler) shows that it underestimates withdrawals. This raises concerns regarding the previous use of this estimation by Bonnet (1995) in his model of the Quaternary aquifer for the Chari-Bagurimi region. Indeed, the main goal of the model was to assess the impact of human abstractions on the water table.

Leduc's estimations only concern the Niger part of the Quaternary aquifer. Schroeter-FAO (1973) estimated the abstractions throughout most of the aquifer at the end of the 1960's. However, no geographical distribution of these abstractions is given. Therefore, Eberschweiler's report (1992) is the most comprehensive assessment and will be used as a reference for the modelling of the Quaternary aquifer undertaken in the next chapters. It also indicates the geographical distribution of abstractions, and this is necessary for the groundwater model. The two inventories of 1970 and 1990 should allow us to assess the impact on the water table of the increase in abstractions.

However, in Eberschweiler (1992) the average consumption rates attributed to human consumption and animal breeding can be contested (Table 7-5). Leduc and Schroeter propose 15 and 20 l/d/pers in rural areas while Eberschweiler uses 36 l/d/pers. With regard to livestock, Eberschweiler assigns 25 l/d for 1 L.U., whilst Leduc and Schroeter give 40 l/d/L.U.

Reference	Human		Animal
	Rural	Town	
Schroeter 1973	20 l/day/pers.		40 l/d/L.U.
Leduc (1991)	15 l/d/pers.	55 l/d/pers. "30000 inhabitants of Maine-Soroa, Diffa and N'Guigmi consume 600000 m^3/yr"	40 l/d/L.U.
Eberschweiler (1993) - PNUD (1980)	36.5 l/d/pers.	75 l/d/pers.	25 l/d/L.U.

Table 7-5: Average abstraction rates for human consumption and animal breeding.

Therefore, to obtain the best estimation we decided to apply a rate of 15 l/day/pers. in rural areas and 40 l/d/L.U. to Eberschweiler's inventory. This leads to an overall estimation of the amount of water abstracted from the Quaternary water table of 52.7E+06 m^3/yr in 1970 (25.5E+06 m^3/yr for domestic abstractions and 27.2 E+06 m^3/yr for breeding), and 86.8E+06 m^3/yr for 1990 (41.5E+06 m^3/yr for domestic abstractions and 45.3E+06 m^3/yr for breeding).

Irrigation

The best assessment of the abstractions for irrigation in the whole Quaternary aquifer is also proposed by Eberschweiler (1992, 1993 a). Once again, it has been obtained from technical reports and institutions of the central part of the basin. The appraisal gives a spatial distribution of irrigation abstractions throughout the whole aquifer. It also indicates the variation of the withdrawals from 1970 to 1990. The largest irrigation projects are located along the Chari, the Logone and the Komadugu, but they mainly use surface water. It is only in the north of Chad, Niger and the east of Nigeria that groundwater is tapped for irrigation. The figures show an overall consumption of 30E+06 m^3/yr in 1970 and 39E+06 m^3/yr in 1990 (Eberschweiler, 1993 a).

7.2.4 EXCHANGES WITH OTHER AQUIFERS

The possibility of vertical exchanges from the Pliocene aquifer to the Quaternary water table has to be examined. The piezometric levels of the Pliocene aquifer are often higher than the Quaternary water table especially in the centre of the basin (around Lake Chad), where the Pliocene aquifer is artesian. However, a thick layer of Pliocene clay forms an aquifuge that isolates the two aquifers throughout most of the domain. Thus, it is generally considered that, apart perhaps from the lateral borders, there is no vertical exchange between the Pliocene and the Quaternary aquifers (Eberschweiler, 1993 b; FAO-Schroeter and Gear, 1973; Leduc-PNUD, 1991). This hypothesis is confirmed by the presence of piezometric depressions affecting the Quaternary aquifer in the centre of the basin. There would not be any depressions if the Quaternary aquifer were to receive any significant amount of water from the underlying Pliocene aquifer.

On its lateral borders, the Quaternary water table is surrounded by other aquifers. These systems are in hydraulic continuity and exchanges do take place. On the north-east limit in Chad, an outflow leaves the Quaternary aquifer in the direction of the Lowlands. Everywherelse, it is the surrounding aquifers that feed the Quaternary water table. Flows exchanged can be estimated with Darcy's law. To do so, hydraulic gradients are derived from the piezometric map and transmissivities are assessed from pumping tests (where available) and the nature of the deposits. Flows are considered null where the isopiezometric contours are perpendicular to the lateral border of the aquifer.

Results are presented in Figure 7-1. Between Termit and Agadem Mounts, about 2 million cubic metres of water arrive each year from the Oussini water table. Contributions from the Koutous are limited by low transmissivities to about 3E+05 m^3/yr. At the south-west border of the aquifer in Nigeria, inflows are also limited to 1E+06 m^3/yr. In the south of Chad, high transmissivities allow 11E+06 m^3/yr to flow in from the Continental Terminal aquifer. In east central Chad inflows are limited to roughly 1E+06 m^3/yr by a small hydraulic gradient. The sum of inflows from the surroundings aquifers is therefore about 15.5E+06 m^3/yr.

Flow towards the Lowlands is often considered as a major outflow of the aquifer (e.g., Schneider and Wolff, 1992). Nevertheless, if we admit a great uncertainty with regard to the possible range of transmissivities, i.e., between 1E-03 m^2/s and 2E-02 m^2/s, the estimate of the outflow varies between 10E+06 m^3/yr and 200E+06 m^3/yr. To narrow down the actual value, the outflow toward the Lowlands will be tested within this interval during the calibration.

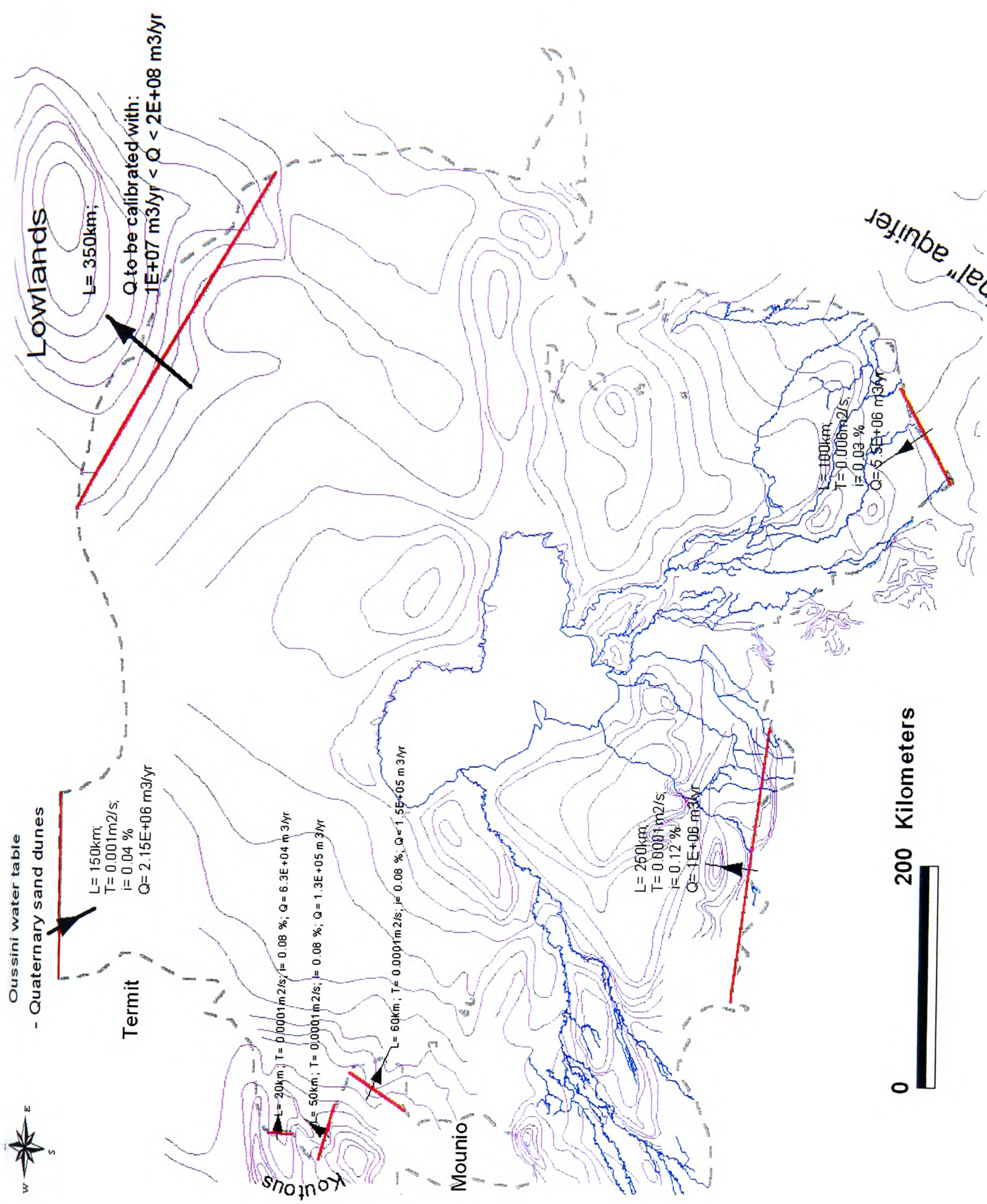


Figure 7-1: Exchanges between the Quaternary and the surroundings aquifers.

7.3 CONCEPTUAL MODEL

7.3.1 NUMERICAL FLOW MODEL

The relevant way to model the Quaternary aquifer is to use a finite-difference groundwater flow model, which simulates groundwater flow for porous aquifer systems in transient or steady-state (Bear and Verruijt, 1994; Anderson and Woessner, 1992; De Marsily, 1986). The calculations are based on fundamental principles of hydrogeodynamics: Darcy's law, diffusion equation. The partial-differential equation (diffusion equation) describing movement of groundwater is solved using the finite-differences method. A spatial discretisation of the aquifer in a mesh of rectangular blocks is required. Likewise, in transient it is necessary to divide the overall simulation period in time steps. The head calculated for each cell accounts for hydrodynamic properties (transmissivity and specific yield), recharge and discharge (rainfall recharge, evapotranspiration, human abstractions), and head or flux boundary conditions (rivers, lakes, no-flow, exchanges with bordering aquifers, etc.)

Throughout the whole of the Quaternary aquifer, one observes small hydraulic gradients (see, Figure 2-14). We can assume that groundwater flow is essentially horizontal and, therefore, that Dupuit assumption can be applied: (1) flow lines are horizontal and equipotential lines are vertical (no change of head with depth), and (2) the horizontal gradient is equal to the slope of the free surface and is invariant with depth. Dupuit assumption is often used in regional studies and modelling of unconfined aquifer because of its simplicity and relatively small error (Bear and Verruijt, 1994; Anderson and Woessner, 1992). It treats groundwater flow as a two-dimentional areal problem instead of a three-dimentional one. Therefore, the model of the Quaternary aquifer is a two-dimentional areal model with one single layer and depth-averaged conditions. The general form of the governing equation of groundwater flow for an unconfined aquifer with the Dupuit assumption is given in equation 7-1.

$$\frac{\partial}{\partial x}\left(Tx \times \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Ty \times \frac{\partial h}{\partial y}\right) = Sy \times \frac{\partial h}{\partial t} - R$$

Where: Sy is the specific yield;
Tx and Ty are components of Transmissivity (hydraulic conductivity times the aquifer's saturated thickness) in the x and y directions;
R is the source/sink term which is positive to represent a recharge;
t is the time.

Equation 7-1 General form of the governing equation for an unconfined aquifer with Dupuit assumption.

The groundwater model, MODFLOW, which was developed by the United States Geological Survey, has been chosen for our study as it is well documented, reliable and widely used. The verion used is MODFLOW96, an update of MODFLOW88 (McDonald and Harbaugh, 1988; USGS., 1996).

It is integrated into GMS® software (Groundwater Modelling System), a product of the Environmental Modelling Research Laboratory (EMRL) of Brigham Young University. GMS acts as a pre and post-processor for MODFLOW. One of the main reasons for choosing GMS is that it offers advantageous GIS functions and interoperability with Arcview® and Arc/Info® (EMRL, 1999; EMRL, 2000).

7.3.2 THE GRID

The aquifer covers a large region, so one of the particularities of our model is that it is a small-scale one. The model has a single layer that represents the whole of the Quaternary aquifer. In principle, the top of the layer should correspond to the topography of the ground and the bottom to the surface between the Quaternary aquifer and the aquitard (Pliocene clay layer). However, what matters in the calculations are the values of the transmissivities (transmissivity= hydraulic conductivity×aquifer's saturated thickness) (McDonald and Harbaugh, 1988; U.S.G.S., 1996). As a consequence, there are 'mathematical equivalents' to the 'real' transmissivity, and consequently to the piezometric solution, if the change in thickness is accompanied by a proportional change of the hydraulic conductivity. Moreover in the model, unlike for a confined aquifer, the elevation of the top of a phreatic water table, such as the Quaternary aquifer, has no influence on groundwater flow.

In our case, given the size of the grid cells on the one hand, and the lack of knowledge on the topography on the other (see Ch. 4), it is wiser to increase arbitrarily the thickness of the aquifer. To avoid the appearance of springs (outflows), which could affect the budget of the model by changing the water budget, the top of the layer is fixed at 500 m. Likewise, although the elevation of the bottom layer is documented in Eberschweiler (1993), in order to avoid drying problems in the simulation of the piezometric depressions it has been decided to lower the bottom arbitrarily by 20 metres throughout the whole aquifer (see Annexe 7-1).

Any values of the permeabilities presented later in the thesis are corrected to account for these modifications, and represent 'real' permeabilities.

The grid of the model is presented in the Figure 7-3. The grid is very coarse in the north, with cells of 20 km by 20 km and 20 km by 10 km, because there are few inhabitants (desert area) and hydrological phenomena are relatively large and simple (regional gradient towards the lowlands and no surface water). However, the grid must be refined in the south where human activity is significant, and groundwater features are more complex, namely: interaction with surface water (Lake Chad and rivers) and piezometric depressions. The grid is thus reduced to cells of 10 km by 10 km in the south. The representation of such a large area using a groundwater flow model based on finite difference can be questionned. However, it was possible in this case to develop such a model because of two particular characteristics of the aquifer:

- The hydraulic gradients are very small (piezometry relatively flat), so that even the cells of a coarse grid are in hydraulic continuity with their neighbours;

- The aquifer is affected by large-scale phenomena (piezometric depressions and domes, Lake Chad, Bahr el Ghazal valley) as indicated by the map of the piezometry (see Figure 2-14). Only such a large model can represent the interaction between these features and the aquifer as a whole.

Smaller cells would be necessary to represent small areas or to study in detail seasonal fluctuations. For this project, it is not expected to work with smaller cells, because we only want to model the aquifer at a regional scale and a significant increase of the number of cells would make calculations and data handling heavier. Ideally the impact of the cells size on the model outputs should be tested in the sensitivity tests.

7.3.3 BOUNDARIES AND INTERACTIONS WITH SURROUNDING ENVIRONMENTS

Exchanges with other aquifers

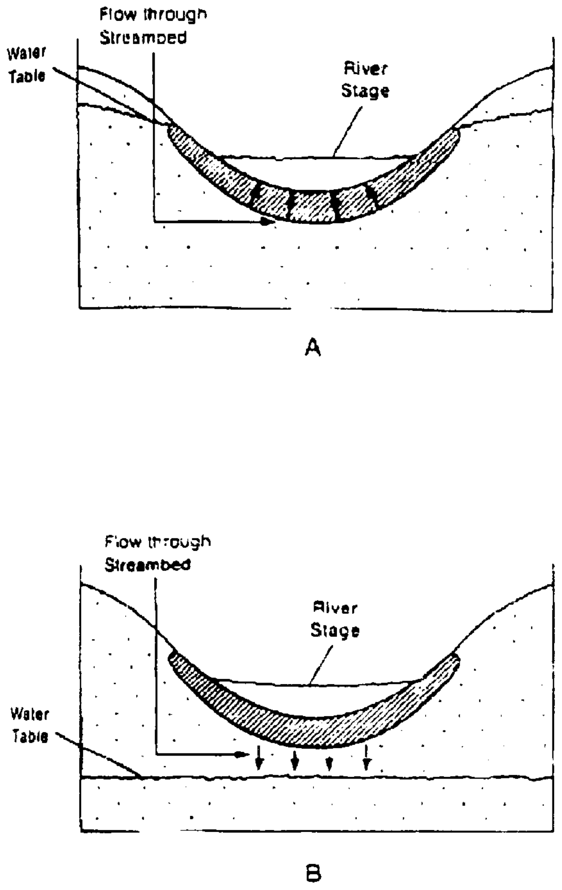
The flows exchanged with other aquifers on the lateral borders of the Quaternary aquifer are assigned to the model using the *Well* package of MODFLOW. A flow rate, whose overall figure corresponds to the amount of water exchanged, is imposed on a series of wells in the edging cells. The pumping rate is positive for the outflows and negative for the inflows. The flows thereby exchanged are fixed and equal to our estimations (see section 7.2.4), except for the outflows towards the Lowlands which are to be calibrated.

Rivers

Major rivers of the Lake Chad Basin are represented in the model. The regions bordering the rivers have a very flat topography and they are covered by impermeable soil. They are subject to seasonal inundation due to the combination of heavy rainfall and overbank flooding.

The relation between these rivers and the Quaternary aquifer has been reviewed and is detailed in chapter 2. In theory, surface water may recharge the Quaternary aquifer in two ways: by channel seepage or by flood plains infiltration. However, it is commonly agreed that due to the very low hydraulic conductivity of the soil there is no recharge to the water table from the flood plains (see Ch 1 and Ch. 3). Therefore, surface water is reported to recharge the aquifer only via channel seepage.

Interactions between river channels and the aquifer is represented in the groundwater model using MODFLOW *River* package, which is designed mainly for this task. The channels are considered to be separated from the aquifer by a low hydraulic conductivity layer. The river-aquifer connection is ideally represented as a simple conductance through which one-dimensional flow occurs. However, as observed in reality, in many cases no discrete low-hydraulic conductivity streambed is present. The technique of simulation can still be applied but the representation through a single conductance is more approximate. Therefore, adjustments during the calibration are almost always required (McDonald and Harbaugh, 1988).



—Cross sections showing the relation between head at the bottom of the streambed layer and head in the cell Head in the cell is equal to the water-table elevation.

Case A: Level of the water table is above the bottom of the streambed layer. Thereby the flow through that layer is proportional to the head difference between the stream and the aquifer.

$Qriv = Criv*(Hriv-Hi,j,k)$ .... (A)

Case B: Level of the water table has fallen below the bottom of the stream-layer, leaving an unsaturated interval beneath that layer. If it is assumed that the streambed layer itself remains saturated, the head at its base will simply be the elevation at that point. The flow through the streambed will then be constant and independent of the head of the water table. It is given by:

$Qriv = Criv*(Hriv-Rbot)$ .... (B)

With Qriv being the flow between the river and the aquifer; Criv the hydraulic conductance of the stream-aquifer interconnection; Hriv the head in the river, and Hi,j,k the head of the aquifer at the node in the cell underlying the river reach.

Figure 7-2: Representation of river and aquifer interaction in Modflow River Package (from McDonald, 1988).

The rivers can either contribute to the aquifer or drain water from it. The interaction between the river channel and the aquifer is governed by a relationship similar to that of equations A and B (see Figure 7-2).

Such a representation of river-aquifer interaction is satisfactory in the case of the Quaternary aquifer, whether or not a discrete streambed is present. It gives the possibility to regulate the flow exchanged by calibrating the conductance of the riverbed. In the central part of the basin, locations where the aquifer and the river are disconnected (case B) might exist. Drying processes also occur in the basin (Komadugu Yobe). Though they are not rigorously formulated here, they can be represented by assigning a river stage equal to the river bottom.

The data required are time series of the river heads. These are measured at the staff gauge stations of the rivers. Between stations, the levels are assumed to vary linearly. Long-term time series of river head fluctuations are available for the Chari and the Logone rivers. Daily measurements and mean annual values were obtained from the DREM-N'Djamena (Chad) and the DHA-Diffa (Niger). The riverheads of the Chari and Logone, implemented in the model for the simulation in steady-state in the late 1960's, correspond to the mean annual value between 1960 and 1970. The value of the river bottom for these rivers is assumed to be the zero of the staff-gauge. However, there is no information on the levels of the Komadugu Yobe in Nigeria. The solution adopted there is to represent arbitrarily the river head of the Komadugu Yobe as 5m above the water table and the river bottom as 1 m above the water table, which is a typical configuration for the river.

As far as we know there has never been any field measurement of river conductance. Even if few measurements were available, what would be their significance? Therefore, conductance values are first chosen more or less arbitrarily and adjusted during the calibration (McDonald and Harbaugh, 1988).

Lake Chad

Lake Chad is also represented with the MODFLOW *River* package. The lake-aquifer interconnection is thus represented as a simple conductance through which one-dimensional flow occurs (Figure 7-2). There is a linear relationship between the flow into a cell and the head in the cell. Depending on the head gradient between the lake and the water table, flows can be in both directions: either from the lake to the water table or the reverse. As Lake Chad has a very large extent (end of 1960's) it is, in principle, possible to have regions of the lake with different flow directions.

As with the rivers, a dry lake is represented by allocating a stage which is equal to the lake's bottom elevation (see Ch. 9).

Discharge processes

Discharge processes might affect a large part of the aquifer (see Ch. 3 and Ch. 6). They are applied to the aquifer model using Modflow *Recharge* Package, which accepts negative values.

The depth to the water table generally exceed 20 m in the depressions (see section 6.2.4). For such depths the relationship established by Coudrain-Ribestein (1998) can be used to estimate the evaporation affecting the water table. However at present, there are no estimations available of the quantities that could be taken off from the water table by transpiration. Different values within a restricted range of error have to be tested during the calibration (see section 3.6)

7.4 CONCLUSION

In the case of the Quaternary aquifer of the Lake Chad Basin – a vast and continuous water table in a porous medium – a groundwater model represents the best tool to analyse the hydrogeological processes involved, and to quantify the flows to or from the aquifer in order to better manage the water resources.

At the lateral limits of the model presented here, the boundaries are represented either as no-flow conditions or as exchanges with surrounding aquifers (represented by a series of wells). Across the aquifer domain, one can find other internal boundaries such as Lake Chad, the Komadugu Yobe, the Chari and the Logone. They are all simulated using the Modflow *river* package.

This model is a regional one and represents the whole Quaternary aquifer. Given the vast extent of domain modelled, the size of the grid is coarse. Local interpretations are not permitted with such a model and the simulation of seasonal fluctuations is also compromised.

In the model, inflows are rainfall recharge, surface water recharge and exchanges with other aquifers, whereas evapotranspiration, human abstractions, flow to the Lowlands and possibly exchanges with surface water bodies are outflows.

The lack of knowledge on the aquifer and on the surrounding environment is a limitation to this model. As examples, human abstractions are difficult to estimate and there are limited data to indicate hydrodynamic properties of the aquifer. Even the piezometry is not accurately known. Thus, results of the model must be taken with caution and values mentioned later in the thesis represent more an order of magnitude than an `ultimate´ quantification. It is also out of the question, in such conditions, to pretend to be developing the definitive groundwater model of the Quaternary aquifer. We propose, on the contrary, an open and progressive model that we see as a first step and that we hope will evolve as our knowledge of the area improves and more data are gathered. Nevertheless, this model constitutes a great improvement with regard to the hydrogeological modelling tools developed so far in the basin (see section 7.1)

The use of GIS has been constantly present so far - for example, to give the best indication of hydrodynamic properties, to work out the bottom elevation or simply to efficiently handle and implement the data in the model. Yet, there has not been any truly original use of GIS or remote sensing up to now for groundwater modelling. Novel applications of GIS and remote sensing will appear in the following chapters: firstly, when comparing the results of the steady-state calibration with the outcomes of applying GIS and remote sensing to map recharge and discharge areas (see part II); and secondly, when simulating hydroclimatic changes and, in particular, the simulation of the impact of Lake Chad's shrinkage on the Quaternary aquifer.

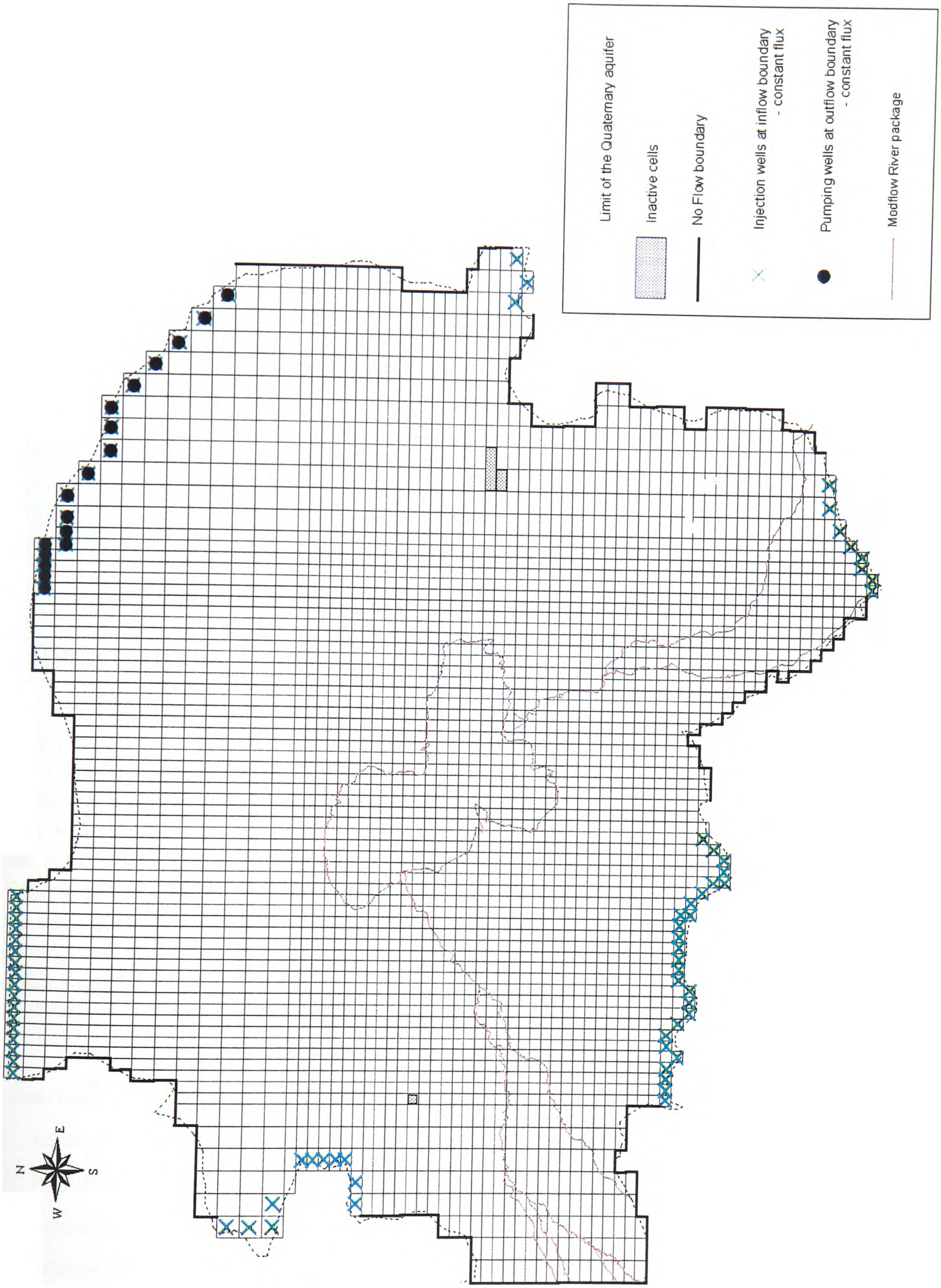


Figure 7-3: Grid and boundary conditions for the regional groundwater model of the Quaternary aquifer.

Chapter 8

STEADY-STATE MODEL

8.1 INTRODUCTION

A steady-state model is developed and calibrated with observed piezometric levels in the late 1960's. A more recent representation of the quaternary aquifer would have been appealing. However, the degradation of hydro-climatic conditions since the 1970's with the shrinkage of Lake Chad, a decrease of river discharges and a reduction in rainfall imply more transient conditions in the aquifer. For example, Leduc (2000) reports that between the 1970's and the 1990's the water table has fallen by several metres (up to 7m) around what used to be the northern shoreline of Lake Chad. On the other hand, the situation in the late 1960's appears much closer to a steady-state. There is also a large amount of data that has been collected during this period which allow for a better simulation of the aquifer (FAO-Schroeter and Gear, 1973; Schneider, 1966; Schneider and Wolff, 1992; UNESCO-PNUD-CBLT, 1972).

Outcomes from the steady-state calibration are expected to:

1. Enhance current understanding of the mechanisms of the aquifer;
2. Provide estimates of major recharge and discharge areas;
3. Assess the value of the outflow towards the Lowlands;
4. Indicate the value and distribution of transmissivities values;
5. Propose a first assessment of the water resources available.

The method used for the calibration consisted of testing different values, including the usual variables of permeabilities and conductances of the rivers and of Lake Chad. In addition, the values and spatial distribution of rainfall recharge and discharge areas, and the outflow towards the Lowlands were also calibrated.

In the first instance, the calibration is `typical' of groundwater modelling and does not involve remote sensing or GIS. Later on, results from this independent calibration will be compared with the results of GIS and remote sensing applications to map groundwater recharge and discharge areas (see part II). The proposal is to then investigate how a novel application of GIS and remote sensing can provide further details and enhance the `classical' calibration of groundwater flow models in semi-arid environments.

8.2 'CLASSICAL' CALIBRATION

8.2.1 METHODOLOGY

The calibration process involves searching for hydrogeological terms (input parameters of the model) by testing different values of these parameters within an interval until a set of data is found for which the model matches the observed piezometry and respects the water balance (steady-state). The calibration here is not an automated process; the user proceeds by trial and error, and as such the values of the model are changed incrementally.

In general, for the modelling of an aquifer in steady-state only the transmissivities and boundary conditions are calibrated. However, for the present aquifer, a review of recharge and discharge processes shows the need for a better assessment of these terms. Therefore, the calibration of the model consists of testing together values of transmissivities, internal boundary conditions (conductance of Lake Chad and of rivers), recharge, discharge and outflow to the Lowlands. Table 8-1 recaps the interval within which these terms were tested.

A diagram of the methodology adopted for the calibration is presented in the Figure 8-1. A first scenario is chosen that fixes the characteristics of recharge, discharge and outflow to the Lowlands. An arbitrary spatial distribution of rainfall recharge and of discharge is used, while maximum values are imposed for the outflow to the Lowlands, the recharge and discharge rates. Given these fixed characteristics for the recharge, discharge and outflow to the Lowlands, a search for transmissivities and conductances (rivers and lake) that would allow matching of the observed piezometry and give a water balance close to zero (steady-steate) is carried out. If it appears impossible to calibrate the transmissivities and the conductances then another scenario is taken for the outflow to the Lowlands, the recharge and the discharge. Changes in the distribution of recharge and discharge conditions are made according to the locations where the piezometry is not matched. With this new scenario, transmissivities and conductances (rivers and lake) are tested again to search for a good simulation of the aquifer. The whole process is repeated through the range of possible values for all the parameters in order to screen the most feasible combinations. All changes are made incrementally to avoid missing a solution.

Calibrating the transmissivities, boundary conditions, recharge and discharge areas for such a large model at the same time represents a long process. The range of possible sets of flows is, however, restricted by particularities of the water balance that must be respected. Firstly, as the model is in steady-state, the sum of inflows must be equal to the sum of outflows. Secondly, the only outflows of the model are: human withdrawals, evapotranspiration and the flows to the Lowlands. Human withdrawals are known approximately, the water table depth limits evapotranspiration processes, the flow to the Lowlands is limited by realistic transmissivities and, therefore, both outflows and inflows are restricted to a small range.

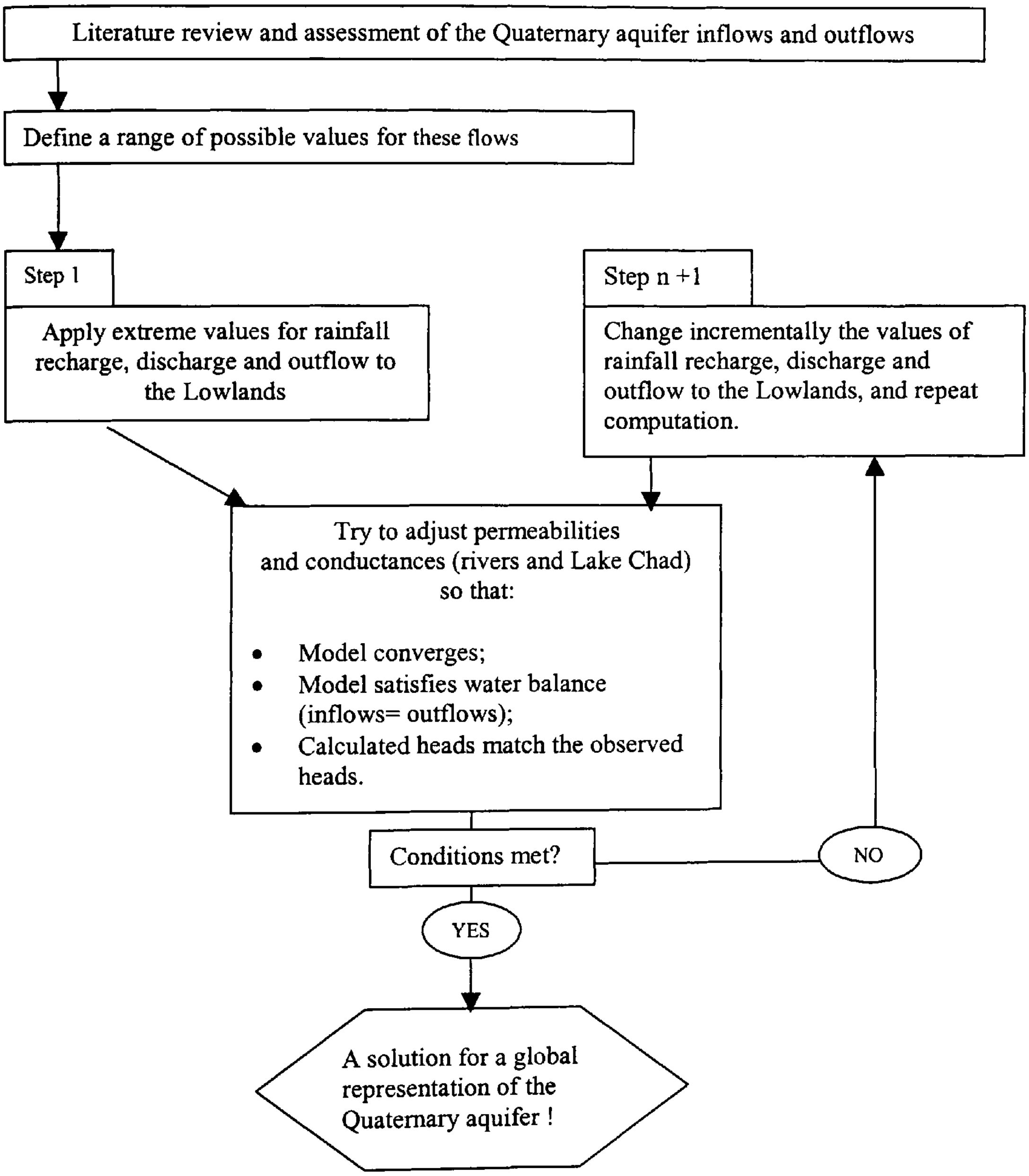


Figure 8-1: Diagram of the 'classical' calibration methodology used in our modelling process.

Adjustment of outflows and inflows

Human abstractions as well as the flows exchanged with the surrounding aquifers are considered to be known. They will not be adjusted but directly implemented into the model. All the other flows need to be tested within a realistic interval.

The outflow towards the Lowlands is to be calibrated within an interval restricted by realistic transmissivities, i.e: between 10E+06 m^3/yr and 200E+06 m^3/yr (see section 7.2.4). There are few outflows possible in the model and the Lowlands flow is the major one. The calibration of the model starts with the maximum outflow possible to the Lowlands.

The minimum discharge flow in the piezometric depression is zero (no discharge). The maximum proposed in the literature is of 3 mm/yr (Bonnet and Meurville, 1995). Higher values seem unrealistic given the high depth to the water table (see section 3.6)

Rainfall recharge will be adjusted between 0 and 60 mm/yr, which corresponds to the range of values found during the literature review (see Ch. 3). The first scenario tested will try to find a solution with a high recharge (60 mm/yr) and then smaller values.

Flow contribution from Lake Chad to the aquifer is not directly imposed to the model but is regulated by the conductance of the *River* package which will be part of the calibration process.

Inflows and outflows of the Quaternary aquifer			
Inflows	**Calibration Requirements**	**Outflows**	**Calibration Requirements**
Rainfall recharge	To be calibrated Range from 0 mm/yr to 60 mm/yr (from literature review-see Ch. 3)	Human withdrawals	Known from estimates
Rivers	To be calibrated as conductance	Evapotranspiration	Limited by water table depth range 0 mm/yr < discharge< 3 mm/yr. (from literature review - see Ch. 3)
Lake Chad	To be calibrated as conductance	Flows towards the Lowlands	To be calibrated – within an interval (between 200E+06 m^3/yr and 10E+06 m^3/yr) restricted by a realistic range of transmissivities.
Surroundings aquifers	Known from estimates		

Table 8-1: Inflows and outflows of the groundwater model requiring calibration.

Adjustment of transmissivities

The adjustment of transmissivities is made according to the results of pumping test available and the nature of the deposits or the aquifer formation. In steady-state, once the boundary conditions are defined and fixed, water table levels then depend on the distribution of the transmissivities.

8.2.2 FIRST RESULTS

Major mechanisms of the Quaternary aquifer

Among all combinations of sources and sinks possible, the `classical' calibration process outlined above has shown that, the number of scenarios which allow for the representation the Quaternary aquifer in steady-state (Figure 8-2) is limited. For each of these solutions, the model has a water balance error of less than 0.1%, and the simulated piezometry matches quite well the major features observed. We obtain at the end of the calibration a limited range of values for the transmissivities, recharge, discharge and outflows towards the Lowlands. This is an important result that allows us to begin to draw certain conclusions on the mechanisms of the aquifer and have first estimates.

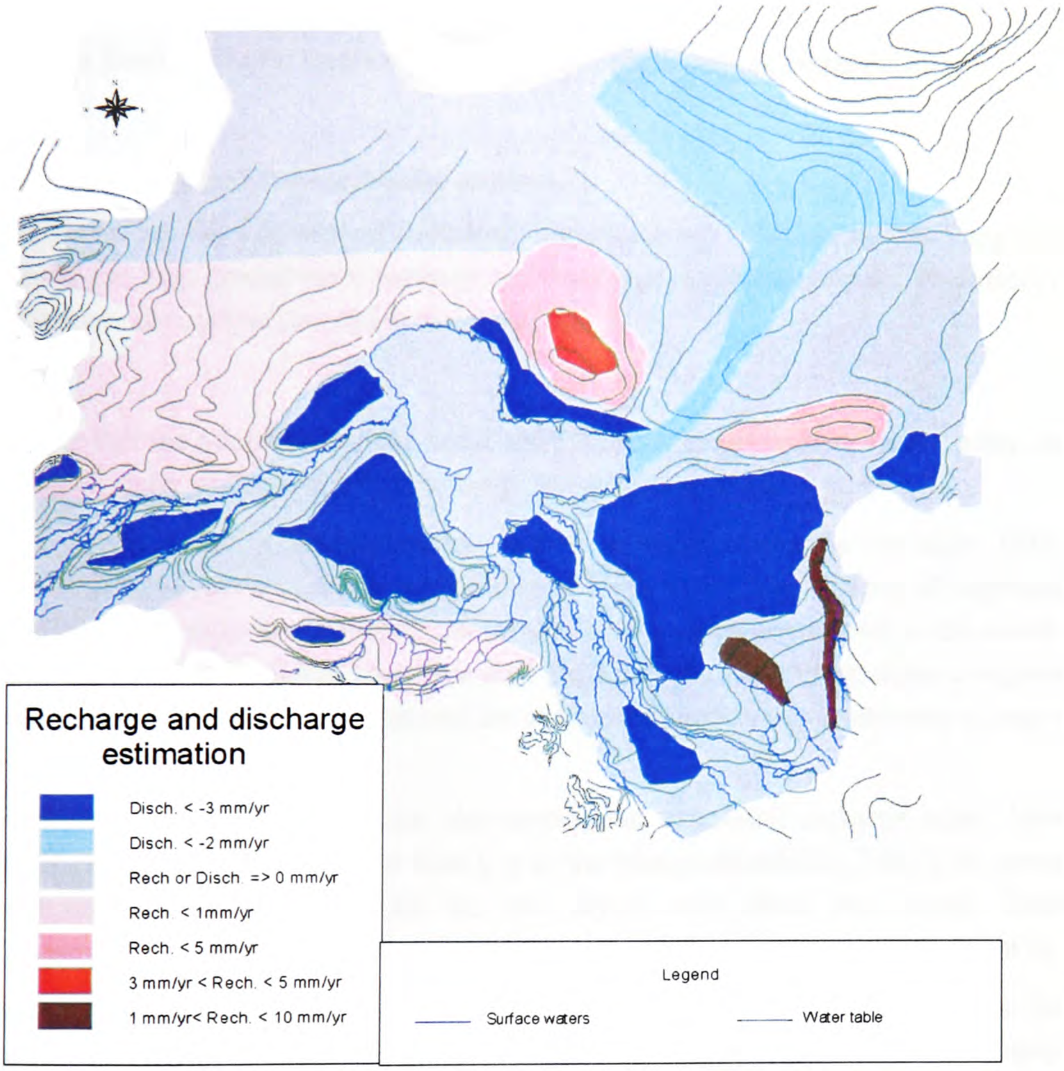


Figure 8-2: Distribution and estimation of recharge and discharge areas from the `classical' calibration.

First, the model clearly reveals that in order to reproduce the piezometric depressions, it is necessary to assign to the affected zones a vertical outflow, in addition to low transmissivities. The depression is created by the vertical outflow which cannot be compensated by lateral flows given the mediocre transmissivities. This assumes that the piezometric depressions correspond to areas of excess evapotranspiration (discharge areas).

The Manga corresponds to a rainfall recharge area. However, the model only accepts a small recharge: i.e. it is no possible to reproduce the piezometry if the value of the rainfall recharge is too high. A good simulation is obtained for a rainfall recharge below 1 mm/yr.

Piezometric domes of Kanem and Harr can only be represented if they correspond to preferential rainfall recharge zones. Like in Manga, they are a zone of rainfall recharge, but the values that have to be imposed are higher. The other alternative, which is to decrease the value of the transmissivities, is not satisfactory because the resulting permeabilities would become so small that they are outside the range corresponding to the geological materials concerned.

The Massenya flood plain and Batha de Lairi must be represented as recharge areas.

Comparison with GIS and remote sensing outcomes

So far, the model has been developed completely independently of outcomes from applying GIS and remote sensing to map groundwater recharge and discharge areas (see part II). Therefore, it provides objective matters for comparison and cross-checking.

It seems clear that the model on the one hand, and GIS and remote sensing on the other, converge to the same conclusions on the location of recharge and discharge areas.

In the Manga, the model indicates that the rainfall recharge cannot be too high. This is clearly confirmed by satellite data that detect a multitude of oases with a high activity of vegetation all year long and thus a high evapotranspiration rate. These active oases correspond to the small discharge areas of a wider rainfall recharge zone (see part II). Since the model calculates a regional and net recharge (balance between the recharge and the evapotranspiration processes over a large area), it is normal that it indicates a small value.

The dunefields of the Harr and Kanem also correspond to rainfall recharge areas. However, the model indicates that it might be higher than it is in the Manga dunefields. This is in agreement with our initial observation that there are no tree layers over these two zones. Therefore the evapotranspiration processes are smaller than elsewhere and thus the net recharge might be higher.

It is not surprising that the model requires a recharge to be imposed to the right of the Bahr Erguig bank and along Batha de Lairi. In fact, many ponds and more generally a topography favoring ponding have been mapped in these regions, all of which indicate a concentrated (or indirect) recharge zone.

For the piezometric depression, the analysis with GIS and remote sensing data indicated that these zones meet all the conditions limiting rainfall recharge, namely: low soil infiltrability, very flat topography and absence of ponding (concentrated recharge). The model clearly identifies these zones as discharge areas, in other words, where the rainfall infiltration is highly limited.

8.3 REFINING THE CALIBRATION WITH REMOTE SENSING AND GIS

The results obtained from the calibration so far are already satisfactory in themselves. Yet at this stage, there is a weakness in this groundwater model. It gives a rough estimation of where discharge and recharge areas are needed and of their values, but the model is unable to show precisely the location of the boundaries of these recharge and discharge areas. That is, in the model the limits of recharge and discharge zones are not well defined.

Figure 8-3, for instance, shows a series of scenarios for which the position of the limits of the recharge and discharge zones have been changed. Unfortunately, the model allows a satisfactory representation of the observed piezometry for any of them.

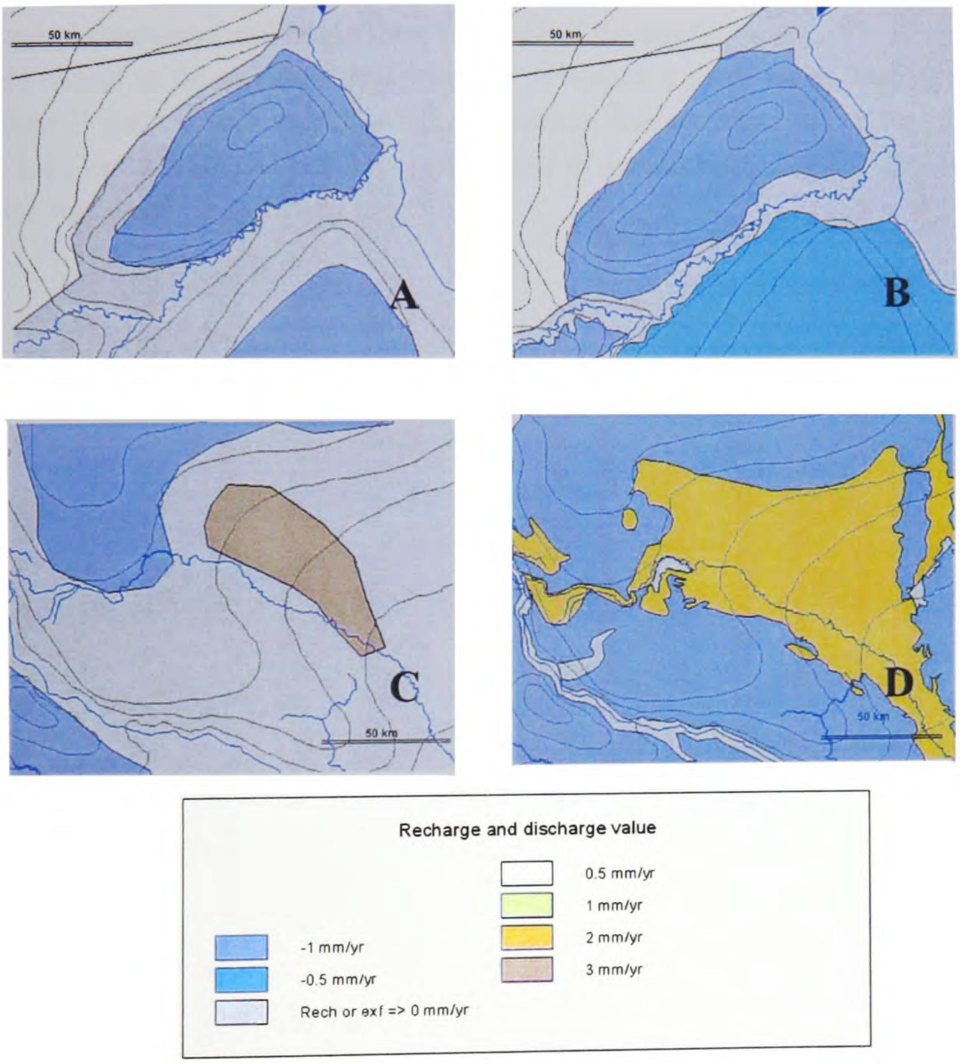


Figure 8-3: Examples of the difficulty in defining an accurate boundary for recharge and discharge areas with a 'classical' calibration process.

This is where, thanks to a novel application (regarding Hydrogeology of semi-arid areas), GIS and remote sensing can contribute to enhance the conventional way of groundwater modelling employed so far. Indeed, remote sensing and GIS have proved to be valuable tools for mapping groundwater recharge and discharge areas (part II), and the independent calibration of the groundwater model has confirmed these outcomes (see section 8.2.2). Therefore, remote sensing and GIS can be used to improve our groundwater model and offer a better definition of the actual limits of recharge and discharge areas input in the model.

To give an example, we can start with the Kadzell (Figure 8-3 A and B). To the north and the west, the flat topography, the impermeability of the soil and the absence of ponding indicate that the discharge area extends to the limit of the Kadzell region and its border with the Manga dunefields. This is also backed up with the study of the soil moisture thanks to Meteosat thermal data. To the south, the detection of ponds and of small flood plains together with a topography showing more variations, indicate a `buffer zone' about 3 to 10 km to the main river channel that is not favourable to discharge phenomenon and might form the limit of the discharge area. To the east, the discharge zone could extend as far as Lake Chad. There is, however, a small band, 7 to 10 km wide, west of the "Standard" Lake Chad shoreline where surface charactristics are favourable to a rainfall recharge: high variation in the local topography, end of the impervious soil of the Kadzell region and depth to the water table is relatively important.

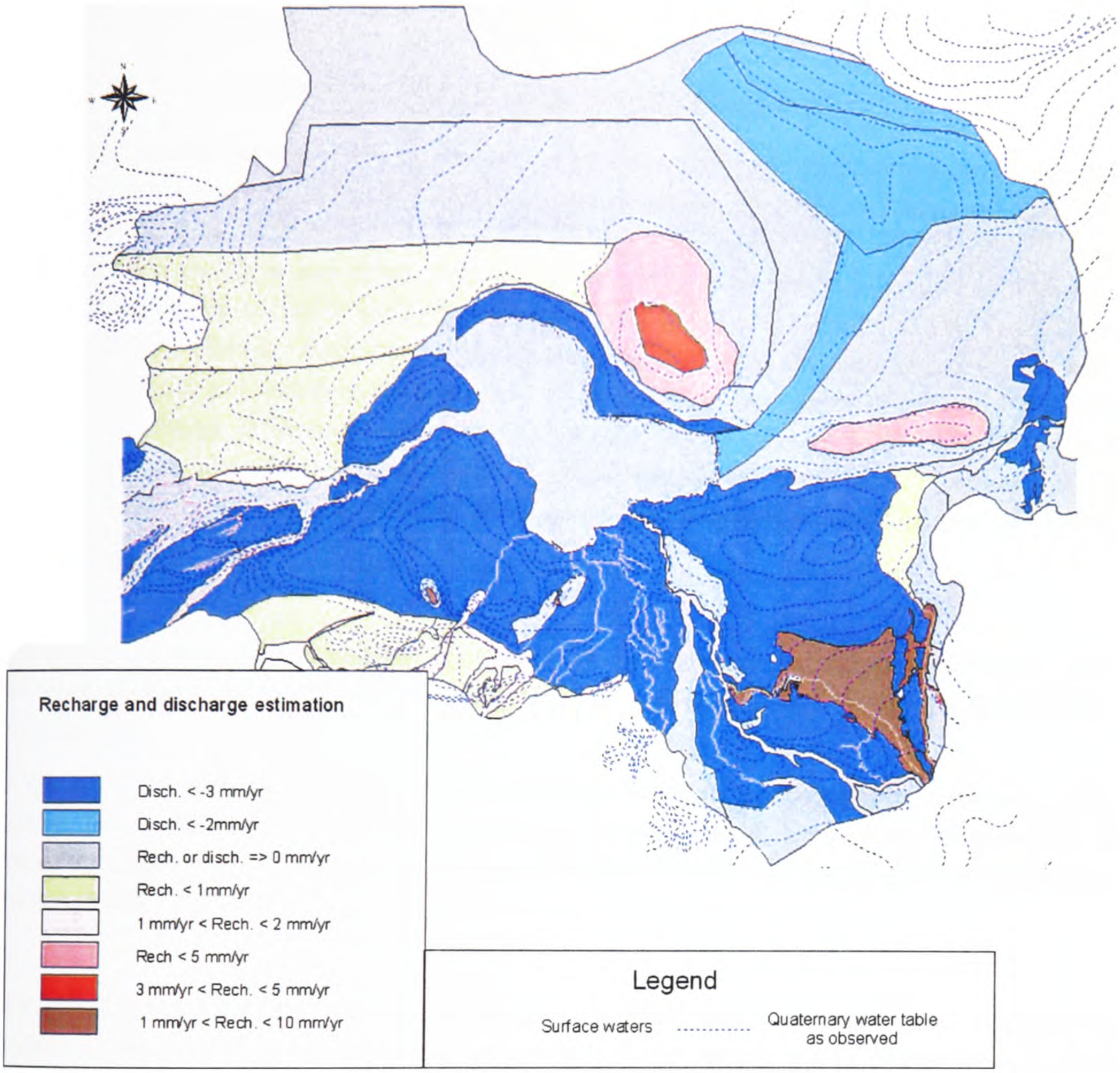


Figure 8-4: Enhanced estimation of recharge and discharge distribution and value, thanks to GIS and remote sensing.

In the interfluvial zone of the Komadugu from the southern edge of this area to a limit drawn by a line between Burula, Kurawa and Gumsa, the conditions seem favourable to discharge: presence of a flat topography, geomorphology and soil types both very similar to those are observed in the Kadzell region. Further east, discharge processes might prevail again near the intersection of the Yobe and Gana (end of interfluvial zone).

To give another example, the recharge zone in the region of Massenya is not small, but follows the extent of large ponding areas, also shown in the variation of the local topography (Figure 8-3 C and D).

By progressing in this manner and testing the hypothesis in parallel with the groundwater model, we finally obtain the map of recharge and discharge area for the whole Quaternary aquifer (Figure 8-4).

8.4 OVERALL CALIBRATION RESULTS

8.4.2 HYDROGEOLOGICAL CHARACTERISTICS REQUIRED

Results obtained at the end of the calibration are very interesting and enhance our knowledge of the region's water resources. The most important result is certainly the map indicating the distribution and values of rainfall recharge and discharge (Figure 8-4). At the end of the calibration, we also have the distribution and the values of transmissivity (Figure 8-7). Therefore, it is possible to have a clear picture of the characteristics of the hydrogeological sub-regions of the aquifer and how they interact with each other. The best simulation of the observed piezometry is obtained for a discharge rate of less than or equal to 1 mm/yr in the regions of the piezometric depressions (Figure 8-5). For higher values of discharge, it becomes harder to calibrate the model. Also, it is difficult to find in the literature higher values of evapotranspiration for high depths to the water table. Therefore, the most probable scenario, and the one kept for the transient calibration, is with a discharge of -1 mm/yr (Figure 8-5).

Although a scenario with a discharge of –1 mm/yr is the most probable, it is more prudent to report the water budget obtained for the broadest estimation (with a discharge rate in the depressions up to –3 mm/yr).

In the Harr and Kanem dunefields, rainfall recharge has been estimated to be between 2 and 5 mm/yr. The associated transmissivities values are generally good, but in order to reproduce the domes the model requires transmissivities slightly smaller than the average encountered in the rest of the dunefields.

In the Manga, the piezometry can only be matched if a small rainfall recharge is used. A good result is obtained for a recharge rate of 0.5 mm/yr or lower. In the eastern part of Manga, towards Chad, the calibrated transmissivities are high, but they decrease in the direction of the Mounio and Koutous massifs (west).

In the south-east area of the aquifer in Nigeria, small transmissivities are necessary to reproduce the high piezometric gradients observed. A small recharge, equivalent to the one of the Manga, ought to be assigned to this region. A higher recharge does not allow matching of the observed piezometry and fills the known piezometric depression of Bornu.

The Batha de Lairi and the Massenya floodplains correspond to recharge areas, whose recharge rates are between 1 and 10 mm/yr. The model has not allowed a more accurate estimation; i.e. solutions have been found for 1 mm/yr, but also up to 10 mm/yr (with varying the discharge rate over the depression and the conductance of the Chari).

In the depression regions, discharge is estimated to be less than 3 mm/yr. A uniform discharge as small as – 0.5 mm/yr has been tested and gives good results. A uniform discharge of -3 mm/yr still gives an acceptable representation of the piezometry, but matching with the observed piezometry becomes poorer. Within this interval, the smaller the discharge the smaller the transmissivity to apply to the depression. Surprisingly, large depressions – the Bornu and particularly the Chari-Baguirmi depression – do not necessarily require a low transmissivity. This shows that spatial scale also matter in the mechanism of the piezometric depressions. All depressions are represented as discharge areas surrounded by sources (here, surface water). Small depressions are always close to the sources, whilst across large depressions the effect of the surrounding sources diminishes.

Flows towards the Lowlands cannot be very high – i.e., they are smaller than 100E+06 m^3/yr. Values up to 200E+06 m^3/yr have been tested, but they do not give a good representation of the piezometry, and especially so for the domes. Furthermore, they might cause problems of convergence. In the case of a rainfall recharge of 3 mm/yr in the Harr and Kanem and of 0.5 mm/yr in Manga and south of the aquifer in Nigeria, together with a uniform discharge over the depressions of -1 mm/yr, then the outflow to the Lowlands is only about 30E+06 m^3/yr.

Rivers are estimated to contribute to the aquifer between 70 and 200E+06 m^3/yr. All along the rivers the transmissivities are relatively small. This is necessary to reproduce the relatively high piezometric gradient observed.

Finally, an important result is the estimation of the contribution from Lake Chad. Until now, Lake Chad's contribution was estimated to be very important (Carmouze et al., 1983; Isiorho et al., 1996; Roche, 1980). However, the model shows that Lake Chad feeds the aquifer by only 40E+06 m^3/yr to 100E+06 m^3/yr.

Verification of the simulated piezometry

Figure 8-6 shows a comparison between the observed piezometry and the best adjustment obtained with a discharge rate of –1mm/yr. The model simulates the observed piezometry with a good degree of satisfaction. All the major depressions are reproduced in accordance with their actual shape, location and magnitude. Similarly, the domes are well simulated. However, the simulated piezometry does not match the observed measurements in the region of Maiduguri. Because of high abstractions for the supply of Maiduguri, instead of having a piezometric dome along the river, the model shows a depression. There are two plausible explanations. First, in the 1960's, the increase in urban population and thus of the water consumption implied a transient regime regarding the Quaternary aquifer. The piezometry as mapped by UNESCO (1972) might reflect the situation before the development of Maiduguri had a significant impact on the aquifer. Alternatively, the model represents the situation as it should be seen on the very long-term (steady-state), with significant and constant abstractions to supply Maiduguri. Secondly, the reliability of the water withdrawal estimation may not be fully satisfactory (see section 6.2.3). In the case of Maiduguri one wonders whether or not a significant portion of the water reported to be tapped in the Quaternary aquifer does not actually come from the Pliocene aquifer.

Verification of the calibrated transmissivities

The transmissivities obtained at the end of the calibration process and for a discharge rate of –1 mm/yr are shown in Figure 8-7. The results agree with the nature of the deposits and the values generally match the transmissivities obtained by pumping tests (see section 7.2.2 and Map 6). The transmissivities of the calibrated model spans over a similar range as the field measurements (Table 8-2). The maximum transmissivities from the field and the calibrated model are similar and the average values are also close. Only the minimum value of the calibrated model is higher than the observations, but it remains comparable. The overall figure shows that the transmissivity values are relatively good, which confirms the exploitation capacity of the Quaternary aquifer. The distribution of the transmissivities also coincides with geological information. All the north-east of the aquifer and the north of Manga appears to be a high transmissivity zone. This is confirmed by the permeable sediments covering the region and the thickness of the Quaternary deposits (Eberschweiler, 1990; Eberschweiler, 1992; FAO-Schroeter and Gear, 1973; Schneider and Wolff, 1992). Towards the edges of the massifs, one notices a decrease of transmissivities. Small transmissivities are found all along the main rivers. This might correspond to fine fluvial deposits brought in by the drainage network. However, comparisons are limited as the works quite often only tap a small part of the water table (the top) and the pumping tests then only reflect a transmissivity of the top of the aquifer.

	Transmissivity values		
Transmissivity source	**Min.**	**Average**	**Max.**
Field measurements	6.3E-05 m^2/s	8E-3 m^2/s	7E-02 m^2/s
Model, calibrated T.	2.02E-4 m^2/s	1.2E-2 m^2/s	8.5E-02 m^2/s

Table 8-2: Comparison between the observed values of transmissivity and the values of the calibrated model.

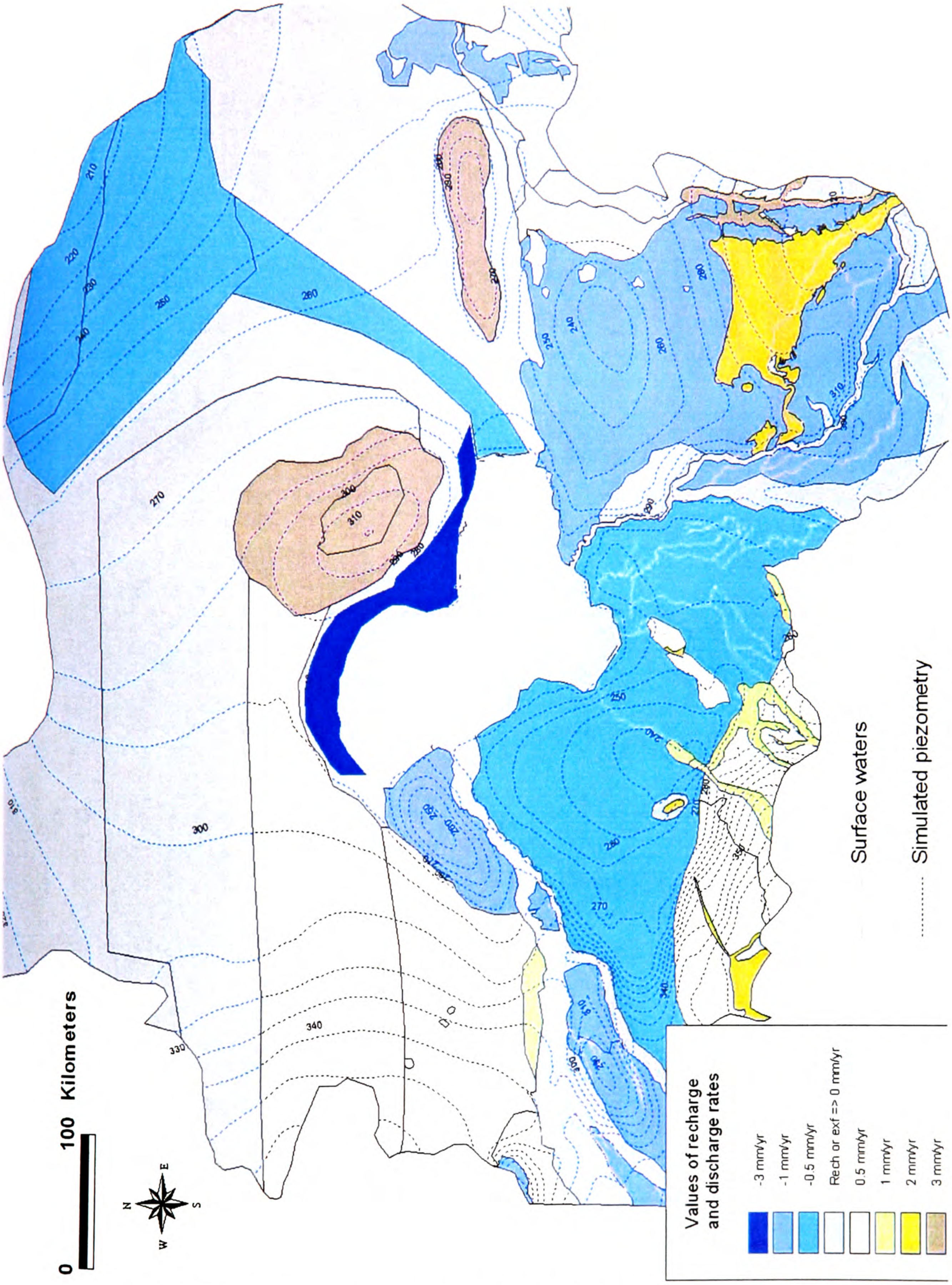


Figure 8-5: Simulated piezometry and distribution of rainfall recharge and discharge with a discharge rate of –1 mm/yr.

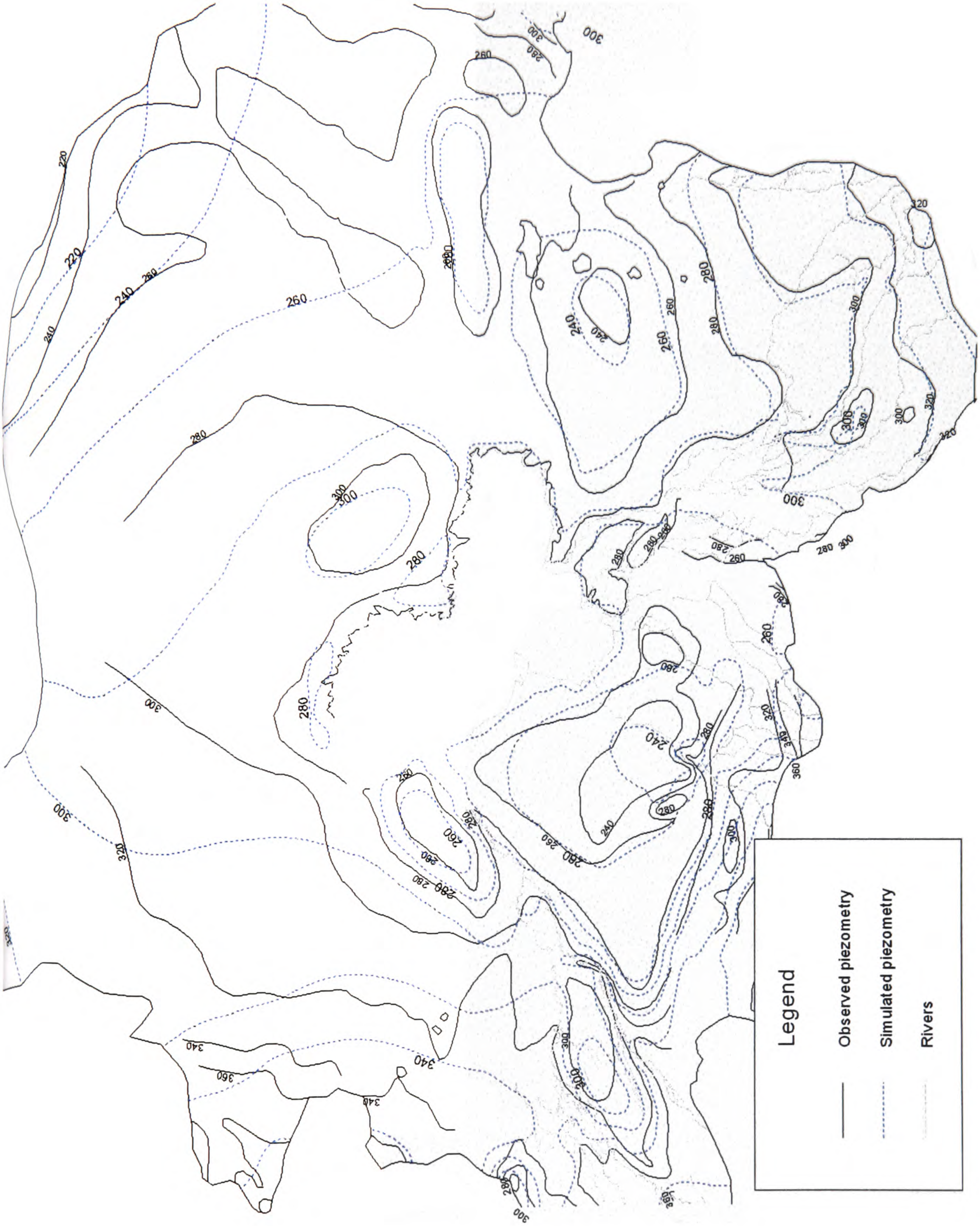


Figure 8-6: Comparison of the observed with the simulated piezometry obtained at the end of the calibration.

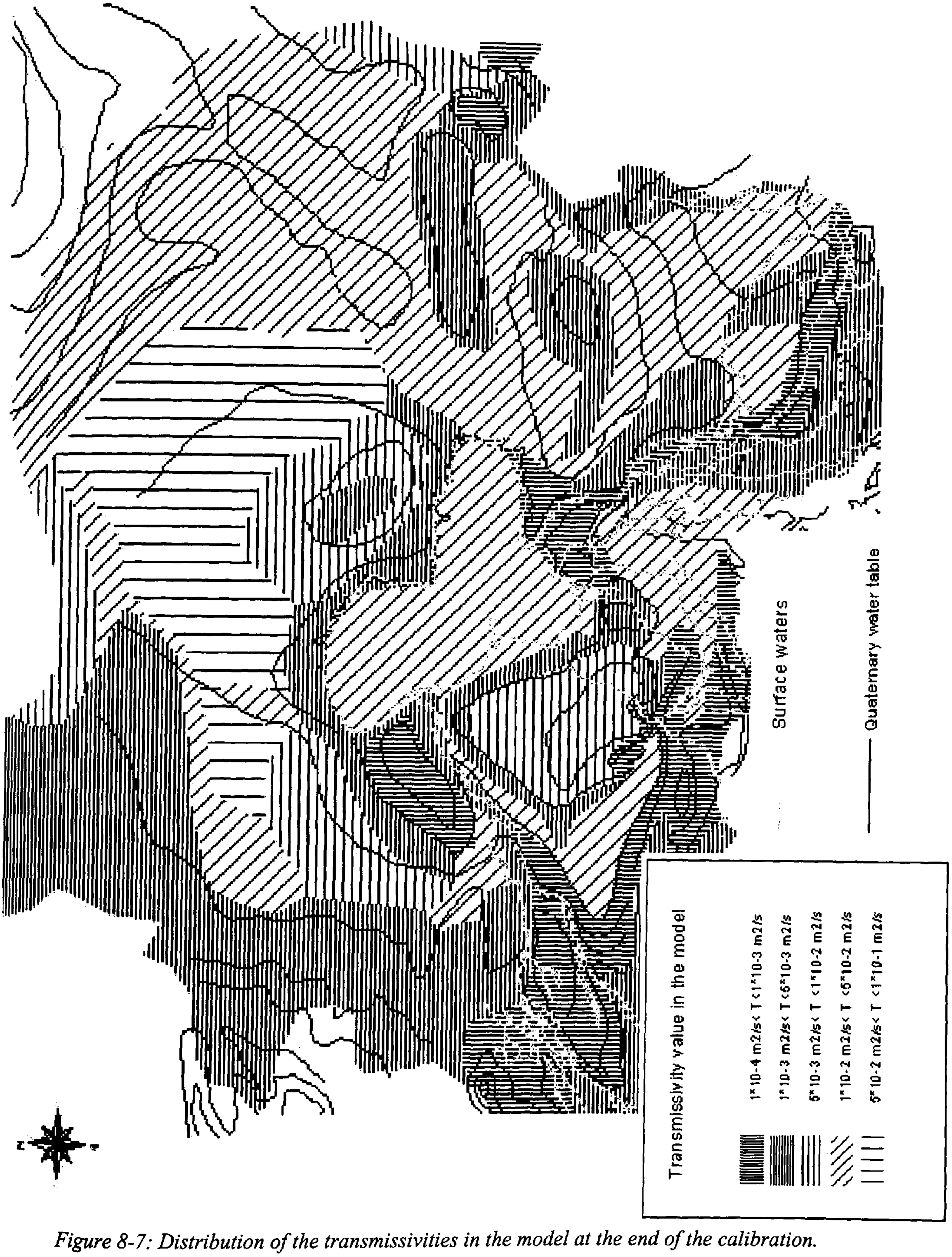


Figure 8-7: Distribution of the transmissivities in the model at the end of the calibration.

8.5 SENSITIVITY TESTS

Sensitivity tests have been carried out on the most probable scenario obtained at the end of the calibration process (discharge rate of -1 mm/yr in the regions of the piezometric depressions). They are an important step of the groundwater modelling process. The sensitivity analysis recognises that the calibrated model may not represent a unique match to the calibration target and assesses the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters. Sensitivity analysis is typically performed by changing a parameter value at a time. Nevertheless, in our case, it appears particularly relevant in the regions of the piezometric depressions to change hydraulic conductivity and discharge rate together to determine the existence of equivalent solutions. The measure of the sensitivity is reported as the magnitude of change in the heads and in the water budget of the model.

8.5.1 HYDRAULIC CONDUCTIVITY

First, the sensitivity tests have consisted of varying only the hydraulic conductivity values, while all the others parameters remain as they were at the end of the calibration.

Appendix 8-2 shows the impact on the simulated piezometry of multipling the hydraulic conductivities by 10 in the Kanem region. The change causes no significant impact on the global water budget (Appendix 8-5). On the piezometry, nevertheless, it causes a drop of the piezometric dome and an increase by several metres of the piezometric levels in north Chad.

A similar test was carried out this time by mutliplying by 10 the hydraulic conductivity over the piezometric depressions of the Kadzell and the Chari-Bagurimi. The results are shown in Appendix 8-3. They indicate that such an increase in the hydraulic conductivity causes a rise of the water table in the depressions. The rise reaches more than 25 m in the centre of the depressions, so that the depressions are partially disappearing.

While maintaining the hydraulic conductivity in the depressions at a value multiplied by 10, another appropriate test was to search for an equivalent solution that allows for the representation of the piezometric depressions. This was done, complementary to the increase of the transmissivities in the depressions, by changing the discharge rate in the depressions as well as the conductance and the hydraulic conductivity in the vicinity of the rivers. This test was carried out, once again, on the Kadzell and the Chari-Baguirmi. An equivalent piezometry was found for an increase of the discharge rate from -1 mm/yr to -5 mm/yr in the Kadzell and from -1 mm/yr to -2.5 mm/yr in the Chari-Baguirmi. Meanwhile the conductances of the rivers and the transmissivities in their vicinity needed to be significantly increased. On the water budget, this 'new' representation of the depressions implied an increase in the contribution from the rivers by about 30E+06 m^3/yr and from Lake Chad by about 28E+06 m^3/yr (Appendix 8-5). This test shows that there are other combinations that can reproduce the depressions. Nonetheless, a wide range of possible solutions is not feasible. An increase in the hydraulic conductivity must be accompanied by a significant increase of the discharge rate. The depth to the water table in the depressions limits the discharge rate (see section 6.2.4) and, on the other hand, the hydraulic conductivity must respect the material observed and the field measurements. So the set of solutions is limited because of likely hydraulic conductivities and maximum discharge rate.

8.5.2 RECHARGE AND DISCHARGE

A series of sensitivity tests have been carried out by changing the rainfall recharge and discharge rates by ± 20% (all other parameters being fixed).

The model appears sensitive to these changes: i.e. an important variation in the piezometry is noticed. This sensitivity is noticed over the whole aquifer (Appendix 8-4). Regions with the strongest impact are: the piezometric domes, Manga, south-east region of the aquifer in Nigeria (border of Mandara massif), towards the Lowlands, and the interfluvial zone of the Komadugu. In these regions, the change in recharge and discharge rate by only 20% can change the piezometry by over 10 metres.

8.6 CONCLUSION

Again, it is necessary to express our concern about the sparse hydrogeological data available. Results must, therefore, be interpreted and used with caution.

An independent calibration has strongly confirmed the results of applying GIS and remote sensing to map groundwater recharge and discharge areas. In order to reproduce the piezometry and comply with realistic transmissivities, the groundwater model shows that it is necessary to respect a certain distribution of recharge and discharge areas. That particular distribution matches clearly with the information obtained separately from remotely sensed data and GIS (see part II). From there, it was possible to use GIS and remote sensing to narrow down the location of recharge and discharge areas and thereby the calibration. This, to the best of our knowledge constitutes a novel application of GIS and remote sensing in hydrogeology of semi-arid areas.

The piezometric depressions largely occur in the southern parts of the aquifer (Figure 2-14). The calibration shows that to reproduce these depressions it is necessary to assign to the concerned areas a discharge and relatively small transmissivities. This validates the conceptual scheme by which piezometric depressions are generated by evapotranspiration processes, whose effect on the water table cannot be compensated by lateral flows given the small permeabilities (Aranyossy and Ndiaye, 1993). However, it raises a contradiction between the dry north that receives a rainfall recharge and the more humid south that does not. Here again, remote sensing and GIS come in to support and complement the groundwater model and show that not only rainfall but also characteristics of the ground have a significant effect on recharge and discharge processes, so much so that, with the high evapotranspiration rates and the presence of deep rooting trees, discharge areas can occur even in the south (see part II).

Flows towards the Lowlands and evapotranspiration in the Bahr El Ghazal valley are estimated to be less than 100E+06 m^3/yr. Since the flow to the Lowlands is the only natural outflow towards an external system and it is small, the water budget points to the endorheism of the aquifer. The major natural outflows are assured to occur internally by evapotranspiration processes. There are no estimations available on what are, in such conditions, evapotranspiration rates that affect the water table. Thus, in terms of water budget, the major uncertainty in the model is due to the uncertainty about the discharge rate in the depressions. Sensitivity tests show that there are equivalent solutions to represent the piezometric depressions if the discharge, the transmissivities and the contribution from the surface water are changed together. Nonetheless, the depth to the water table limits considerably the evapotranspiration that can occur and thus limits the range of possible solutions. Sensitivity tests also show that a significant increase of the transmissivity would need to be followed by a significant increase of evapotranspiration rates, in which case both parameters would not agree with the observations. Thus, the upper limit of the possible range is soon reached.

Therefore, we consider that an assessment of the water budget is given with a reasonable uncertainty for a range of discharge rates in the regions of the depressions varying between -1mm/yr and -3 mm/yr.

The model indicates that rainfall recharge cannot be too high, otherwise there is no agreement with the piezometric observations and groundwater would flow out massively through Lake Chad and the rivers, and fill up the depressions. Besides, as explained above, outflows are limited and thus inflows are limited too in order to maintain water balance.

In the dunefields, the regional rainfall recharge is estimated between 5 mm/yr to less than 1mm/yr. In the areas of rainwater ponding the regional rainfall recharge is less than 10 mm/yr.

The present model suggests that Lake Chad has more of a qualitative role than a quantitative one. From the model, we can estimate that the "Standard" Lake Chad contributes to the aquifer only 30 to 100E+06 m^3/yr.

The present estimation of Lake Chad's contribution to the water table is much lower than previous assessments for the same period (end of the 1960's) reported in the literature (see Ch. 3):

- 15E+09 m^3/yr from results of a groundwater model of the southern region of Lake Chad later extended to the whole Lake; (Isiorho et al., 1996);
- 2.1 to 3.6E+09 m^3/yr from reuslts of a salt-water budget analysis (Carmouze, 1983; Roche, 1980).

Roche (1980) and Fontes (1976) mentioned a factor that could limit the actual recharge from the lake to the Quaternary aquifer. Near Lake Chad, the water table is very close to the surface and evaporation processes are probably very important. Therefore, an important part of the water that infiltrates from the shorelines may be subject to high evapotranspiration (Fontes, 1976; Roche, 1980).

Thus, the overall recharge effectively reaching the aquifer could be much smaller than the initial infiltration from the lake (Fontes, 1976; Roche, 1980).

Isiorho's model (see Figure 8-8) does not follow essential rules of groundwater modelling and its results should be rejected (see also section Ch. 3.5). The model is too constrained by the high number of constant heads, which bounds the piezometry through a large part of the model and does not give enough importance to the value of the flows circulating in the model. Arbitrary limits of the model's coverage do not allow the representation of the system as a whole. In other words, the piezometric depression of Bornu is not represented in Isihoro's model. However, it should be the major outflow of the model, thereby limiting the inflow from the lake to a much smaller range.

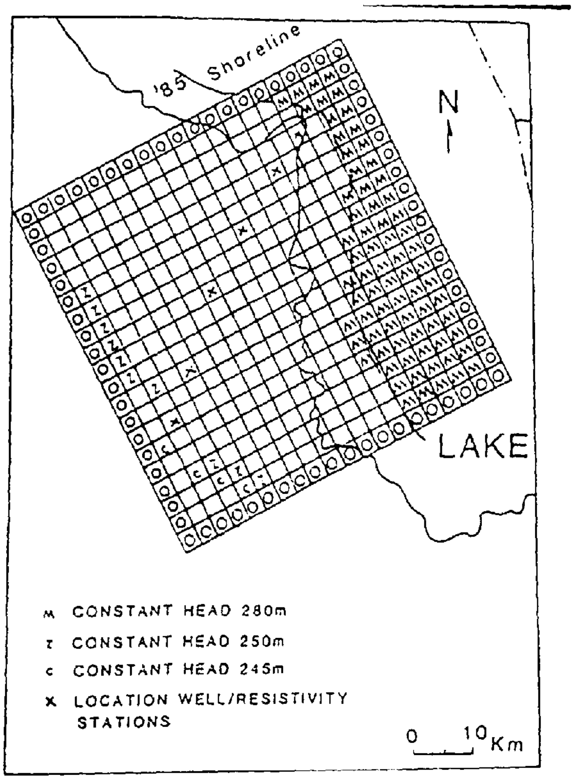


Figure 8-8: Boundary conditions and grid in Isiorho's model (Isiorho, 1996)

To conclude, from the very large range of estimations of recharge and discharge from the literature review (see Ch. 3), our model rejects many values and only allows few data sets to represent the piezometry observed in the 1960's. Regarding the water resources management of the basin, this confines the realistic range of estimations and, therefore, represents a significant contribution.

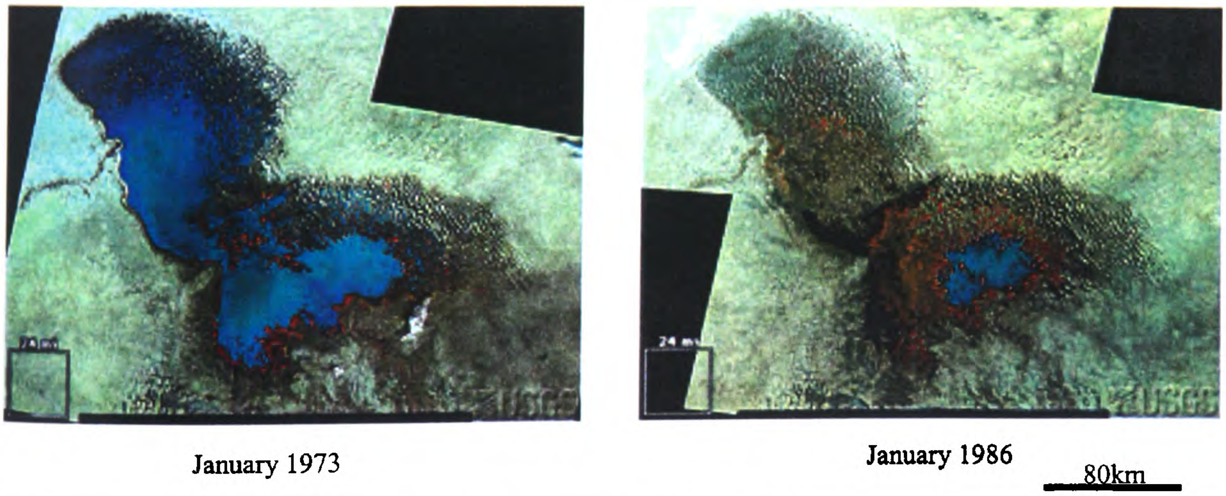
In general, the quantities of water involved as sources and sinks of the aquifer are very small. With a fairly flat piezometry all over the aquifer, lateral flows are limited. Consequently, a small source or sink is enough to reproduce major features of the piezometry. Overall, the aquifer is thus characterised by large reserves (good transmissivities over a wide aquifer) but a small renewable resource (small regional recharge rate).

Chapter 9

TRANSIENT MODEL AND HYDROCLIMATIC CHANGE ASSESSMENT

9.1 INTRODUCTION

This chapter aims to extend the steady-state groundwater model developed so far to a transient simulation that reproduces the evolution of the aquifer from 1960 to 2000 - a period characterised by significant changes in the basin.



January 1973

January 1986

Figure 0-1: Landsat MSS images showing Lake Chad in January 1973 and January 1986 (Colour composition: Band 4=Red; Band 2=Green; Band 1=Blue); Source Earthshots-USGS.

Since the 1960's, rainfall and surface water regimes have been affected by serious droughts. Meanwhile, human abstractions have increased and put even more pressure on the water resources (see Ch. 2 and section Ch. 7.2.3). The most severe change is undoubtedly the shrinkage of Lake

Chad. It is clearly shown in satellite images (Figure 9-1), and it is often quoted as one of the most drastic environmental changes recently observed (see for example, USGS's Earthshots or NASA's Earth Observatory Web sites). Large areas of what used to be Lake Chad, and particularly the north pool, are now often dry. According to the hydroclimatic conditions, this area of the lake can be partially re-flooded, but this is generally for short spells only. For the Quaternary aquifer, a large part of what used to be a recharge area is now subject to evaporation. This phenomenon is probably strong as the water table is very shallow. As far as we know, the impact of these fluctuations on the aquifer has never been studied, although this seems to be essential for a sustainable management of the water resources of the basin.

The first objective of this chapter is to assess what impact these environmental changes have had on the Quaternary aquifer, with a particular interest in the shrinkage of Lake Chad. Worldwide, this study also represents a unique situation to study the impact of a large hydroclimatic change (Lake Chad shrinkage) on a superficial aquifer (see also Aral Sea). This involves overcoming a major challenge: to obtain the history of the fluctuations of Lake Chad. The challenge arises mainly from the vastness of the area, the complexity of the process, the rapidity with which changes occur, and finally the need to retrace the evolution over a long period (40 years). The second objective is to explore the use of long-term archive satellite data to reveal the history of the extent of Lake Chad and the application of GIS to store the data and implement them in the groundwater model. If successful, this work would constitute a novel application of GIS and remote sensing for long-term groundwater modelling.

This chapter starts with an analysis of long-term piezometric data in order to reveal the evolution of the water table in the second half of the 20th Century. We then move on to the reconstruction of the fluctuations of Lake Chad extent. These data, with the results of the steady-state calibration should allow the calibration of the transient model of the Quaternary aquifer. After sensitivity tests, the model is used to seek answers to the water resources management issues raised above.

9.2 PIEZOMETRIC FLUCTUATIONS RECORDS

9.2.1 DEVELOPMENT OF A GIS DATABASE

Favreau (2000a, 2000b) offers an example of a thorough analysis of the long-term variation of a free water table in the Sahel. This study, though in one of the most studied region of the Sahel (Niamey, Niger), illustrates the numerous difficulties encountered in this kind of exercise.

Within the Lake Chad Basin, Leduc et al. (1998) and Bichara et al. (1989) have interpreted the evolution of the water table level, respectively, in Niger and Chad. Eberschweiler (1992) also attempted this analysis but for the whole of the Quaternary aquifer. Our contribution to these previous works is to provide:

- The first attempt to gather all the archived data available. A part of the measurements comes from technical reports, but the databases maintained at the DHA-N'Djamena and DDH-Diffa have provided the majority of the data;
- An update with recent measurements;
- A critical analysis of the data in order to select only the most reliable observations;
- The integration of the data in a GIS to allow a spatial interpretation of the data at the scale of the whole aquifer and to offer an efficient management tool.

The quantity of the data is unfortunately not ideal to offer a proper assessment of the long-term evolution of the lake's extent (see also, Ch. 4). Yet the most delicate problem for the interpretation of these long-term data is the assessment of their quality. There are some piezometers in the Quaternary aquifer, but nothing akin to a real monitoring network. Therefore, the water table level is measured in a variety of hydraulic works: cemented wells; bore-holes; and in the best cases, piezometers. Several factors prevent the gathering of good quality data, particularly in the long-term, when several modifications can happen to the observation point (Bonnet and Meurville, 1995; Eberschweiler, 1992; Leduc et al., 1998):

- The level measured is often a dynamic level and not a static one – this happens when the well is used at the time or prior to the measure. More generally, the human abstractions might also affect all the measurements made during the dry season as the aquifer is more solicited than in the rainy season (Favreau et al., 2000 a);
- Errors can also occur regarding the identification of the well – the same village can have several wells and, as observed during the field mission of 1999 in Niger, identification numbers do not always figure on the wells;
- The height of the top of the well is sometimes increased. This often happens in the dune areas in order to fight against sanding up. It leads to a change in the altitude of the reference mark;
- Pastoral wells are often closed during part of the year, and so no measure can be taken;
- The reference mark for the measurement is often mistaken between the ground and the pit of the well, and even if the latter is generally chosen, its shape is not always regular which means that without precise indication it can lead to a significant error;
- Although we do not know the number of works susceptible to being affected, it is probable that, in the south, a number of wells are subject to seasonal flooding.

It is clear that all these sources of error can significantly affect our interpretation. Consequently, we have chosen to use in our analysis only the best observation points available: i.e., the piezometers and the exploration or unexploited bore-holes; and the observation points offering a long and reliable time series (only static levels and no change in the head of the hydraulic work reported).

In total, 26 observation points of sufficient quality were selected to interpret the long-term evolution of the water table.

9.2.2 INTERPRETATION

The long-term piezometric records are reported on Maps 7 and 8. Regionally, one notices a drop of the water table.

Both Kadzell and Chari-Baguirmi depressions, where the piezometers are installed, show a strikingly similar trend: a slow and very regular drop of the levels by 3 to 6 cm/yr. In the Chari-Baguirmi, this drop has been recorded since the beginning of the measurements in 1963. In the Kadzell, unfortunately, the time series is shorter and only concern the 1990's.

In the dunefields, there are fewer long-term data series to relate to the piezometric evolution and no piezometer. The data available show a decrease of the water table, which appears stronger than in the piezometric depressions (see Map 8 and Table 9-1).

Observation point	Record period	Change (m)	Change rate (cm/yr.)
Kalimba - Kanem	1987-1994	-0.25 m in 7years	-3.5 cm/yr.
Abani - Kanem	1987-1994	-0.6 m in 7years	-8.6 cm/yr.
Ngile-Kanama - Kanem	1966-1992	-2.6 m in 26years	-10 cm/yr.
Kouri kouri - Harr	1964-1994	-1.7 m in 30years	-5.6 cm/yr.
Ouadiounga - Harr	1987-2000	-1.3 m in 13years	-10 cm/yr.

Table 9-1: Records of the evolution of the water table in the dunefields.

Overall, the drop of the water table appears moderate with regard to the severe decrease of rainfall, rivers discharges and the extents of the surface water bodies. It is also the conclusion of Leduc *et al.* (1998) who compared statistically all the data of the water table available for the whole of Manga in 1975/76 with those in 1989. The data show a median drop of only 0.4 m across the whole region (drop is in excess of 1.5 m for only 1 out of 8 wells). This interpretation is confirmed by the fact that none of the basin's Institutions visited reported a major drop of the water table.

Nearby the northern pool of Lake Chad the situation is different. The drop there is reported to be much stronger. Arikoukouri, which is located on the shoreline of the "Standard" Lake Chad, recorded a drop of its level by 1.6m between 1988 and 1995 (23 cm/yr). Leduc *et al.* (1998) also reported in comparing the water table in 1975/76 with 1989, that the level in the vicinity of Lake Chad had dropped by 3 to 8 metres. This more severe decline is to be correlated with the shrinkage of Lake Chad and its disappearance from the northern pool (see also, Ch. 3).

Unlike the regional trend, Moussoro's well in Chari-Baguirmi rose by 1.5 m in 31 years (1964-1995) - a rate of 5 cm/yr, and Djadjeri in Manga rose by 1m between 1990 and 1997 - a rate of 14 cm/yr. It would be necessary to see if this could be explained by local conditions.

The general evolution of the quaternary water table contradicts recent results obtained elsewhere in the region of Niamey (Sahel), which show an important rise (0.3 m/yr) of the Continental Terminal water table. Following deforestation, the increase of ponding and, thus, of localised recharge is the cause of this rise (Favreau and Leduc, 2001 a; Leduc et al., 2001). Although the extent of deforestation is not known precisely in the Lake Chad Basin, as far as we could investigate, satellite images do not show an increase in ponding or any modification of the geomorphology in that sense (unlike in the region of Niamey).

9.3 HYDROCLIMATIC CHANGE: RECONSTRUCTING THE FLUCTUATIONS OF THE EXTENT OF LAKE CHAD

The objective is to reconstruct the history of the fluctuations of the extent of Lake Chad from 1960 to the present day (2001). Later, this information is to be implemented into the groundwater model, in order to define the impact of such hydroclimatic fluctuations on the surrounding Quaternary aquifer. Given the extent of the Lake it seems appropriate to use the synoptic capability of remote sensing to achieve this. The frequency of the mapping must be sufficient to allow for a fine reproduction of the phenomenon in the groundwater model.

9.3.1 METHODOLOGY

Lemoalle (1979, 1995) proposed a relationship between the level of Lake Chad and its surface area for the period extending from January 1973 to October 1975. An idea for reconstructing the fluctuation of the extent of Lake Chad is to stretch out such a relationship and to build a geographical model describing the extent of Lake Chad according to its level. However, some arguments tend to show that it is rather preferable to detect systematically the extent of Lake Chad directly from remote sensing data rather trying to develop such a model:

- There are several factors (especially wind) that could lead to errors (up to 20 cm) in the measurement of Lake Chad's level (Olivry et al., 1996);
- Staff gauge stations are subject to disruption and there are gaps in the records of Lake Chad levels (Olivry et al., 1996). On the other hand, satellite data are becoming more available, affordable and accurate (for example MODIS and the future Meteosat second generation, see Ch. 4);
- Below a certain level, Lake Chad splits into two major pools (north and south) separated by the "Great Barrier" (Olivry1995; Lemoalle 1979 - see also Poster1). When this situation

occurs, the two pools receive distinct inputs and their stages vary independently. Ultimately, this leads to a more complex relationship between the level(s) of Lake Chad and its extent;

- This phenomenon (isolated pools with different stages) is also likely to happen on a larger scale. Indeed most of the shoreline offers a complex topography with domes and humps, so that substantial variations in the lake stage can lead to the isolation of numerous cut-off ponds;
- The drying of regions of the lake and their subsequent rewetting is not entirely a reversible process. First, owing to the soil desiccation during periods of drying out, it is possible that the areas that have dried out are lower than they were before (Africa, 1996; Dupont, 1970; Lemoalle, 1979 a). Second, the vegetation has changed considerably with the fluctuations of the lake. Vegetation has developed in dried areas and aquatic vegetation has invaded surface water. This too can modify the elevation of the bottom but above all, it affects the flows within the lake. One notices that the development of vegetation on the "Great Barrier" considerably slows the rewetting of the north pool (Lemoalle, 1979 a; Olivry et al., 1996).

For all these reasons, it appears that there is no simple geographical model between the stage of Lake Chad and its extent. The use of satellite data, on the other hand, appears an appropriate technique to monitor the surface variations of Lake Chad.

Yet, reconstructing the fluctuations of Lake Chad since 1960, even with remote sensing, is a challenging task. Indeed, it requires the acquisition of:

- Affordable data;
- Sources of high temporal resolution data that span a long period of time;
- Sensor(s) with good synoptic capability in order to cover a large area (Lake Chad);
- A method of mapping the extent of all waters (not only open water, but also water under aquatic vegetation).

Such requirements can only be met with the use of information from multi-sources. For certain periods, the lake extent has already been mapped. The results of these previous works will be integrated into the present reconstruction. Additionally, it is expected that various sources of satellite archive data will provide updates with recent data and complement existing data sets with more frequent information.

Both AVHRR and Meteosat offer the synoptic capability and the temporal resolution required. They are available over a long-term span and are offered without charges to the research community (see Ch. 4). The difficulty of mapping water under aquatic vegetation seems to be overcome by using thermal AVHRR and METEOSAT data. The rationale of the methodology is that both open water and water covered with aquatic vegetation have a higher thermal inertia than the surrounding bare dry land and non-aquatic vegetation. That is, they warm-up less during the day. Rosema (1990) shows that, in the region of Lake Chad, Meteosat thermal data make a clear distinction between dry and wet lands. Travaglia (1995) applied this method of thermal inertia to map water bodies extent of the Sudd wetlands in Sudan. This region has a similar environment to that of Lake Chad with wetlands covered by dense mats of floating vegetation within which areas of open water occur. The author reports that AVHRR/LAC thermal data (channel 4) make the distinction of both open water and water under vegetation from the bare soil and soil with active vegetation (Travaglia et al., 1995). When available, AVHRR/LAC data will be employed as they have a higher spatial resolution (1km) than Meteosat (5km). These data, however, are not always available. Therefore, they will be complemented with Meteosat Tmax 10-days thermal composite data (see sections 4.4.4 and 6.3.4).

GIS is used to store and manipulate multi-source information but most importantly, it is used to pre-process the data to be input into the groundwater model.

9.3.2 RESULTS

Using multi-source information, we were able to propose a thorough reconstruction of Lake Chad's fluctuations from 1960 to date. Results are synthesised and displayed on Poster 1.

The international map of the world 1/1 000 000 N'Djamena ND-33 (published in 1969) offers a record of the lake. It is difficult to relate it to a particular date as the map itself is probably issued from a mosaic of previous maps. However, it is representative of Lake Chad extent in the 1960's and early 70's, as one can assume that variations of the extent at this period were relatively small.

The period that spans from June 1973 to October 1977 has been studied by Lemoalle (1979) using Landsat MSS data and aeroplane surveys. Later Lemoalle (Lemoalle, 1991; Lemoalle in Olivry, 1995) synthesised and updated his work with the use of Meteosat data. This led to the publication of the extent of Lake Chad north pool in January ("maximum annual extent") from 1973 to 1990.

Thanks to AVHRR/LAC and Meteosat thermal data, we have been able to complement these works with a comprehensive monitoring of the lake from 1986 to date (see also Ch. 4 for origin of the data set). At first sight, NOAA/LAC data with 1 km resolution seemed more attractive than Meteosat data. They were used whenever possible. However, there are many periods for which LAC data are simply not available or too cloudy to be interpreted. This is why the Meteosat Tmax archived data set has proved to be very valuable. Due to the sensor's high temporal resolution, 10-day and monthly Tmax (Maximal Value Composite) offer the possibility to bypass cloud cover. These Meteosat data have been archived systematically from 1986 to 1987 (April to October) and 1988 to date (all year long).

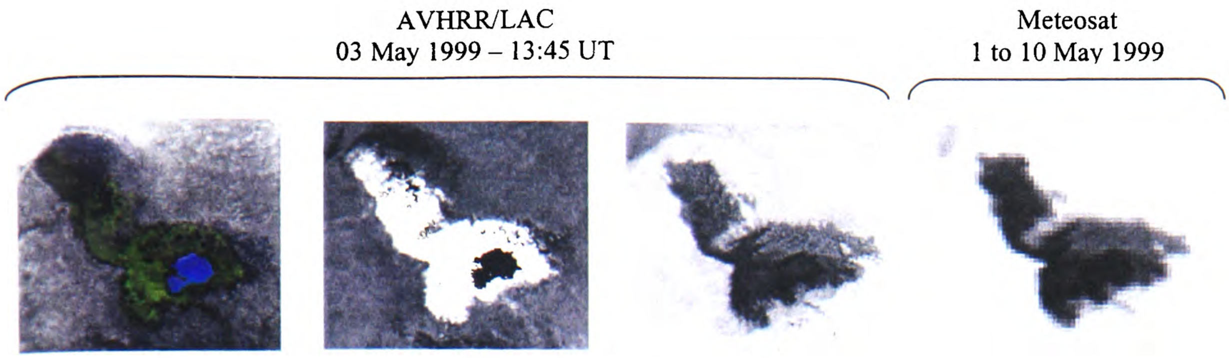
The detection of water, thanks to thermal inertia, appears as a robust method. Near Lake Chad, a strong discrepancy between diurnal and nocturne temperature is observed all year long (Olivry, 1995). This certainly enables an optimum application of the thermal inertia approach. Figure 9-2 illustrates how all the lake's waters are picked out by thermal inertia. An AVHRR image (see Figure 9-2A) shows the active vegetation in green and the open water in blue. Near infrared bands would only permit to detect the open water, but the AVHRR NDVI (see Figure9-2B), shows that the vegetation around this open water is very active. In fact, at that time of the dry season such active vegetation can only be sustained by the lake's water. This is aquatic vegetation. The thermal images, Figures 9-2C and D, detect both the open water and the aquatic vegetation and enables mapping of all the waters of the lake. Note the similarity of the water area detected by thermal AVHRR data and METEOSAT.

Nevertheless, there are some cases where a relatively weak thermal inertia is observed and one can have reservations about qualifying the area as surface water. These are situations when the bottom of the lake is only covered by a shallow layer of water as, for example, during drying processes (Figure 9-5) or when small pools (archipelagos) are scattered (Figure 9-3). Our guiding principle has been to map such areas in order to define the entire extent of Lake Chad, including areas with little water. Because of the persistence of clouds during the rainy season, for some years no detection was possible, even with Meteosat (see for example Figure 9-4).

Apart from this, the reconstitution is thorough, with a time step of one month from 1986. This provides us with a reasonably accurate data set as input.

Since 1974, a typical annual cycle is characterised by the flood of the Chari that begins to affect the lake's extent in December. After a big flood, the extension of the lake stays relatively wide until May. In June at the latest, the surface area starts to shrink. This prevails until November, and then in December the Chari flood arrives again and the cycle is repeated. However, the most important information revealed by this work concerns the interannual variations of Lake Chad. A small pool in front of the mouth of the Komadugu Yobe, is often the only remaining water area when the north pool is dry (see for example the images from 1992 to 1996 -Poster 1). In 1988 and 1991, a very small lake was detected. The north pool is entirely dried and south pool is seriously affected and restricted to an area of about 1,400 km^2 in front of the Chari delta. Between these two periods was a period in 1989 with a high extent of Lake Chad and a replenishment of the north pool to more than a half of its surface area of before 1973. Images show that since 1995, the situation has started to improve. In 1999, 2000 and 2001 one could see the reappearance of a large Lake Chad. In both 1999 and 2000, the north pool does not dry out for the whole year for possibily the first time since 1974. This information from satellite data was supported in the field by our observation of Lake Chad during our field visit to the northern pool in June 1999 (Photo 2).

Photo 2: The return of Lake Chad in the northern pool as observed in June 1999 (vicinity of Doro fishing village 10°04'48"N - 13°29'46"E).



A:
Lake Chad as perceived in the visible with AVHRR. False colour composition: Band 2= R; Band 2= B; Band 1=G.

B:
NDVI (vegetation index). Active vegetation appears bright.

C:
Band 4 (thermal infrared). Cool temperatures appear dark.

D:
Thermal infrared Band Maximum Value Composite. Water, which stays cool all day long, appears dark.

Figure 9-2: Thermal inertia of Lake Chad waters.

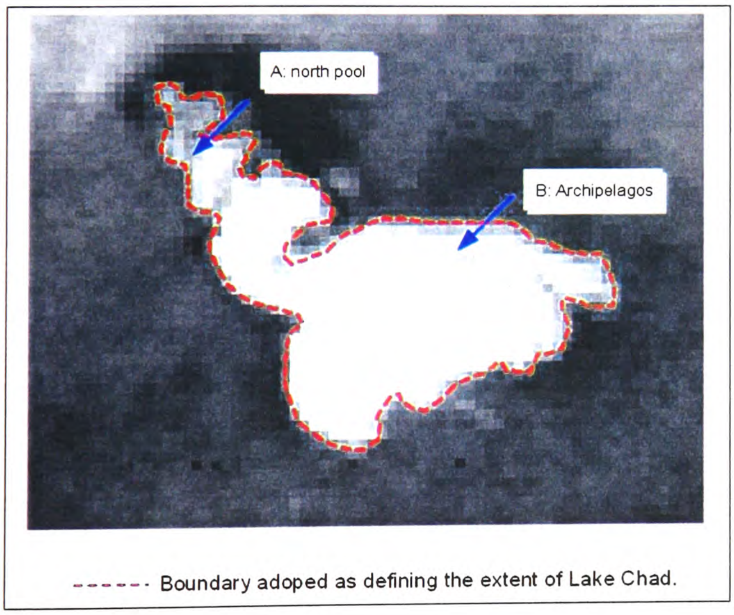


Figure 9-3: March 1998 - Guideline of mapping the whole extent of Lake Chad including very shallow and shattered pools of water. The regions with a weak thermal signature (archipelagos and other areas with little water) are still mapped as part of Lake Chad.

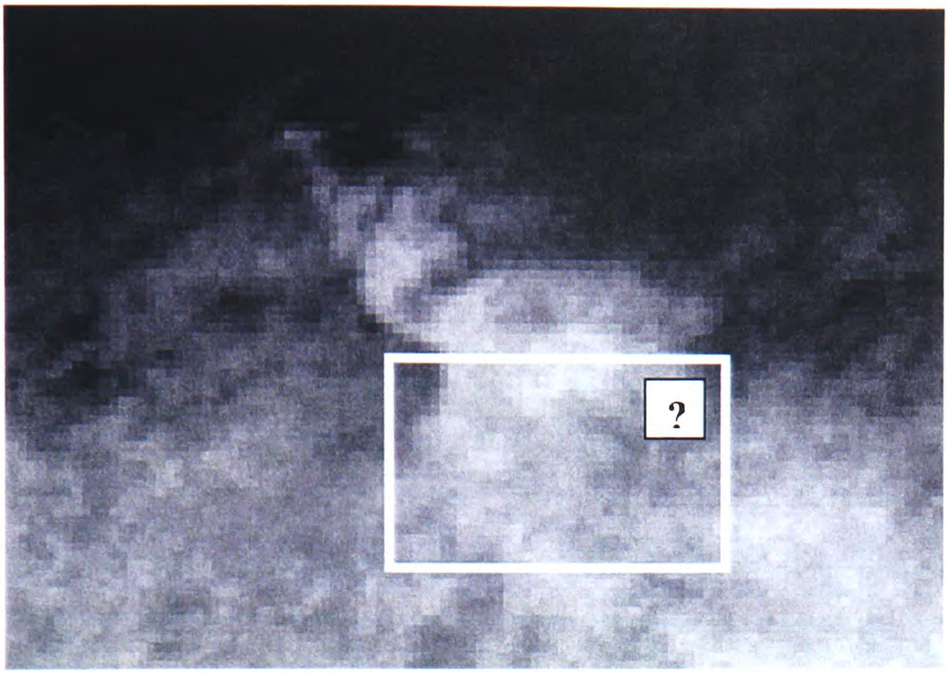
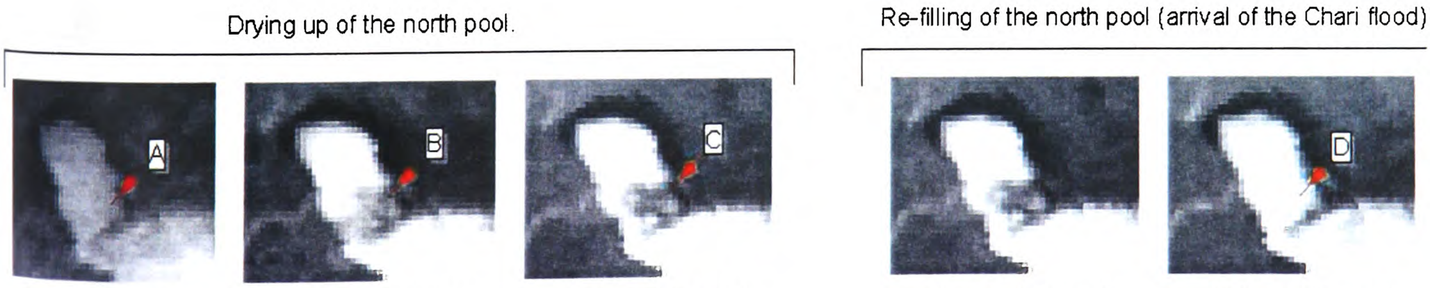


Figure 9-4: Difficulty of mapping Lake Chad extent with Meteosat thermal data during sustained cloudy spells, example of August 1995.



Meteosat thermal MVC composite 1 to 10 Sept. 2000

Meteosat thermal MVC composite 10 to 20 Oct. 2000

Meteosat thermal MVC composite 20 to 30 Oct. 2000

Meteosat thermal MVC composite 10 to 20 Nov. 2000

Meteosat thermal MVC composite 1 to 10 Dec. 2000

Figure 9-5: Difficulty of differentiating water from land during drying-up process.

At stage B, the southern part of the north pool appears neither as water (stage A) nor as dry soil (stage C). It might correspond to wet soil. However, we observe that such stage does not generally last long (high evaporation rate). Also, note that this problem does not occur during the refilling process.

9.4 MODEL DEVELOPMENT AND CALIBRATION

9.4.1 CHANGES IMPLEMENTATION

From 1960 to 2000, many conditions have changed, and this needs to be implemented into the model. We have just seen the numerous variations of Lake Chad's extent. The fluctuations in the stages of the Rivers and of Lake Chad also need to be taken into account. The model should finally include the modifications of the rainfall recharge and the human abstractions.

On the other hand, some parameters have remained constant (i.e., transmissivities, exchange with other aquifer and discharge rate). They are input into the transient model with the values obtained from the steady-state calibration. Among the limited sets of scenarios possible for a discharge and an initial recharge, a discharge rate of -1 mm/yr has been selected for the transient simulation. In fact, a higher recharge rate seems improbable and did not allow for an optimum steady-state calibration (see Ch 8.3).

With regard to the high variability of Lake Chad's extent and the fluctuations of the rivers stage, a stress period of 1 month was chosen in order to reproduce closely the hydroclimatic variations.

Lake Chad's representation

Thanks to data from multiple sources and especially from satellite images, it has been possible to rebuild the comprehensive history of the fluctuations of Lake Chad's extent (see Ch. 9.3). Variations of Lake Chad's stage were obtained from the DREM-N'Djamena. All these data were stored in the GIS from where they could be manipulated and implemented into the groundwater model.

The representation of Lake Chad's changes over the simulation period requires the use of both MODFLOW River and Evapotranspiration packages. The polygon representing the "Standard" Lake Chad in the steady-state simulation was discretised in smaller areas. Wherever the lakebed was flooded, the stage of Lake Chad was assigned to the River package according to the archived data, and meanwhile the evapotranspiration was assumed to be nil. As soon as the lakebed became dry, a stage corresponding to the bottom of Lake Chad was assigned to the river package so that the lake no longer fed the water table. When the lakebed was dry, we also assumed that the water table was affected by evaporation processes. In fact, we can consider, at least at the beginning, that the vegetation had no time to develop and that transpiration processes could therefore be neglected. In this case, the discharge flow affecting the water table only corresponded to evaporation and could be estimated with the generalised relationship established by Coudrain-Ribstein *et al.* (1998) of which an approximation was used in Modflow *Evapotranspiration* package (see Table 9-2).

$q= 71.9z^{-1.49}$ *with q the flow evaporated in mm/yr, and z the depth to the water table in metres.*

Depth to the water table (m)	2	5	10	15	20	25	30
Evaporation (mm/yr)	26	6.5	2.3	1.3	0.8	0.6	0.5

Table 9-2: Evaporation values for a free water table in arid and semi-arid areas (from Coudrain-Ribstein et al., 1998)

Rivers

Fluctuations of the rivers stages are imposed into the model according to archived data collected from the basin's institutions.

Human abstractions

Human abstractions and their evolution are applied according to estimates available (see Ch. 7-2-3).

Rainfall recharge

The rainfall recharge and discharge scenario with a discharge rate of -1 mm/yr was selected as it corresponds to the most probable situation (see Ch 8). There is no other alternative to assess the rainfall recharge change than to test various decreases of the initial values (10%, 20%, 50%).

9.4.2 CALIBRATION

The calibration consisted of minor adjustments of the transmissivities obtained from the steady-state calibration and of a search for the specific yield values in order to reproduce the observed piezometric evolution.

The model shows that over the piezometric depressions of the Chari-Baguirmi and Kadzell it is necessary to moderately decrease the values of the transmissivities in order to reproduce the decreasing trend of the piezometry. Elsewhere the values of the transmissivities do not require significant re-adjustment.

The specific yield is 25% in the dunefields. For the rest of the aquifer, a good fitting with the observed piezometry is obtained with a relatively small specific yield of 10 to 3%.

The simulated piezometry fits well with the observed data series (Figure 9-6 and Figure 9-7). There is a small shift between the observed and simulated time series, for example in Kalimba, Marbat and Kaola Djima. This can be attributed to the fact that, given the size of a grid cell, the model does not allow for a fine calibration on point measurements. Whatever the reason, the evolution trend is generally well reproduced in the southern part of the aquifer.

The drop of the water table in the dunefields can only be reproduced if an important decrease of the rainfall recharge is assigned in the model (see Ch. 9.6.3)

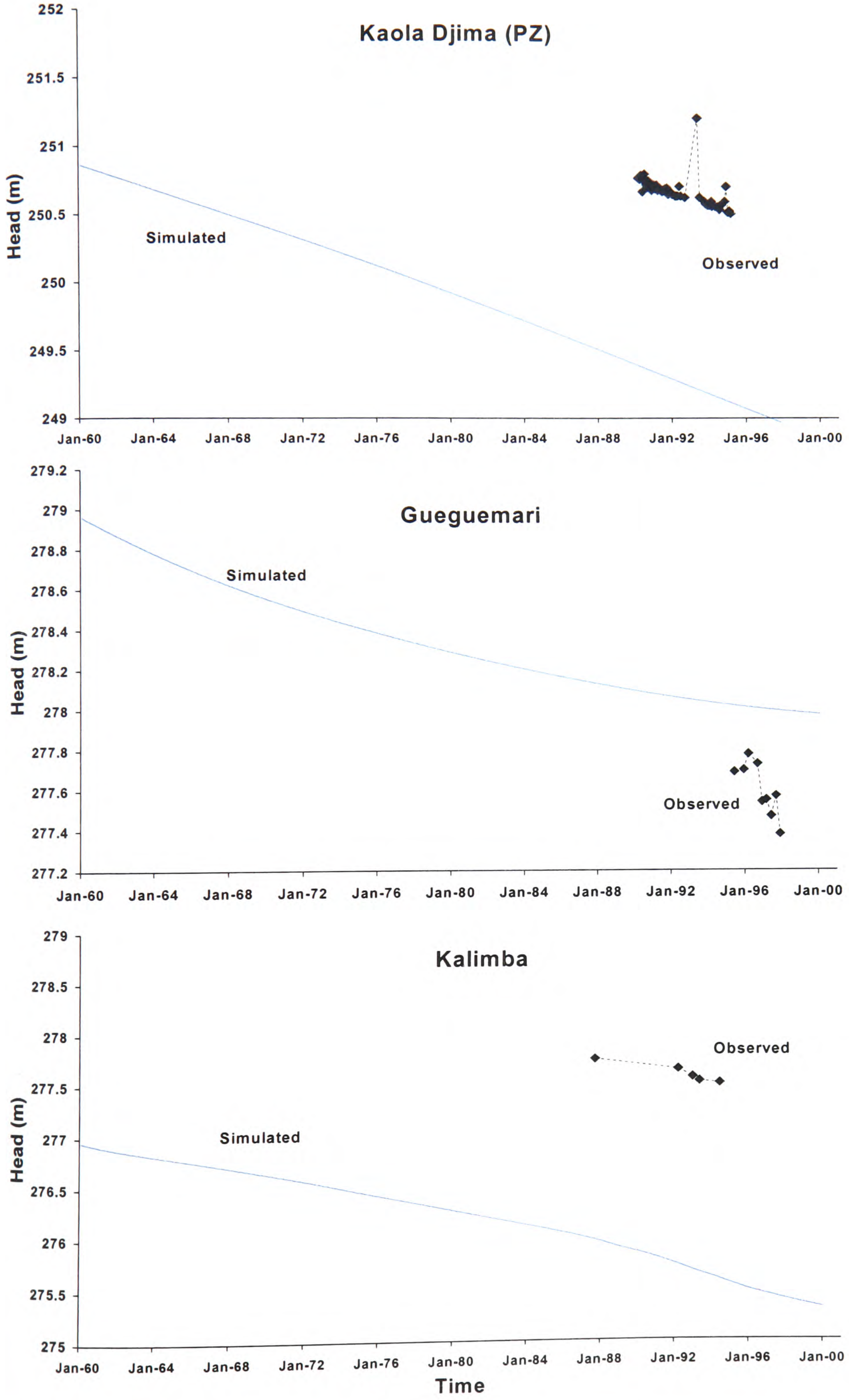


Figure 9-6: Simulated versus observed piezometry.

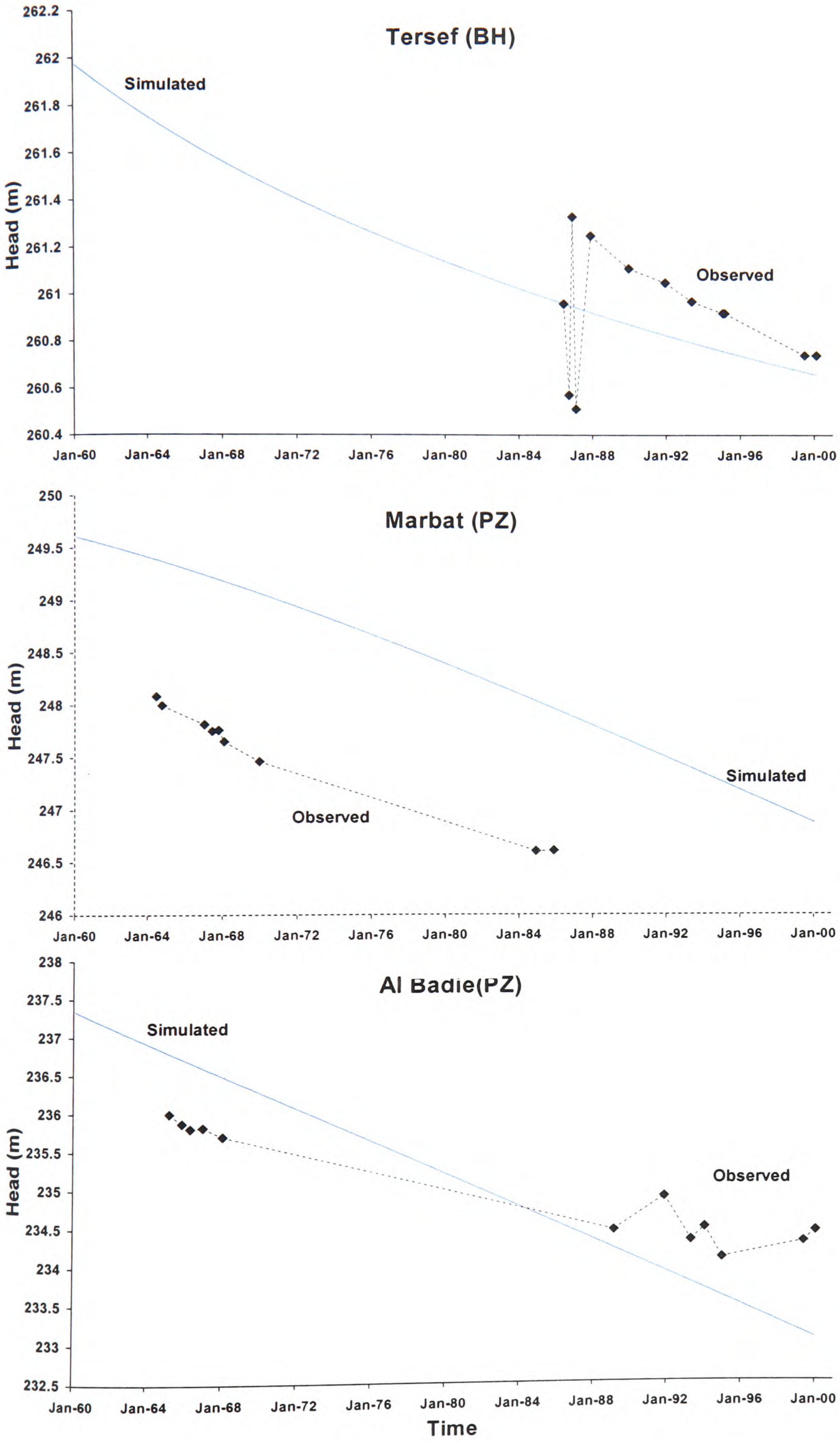


Figure 9-7: Simulated versus observed piezometry.

9.5 SENSITIVITY TESTS

With the transient simulation, it is relevant to test the sensitivity to the specific yield. The scope of the sensitivity tests is to assess what effect the uncertainty in the value of the specific yield has on the groundwater model. The magnitude of change in heads from the calibrated solution is a measure of the sensitivity of the model to the specific yield value. Tests were conducted by changing the value of the calibrated specific yield by ±20% across the entire study area. Meanwhile, other parameters remained unchanged. Results of the sensitivity tests are reported on graphs showing at a particular point the evolution of the simulated piezometry from the beginning to the end of the simulation period with the specific yield as calibrated and changed by ±20%.

Two points were selected: one in the centre of the piezometric depression of the Chari-Baguirmi (Marbat), and the other in the centre of the Kanem dunefield, piezometric dome (Ngile Kanama).

The tests at Marbat indicate that, after a simulation period of 40 years, the head is 51 cm higher with a specific yield of +20 % and 78 cm lower for a specific yield of –20 % (Appendix 9-1). At Ngile Kanama, the tests show that at the simulation period the head is 18 cm higher with a specific yield of +20% and 24cm lower for a specific yield of –20% (Appendix 9-2).

All the tests respect the decreasing trend of the observations that is observed on the water table. Sensitivity tests show that the results delivered by the model are not strongly affected by a change in the specific yield. In other words, these sensitivity tests demonstrate, to a certain extent, the veracity of the model.

9.6 MODEL APPLICATIONS: CHANGE IMPACT ASSESSMENT

9.6.1 LAKE CHAD SHRINKAGE

The model shows that the impact of Lake Chad's shrinkage on the water table is strong but limited to the lake's surroundings (Figure 9-10).

The simulation reveals that the lake's shrinkage affects all the north pool and its shoreline (Figure 9-10C). On the western shoreline of the northern pool, simulated levels have dropped by more than 10m. This is supported by field observation available in Niger (see Ch. 9.2). In the model, piezometric head at Arikoukouri appears to closely follow the interannual fluctuations of the lake. Levels drop severely as soon as the lake dries (Figure 9-8). This drop is also observed in the south-east and south-west extremes of the lake (Figure 9-10C). In fact, satellite images had earlier revealed that these areas are particularly affected by the retraction of the lake (see Poster 1).

However, an important result is that the impact on the water table of the lake's shrinkage is limited in space and does not extend far beyond the shoreline of the Lake.

The model also reveals that the situation is reversible. Figure 9-10D shows the simulated water table in the region of the lake in December 1999. It is to be analysed in parallel with Poster 1, which shows the return of a larger lake in the second half of the 1990's. One notices the important rise in the water table when comparing it with the piezometry in 1990. Levels tend to regain positions prior to the lake shrinkage.

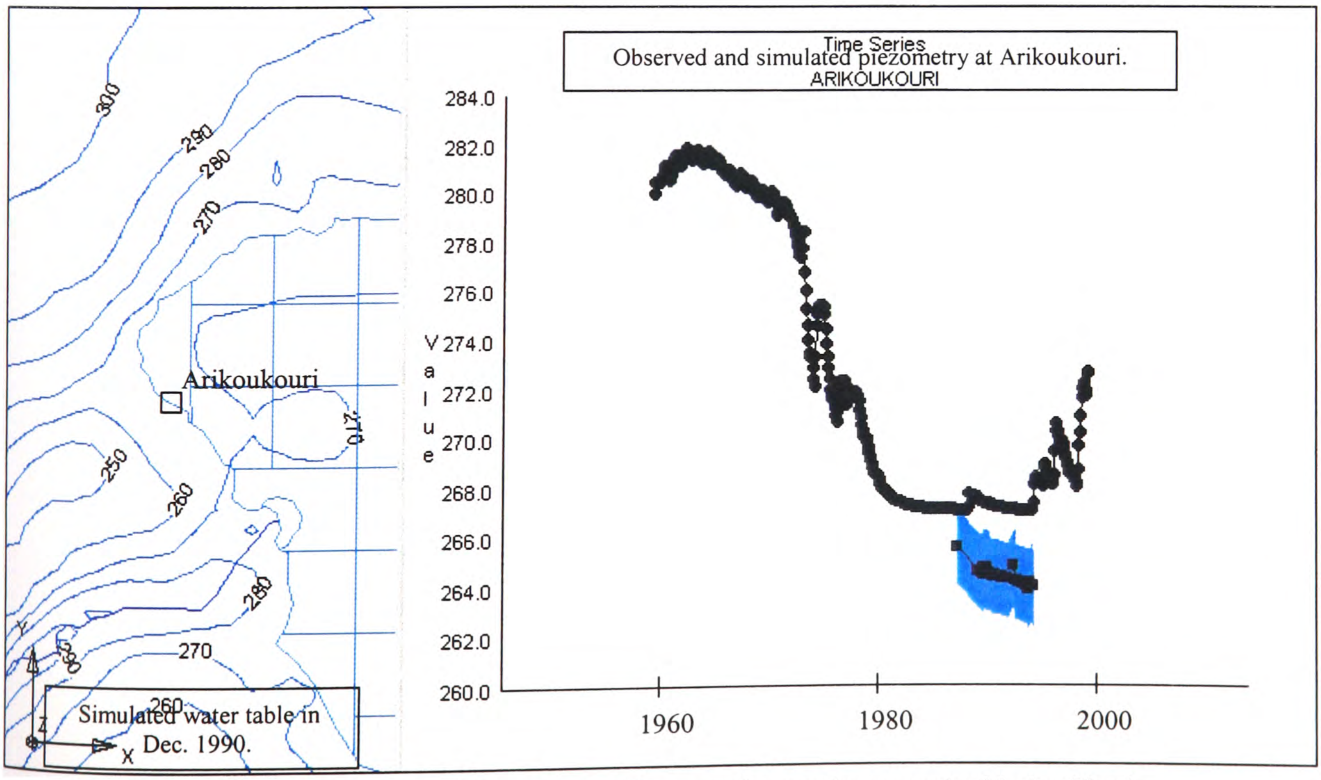
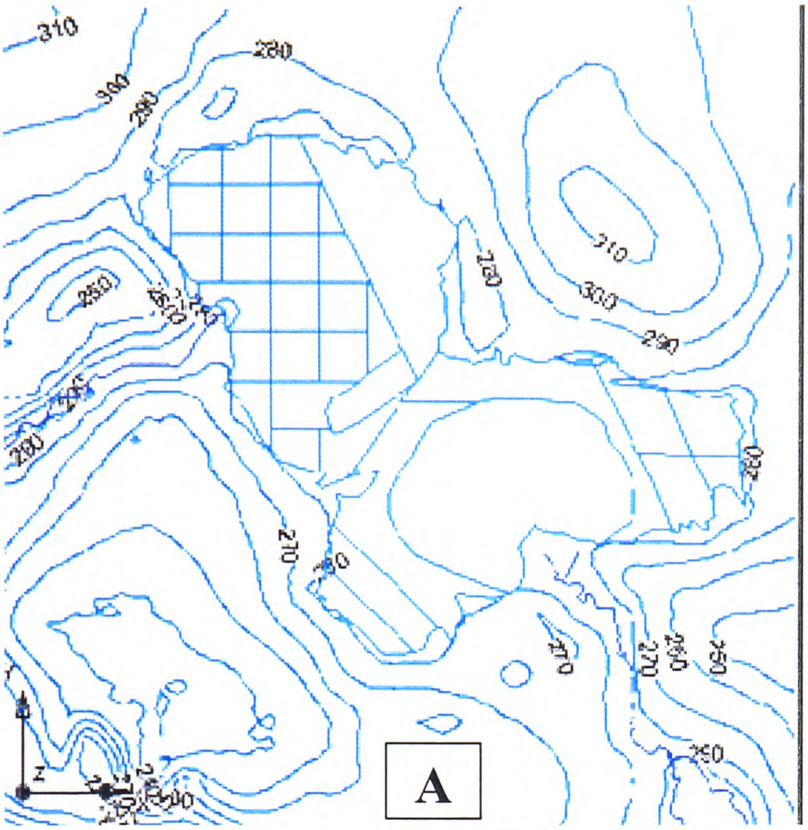
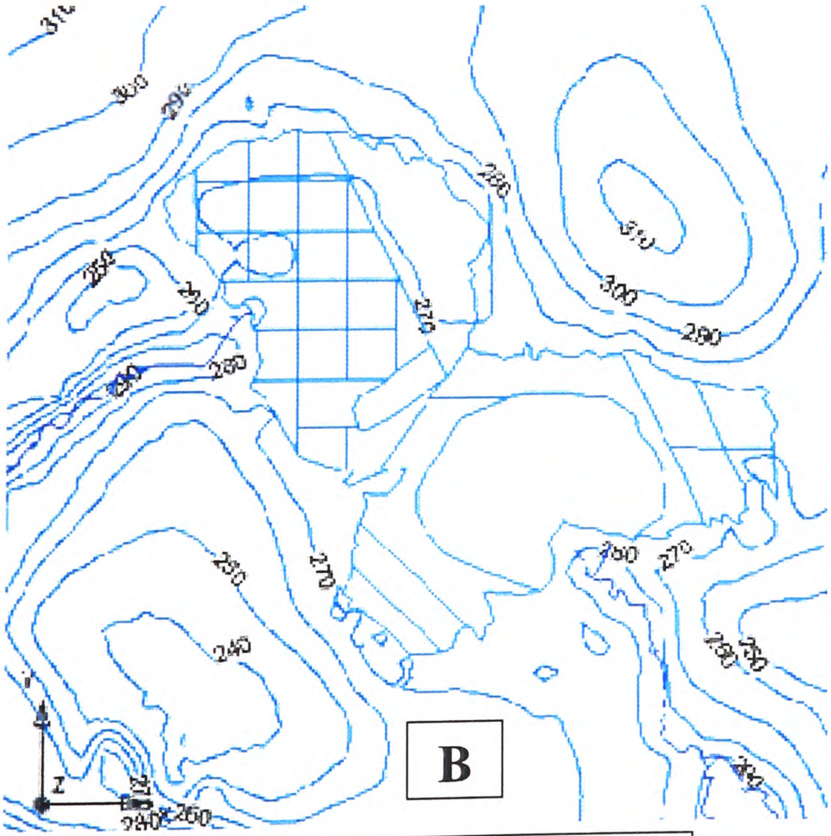


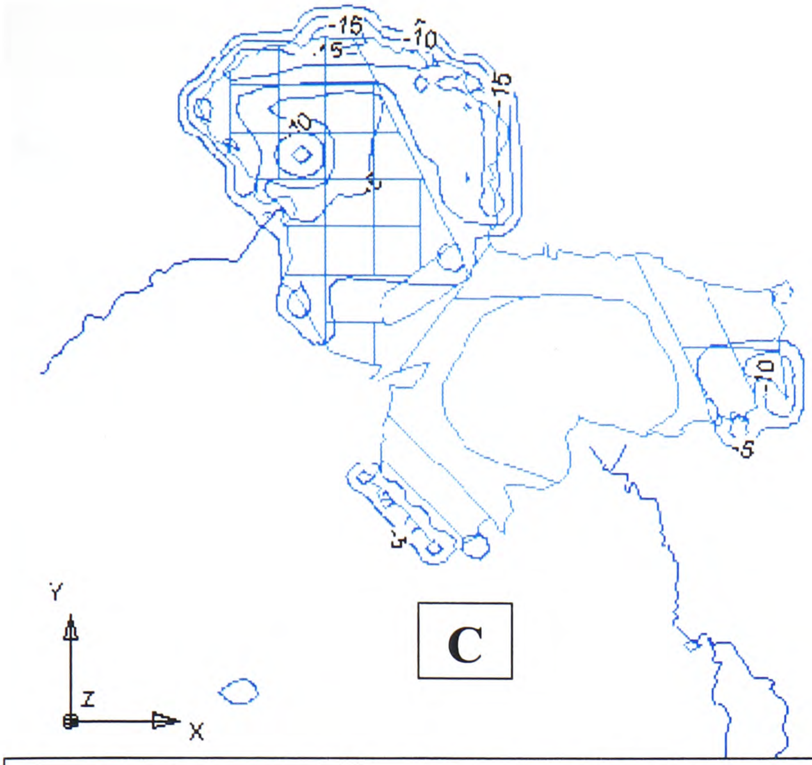
Figure 9-8: Evolution of the water table near the northern pool of Lake Chad.



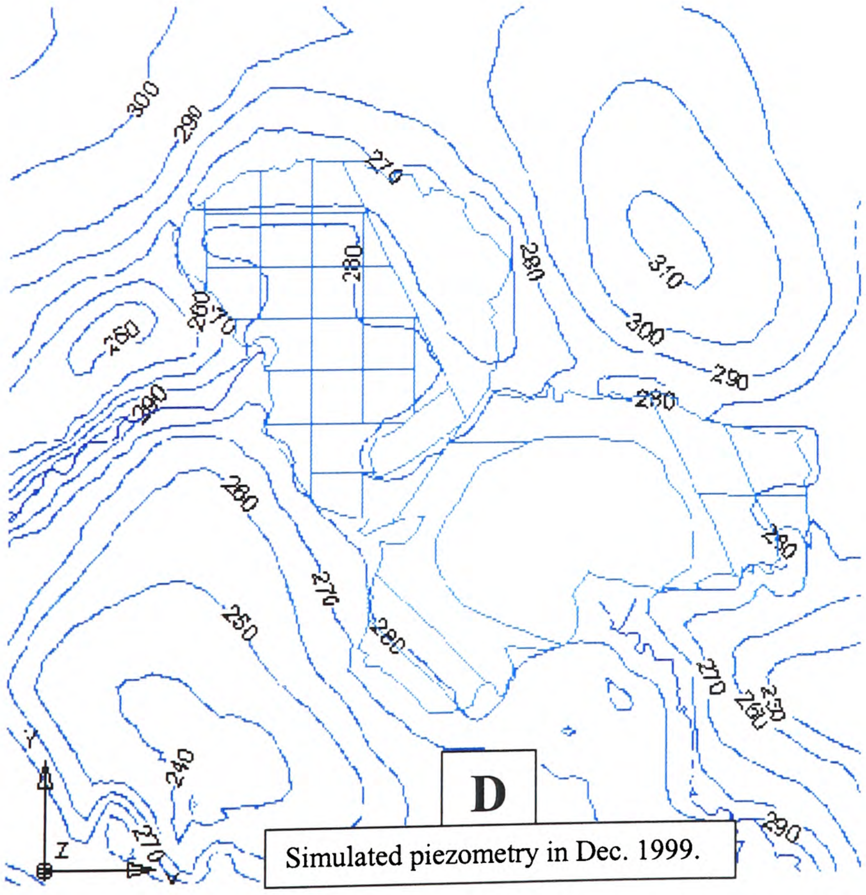
Simulated piezometry in Dec 1970.



Simulated piezometry in Dec. 1990.



Evolution of the simulated piezometry between 1970 and 1990. Contours represent the difference between the water table in 1990 and the water table in 1970 (Negative values show a drawdown).



Simulated piezometry in Dec. 1999.

Figure 9-10: Impact of Lake Chad's shrinkage on the water table.

9.6.2 HUMAN ABSTRACTIONS IMPACT

The impact of the increase in human abstractions can be assessed by comparing the results of a simulation that takes into account this change, with another simulation which assumes that abstraction rates have not changed since the 1970's.

Figure 9-11 shows the drawdown in December 1999 caused by the increase of human abstractions since 1970. The increase of the abstractions to supply the major cities (N'Djamena and Maiduguri (Table 9-3)) causes a serious drop of the water table. A small drop is also noticed in the interfluvial zone of the Chari-Logone also called "concentration zone". In fact, the population has increased considerably in this area, as people find there a "safe haven" to the drought (CIRAD-CTA, 1996).

The water table has also decreased in the region of Bol. The cause here is not the increase of the population but the intensification of irrigation. Eberschweiler (1992,1993) reports that withdrawals have increased from 1E+07 m^3/yr in 1970 to 1.8E+07 m^3/yr in 1990. The effect on the water table is certainly accentuated by the shrinkage of Lake Chad.

Unfortunately, there is not enough information available to provide an accurate calibration of the model in these areas, so that the values should be taken qualitatively. Whatever the case, it seems clear that the water table in these areas must be the object of a careful monitoring exercise.

Elsewhere, the increase of the human abstractions is not strong enough to have a significant impact on the water table.

Town	**Domestic abstractions in 1970 (m^3/yr)**	**Domestic abstractions in 1990 (m^3/yr)**
N'Djamena – Kousseri	1.18E+07	2.06E+07
Maiduguri	2.05E+06	7.16E+06

Table 9-3: Estimation of the evolution of the abstractions to supply major cities of the central part of the Basin from Eberschweiler (1992,1993).

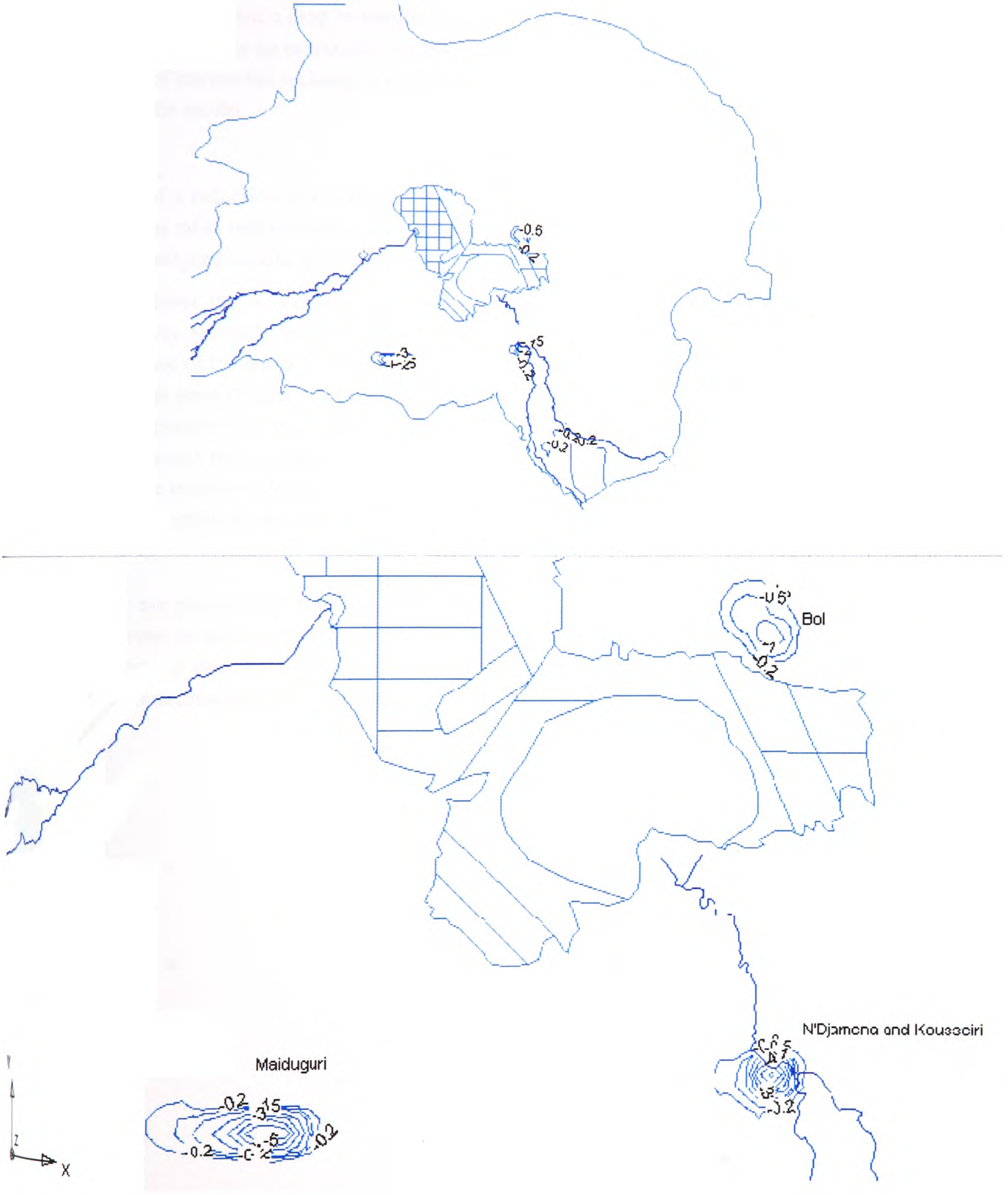


Figure 9-11: Impact of the increase of the human abstractions between 1970 and 1990 on the piezometry observed the Dec. 1999.

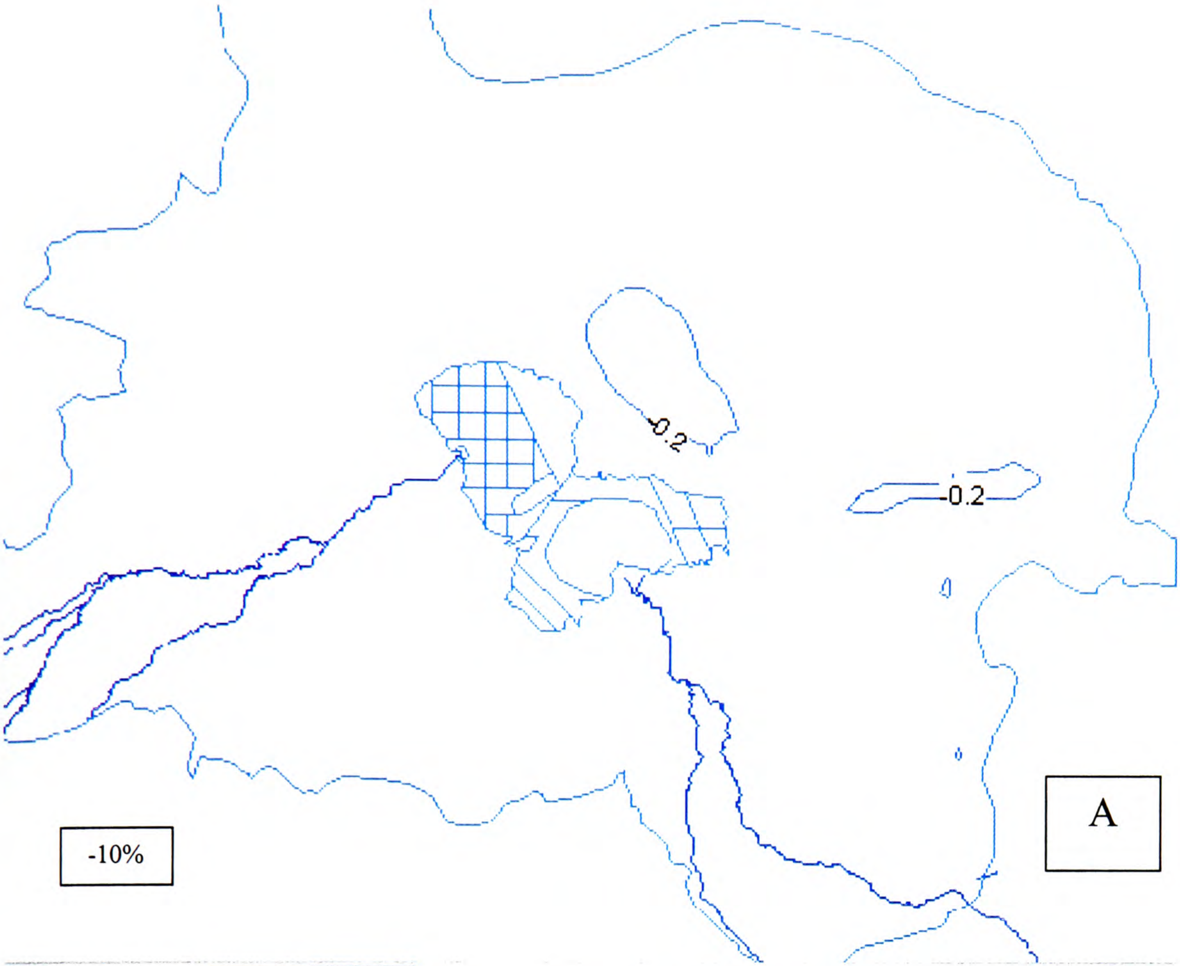
9.6.3 RECHARGE RAINFALL DECREASE

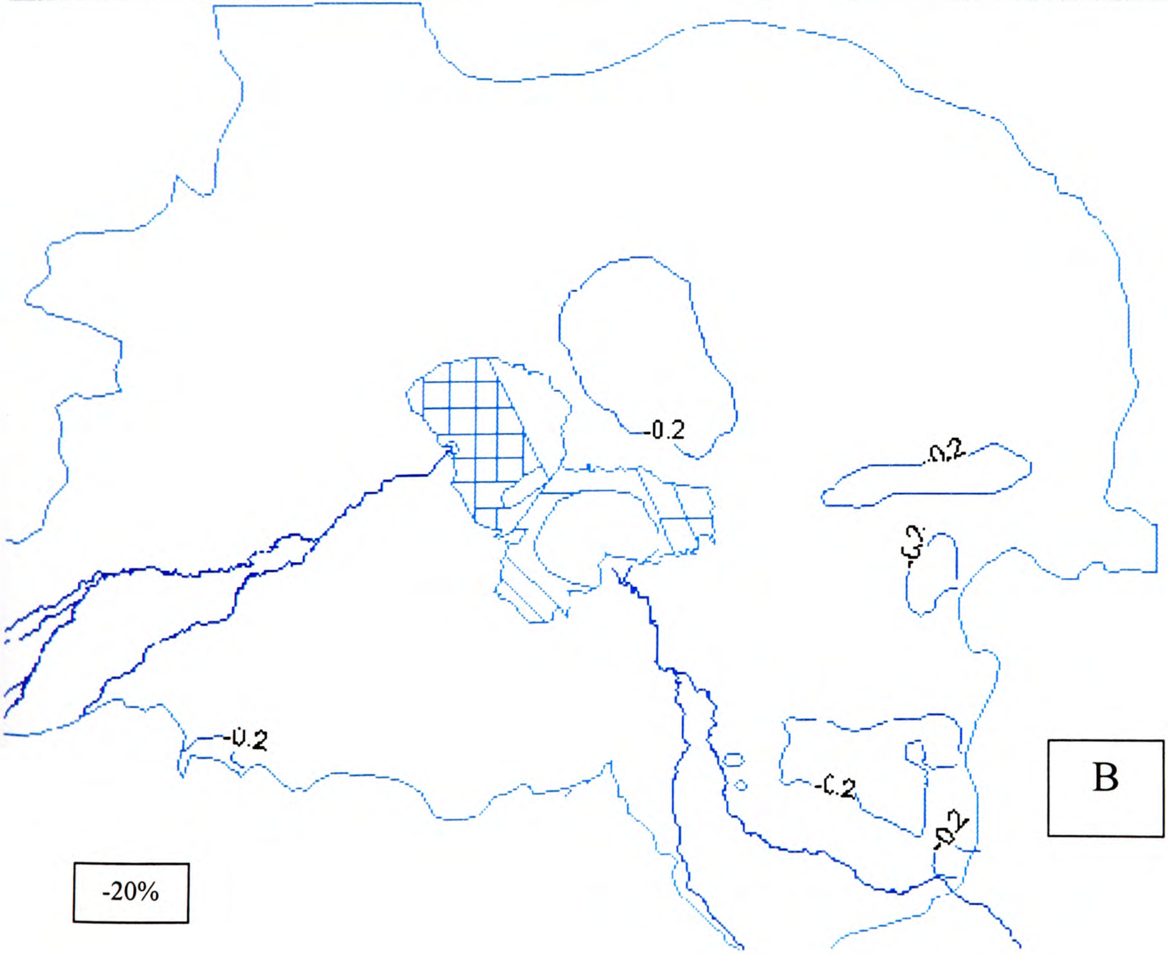
It is highly probable that a drop in rainfall recharge has followed the decrease of rainfall. Over the basin, however, there is no estimation available to quantify this phenomenon. The best way to assess the decrease of the rainfall recharge is to test several scenarios (rainfall recharge decreased by 10, 20 and 50%) in the model.

The impact of a reduction of the rainfall recharge is quantified by comparing the piezometry of a simulation that takes into account a drop in the rainfall recharge with another that does not (all other changes are assigned in both simulations).

The model shows that a decrease of 10% does not have a significant impact on the water table (Figure 9-12 A). Similarly, a decrease of 20% has a small effect on the water table (Figure 9-12 B). Only a decrease of the rainfall recharge of 50% starts to have a significant impact on the piezometry of the recharge areas (Figure 9-12 C). In the Manga, it engenders a drop of the water table by 0.2 m, which is comparable with the 0.4 m fall observed by Leduc *et al.* (1998). The centres of the Harr and the Kanem record the strongest drop with levels falling by more than 1m. This drop matches in magnitude the records of Ngile Kanaman, Abani, Ouadiounga, and Kouri Kouri, and more broadly, with the observations for the whole Kanem and Harr (see for example Eberschweiler, 1992).

Except for the piezometric depression of South Mounio, one notices that the decrease of rainfall recharge, even as strong as 50%, has no impact on the piezometric depressions. Thus, the model indicates that the slow and regular drop observed in the piezometric depressions does not seem to be related to the decrease of rainfall recharge.


-0.2
-0.2
A
-10%


-0.2
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B
-20%

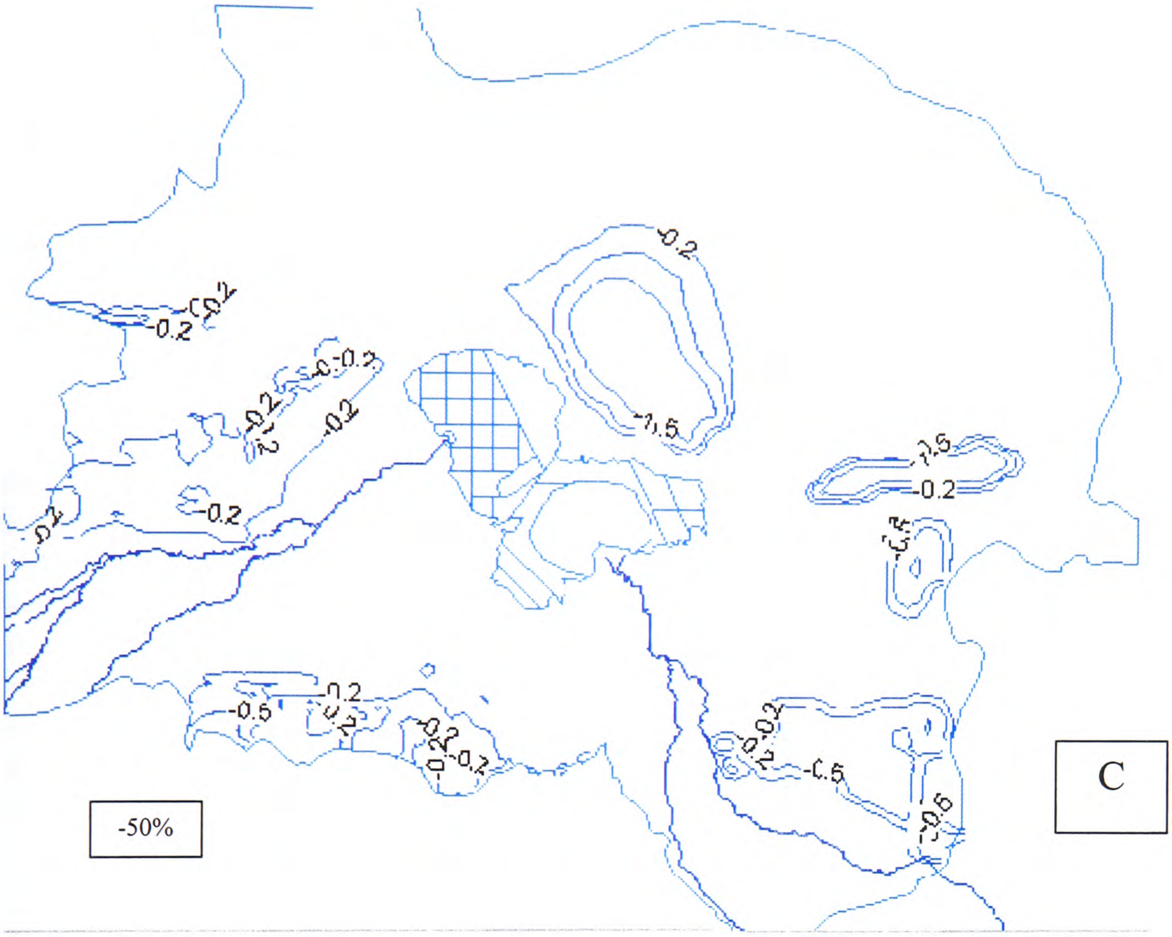


Figure 9-12: Impact of the decrease of the rainfall recharge by 10 %, 20% and 50%.

9.7 CONCLUSION

Few quality data are available to relate to the long-term evolution of the Quaternary water table. The best data available reveal, however, a regional drop of the levels. This drop is moderate in comparison with the decrease of rainfall, rivers discharges, and the extents of the surface water bodies.

Data from multiple sources, have enabled to retrace a comprehensive history of Lake Chad's surface area variations. Meteosat has proved particularly to be an excellent tool to monitor the lake's extent, which is further encouraging considering the prospect of higher resolution images with Meteosat second generation. Images have captured the harsh and long-term shrinkage of the lake, which has already been reported many times. New information shows a recent improvement of the situation, with the north pool being flooded all year long in 1999, for the first time since 1974. Beyond the regional interest, it also shows the value of satellite archive data. They are increasingly becoming an excellent way to analyse the changes in our environment, and can be used in applications such as long-term groundwater modelling.

The application of the transient groundwater model reveals that the impact of Lake Chad's shrinkage on the water table is strong, but limited in space to a relatively small area around the lake. This corroborates the field observations available.

In the model, the increase of human abstractions in major cities of the basin (N'Djamena and Maiduguri) has had an impact on the water table. Similarly, in the region of Bol irrigation affects the aquifer. Meanwhile, elsewhere the changes in human abstractions do not appear to have a significant impact on the water table.

A decrease of rainfall recharge by at least 50% fits with the existing observations. The model shows that such a decrease only generates a moderate drop, which is what one could have expected given the fact the recharge is initially small (see also, Ch. 3 and Ch. 4). The influence of the rainfall recharge decrease is limited in space to the dunefields and other recharge areas. It does not appear to affect the piezometric depressions.

On the whole, the water table has a small responsiveness or a certain inertia to external change. This can be attributed to the vast reserves of the aquifer (good hydraulic conductivity and relatively good specific yield over a large extent). This huge reserve opposes with the small recharge rates and the endorheism that also characterise the Quaternary aquifer. Therefore, with regard to water resources management, the Quaternary aquifer offers a paradox: it is characterised by vast reserves but a small renewable resource (i.e., recharge).

Chapter 10

DISCUSSION AND CONCLUSION

10.1 SYNTHESIS OF THE RESULTS

10.1.1 THE WATER RESOURCES OF THE LAKE CHAD BASIN: THE NEED FOR GIS

The scope of the thesis was to investigate the use of GIS and remote sensing for water resources assessment and management in large semi-arid areas using the Lake Chad Basin (Africa) as a case study. The introduction illustrates the worldwide relevance of this subject. In semi-arid areas, water is scarce and hydrological processes are complex and difficult to quantify. The vastness and the remoteness of most semi-arid regions have so far limited the scope of many studies. In this context, remote sensing and GIS offer valuable alternatives as, indeed, they enhance data collection, management and interpretation. Yet, up to now very few studies have fully exploited, for this kind of environment, the benefits of these technologies.

The thesis focuses on the central part of the Lake Chad Basin, and more specifically on the Quaternary aquifer. In this region, hydrological and hydrogeological processes are varied, complex, and sometimes elusive. The scarcity of water in the area means that its future development depends very much on the sustainable management of the water resources. Therefore, an understanding and a quantification of the processes affecting these resources are vital.

In the second chapter we have seen that, to date, few studies have been carried out on the Quaternary aquifer, although it is the most important water resources in the central part of the Lake Chad Basin. This aquifer presents many challenging issues to tackle: the impact of the drastic hydro-climatic change since the beginning of the 1970's (see Ch. 2); the presence of five important piezometric depressions (see Ch. 2); and the lack of consensus regarding estimations of recharge and discharge processes (see Ch. 3).

Too often the use of remote sensing in water resources remains an occasional practice (Meijerink, 1996; Rango, 1994; Rango and Shalaby, 1998). We have proved, in the fourth chapter, that the exploitation of remotely-sensed data to complement field data in a GIS greatly enhances the current level of information available to hydrologists and hydrogeologists. Therefore, in the case of the Lake Chad Basin, it offers the perspective of a better understanding of the Quaternary aquifer. Furthermore, now is an appropriate time for hydrologists and hydrogeologists to reconsider the use of satellite data because of the launch of new sensors, the willingness of satellite operators to make data readily accessible and the increase in hardware and software capacity.

10.1.2 USING GIS AND REMOTE SENSING TO MAP RECHARGE AND DISCHARGE AREAS OF SUPERFICIAL AQUIFERS IN SEMI-ARID REGIONS

The work presented in the second part of the thesis does not pretend to be exhaustive. Yet, it represents an original use of remote sensing in hydrogeology of semi-arid areas. Defining recharge and discharge areas in semi-arid regions is more than ever a hot topic. In the Lake Chad Basin, it is proposed to apply remote sensing and GIS to map groundwater recharge and discharge areas. As far as we know, never before have remote sensing and GIS been applied in such an environment - unconsolidated deposits and semi-arid area - for mapping groundwater recharge and discharge areas. This is also the first time that a comprehensive investigation of the links between surface characteristics and the Quaternary aquifer is given.

Over the piezometric depressions, we have observed for the first time with Meteosat thermal data a generalised low infiltrability of the ground (see section 6.3.4). Higher resolution Landsat data also show the absence of ponding, and therefore of localised recharge, in what appears to be very flat regions (see section 6.3). All of this reduces considerably the rainfall recharge over the depressions, so much so that evapotranspiration processes are certainly dominating vertical exchanges. The presence in the landscape of phreatophytes (Gaston, 1996), or deep rooting trees, corroborates this assumption. All these observations are the first data to support clearly the theoretical schema proposed by Aranyossy and Ndiaye (1993) in which some piezometric depressions of the Sahel are generated in areas of low recharge, and where the deficit generated by evapotranspiration processes is not compensated by lateral groundwater flows given the low hydraulic conductivity of the geological material.

In contrast with these regions, the areas where the local topography allows for dense ponding are not affected by piezometric depressions (see section 6.3). The quantitative difference between localised and direct recharge was already noticed in semi-arid areas (Favreau, 2000 b; Leduc and Desconnets, 1994 b; Leduc et al., 2001; Simmers and Hendrickx., 1997). This latest evidence confirms the importance of this fundamental distinction, which at a regional scale can make the difference between groundwater recharge and discharge regions.

It is reported that there are no tree layers over the centre of the two piezometric domes of Kanem and Harr (Gaston, 1996). This, in addition with the relatively deep depth to the water table, implies very small evapotranspiration processes and thus a higher regional recharge (see section 6.2.3).

Elsewhere in the dunefields, active oases can be spotted easily during the dry season, as they are the only remaining areas with high vegetation activity. To sustain this high activity during the dry season it is interpreted that oases are pumping water from the Quaternary aquifer and thus correspond to small discharge areas (see section 6.3.5).

Overall, our results highlight the importance of surface characteristics in groundwater recharge and discharge processes of semi-arid areas. Remote sensing and GIS appear to deliver considerable information on this matter.

Elsewhere, the same methodology could be used to map other recharge and discharge regions. We do not believe in the uniqueness of the results obtained on the Quaternary aquifer. Many superficial aquifers of semi-arid areas appear to be sensitive to surface characteristics (Dillion and Simmers, 1998; Simmers and Hendrickx., 1997).

In the Quaternary aquifer, as probably in other unconsolidated formations, factors of recharge and discharge distribution do not only depend on the rainfall but are also embedded in the surface characteristics (the topography, the vegetation, the geology and the soil infiltrability). The key of a successful method relies in the combined use of remote sensing to gather new data, and GIS to analyse multi-source information. The study should start by the gathering of all maps available. However, as we have illustrated (see Ch.4) one should not be satisfied with these maps, and use satellite data for further investigations. Satellite data can provide spatially accurate information which allow change detection. Yet, the utmost advantage of satellite data is to offer specific key indicators that are not reported on published maps. For example, we used them to detect ponding and make the distinction between regions where diffuse recharge takes place from regions where localised recharge occurs. Very low infiltrability areas can be mapped at the end of the rainy season with remotely sensed data on soil moisture. In the dry season, discharge areas might be indicated by active vegetation.

As a general rule in semi-arid areas, it is necessary to cross-check the results. In our case, this was done via the groundwater model.

10.1.3 GROUNDWATER MODELLING WITH GIS AND REMOTE SENSING

We developed a groundwater model because it is an ideal tool to comprehend and manage the Quaternary aquifer. For instance, it could provide the first step towards an integrated system for the water resources management in the central part of the basin.

Enhancing the groundwater model with GIS and remote sensing

Thanks to GIS and remote sensing, the model makes a comprehensive and avant-garde use of field and remotely-sensed data. This has enabled us to represent the Quaternary aquifer (500,000 km^2) as a whole and also to simulate all the major changes that have affected the Lake Chad Basin from 1960 to 2000 including hydroclimatic variations. This is, as far as we know, the first time that such a large superficial aquifer of the Sahel has been modelled so thoroughly.

In steady-state, the calibration has indicated a restricted set for the distribution and the value of recharge and discharge processes. These results of the model calibration clearly corroborate the outcomes of applying GIS and remote sensing to map groundwater recharge and discharge areas (see section 8.2). Hereafter, it was possible to use GIS and remote sensing in order to delineate more precisely the recharge and discharge areas assigned in the model (see section 8.3). This constitutes, to the best of our knowledge, a novel application in groundwater modelling of semi arid areas.

The model was then extended in transient mode to simulate the evolution of the water table from 1960 to 2000. Thanks to GIS and satellite data it was possible to build and implement in the groundwater model the fluctuations of Lake Chad's extent for the whole period (see section 9.3). Such an extensive use of remotely sensed data in a hydrogeological model represents a novelty. This shows the value of archived satellite data to relate of environmental changes and to build long-term groundwater models.

Water resources assessment

The steady-state model indicates that the aquifer dynamics are characterised by small flows. This is supported by the small hydraulic gradients observed throughout the whole of the aquifer, and the fact that the system has only limited outflows possible. In fact, the model shows that the outflow towards the Lowlands, to the north-east of the aquifer, is limited to less than 100E+06 m^3/yr. Other regional discharge areas are the piezometric depressions where evapotranspiration processes dominate vertical exchanges. The model indicates that even a small discharge is enough to recreate the piezometric depressions as observed. Thus, this simulation endorses the conceptual schema of the piezometric depressions described earlier in the conclusion (see above).

A regional rainfall recharge takes place in the dunefields and the areas of ponding (localised recharge). The figures are small, but one must notice that in the dunefields the regional recharge estimated with the model represents the net difference between rainfall recharge and discharge taking place in the active oases.

Recharge from Lake Chad is assessed to be approximately between 40E+06 m^3/yr to 100E+06 m^3/yr, which is much lower than previous estimations (Carmouze et al., 1983; Isiorho et al., 1996; Roche, 1980).

The analysis of the most reliable long-term piezometric data available shows that from the beginning of 1960's to the end of the 1990's the water table has, regionally, recorded a relatively small drop (see section 9.2).

In agreement with field records, the transient model shows that the severe shrinkage of Lake Chad has a strong impact on the water table, but that this effect is limited in space to the vicinity of the shoreline of the earlier "Standard" Lake Chad (see section 9.6.1).

In the densely populated areas that are N'Djamena, Maiduguri and the interfluvial zone of the Chari-Logone ("concentration zone"), the model shows a strong impact of the increase in human abstractions. In the region of Bol, intense irrigation also produces a drop of the water table. Throughout the rest of the region, human withdrawals do not appear to cause a noticeable drop of the water table (see section 9.6.2).

In the recharge areas, a decrease of the rainfall recharge by at least 50% is in accordance with the drop of the water table observed (see section 9.6.3).

Overall, the water budget of the aquifer points towards the endorheism of the system with most of the outflows assured internally. Also, with regard to water resources management, the Quaternary aquifer present a paradox: it is characterised by vast reserves (good hydraudynamic characteristics over a large extent), but a small renewable resource (recharge). These characteristics explain why the hydroclimatic change since the 1970's has had a limited impact on the observed water table levels.

Because of these huge reserves, it is recommended to use transient rather than steady-state simulations to work out the impact of the increase of human abstractions. Bonnet and Meurville, 1995 obtained, with a steady-state model, that the increase of N'Djamena abstractions causes a drop of the water table over most of the Chari-Baguirmi region and particularly in the centre of the piezometric depression, an area located some 150 km away from N'Djamena. In fact, such a steady-state would only be observed after a very long time (probably several thousand years).

Nevertheless, in areas of intense abstractions (major populated zones and irrigation areas) the transient model we developed shows that the aquifer may be at risk. Therefore, we specifically recommend a close monitoring of the Quaternary water table in the region of Lake Chad, as well as in major populated and irrigation areas. These latest sensitive zones could also be the subject of local groundwater models.

Groundwater modelling with sparse data. What confidence can we have in the groundwater model of the Quaternary aquifer?

The groundwater model of the Quaternary aquifer has been done in the absence of much hydrogeological data and with a high degree of freedom. Under such circumstances, it is necessary to comment on the quality of the outcomes and on the degree of confidence one can have in the groundwater model.

Compelling arguments

A series of facts support the reliability of the groundwater model we developed. Because of this, it is reasonable to say that despite the sparse data available we can have a relatively good degree of confidence in the groundwater model.

The first point is to reaffirm that the finite difference model employed (MODFLOW) is perfectly adapted to the problem: groundwater flow in porous media. Similarly, we have no reason to believe that Dupuit's assumption cannot be employed (2D areal model).

Efforts have been made to offer the best simulation of the Quaternary aquifer possible:

- Critical review of recharge and discharge processes;
- Critical review of human abstractions;
- Critical review of all hydrodynamic parameters available (piezometry, transmissivity, specific yield);
- Discussion on the best way to represent the boundary conditions – Lake Chad and the rivers are represented with MODFLOW river package. Exchanges with lateral aquifers represented with MODFLOW well package (series of wells) ;
- Improvement of the groundwater model thanks to GIS and remote sensing.

The steady-state model at the end of the 1960's is largely dedicated to the estimation of the aquifer's recharge and discharge. The literature review highlights the wide range and the discrepancies between the estimations proposed by various authors to date (see Ch. 3). The approach adopted was to test during the calibration of the groundwater model many different scenarios to screen most of the range of possibilities. It appears that the characteristics of the piezometry and of the geological material are such that only a limited range of recharge and discharge allows the representation the aquifer. In other words, although we have started the modelling with a high degree of freedom regarding the recharge and discharge, it is not possible to model the Quaternary aquifer with most of the values. For the relatively small range of possible recharge and discharge, the simulated piezometry and the model's transmissivities match correctly the field observations. This reinforces the confidence we have in the model.

Another argument supporting the groundwater model is the fact that the calibration of the steady-state model points to a similar spatial distribution for groundwater recharge and discharge areas as the one obtained independently with remote sensing and GIS. There is coherence between the groundwater model and the outcomes of remote sensing and GIS (see Ch. 6). For example, the model indicates that there is rainfall recharge in Manga, but that it is not very high (less than 1 mm/yr). Satellite images of vegetation activity reinforce this result. They reveal that in fact this region has many active oases. During the dry season the vegetation of these oases remains active and pumps water from the water table. Therefore, regionally and over one year, the evapotranspiration in the active oases contributes to maintain a small net annual recharge in Manga.

The transient model uses the outcomes of the steady-state model (map of recharge and discharge, map of transmissivity, same type of boundary conditions). It shows coherent results and simulates correctly the observed variations of the water table.

Limitations

The groundwater model has, nevertheless, some limits that must be highlighted. No matter how good it is, this is not the definitive model of the Quaternary aquifer. On the opposite, we regard it as a first step and we hope that it will evolve as our knowledge of the area improves and more data are gathered. Thus, results of the model must be taken with caution and values mentioned in the thesis represent more an order of magnitude than an `ultimate′ quantification.

The steady-state calibration has shown that only a limited range of recharge and discharge is workable. Yet this also means that there is still a certain range of possibilities, and therefore, of uncertainty. In steady-state, estimations reported for the water budget of the aquifer and for the contribution of various features (Lake Chad, rivers, recharge and discharge) account for this uncertainty. However, in transient it was not possible (given the time constrain of this project) to test the various scenarios possible. The simulation was only done for the most probable situation (a discharge rate of −1mm/yr in the piezometric depressions).

Also in transient, there is not enough reliable long-term piezometric measurement to calibrate the model. To improve the quality of the model, a priority is to acquire quality long-term piezometric measurements. This would allow a good monitoring of the aquifer and better transient calibration. Eventually, the finer the calibration and the more reliable the simulations.

At the moment, the transient groundwater modelling results should be taken qualitatively and not quantitatively.

More aquifer pumping tests are also necessary. They would allow a better identification of the aquifers hydrodynamic properties (transmissivity, specific yield) and hopefully to narrow down the model's degree of uncertainty.

Another limitation of the model is the fact that the size of the grid cells is coarse (10 by10 km at least). Therefore, the model cannot be used to study seasonal fluctuations and local problems.

We must emphasise, once again, that the model calculates a net recharge or discharge. This represents the annual budget between seasonal recharge and seasonal evapotranspiration, but it is not possible to work out the value of each individual term.

10.2 FURTHER WORK AND PERSPECTIVES

Lessons, from this research work tell us that surface characteristics have a strong influence on the dynamics of the Quaternary aquifer. In this context, satellite data appear to be a very valuable source of information to hydrogeologists, and can be used to map recharge and discharge areas. In other semi-arid regions of the World, similar interactions between surface characteristics and superficial aquifers are highly probable. Therefore, an extension of the work presented in this thesis would be a similar use of GIS and remote sensing to detect recharge and discharge features in other regions of the Sahel or, more largely, of the World.

Alternatively, GIS and remote sensing brought a great improvement in the groundwater modelling. The example of the Lake Chad Basin shows that applications can go far beyond the traditional use of GIS to store and manipulate data for the model. GIS and remote sensing can reveal concealed and long-term information that significantly enhanced the groundwater modelling. We recommend that the same approach should be considered in the modelling of other superficial aquifers of semi-arid areas. To demonstrate the veracity of this recommendation an extension of this thesis would be to undertake the same modelling approach for a different case study.

Time and budget restrictions have limited the extent of the work that we carried out on mapping recharge and discharge areas with GIS and remote sensing. In the Lake Chad Basin it would be possible thus to investigate this matter in greater detail. Pond detection needs to be improved. We have shown the importance of ponding, but there is still a need for operational method to allow systematic detection of ponds. This involves probably working with high spatio-temporal resolution data and cloud free data. For the vegetation, there is a need to quantify more precisely the density of trees. Also, deep-rooting trees need to be mapped specifically. There is finally a need to assess the change in the vegetation during the 20th Century, and particularity of the tree layer. In the Sahel, near Niamey, Favreau (2000) and Leduc et al. (2001) demonstrate that the impact of deforestation has been even more important than the decrease of the rainfall and has caused a rise of the water table by about 3.5m on average since the 1950's. At the border of the Quaternary aquifer, Barber and Dousse (1965) report a rise of the water table in KeriKeri Formation (Continental Terminal) following deforestation. Deforestation is a generalised problem in Africa. Also it has certainly affected the Lake Chad Basin and the testimonies we gathered confirm this. Yet, in the Lake Chad Basin, the few piezometric data available show regionally a relatively small drop of the water table (see section 9.2). It is not quite clear what in this context leads either human impact on the environment or rainfall change to govern the evolution of superficial aquifers. Here, satellite imagery could be used for a detailed and comparative study of the evolution of the surface characteristics and could provide some answers.

In semi-arid regions, transpiration processes depend on the species, the soil moisture content, and above all the depth (Brunel et al., 1997; George et al., 1998). To date, little is known about transpiration processes at great depth (more than 10 m) in semi-arid areas. The map of the water table reveals that in the regions where evapotranspiration is believed to be predominant (piezometric depressions) the depth to the water table generally exceeds 20 m. Unfortunately, as far as we know, there is no estimation available on the quantity that the trees, and particularly the phreatophytes, can extract from the water table at such depths. These estimations are needed. They would allow us to quantify more accurately the discharge processes taking place in the depressions and to narrow down the water budget of the Quaternary aquifer.

The use of radar data needs to be explored as soon as their cost becomes more accessible. They could be used to measure soil moisture change circa the rainy season and to build a high-resolution DEM of the region. We have no doubt that such data set would be very valuable. It would help to fill the gaps in lack of data regarding topography measurements (see Ch. 4). This would give more information on the variation of the local topography and could indicate more accurately where ponding can take place.

The future of the Lake Chad Basin is very much dependent on its water resources. Climatological models show different forecasts for the Sahel and Central Africa (Houghton et al., 2001; Hulme et al., (in press); McCarthy et al., 2001). Nevertheless, all the models seem to agree on relatively modest future rainfall changes, at least in relation to present day variability. The groundwater model could be used to test different scenario such as the impact on the very long-term of a decrease of the rainfall recharge, an increase in human abstractions, a reappearance or, more sadly, a total disappearance of Lake Chad.

NOTES ON PERIPHERAL FINDING

10.3 SATELLITE EVIDENCE OF A MEGA LAKE CHAD

While examining satellite images of the basin, particularly the large high-resolution mosaics, we collected some interesting information. Although it is peripheral to the thesis, it is still of great interest and needs to be reported. More details will be published in a forthcoming paper.

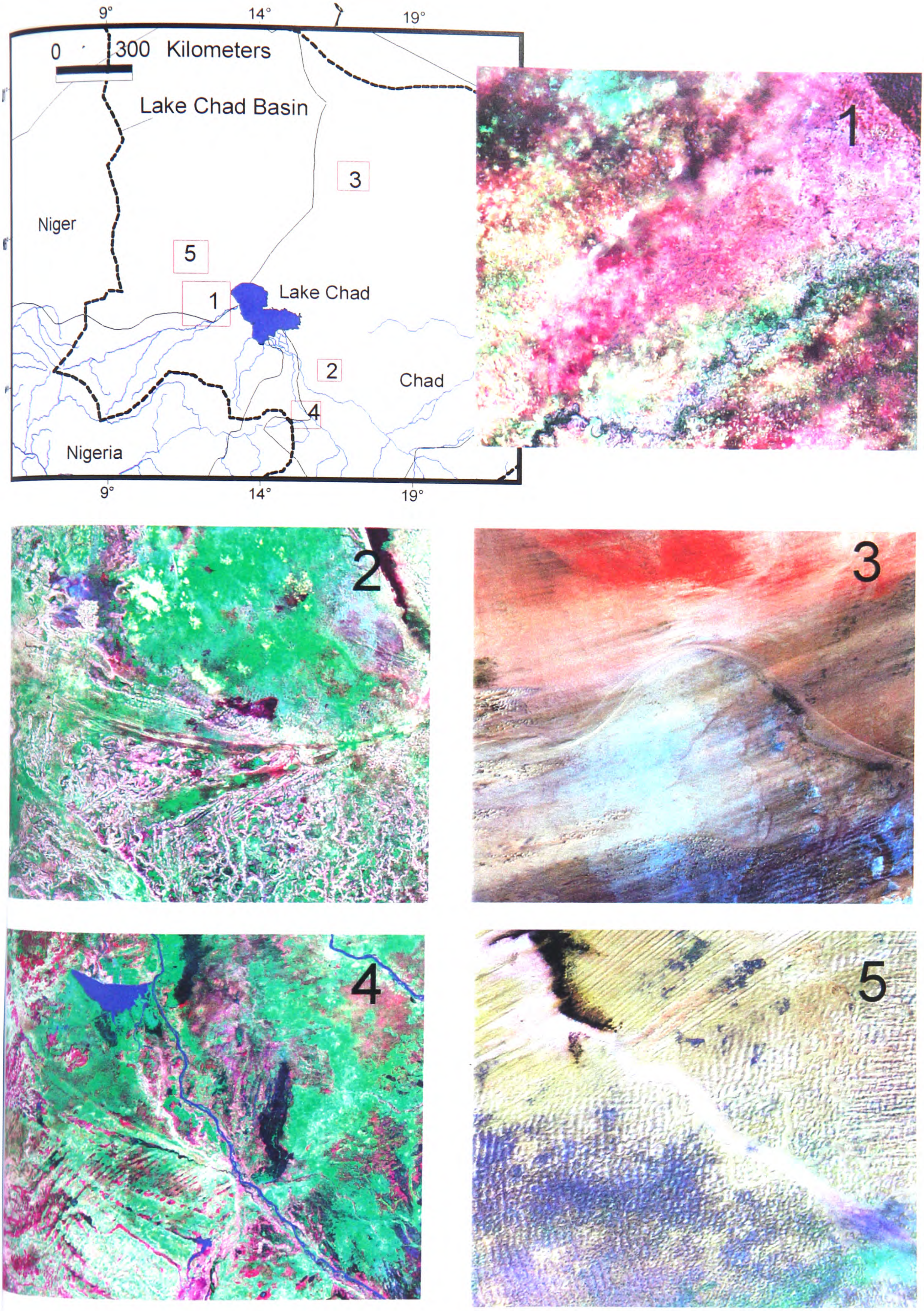
Tilho (1925, 1926) was the first to mention the possibility of huge paleo Lake Chad. Later, Schneider (1967, 1992, 1995) and Pias (1970) reinforce this hypothesis and affirmed the existence of what is now called a Mega Lake Chad. However, recent works have refuted the reality of this Mega Lake Chad (Durand, 1982, 1995; Fontes and Gasses, 1991). For Durand (1982, 1995) particularly, the pseudo perilacustrine ridge described at the 320m level is discontinuous with various morphology, altitude and facies. For the author, the geological features that are observed correspond in fact to neotectonics structures.

Our contribution to this debate is the following. High resolution satellite images show evidence supporting the existence of a Mega Lake Chad (see Figure-note1):

- We observe clearly what is an almost *continous* boundary feature drawing a very large and closed loop all around the central part of the Lake Chad Basin. It occupies the position that Schneider mapped as the paleoridge of a Mega Lake Chad at 320 m;
- On the satellite images this feature can be interpreted as a paleo-ridge because of its shape, disposition and sharp edges;
- At the location of the Mayo Kebi this feature meets with an outlet to the sea: the Benue basin;
- Satellite images show large paleo-rivers coming from mountainous regions that are now located in the Sahara.

It is really difficult to believe that such a closed loop covering very large extent correspond to a tectonic feature as suggested by Durand 1982.

The centre of the Lake Chad Basin is very flat so that a small fluctuation of Lake Chad level generates large change in its extent. Why would Lake Chad stay at a particular level and create an important paleo-ridge? The fact that Lake Chad had found an outlet to the sea is probably enough to explain that the level of the lake stabilised at this particular stage.



ure - note1: Examples of evidence of a paleo Mega Lake Chad with Landsat TM mosaic from NASA. eo ridge in Kadzell, Niger; 2 Paleo ridge in Massenya region; Chad, 3 paleo ridge in the north of Chad; paleo ridge meets the benue basin and an outlet to the sea; 5 the large river of the Dillia, Niger.

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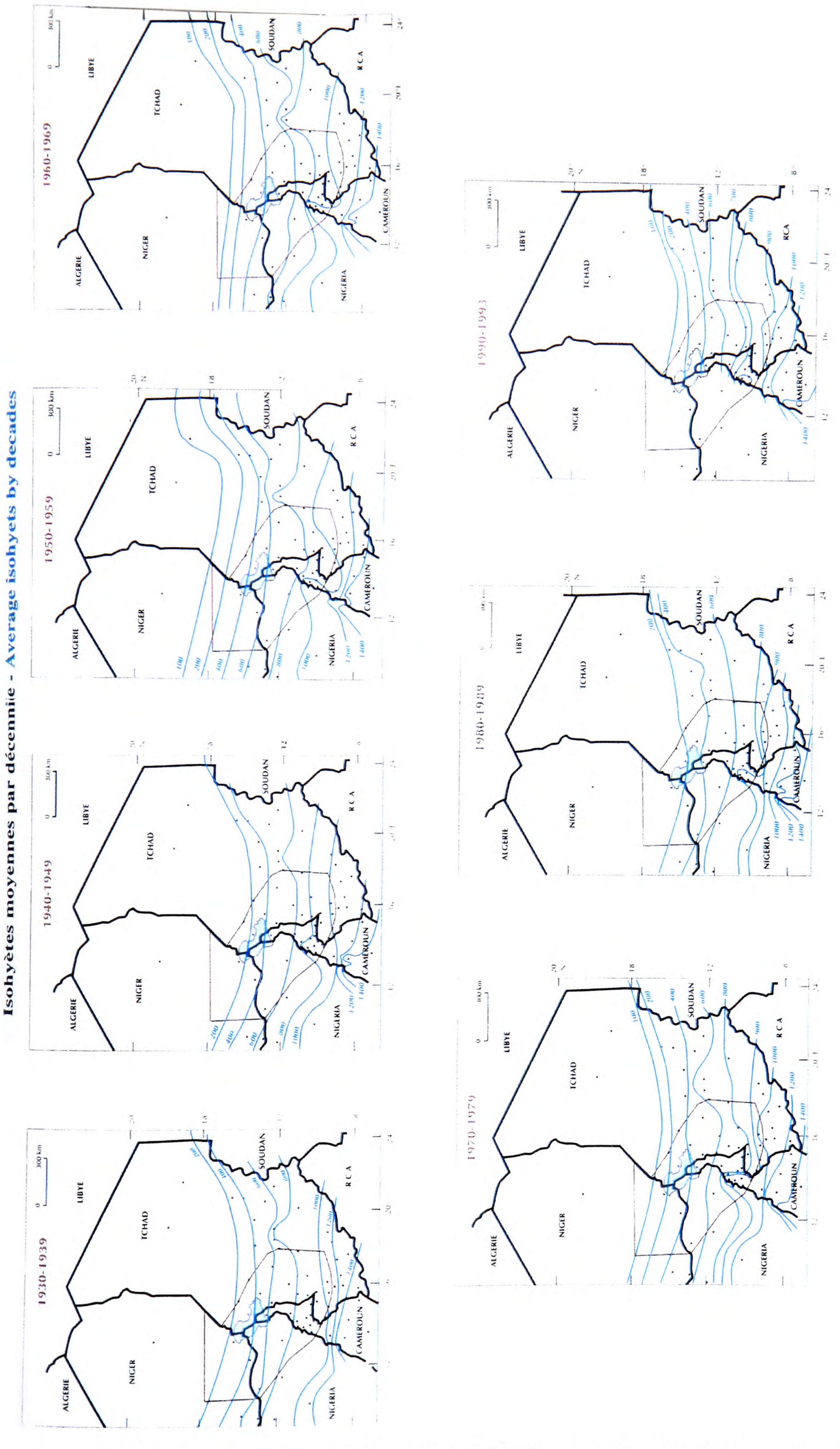
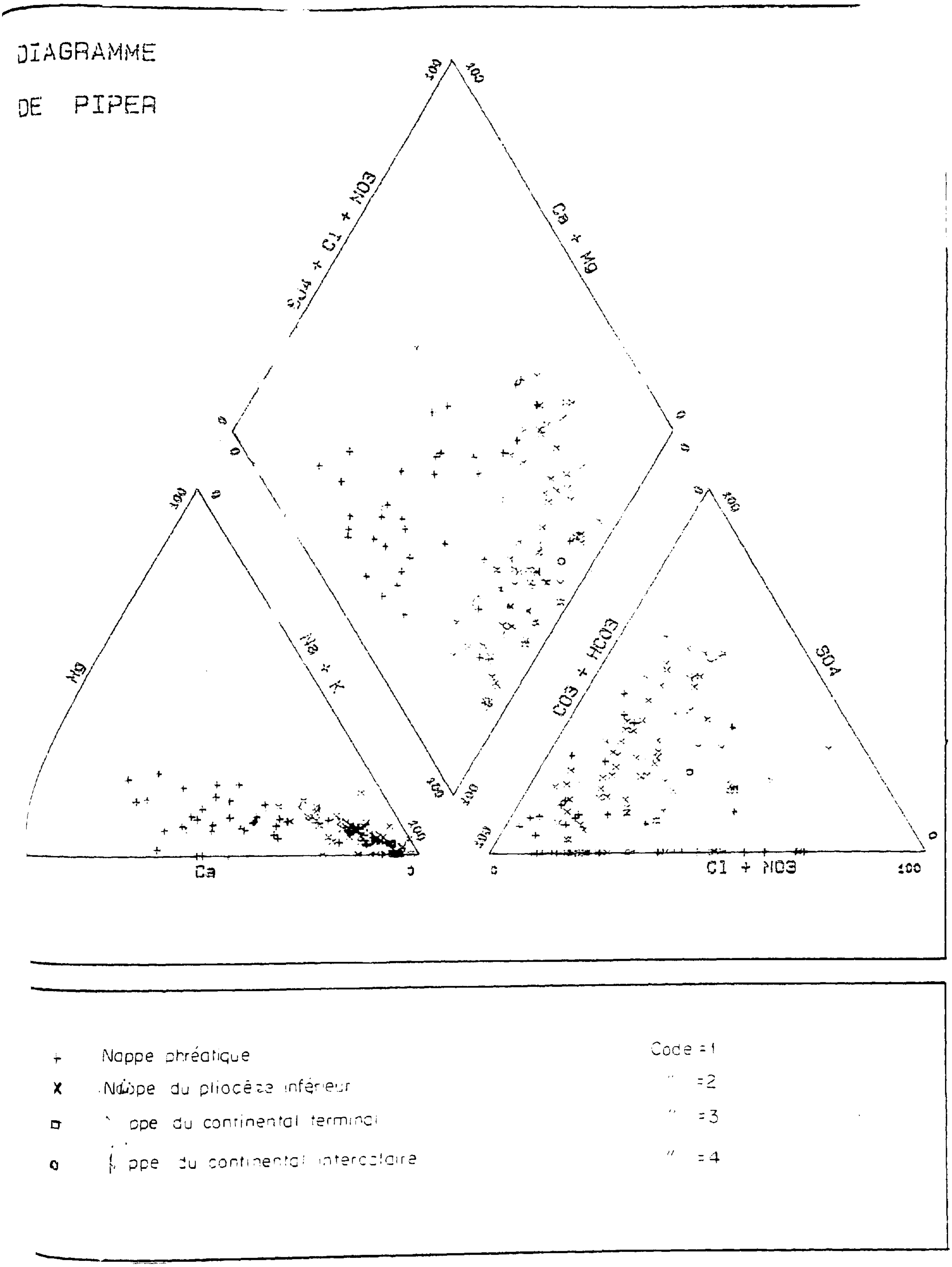
APPENDIXES



Appendix 2-1: Interdecadal variability of rainfall in the central part of the Lake Chad Basin (from Beauvilain 1996).



Appendix 2-2: Hydrogeochemical facies of the main aquifers in the Lake Chad basin (from Eberschweiler 1992).

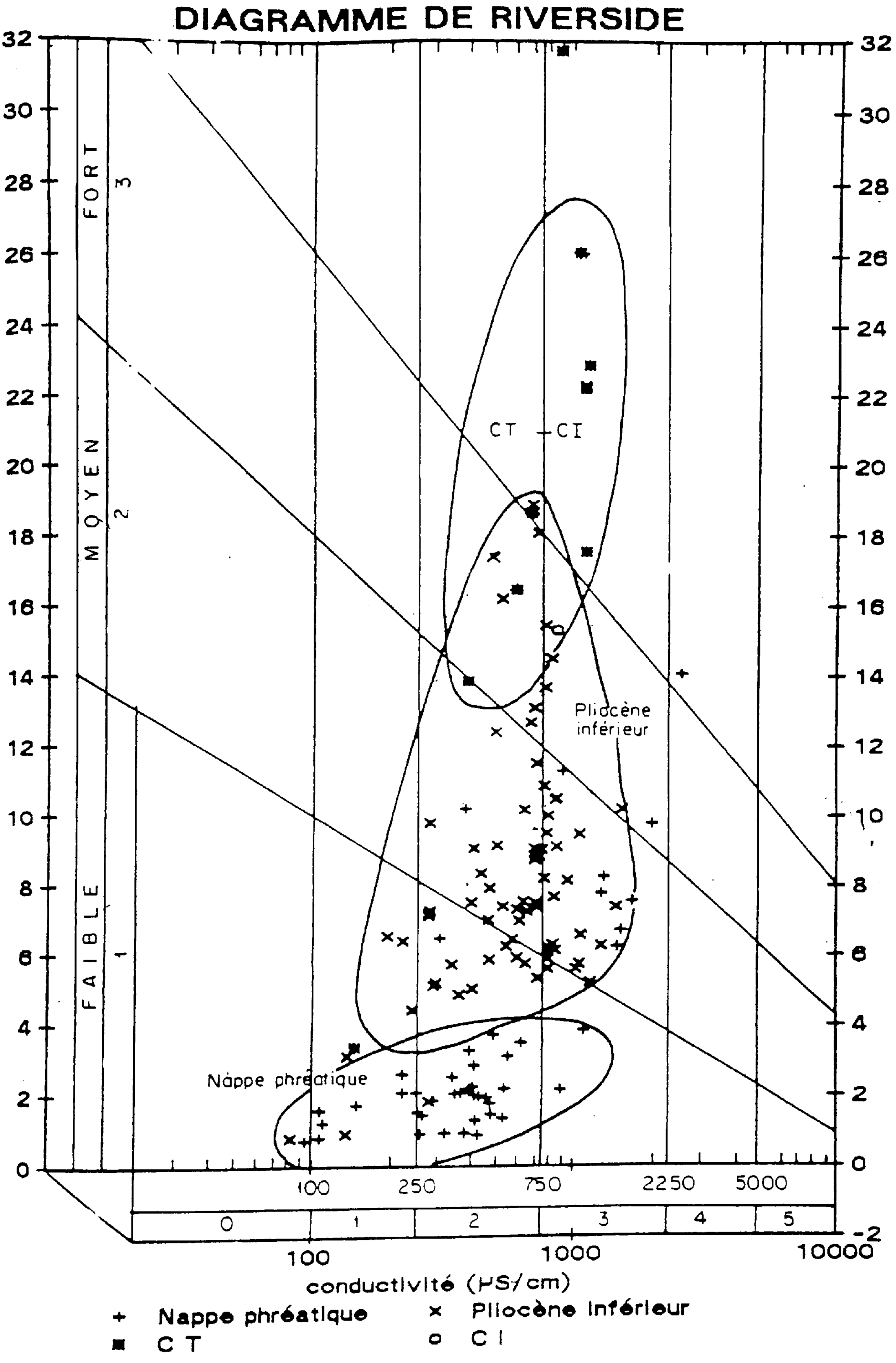
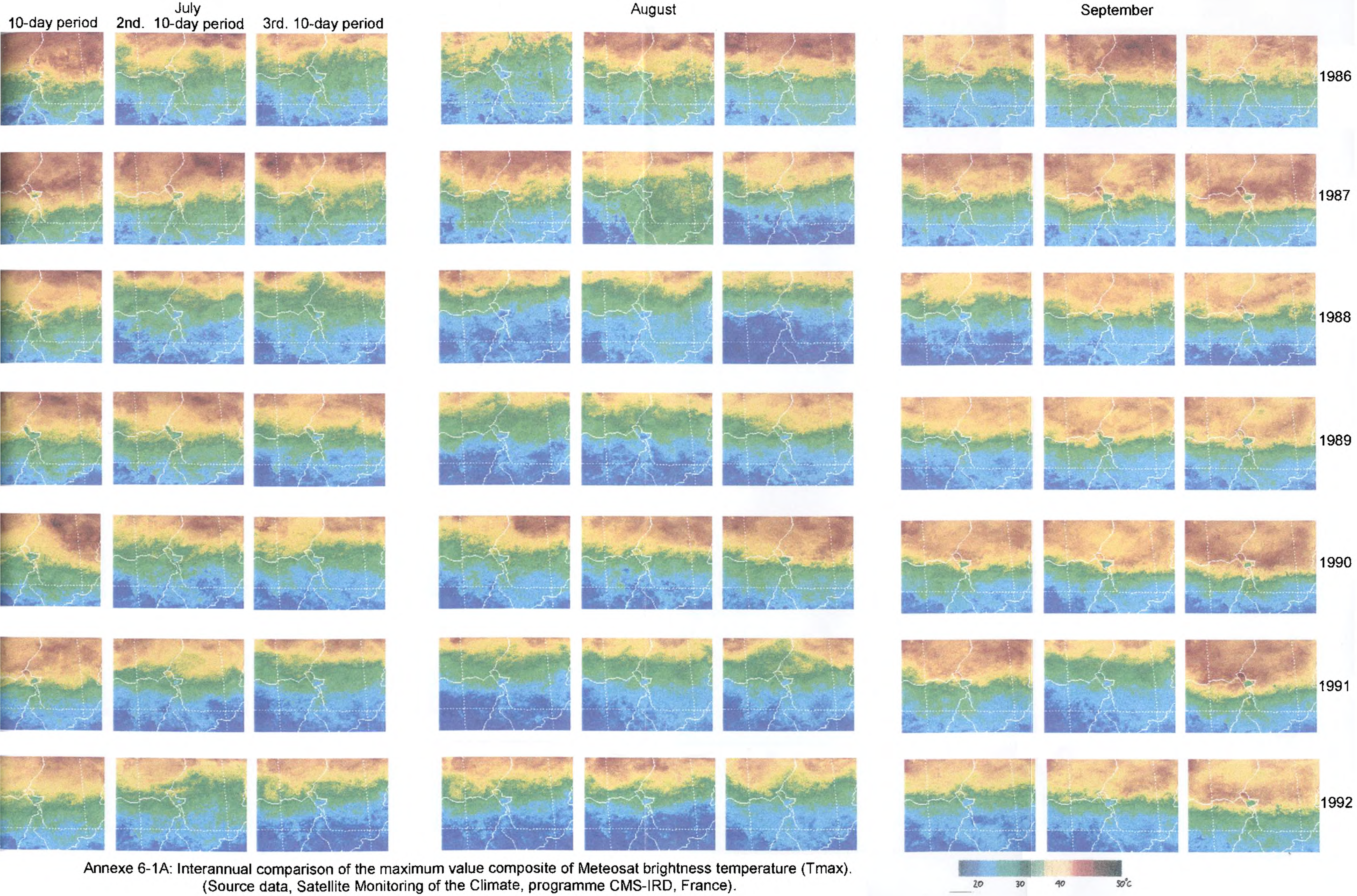
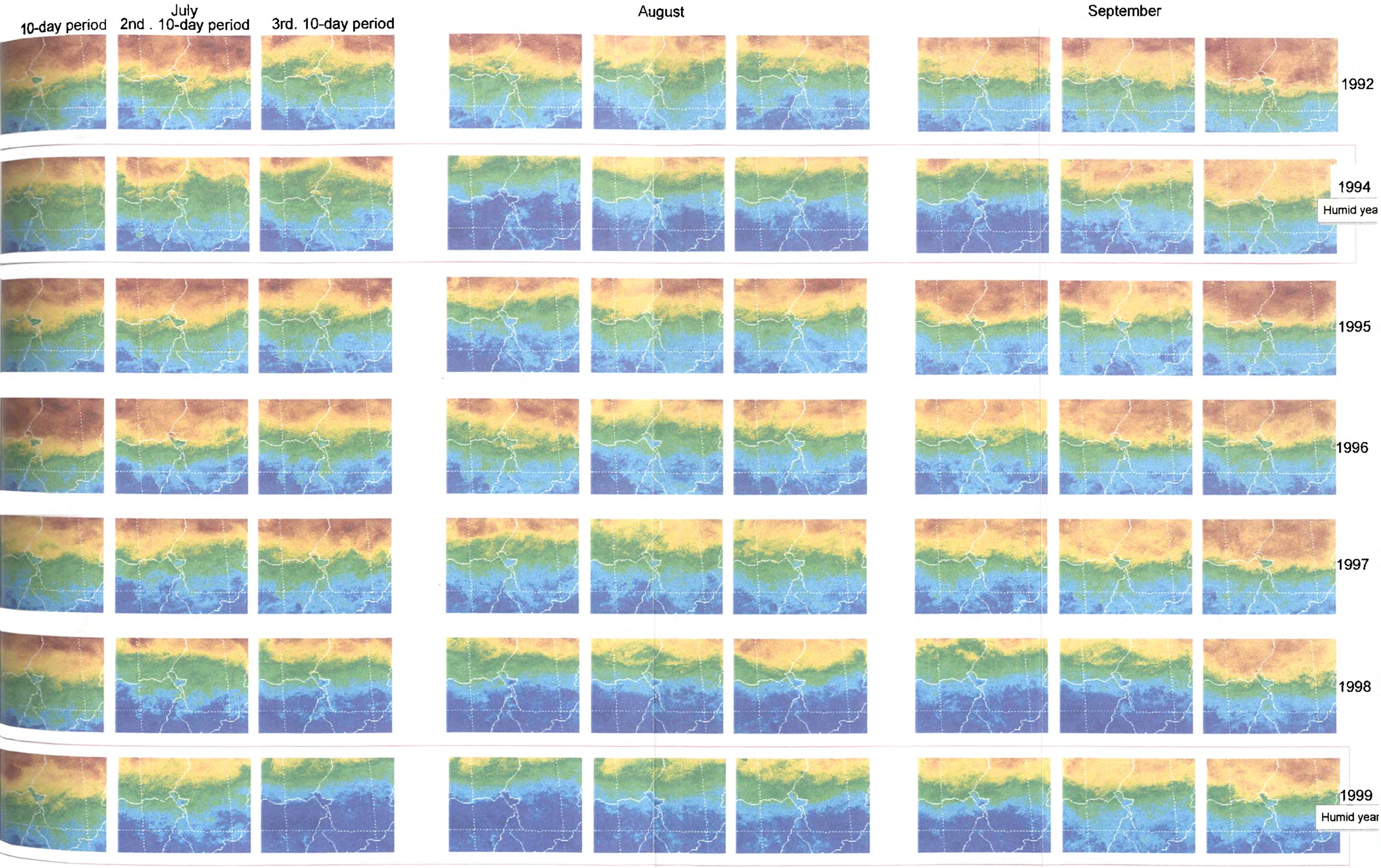


DIAGRAMME DE RIVERSIDE

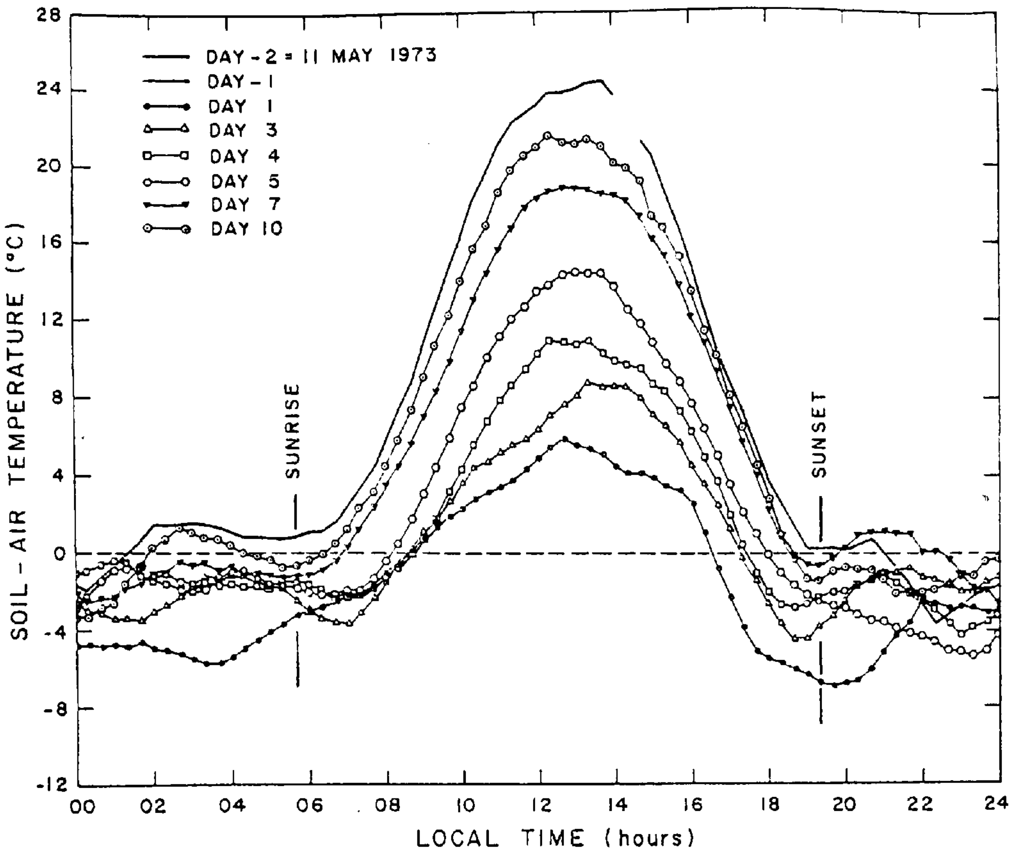
Appendix 2-3: Aquifers suitability for irrigation in the Lake Chad Basin (from Eberschweiler 1992).



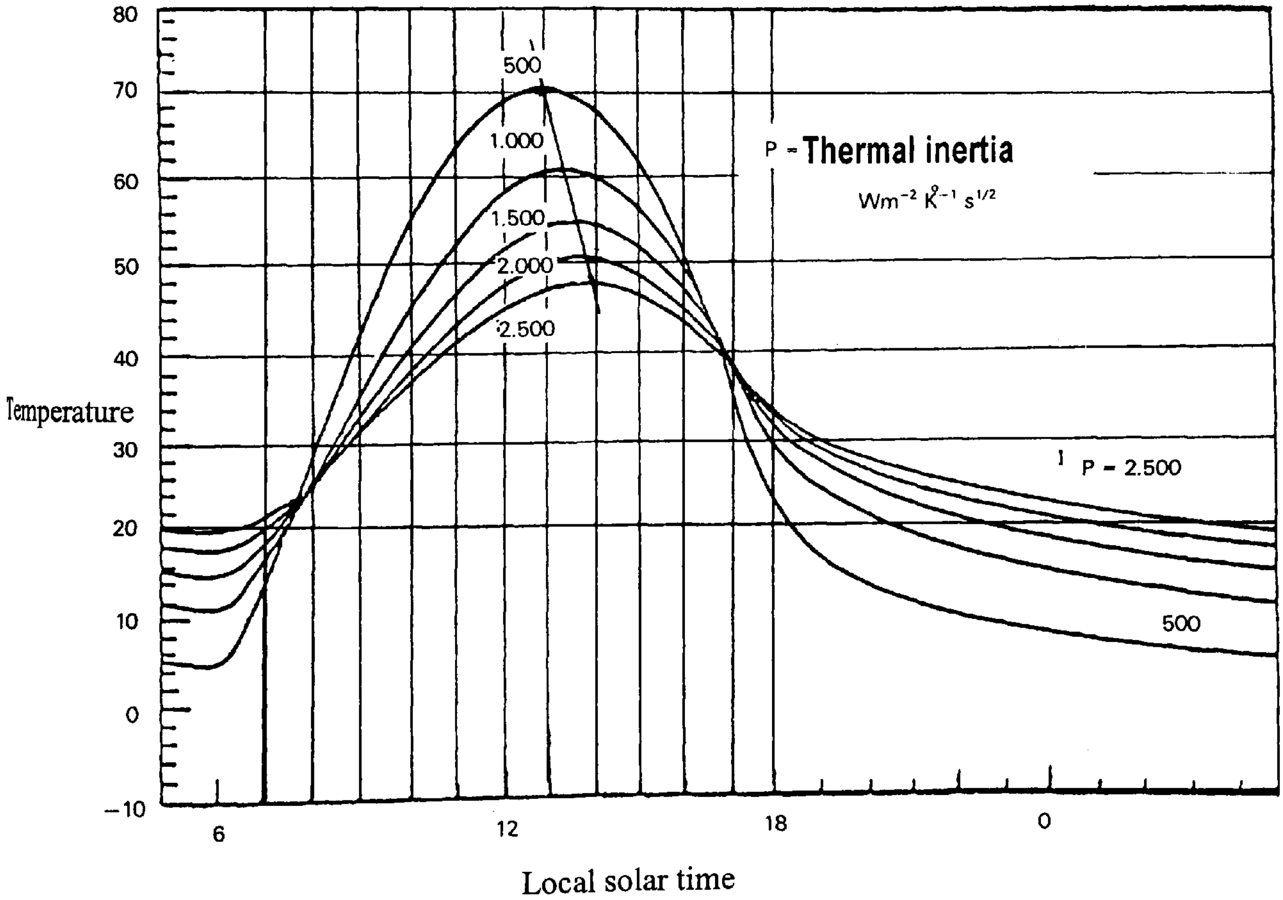
Annexe 6-1A: Interannual comparison of the maximum value composite of Meteosat brightness temperature (Tmax). (Source data, Satellite Monitoring of the Climate, programme CMS-IRD, France).



Annexe 6-1B: Interannual comparison of the maximum value composite of Meteosat brightness temperature (Tmax). (Source data, Satellite Monitoring of the Climate, programme CMS-IRD, France).

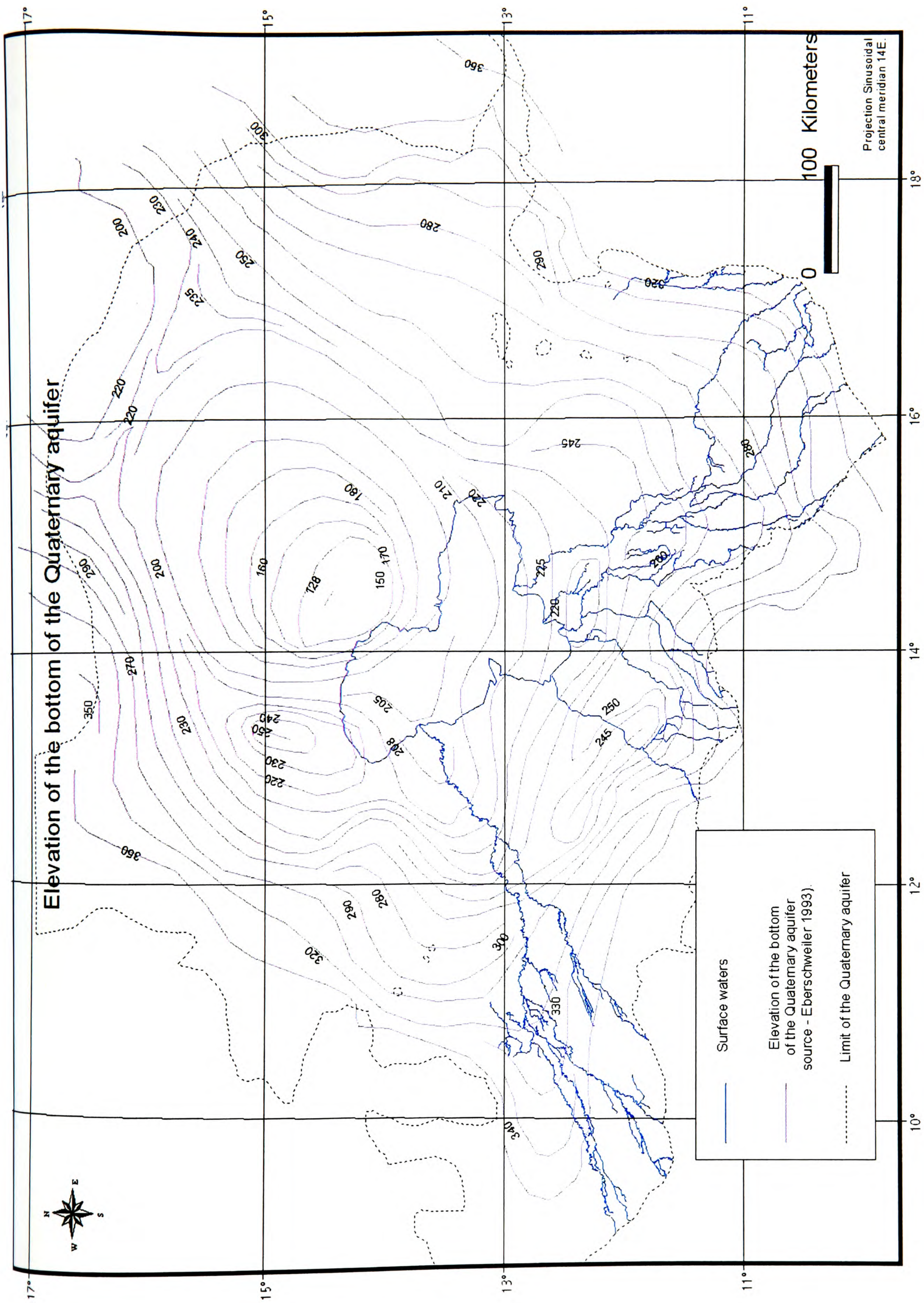


Diurnal plots of measured surface soil-air temperature differential on selected clear day-night periods following an irrigation of 10 cm of water on day zero. Idso et al., 1975

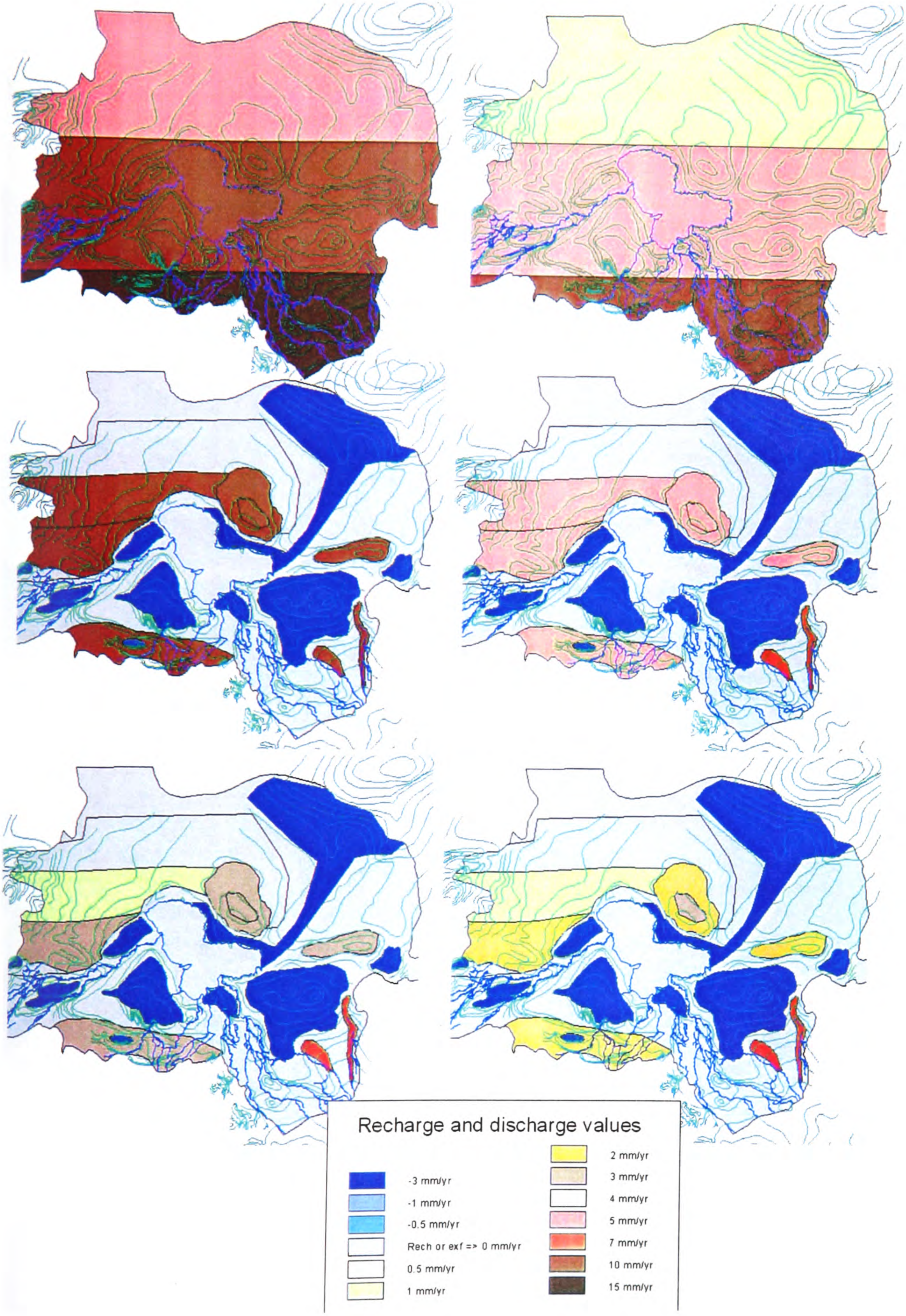


Daily variation of surface temperature for different values of thermal inertia. Viellefosse, 1979

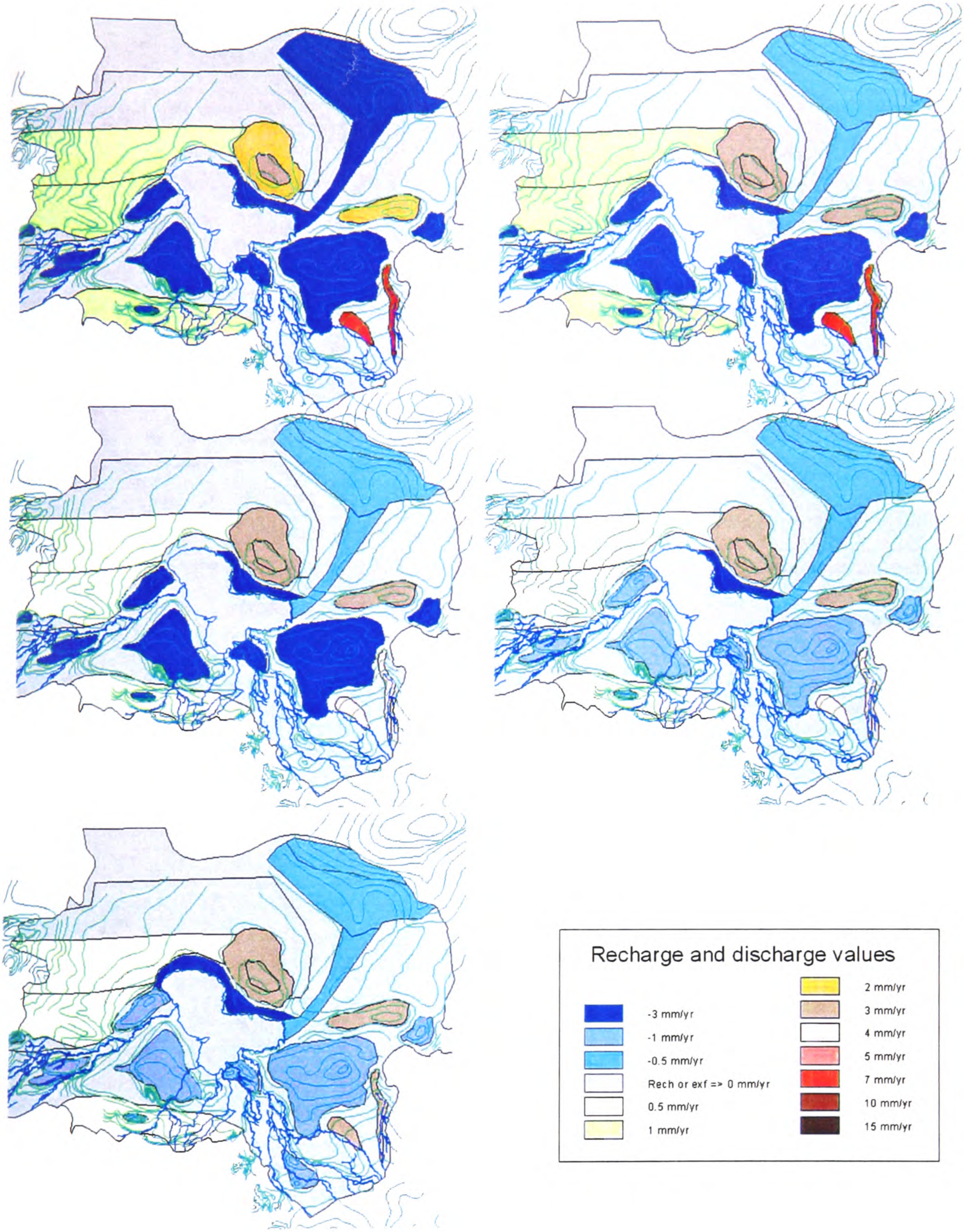
Appendix 6-2: Relationship between surface temperature and soil moisture/thermal inertia.



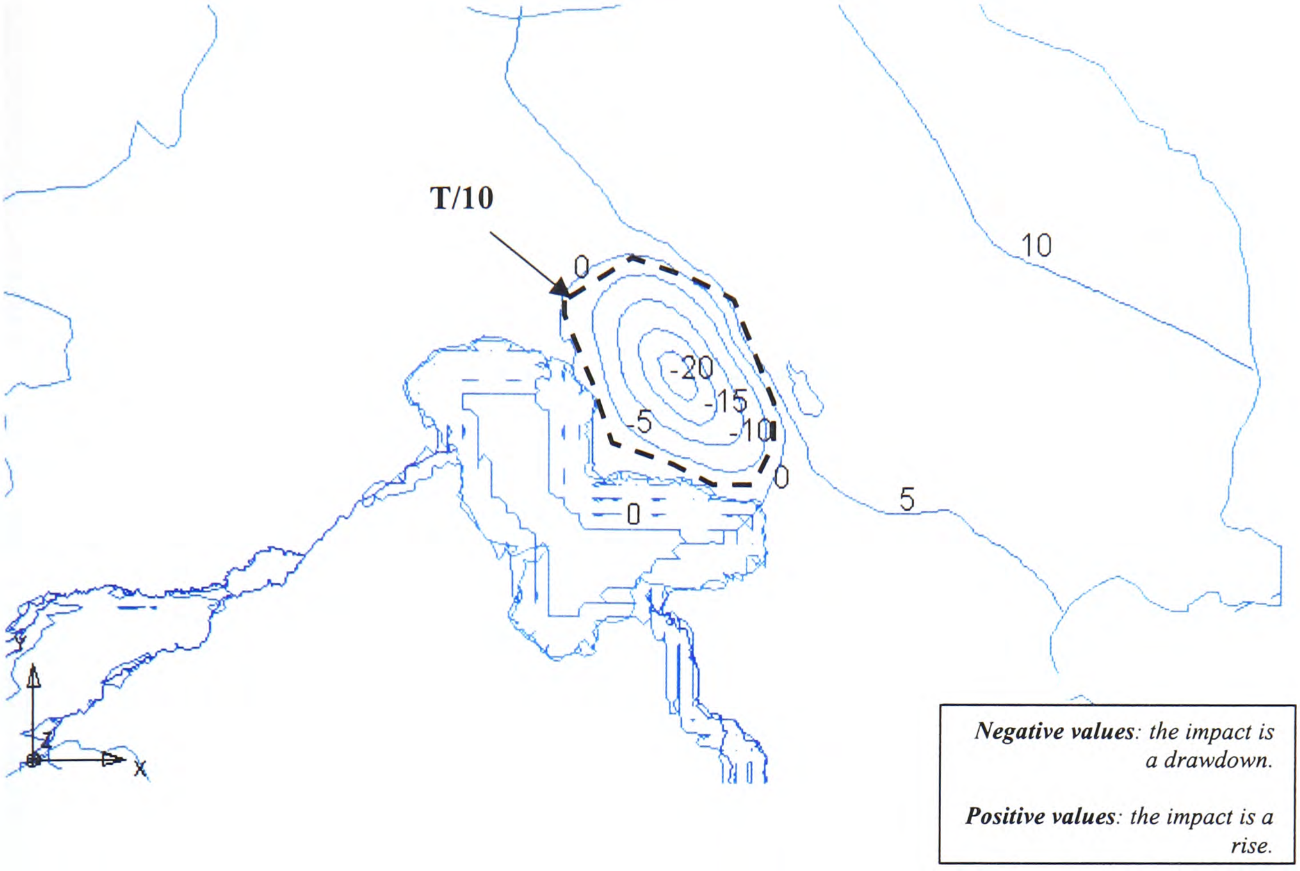
Appendix 7-1: Elevation of the bottom of the Quaternary aquifer (from Eberschweiler, 1993).



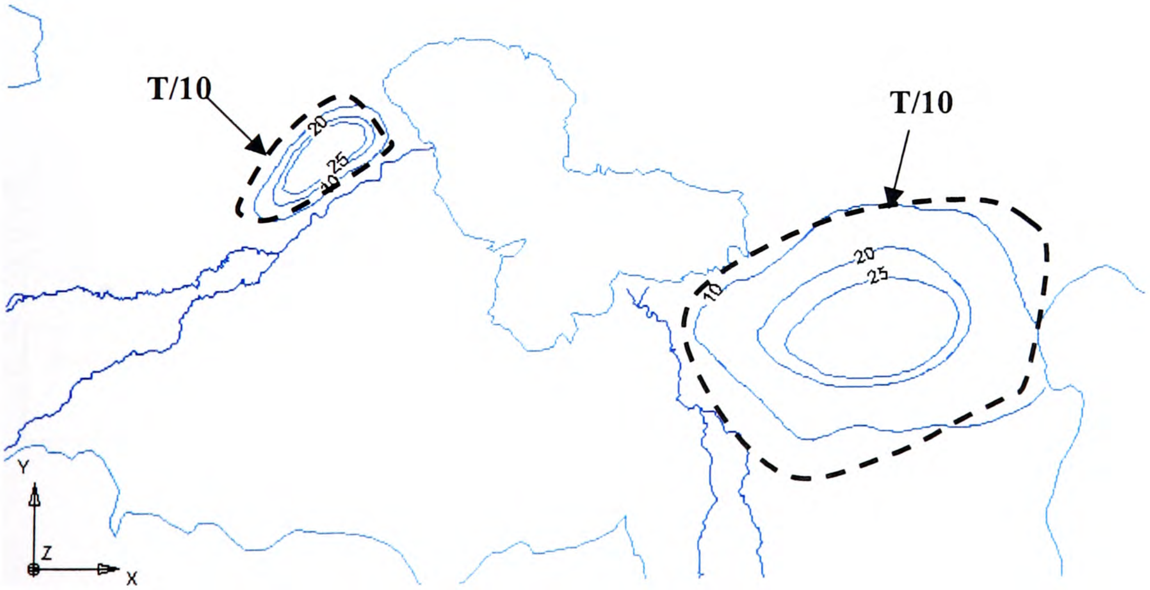
Appendix 8-1A: Some of the scenarios of recharge and discharge distribution, which have been tested during the calibration of the groundwater model in steady-flow.



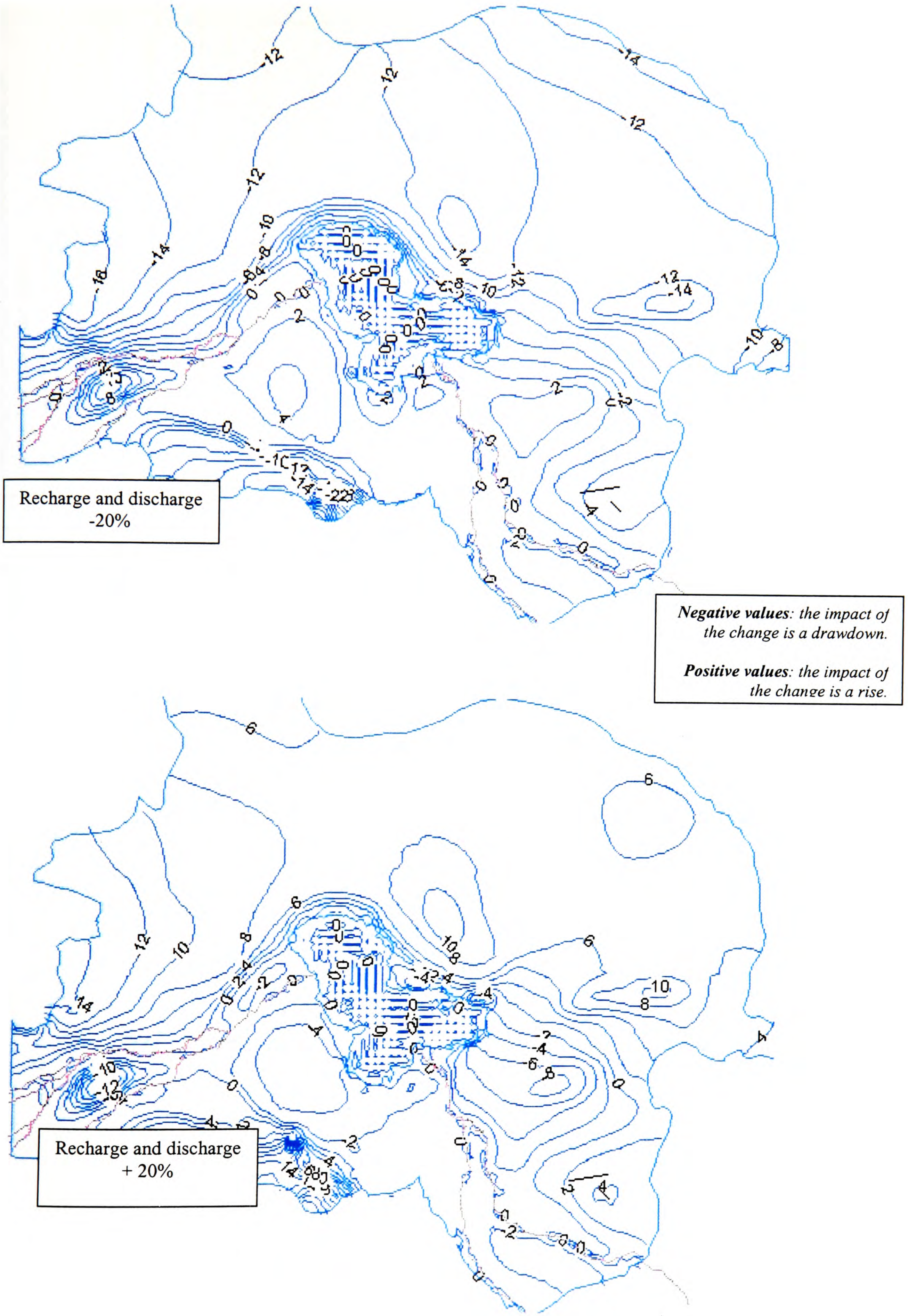
Appendix 8-1B: Some of the scenarios of recharge and discharge distribution, which have been tested during the calibration of the groundwater model in steady-flow.



Appendix 8-2: Sensitivity tests for the steady-state model - Change in the heads after multipling the hydraulic conductivities by 10 in the Kanem region.



Appendix 8-3: Sensitivity tests for the steady-state model - Change in the heads after multipling the hydraulic conductivities by 10 in the Kadzell and Chari-Baguirmi depressions.



***Negative values**: the impact of the change is a drawdown.*

***Positive values**: the impact of the change is a rise.*

Appendix 8-4: Sensitivity tests for the steady-state model - Difference between the simulated piezometry after change of recharge and discharge rates by +/- 20% and the calibrated piezometry.

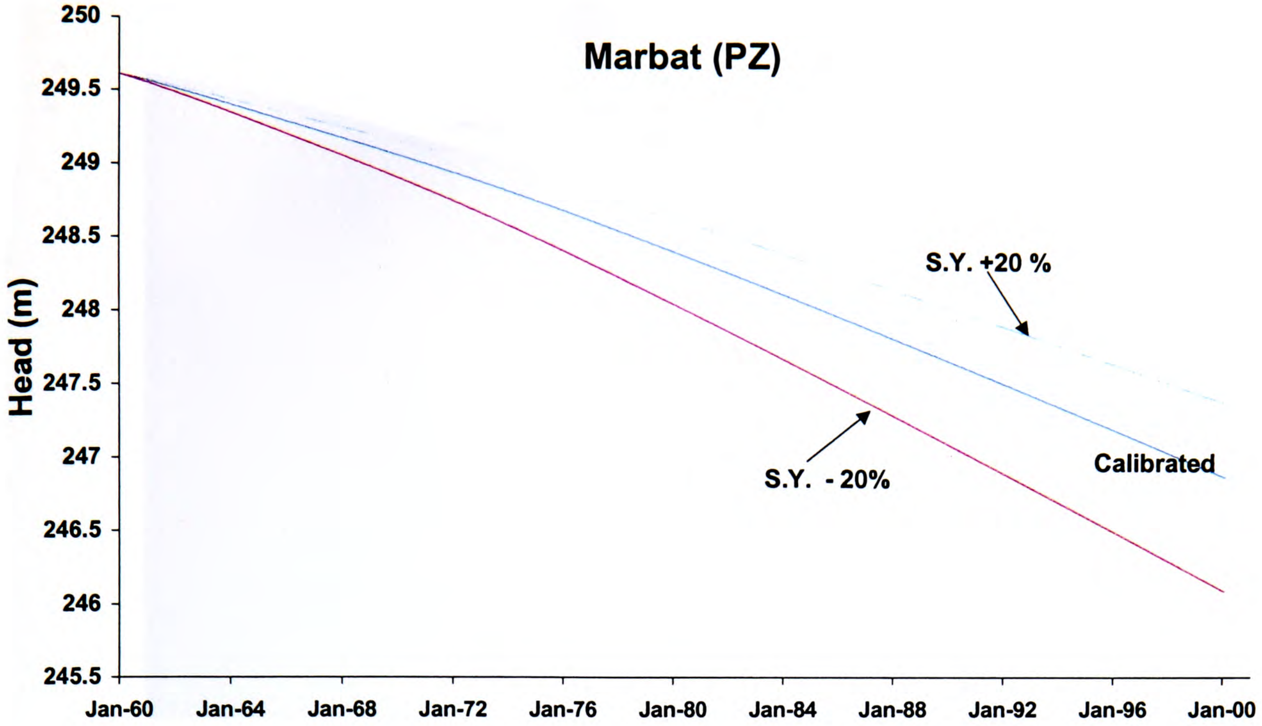
After increasing the T over the piezo. depressions, we searched for an equivalent solution (same piezometry) by changing the discharge rate , the conductance and the transmissivity near the rivers.

An equivalent piezometry was found for an increase of the discharge rate from –1 mm/yr to –5 mm/yr in the Kadzell and –2.5 mm/yr in the Chari-Baguirmi. Meanwhile the conductances of the rivers and the Transmissivities in their vicinity needs to be significantly increased.

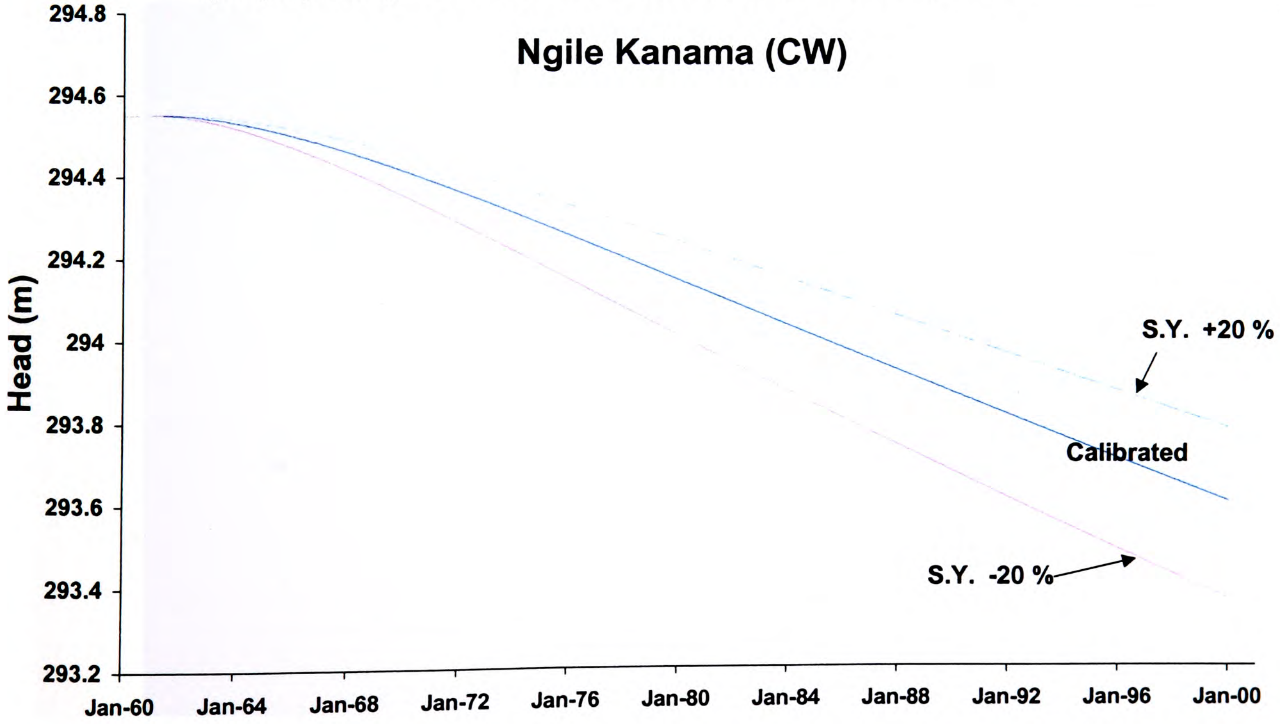
No search of an equivalent solution.

Flow Type	**Calibrated model**		**Rainfall recharge and discharge - 20%**		**Rainfall recharge and discharge + 20%**		T Kanem x 10		T depressions (Kadzell and Chari Baguirmi) x 10	
	IN	**OUT**	**IN**	**OUT**	**IN**	**OUT**	**IN**	**OUT**	**IN**	**OUT**
Rivers (*calculated*)	**81,615,790**	**-2,121,868**	**75,946,654**	**-2,403,390**	**87,722,807**	**-1,971,070**	**81,302,219**	**-2,221,927**	**112,037,824**	**-3,283,433**
Lake Chad (*calculated*)	**43,665,143**	**-1,062,607**	**43,568,644**	**-96,195**	**44,076,837**	**-2,351,292**	**43,530,209**	**-613,690**	**72,013,919**	**-409,293**
Rainfall recharge (*imposed*)	*106,793,380*		**85,463,379**		**128,152,056**		*106,793,380*		*106,793,380*	
Discharge – evapotranspiration (*imposed*)		*-132,875,753*		**-106,351,960**		**-159,450,904**		*-132,875,753*		**-191,015,485**
Exchanges bordering aquifers (*fix*)	*9,150,100*	*-23,220,000*	*9,150,100*	*-23,220,000*	*9,150,100*	*-23,220,000*	*9,150,100*	*-23,220,000*	*9,150,100*	*-23,220,000*
Human activities withdrawals (*fix*)		*- 82,111,610*		*- 82,111,610*		*- 82,111,610*		*- 82,111,610*		*- 82,111,610*

Appendix 8-5: Sensitivity tests for the steady-state model - Impact of the sensivity tests on the global water budget of the model.



Appendix 9-1: Sensitivity analysis of the transient model, showing the effect of varying the specific yield by ± 20 % on the head simulated at Marbat, Chad.



Appendix 9-2 : Sensitivity analysis of the transient model, showing the effect of varying the specific yield by ± 20 % on the head simulated at Ngile Kanama, Chad.