BRITISH GEOLOGICAL SURVEY

GROUNDWATER RECHARGE IN SENEGAL REPORT WD/90/49R

W M EDMUNDS

Final report to Overseas Development Administration December 1990.

Project in collaboration with University of Dakar and University of Paris-South

Natural Environment Research Council

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TECHNICAL REPORT

Hydrogeology Series

Report WD/90/49R

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W M EDMUNDS

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Project carried out in collaboration with the University of Dakar (Department of Geology) and University of Paris – South (Department of Isotope Geochemistry and Hydrology)

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1. EXECUTIVE SUMMARY

1.1 Description of Project

The amount of recharge to aquifers is the major unknown in water resource investigations especially in semi-arid regions. Falling water levels at the present time testify to the fact that overdevelopment is widespread. In order to make long-term predictions of water resources and their rehabilitation it is necessary to determine a realistic water balance in which aquifer replenishment (recharge) is precisely known, or at least not overestimated. Existing methods of recharge estimation tend to be unreliable, relying as they do on formulae involving precipitation, evaporation and various constants. Their application in semi-arid regions of the world, where rainfall patterns are highly variable is subject to considerable error.

The concepts involved in the present project were developed during two previous ODA-supported projects in Cyprus and in Sudan (1978-1986). The recharge technique is based, very simply, upon determining the ratio of chloride (and possibly other inert solutes) in rainfall to that contained in the unsaturated zone, typically to depths of 20-30 m. Unlike water vapour, which is lost by evaporation, chloride remains in the soil and is then transmitted in pulses, annually or seasonally by piston-type displacement, towards the water table. The unsaturated zone therefore acts like a cumulative rain gauge providing not only estimates of recharge over periods of decades, but also a record of recharge history - giving estimates of recharge during drought and wetter interludes.

The method requires samples to be taken at 0.25-0.5 m intervals through the unsaturated zone and the extraction or elutriation of pore waters and the measurement of solutes and isotope ratios as well as moisture contents. The underlying theme of the technique is that it should remain simple and applicable especially in developing countries.

Senegal was chosen for a number of reasons. It is representative of the Sahel region, especially in the north, and has undergone a decrease in mean annual rainfall of some 35% during the recent drought (1968-1986). The geology and hydrogeology of Senegal are also ideal to demonstrate the recharge methods; there has also been a record of recent declining water tables.

1.2. Objectives of the Research in Senegal

The objectives of the current research can be summarised.

1. To develop the geochemical techniques already established in Cyprus and Sudan for wider applicability in semi-arid regions.

2. To apply the geochemical techniques to the estimation of recharge in Senegal, especially to attempt that application on a regional scale.

3. Sampling of rainfall for chemistry and isotopes to provide inputs to the above.

4. To investigate to what extent the unsaturated zone solute profile contains a record of 'recent' climatic or environmental changes and so to determine the recharge history.

5. To disseminate the results of the research by collaboration with the University of Dakar and other local organisations.

6. To examine regional aspects of groundwater quality in this type of area of traditional settlement.

An important component of this work is the collaboration with the University of Dakar in the training to doctorate degree level of C B Gaye. This training is shared jointly with the University of Paris Sud (Professor J-Ch Fontes), and most aspects of the project are being carried out on a tripartite basis.

1.3 Summary of Work Undertaken

Three areas of Senegal - Louga, Cap Vert, Kaolack - located on sands or sandstone, and which represented different rainfall regimes were chosen for this study . A research site was established at Louga, close to a meteorological station where rainfall inputs and chemistry could be measured. Seven profiles (up to 35 m in depth) were obtained from this

1 km^2 control area and a further 6 profiles obtained from the surrounding area. These profiles were obtained using hand auger and samples were processed both in Dakar and Wallingford for chemical and isotopic parameters. Supporting chemical data were obtained from the regional aquifer by sampling shallow traditional wells.

In the Cap Vert region (Niague) and in Kaolack samples were also taken for analysis using either the auger method or by enlisting the help of local well-diggers who collected samples on a daily basis during the course of their work. A total of 4 profiles were obtained in Kaolack and three in Niague.

Samples of sand, collected in Kilner jars, were processed to yield samples of pore waters by centrifugation or by elutriation and these extracts (often only 2-3 ml) used to determine a range of chemical and isotopic parameters using wet chemical (autoanalyser) ICP-OES, ICP-MS and MS methods in the UK laboratory. These data were validated and then stored on a computer database to aid interpretation, data being exchanged frequently between the Dakar and Wallingford laboratories.

1.4 Summary of Results (Abstract)

Unsaturated zone profiles of 10 to 35 m depth have been obtained from the Louga area where the mean rainfall (1969-1986) has been 223 mm yr^{-1} compared with the long-term (1893-1982) average of 356 mm. Seven profiles were obtained in a 1 km^2 research site to determine recharge and its spatial variability using geochemical techniques. At this site, mean chloride concentrations ranged from 24 to 115 mg l^{-1} (mean value 81±48 mg l^{-1}). Using a three year average of rainfall chemistry and a value of 290 mm for rainfall (average of approximately the past 60 years) these chloride values correspond to point recharge rates of 4.6 to 34 mm yr^{-1} (mean 15.2 mm yr^{-1}).

The geochemical method for recharge estimation not only enables the spatial variability at a given location to be determined but also provides long-term (decades) estimates of the recharge rate. The spatial variability is likely to be due to local variations in soil texture (notably clay content) and to vegetation cover; surface runoff is negligible in this terrain. Lower recharge estimates are obtained in the northern Senegal (M'pal) area

(around 1 mm yr^{-1}). The profile recharge estimates have been further verified by using data from traditional dug wells to produce chloride and recharge maps of a 1600 km^2 area based on Louga. There is good agreement between both sets of results and it is concluded that conjunctive use be made of unsaturated and saturated zone data for recharge estimation.

As well as providing information on recharge the interstitial waters of the unsaturated zone also provide a record of recharge events over a period up to 100 years. The chloride profiles have been calibrated using the moisture contents and recharge rate estimates to determine the velocities of movement and hence the residence times of water in the unsaturated zone. In most instances, the shallow groundwater now being exploited, fell as rain during the last century. Within most profiles the 'signature' of the recent Sahel drought may be recognised as zones of high salinity contrasting with low chloride waters corresponding to times of higher-than-average recharge. The unsaturated profile records correlate well with the climatic records provided by the rainfall at St Louis and the flow of the Senegal River at Bakel. Two other drought episodes - during the 1940s and 1900s - may be recognised in this way.

The results of this study have three major implications: 1) the geochemical techniques offer a cheap, effective means of recharge estimation, compared with existing techniques, for semi-arid zones; 2) the information contained in the unsaturated zone may be used to study past climatic and environmental changes and this study is among the first to demonstrate such an application; 3) from a water resources viewpoint, unsaturated zone profiles, once correlated with past climates, can indicate the extremes of recharge. In the present case (Louga 3) recharge is reduced to around 4 mm yr^{-1} during the recent drought, whilst during the high rainfall period of the 1920s the recharge was considered to be as high as 20 mm yr^{-1}.

It is concluded that recent climatic change must therefore contribute to the decline in water tables in Senegal. The improved estimates of recharge derived in this study need to be considered with improved estimates of abstraction and natural losses to provide a better water balance for the country.

1.5 Dissemination of Results and Training

In addition to this final report, the results of this project have been disseminated in a number of different ways which are listed below in chronological order.

i) An video film was made in early stages of the project in French and English which has subsequently been used by Senegal television and for information purposes in UK.

ii) A visit was made to NERC (BGS/IH) Wallingford in November 1989 by President Abdou Diouf and Madame Diouf on the occasion of their Royal Visit to Britain. A presentation of the Recharge Project formed the centrepiece of this visit and included poster and video as well as oral presentation.

iii) A four page A4 coloured leaflet has been prepared both in English and French which summarises the aims and results of this project (see Appendix).

iv) A one-day seminar was held in Dakar on 6 December 1990, hosted by the British Embassy, which was attended by about 100 diplomatic and professional people interested in water resources. The seminar was opened by His Excellency Mr Cheikh A.K. Cissoko, Minister of Rural and Hydraulic Development. The programme of this day appears as Appendix 1. In addition to the technical presentations and discussions, delegates received copies of the project leaflet, together with a programme with abstracts and conclusions of our project.

v) An integral part of this project has been the training to doctorate level of C.B. Gaye, Department of Geology, University of Dakar, with joint supervision by Dr W.M. Edmunds and Professor J-Ch Fontes of University of Paris. This has entailed study visits to UK supported by the British Council, to BGS laboratories. C.B. Gaye successfully defended his thesis for Docteur es Sciences at Dakar University on 4 December 1990. This training forms an important role in the continuity of the project aims, by strengthening the University in the key subject area of hydrogeology.

vi) At the time of reporting, a further MSc scholarship supported by British Council was being implemented at University of Leeds. Mr Serigne Faye is undertaking a two-year course of study in geochemistry and his training will help to build a water quality laboratory and hydrogeochemistry teaching facility at the University of Dakar on his return.

vii) An article on the project is to appear in NERC News (January 1991), and material on the Dakar seminar has also been submitted to ODA for publicity purposes.

viii) Scientific papers arising from this project are in preparation. A paper has already been accepted for presentation at the IAEA Symposium on Isotope Hydrology in March 1991.

1.6 Recommendations

(i) It is proposed that the techniques for recharge estimation described here should become widely used in Senegal as part of water balance investigations.

(ii) The technique is simple to use and to this end a simple procedure is given in Appendix 2. It is recommended that guidance should be sought from hydrogeologists at University of Dakar on details of the method not covered here.

(iii) The laboratory of University of Dakar (Geology) should be supported to enable measurements of moisture content and low level chloride (to 0.2 mg l^{-1}) to be carried out together with other relevant chemical analysis. Basic steps to achieve this have already been set in motion by purchase through ODA of an anion chromatograph and training of MSc student. Other laboratories using the recharge method require the capacity for low level chloride measurements.

(iv) In order to implement the procedures it will be necessary for rainfall monitoring and chemical sampling to be continued. In this study, three years data for Louga and Dakar were obtained. These two stations should continue to be monitored for at least the next 5 years and at least two more stations inland need to be set up, e.g. at Linguere and Bakel, also possibly at Kaolack.

(v) Senegal provides an excellent natural laboratory for the study of recharge history and recharge processes. Development of the research outlined in this report should lead to an improved understanding of recent climate change and its consequences for groundwater hydrology and water resources. The unsaturated zone records need to be linked with other natural archives (e.g. niaye sediments). Profiles of interstitial waters covering several hundred years of information are likely to exist in Senegal and also further north-east in Mali, and are to be the subject of future related research.

(vi) This project has highlighted several important features of the water quality in Senegal; this has been a spin-off of the project rather than its main objective. Acidic groundwaters which contain dissolved metals in high concentrations are quite common. It is recommended that these and other anomalies be followed up, ideally in conjunction with health workers, epidemiologists to check on health and utilisation aspects.

(vii) A considerable amount of data is now being obtained on water quality (and other groundwater information) in Senegal as governmental and non-governmental organisations construct and develop shallow and deep wells and boreholes. These data are generally being recorded but not used to their fullest extent. It is recommended that a water quality database be established for the use of all interested bodies in Senegal, set up initially by the University in conjunction with DHR. This information would have value in future recharge studies and water quality in general (public health, agricultural usage, etc).

(vii) It is recommended that appropriate training in the field of hydrogeology be maintained, if requested, in future years. The training programmes of this project have proved most successful.

1.7 Acknowledgements

This report has been prepared for ODA as the UK component of a three-country project in Senegal. Complimentary data are contained in the Doctorate thesis of C B Gaye. Further support and collaboration with Professor J-Ch Fontes (University of Paris) has led to a balanced and consistent result of this project). We wish to thank Professor O Dia, Department of Geology, Dakar, for his encouragement and full support in this programme of research, training and applied studies. We also wish to thank the Meteorological Department for their assistance in obtaining rainfall samples, and the DHR Brigade des Puits for sampling during well construction. This project has benefited from discussion with colleagues in University of Dakar and with G Aranyossy on secondment from IAEA Vienna on the problems of semi-arid zones.

The author is particularly indebted to John Talbot of BGS Wallingford who carried out much of the sample processing in UK and who also designed the format of most of the graphics for this report. The author also wishes to thank George Darling for useful discussions on the isotopic analysis and interpretation, and Jennifer Cook and Janice Trafford for chemical analysis of interstitial waters and groundwaters.

2. INTRODUCTION

In arid and semi-arid regions, groundwater is generally the only perennially available source of water and the availability and security of these resources is of major concern. Various hydrogeological studies by BGS and other agencies have highlighted groundwater recharge as a major focus for R & D.

The limitations of traditionally existing methods for estimating recharge in semi-arid regions led BGS, in the late 1970s, to consider alternative techniques based on geochemistry. The method was successfully developed in Cyprus and applied to Sudan, the results presented to ODA in two reports (Edmunds et al, 1981, 1987). The present study in Senegal is designed to verify the wide applicability of the technique in an area of the Sahel margin and to investigate its use on a regional basis.

2.1 The Importance of Recharge Estimation

Senegal in common with other Sahel countries has experienced a significant decline in rainfall over the past 25 years, coupled with increasing demands on its water resources - principally groundwater. This means that there is added stress on the resources at a time when there is uncertainty over the total amounts available for development. Some of the available groundwater is 'fossil water' recharged under more humid regimes at least 3000 years ago and is being exploited, especially from some deep wells, under rules of mining. Recharge from rainfall at the present day feeds the shallow aquifer system although this amount is not accurately known. It is probably fair to say that traditional water usage has, until recently, been in balance (steady-state) with the available resources. Exploitation of deeper groundwater from confined and semiconfined aquifers has been common in recent decades with the production either of palaeowaters or a mixture of these and recent recharge. Nevertheless the recharged resource is finite and exploitation of the deeper system may induce recharge of recent water laterally and from above, but often at the expense of the shallow aquifers. This effect, especially at a time of drought and changing climatic conditions, has a serious effect, not only hydrogeologically, but also in socio-economic terms on the populations traditionally dependent on the shallow aquifer system. This effect is seen for example in the

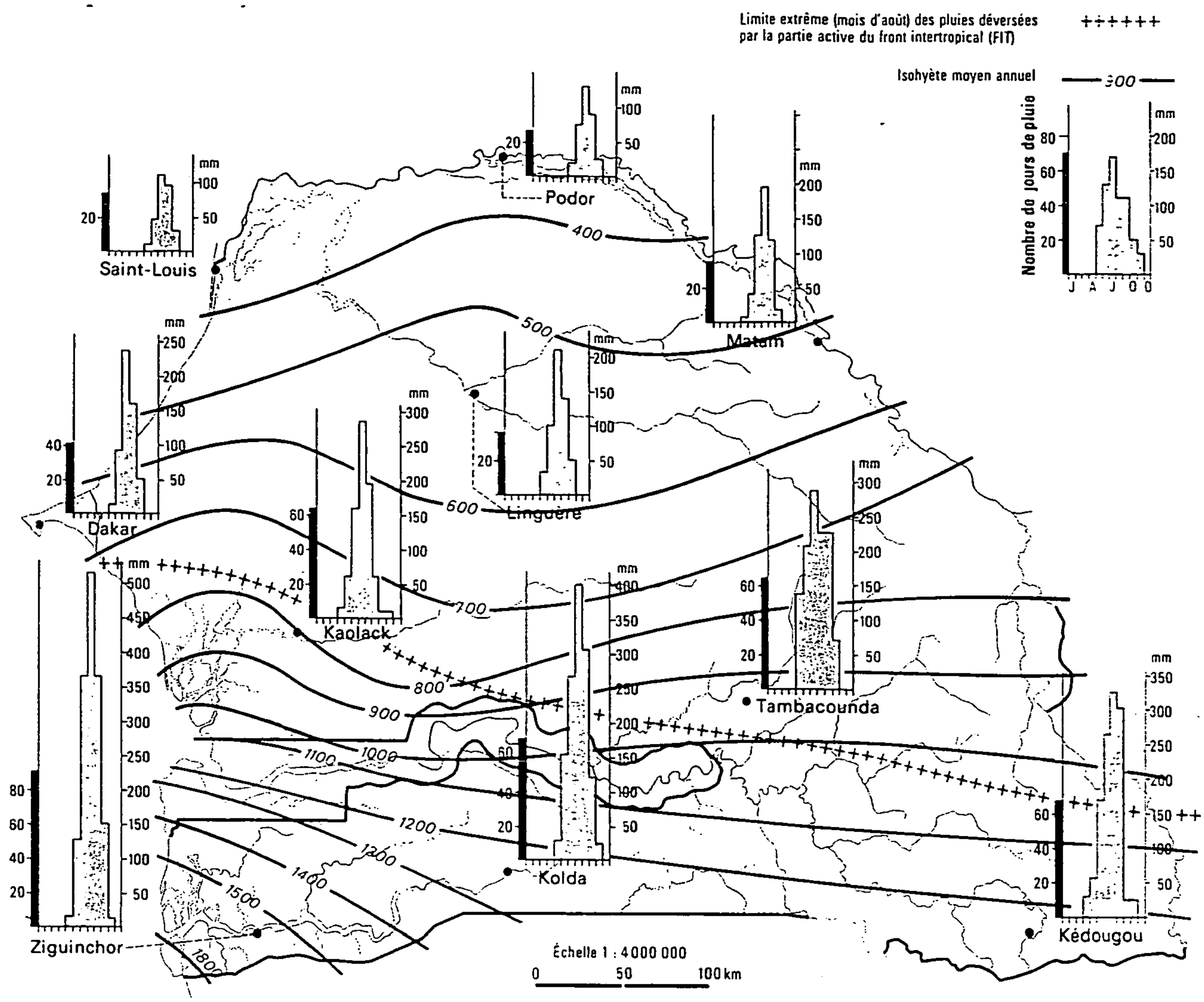


Figure 2.1 Distribution of rainfall in Senegal based on long-term averages (from Leroux M, 1983 in: Atlas Jeune Afrique, 'Senegal').

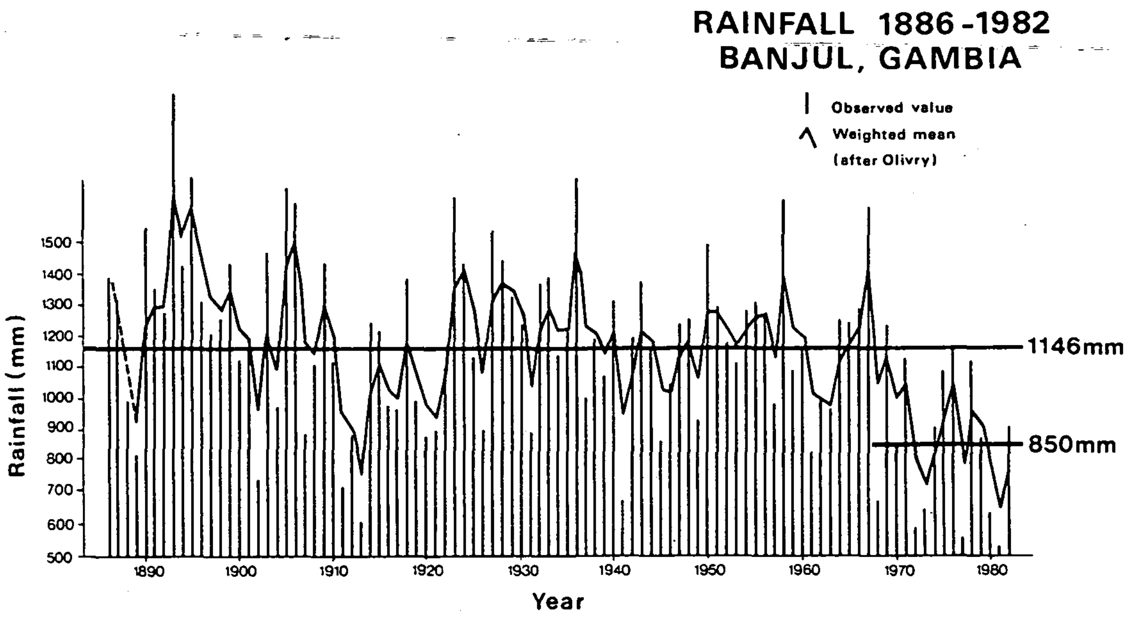


Figure 2.2 Record of rainfall and mobile weighted mean for Banjul since 1886-1982 (after Olivry, 1982).

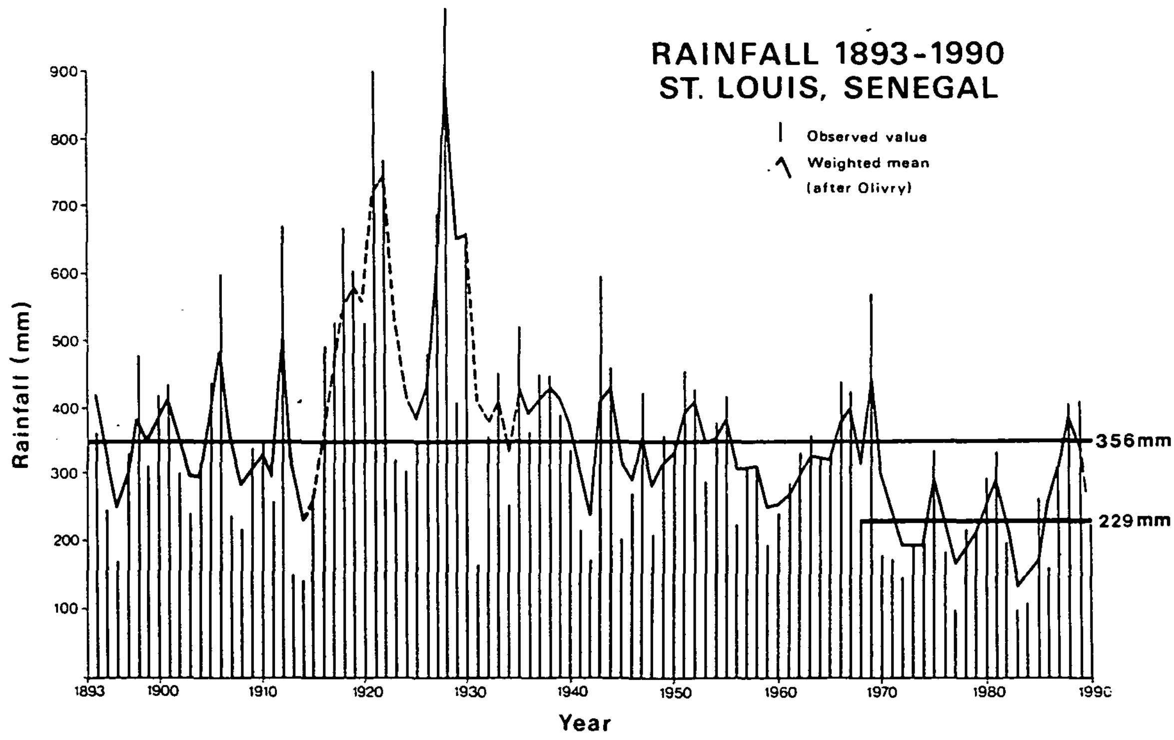


Figure 2.3 Record of rainfall and mobile weighted mean for St Louis (Senegal) from 1893-1990 (after Olivry, 1982) and recent data.

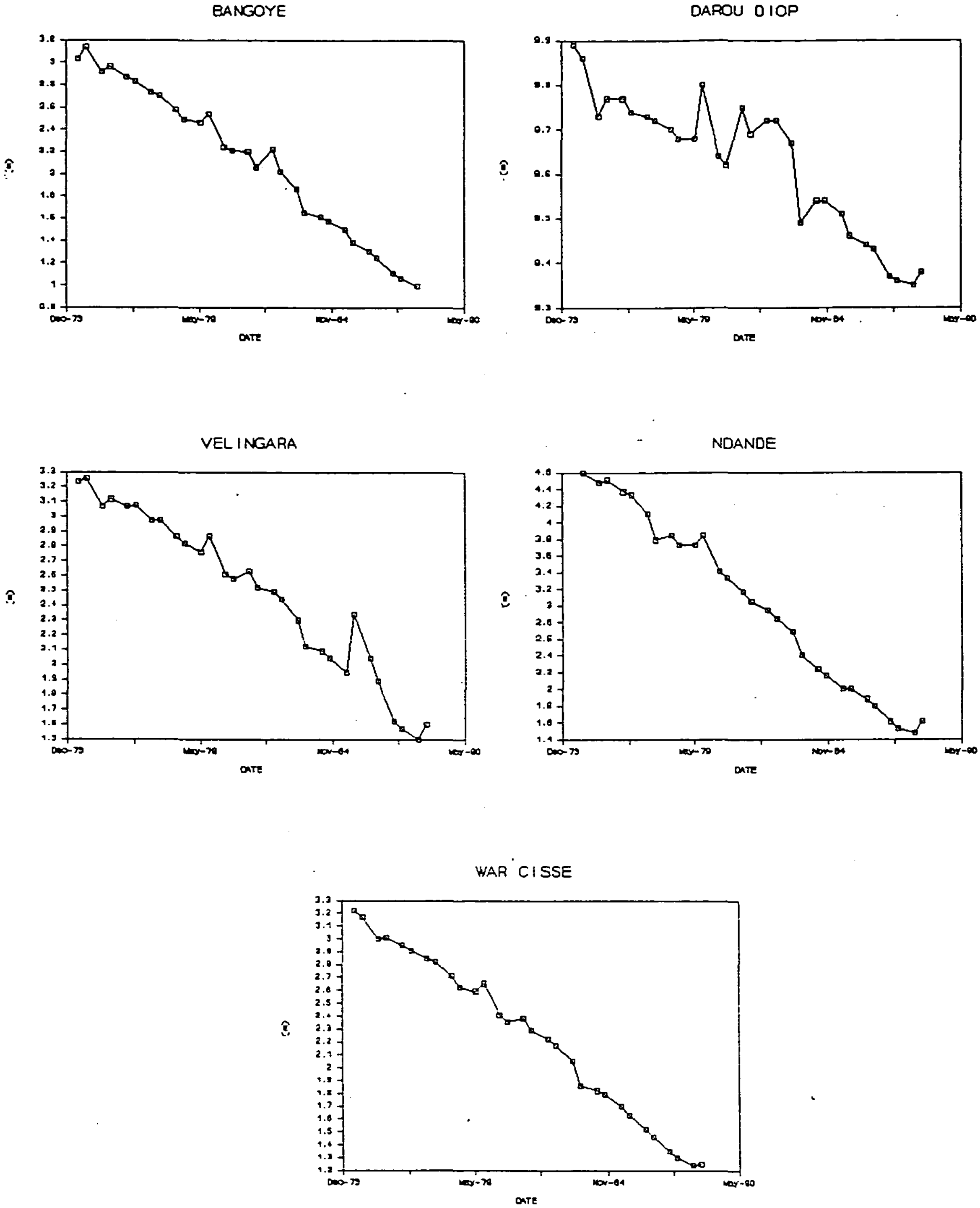


Figure 2.4 General decline in the phreatic water table in northern Senegal since December 1973.

declining water levels and in the numerous requests for well deepening to various government agencies and NGOs.

The present project is set against this background and is designed to provide improved estimates of current recharge to groundwater and if possible to provide information on recharge history, especially during the rather changeable climatic history of the past two or three decades.

2.2 The Water Resource Problem in Senegal

Senegal belongs to the Sahel region and lies directly on the transition zone between the humid tropics to the south and the Sahara desert to the north. The rainfall decreases from over 1500 in the south-west to below 400 in the north (Figure 2.1), yet these values are inaccurate if the climatic change of the past two decades is taken into account. Since 1968 a sharp decline in rainfall can be detected (Figures 2.2, 2.3) based on records at Banjul and St Louis (Olivry, 1982). At St Louis for example the fall in the weighted mean annual rainfall of 223 mm (1968-1986) represents a decline of 36% compared with the long-term average of 356 mm.

This dramatic decline in the rainfall is accompanied by a fall in groundwater levels (Figure 1.4). Data from north-western Senegal (Gaye, 1990) clearly demonstrate the steady decline typically by around 2 m per decade, in the shallow water table. This indicates that the exploitation is exceeding the replenishment and presents a serious problem for an area traditionally dependent on shallow water resources from hand dug wells. The decline is also of concern since saline intrusion from coastal regions is encouraged.

The decline in the water table may have been influenced by increased abstraction as well as by the climatic change. Over recent years there has been an increasing demand for water due to rising population, improved sanitation and a general increase in living standards. Some electric pumps have been installed which allow much greater abstraction rates than hand pumps or hand-drawn methods. Not least, several new wells have been drilled in the region which have penetrated the underlying aquifer(s). This may have led to dewatering of the shallow aquifer exploited by traditional wells, by building centralised water distribution systems based on high yielding pumping sources.

2.3 Geochemical Techniques for Recharge Estimation

Against this background the accurate estimation of natural recharge to the aquifer stands out as a vital need. The measurement of recharge is not at all an easy problem. Rainfall inputs vary from place to place; the soil, bedrock, slope and vegetation vary widely across the landscape and finally the unsaturated zone, which must be traversed before water safely reaches the water table, is usually a zone of considerable heterogeneity. Accumulation of water resources is also a question of time. Many of the resources now being exploited in semi-arid regions have accumulated over centuries and millennia and there is often a large reserve of palaeowater contributing to the resources available for abstraction.

Hydrogeologists have approached the problem by a number of methods including: 1) interpretation of fluctuations in piezometric levels, 2) the calculation of an overall water balance using a variety of equations; 3) the direct measurement of fluxes through the upper unsaturated zone using neutron-flux probes or lysimeters, and 4) physical models. The current state-of-the-art has been reviewed by Simmers et al (1990), Gaye (1990) for example. Each of the above techniques has quite serious limitations especially when applied to the semi-arid regions (Gaye, 1990).

The use of tracer techniques, especially thermo-nuclear tritium, has been successful as a tool for estimating recharge (Fontes and Edmunds, 1989). Tritium, widely distributed as a result of thermo-nuclear testing, may be traced through the unsaturated zone and profiles of its distribution have been used to measure recharge rates over periods often of several decades. Tritium, though, has limitations (Edmunds et al. 1987). The tritium forms part of the water molecule and is lost by evaporation so that it becomes difficult to make budget studies. The sampling and analysis require specialists, making it unsuitable for use in remote locations or on a routine basis. Additionally, the tritium half-life is 12.5 yr and this means that background levels are being approached at the present day in the absence of any nuclear testing.

The use of solute profiles (and especially chloride) has therefore been developed as a simpler alternative to tritium but taking advantage of the fact that both methods provide long-term records and tritium may still be used to verify the solute methods. Unlike tritium, however, chloride has definite advantages:

1) The inputs are conserved in the soil solution and, unlike tritium, (part of the water molecule) are not evaporated during hydrological processes.

2) The sampling, analysis and interpretation is straightforward and the technique is applicable to difficult terrain and requires only basic laboratory facilities.

The main limitation of the chloride method is the need to have good information for rainfall inputs and at least three years' data are needed.

3. REGIONAL CONTEXT OF THE STUDY

Senegal lies in a strategic position on the margin of the Sahel where the two climatic zones of the arid north and the humid south both meet. Topographically it is low lying with a mean altitude of only 50 m. The three areas chosen for research (Figure 3.1) lie in the western, coastal region of the country stretching across the climatic gradient where recharge characteristics may be compared. The choice of areas was also constrained by: 1) the density of population using shallow groundwaters, 2) the depth to water table and 3) the geology and hydrogeology of the area.

3.1 Geology

The main feature of the geology is the sedimentary basin of Senegal which overlies Precambrian basement, exposed in eastern Senegal (Figure 3.1). The formations of the sedimentary basin range from Palaeozoic to Quaternary (Bellion and Guiraud, 1984). The principal formations of interest for water resources are in the Upper Cretaceous and Eocene together with the Quaternary.

- The Maastrichtian. Over most of the country the Maastrichtian is an important confined aquifer. It is a generally sandy facies with some clay, becoming more or less clay-dominated further west as the formation thickens (900-1800 m thick).

- The Palaeocene. Calcareous shales and limestones often karstified (50-100 m thick).

- The Lower Eocene (Ypresien). Clays and shales often calcareous with some limestones (100-400 m thick).

- The Middle Eocene (Lutetien). Clays and shales with some cherts in the west of the basin but elsewhere a carbonate facies. In the area of Tivouane the series gives rise to the important economic deposits of phosphate.

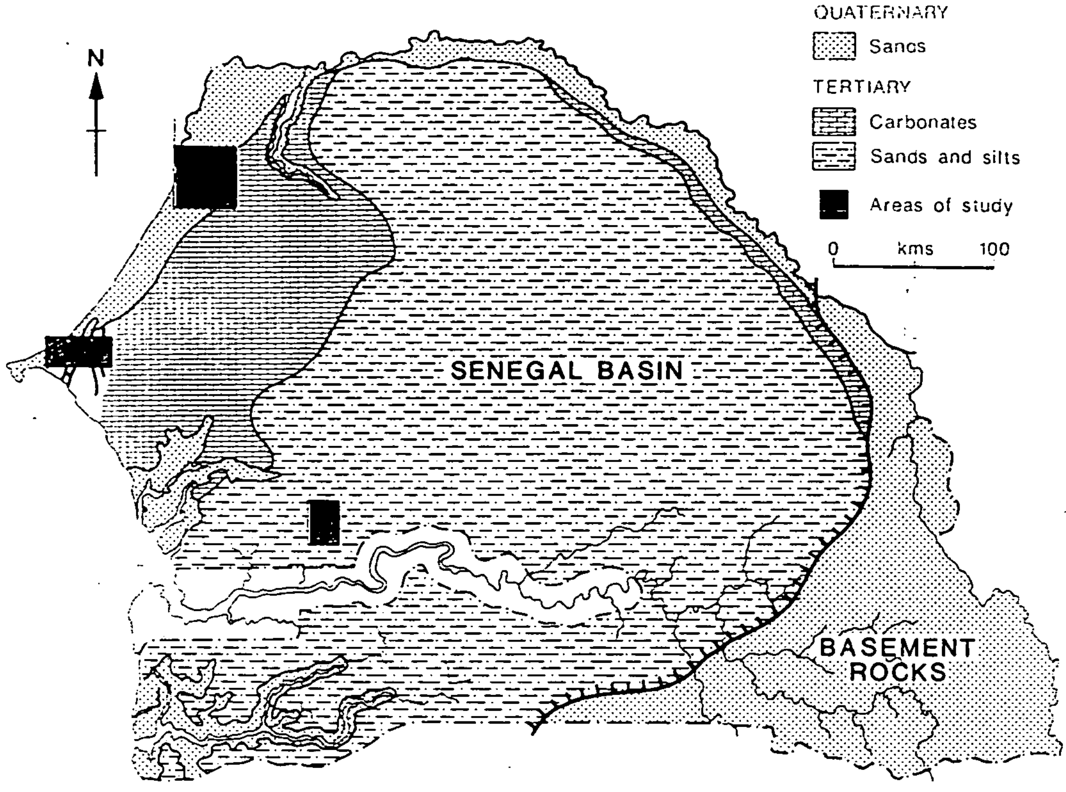


Figure 3.1 Choice of research areas in relation to the outline geology of Senegal.

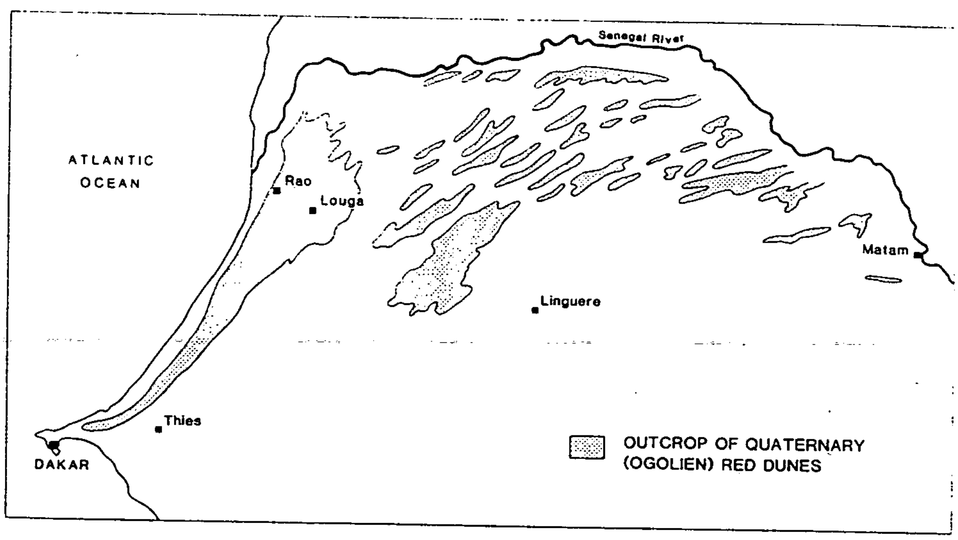


Figure 3.2 Outcrop of Ogolien dune sands (Quaternary) in northern Senegal.

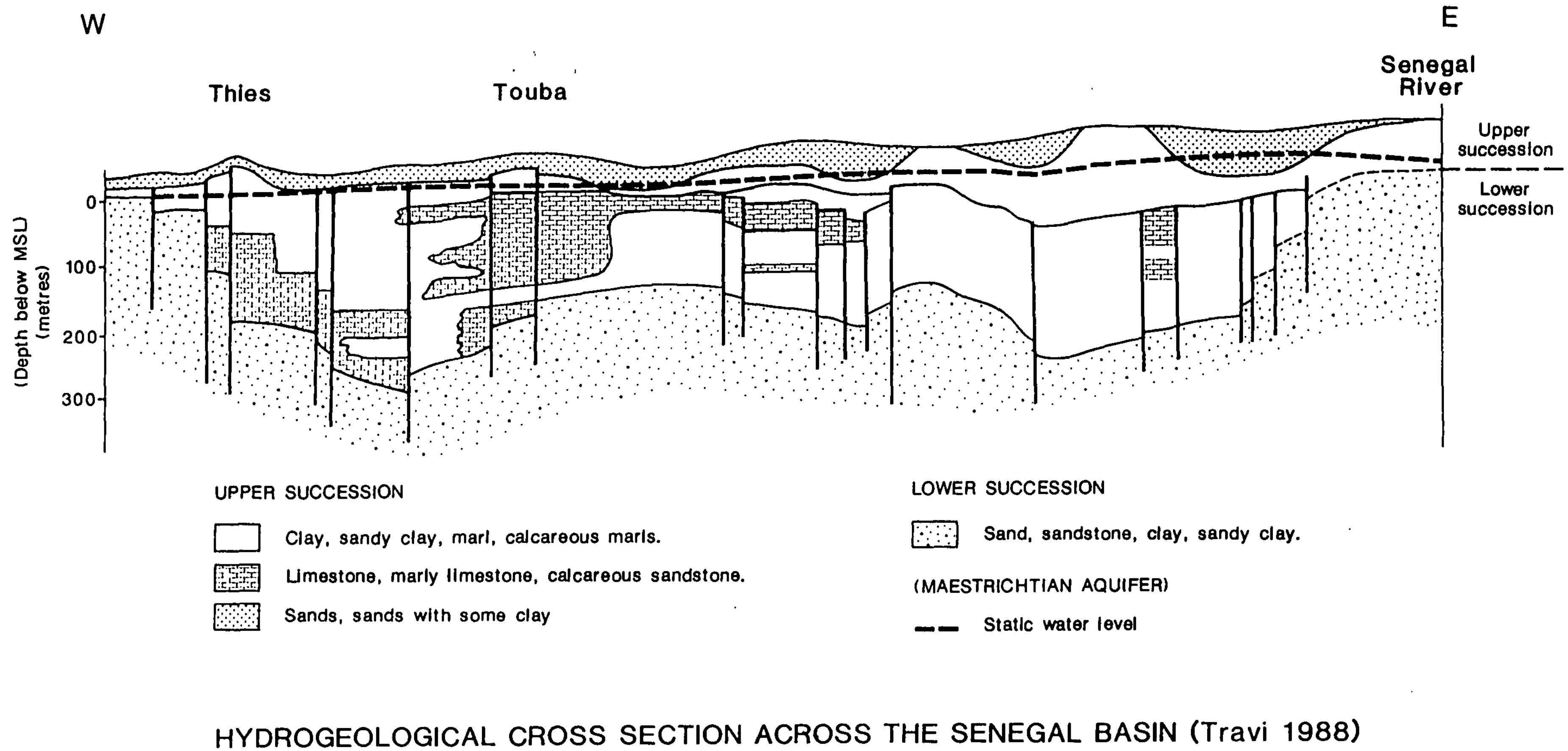


Figure 3.3 Hydrogeological cross-section across the Senegal Basin (Travi, 1988).

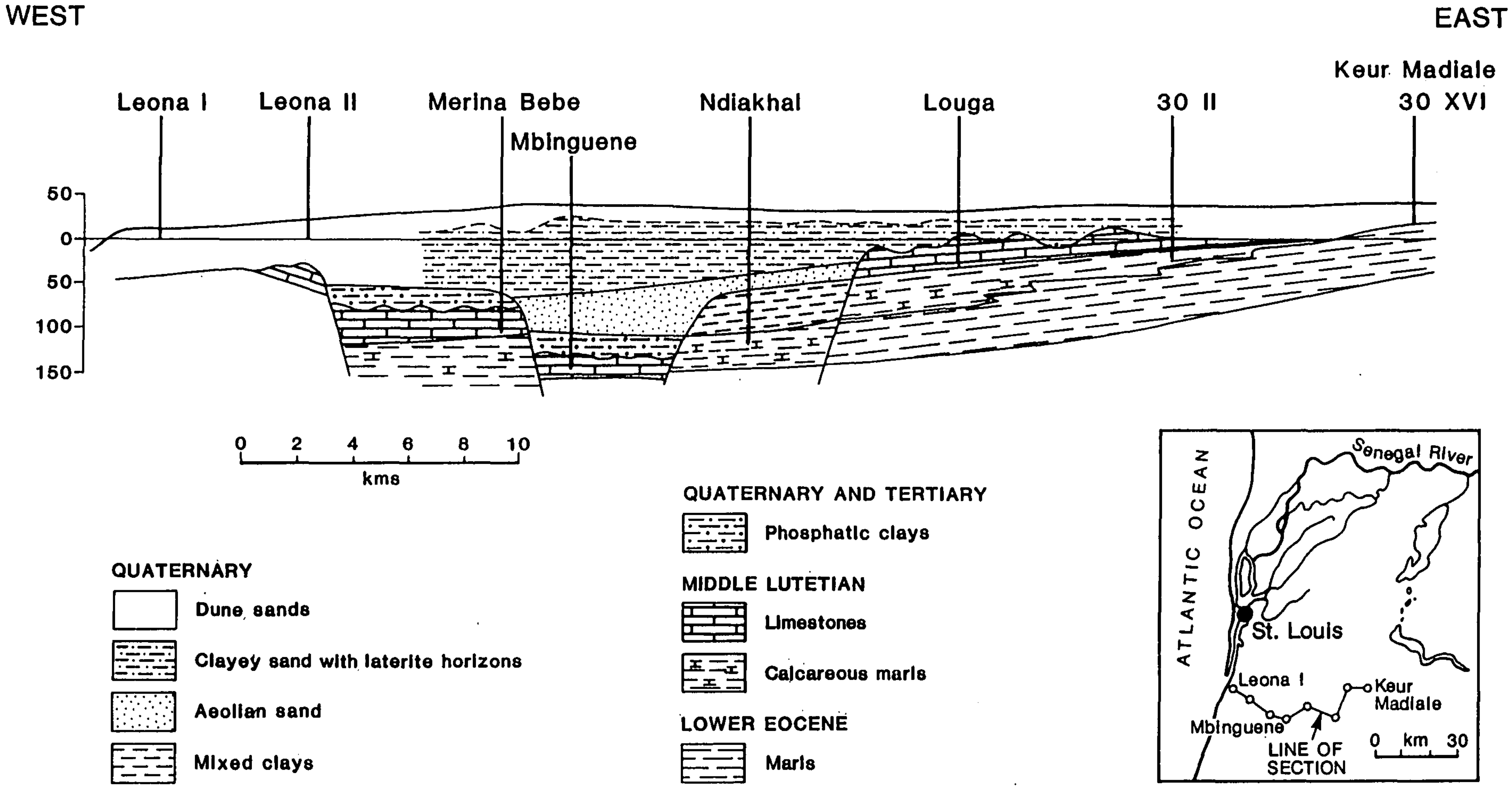


Figure 3.4 Schematic east-west cross-section of the sandy aquifer in the Louga area (after Monteiller, 1986).

- The Miocene (Continental Terminal) is made up mainly of sandy clays with laterites near the top. In southern Senegal there are also marine facies. The CT forms an important outcrop area in Senegal and has been the subject of profiling in this study in the Kaolack area.

- The Pliocene - mainly a detrital surface deposit rich in iron which is related to weathered volcanics from the late Miocene activity.

- the Quaternary - characterised by variations in sea level and climate - has produced important superficial deposits overlying much of the Senegal basin. These deposits have been described especially by (Monteillet, 1986; Diouf, 1989). Apart from two humid periods (1.2-0.8 Ma and 0.4-0.3 Ma) the Quaternary is mainly composed of continental sediments, notably on the north coast of Senegal. The lower sands, called infrabasaltic, overlie the Eocene volcanics, for example near Dakar (Gaye, 1980) and are between 1.5 and 0.8 Ma. The upper Quaternary sands are fine-grained and form an elongated series of NE-SW or NNE-SSW orientated dune deposits. This system, often called the Ogolien, was formed in the last 0.3 Ma of the Quaternary under strong arid conditions. These sands are the main target of research in the Louga region and their outcrop area is shown in Figure 3.2. Lake and marsh deposits are often found in interdune areas and these Niayes are an important topographical feature at the present day.

3.2 Hydrogeology

In this consideration of the hydrogeology, emphasis is placed only on those shallow aquifers of interest for the recharge study together with their interrelationships with the deeper aquifer systems.

The Quaternary Sand aquifer is found along the coastal strip of northern Senegal and contains resources in the region of 3,200,000 m^3/day (Travi, 1988). Nevertheless it is considered that in times of drought, the recharge is not adequate to compensate for losses and a continuing fall in water levels can be seen in nearly all monitoring wells (see Figure 1.4). There is also a risk of saline intrusion (Gaye et al. 1988). Values of t = 3.56 m^3/sec were estimated for wells in Kap Gaye, War Cissé area, and yields of 150 m^3/hr were obtained for a drawdown of 6-8 m (WHO, 1974).

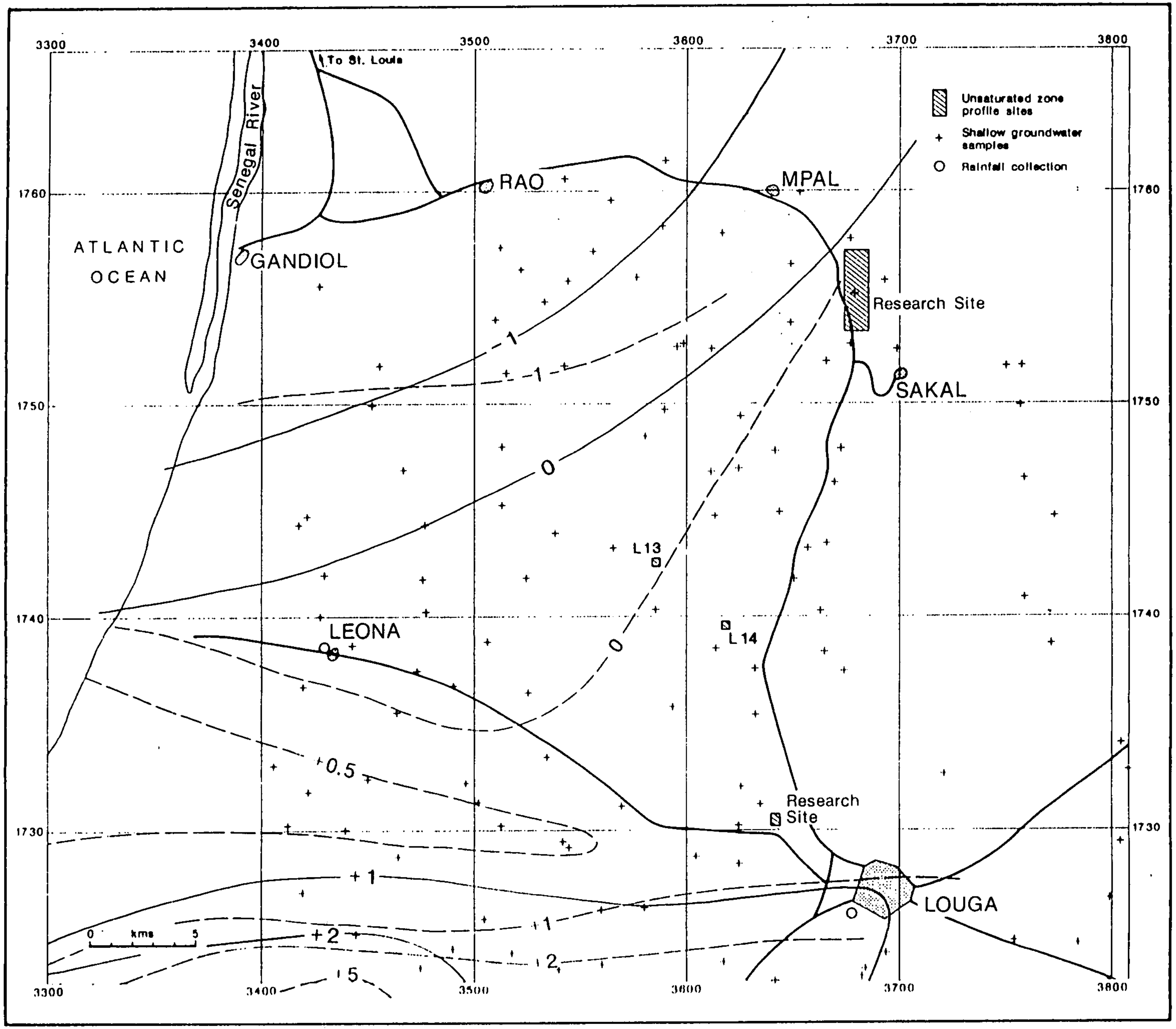


Figure 3.5

PIEZOMETRIC SURFACE OF THE PHREATIC AQUIFER LOUGA REGION

- - +1 - - Water level (m) 1985

—— +1 —— Water level (m) 1990

(Data from Ministry of Hydraulics)

The Continental Terminal aquifer has an effective thickness varying from 10 to more than 150 m, and with reserves estimated at 8,500,000 m^3/day (Travi, 1988). The exploitation is often made difficult by the poor yields and the depth of pumping for village wells - the water table is on average 40-60 m depth. The aquifer is important in central and eastern Senegal.

The Lutetien aquifer is important to the east of the Dakar-Saint-Louis road over an area of some 2000 km^2. The yields vary according to the degree of karstification, but it may regularly produce 150 m^3/hr for a 1 m drawdown (WHO, 1974). It is used to provide Dakar with some 160,000 m^3/day.

The Maastrichtian forms a confined aquifer extending over virtually the whole of Senegal at a depth of 50-500 m. The aquifer is developed by over 100 wells and the reservoir is large, some 35 Mm^3.

The hydrogeology can be seen in cross section in the schematic diagrams (Figure 3.3 and 3.4). The former, across the whole of Senegal (Travi, 1988), shows the subdivision into two main hydrogeological units. The upper group of aquifers comprises the Quaternary, Continental Terminal, Lutetian rocks with Eocene argillaceous sediments generally forming an aquiclude. However, there are important facies changes as well as major faults which mean that there is likely to be hydraulic continuity over much of the upper aquifer system. The lower group comprising the Maastrichtian is mainly confined but has the probability of local interconnection with the overlying aquifers. The recharge to the Maastrichtian must be considered to be via the overlying sequence.

The cross section through the Louga-Leona area (Figure 3.4) crosses the area of study (Monteillet, 1986). Quaternary sands up to 50 m thick overlie Lutetian and Continental Terminal sediments which outcrop west of Louga, where water yields and quality also deteriorate.

Hydrogeological data on the area north-west of Louga is generally sparse. Water abstraction is mainly hand-drawn from open (0.8-1.2 m) diameter hand-dug wells (see specific data in 3.6). No pumping test data is available for this area and few if any deep wells into the Lutetian or Eocene sediments exist. Accurate topographic data for the area is not available, sufficient to draw good piezometric maps. However, a water table map has been drawn by the Ministry of Hydraulics (1985, 1990) based on the whole coastal aquifer, but with only a handful of survey points in the Louga area. This map (Figure 3.5) shows that the piezometric surface declines towards the north and that beneath the survey area is close to 0 m. There is evidence of a decline of up to 0.5 m in certain areas over the 5-year period and this is in line with the continued fall in water levels noted earlier (Figure 1.4).

3.3 Climate

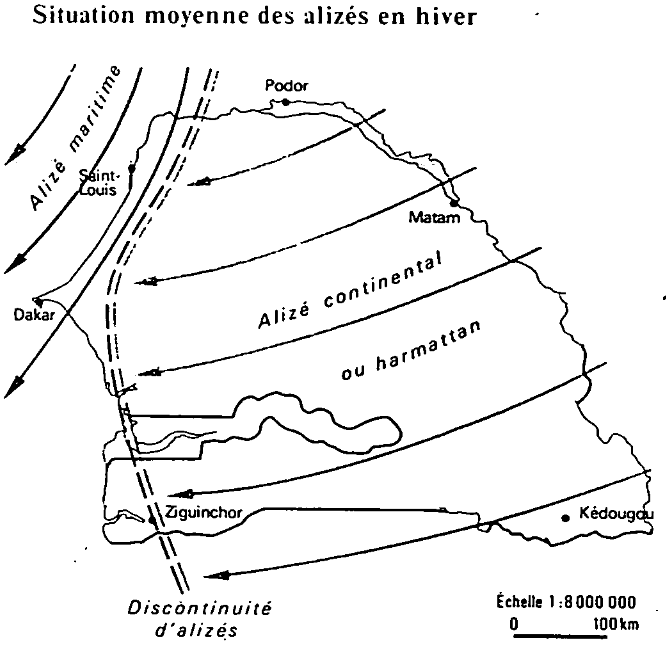
For the purpose of recharge estimation it is necessary to consider the climatic conditions of the present and recent past together with the climatic history over an extended period.

The climate of Senegal (Leroux, 1980) is characterised by the interaction of three principal air masses whose trajectories are facilitated by the low lying relief (Figure 3.6).

The Azores anticyclone produces cool, moist air derived from the north to north-west and which is dominant during winter months, when it may persist in coastal regions north of Cap Vert. Little or no rainfall is associated with this air mass but during the winter season occasional 'heug rains' may occur (e.g. 17 mm in Dakar on 1 December 1978).

The Harmattan brings hot air from the east or north-east from the Sahara, often containing considerable amounts of dust. It rises above the maritime air mass and further inhibits precipitation.

The Monsoon derives from the St Helena anticyclone in the South Atlantic, bringing particularly unstable moist warm air from April to July/August which progresses steadily across the country (Figure 3.6). The boundary between the dry air masses with the monsoon is termed the Intertropical Convergence Zone (ITCZ).



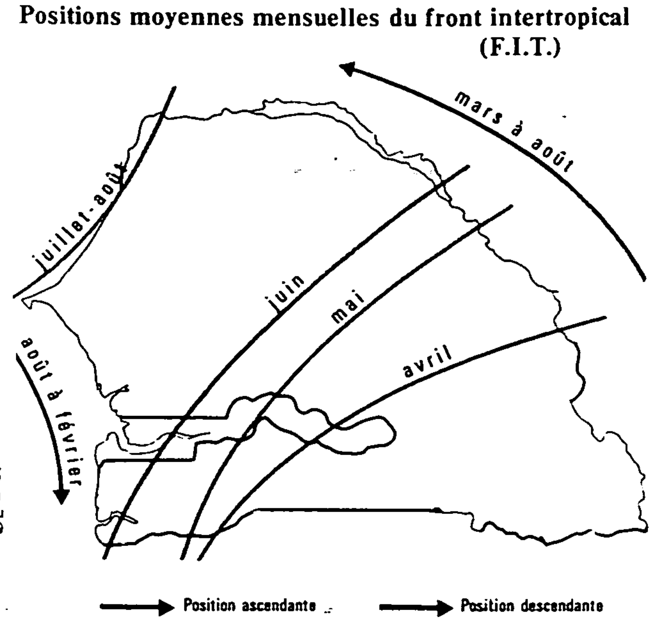


Figure 3.6 Average trade wind directions in winter and the average monthly positions of the intertropical front.

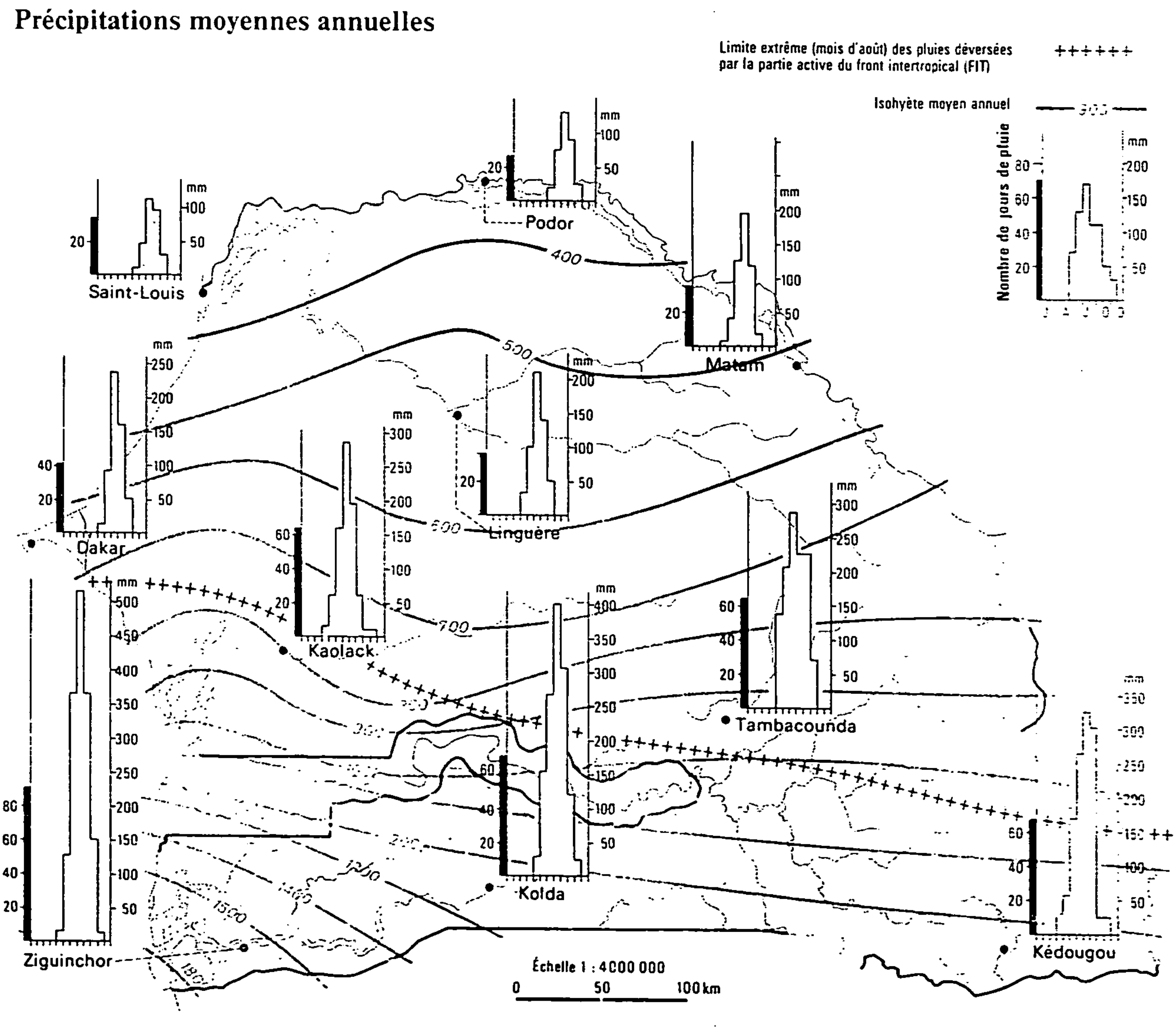


Figure 3.7 Generalised distribution of rainfall based on average conditions obtained during the 20th Century.

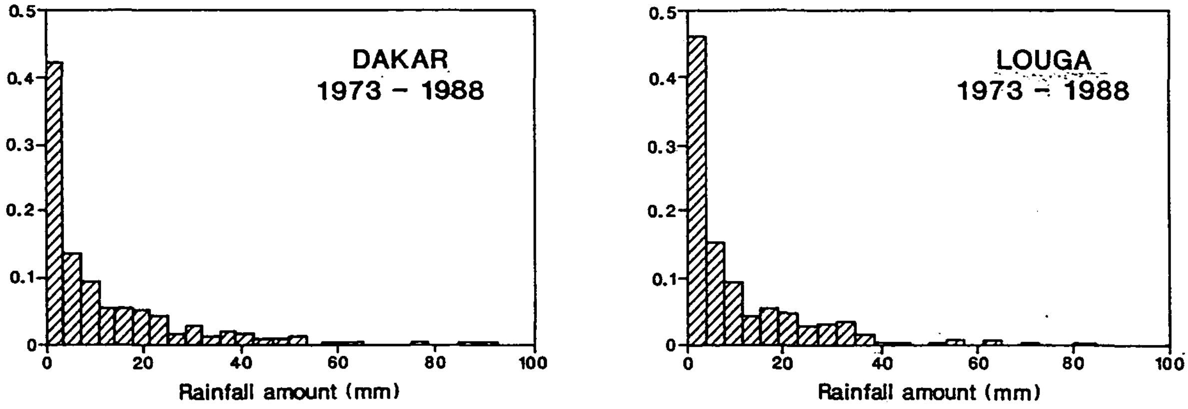


Figure 3.8 Histograms showing the frequency of daily rainfall of a certain intensity at Dakar and Louga, 1973-1978.

The year may be divided into a dry season and a wet season although, as explained above, the dry season may not be exclusively so. Normally, the rains commence in April in the south and increase in intensity before declining in September. The monsoon storms decrease in frequency from south to north and St Louis may have up to 30 rain events compared with over 60 at Kaolack. In the northern half of the country, the rains become more stormy and more spatially discontinuous, so that the climate predictability is less certain. A general rainfall map may be drawn (Figure 3.7) based on the long-term mean annual rainfall (approximately the first 70 years of this century), but this does not represent the present day situation (see below).

The rainfall frequency and intensity is an important factor in consideration of recharge. In Figure 3.8 are shown histograms of the frequency of daily rains measured during the period 1973-1988 for two stations near the study area (Gaye, 1990). In this period the maxima are respectively 92.8 at Dakar and 84.4 at Louga. At these two stations heavy storms are rare with more than 96% of storms between 0.1 and 50 mm. The heavy rainfall may not always be conducive to recharge since runoff and soil erosion are likely. The lightest rains probably also are ineffective since most water will subsequently be evaporated. The timing, intensity and sequence of storms may therefore be very important in determining recharge in a given year.

The mean wind direction in the Louga region is NNE from December-June (harmattan, dry) and west or south-west (monsoon, moist) from June-September, so the trajectory of rains may be from the Atlantic.

3.4 Soils and Vegetation

3.4.1 Soils

The soils of Senegal have been classified by Charreau and Fauck (1965). Details are given here only of those soils of principal interest for this study - at Louga and near Nioro du Rip. Three types are described:

- Sols subarides bruns rouge (semi-arid red-brown soils): deficient in fine-grained components, with a weak capacity for water retention and light in texture.

- Sols subarides brun (semi-arid brown soils): rich in mineral content and of heavier texture (than above), which reduces internal drainage.

These two types form the main soil group at Louga whilst in the Kaolack-Nioro du Rip area we have:

- Sols ferrugineaux tropicaux lessivés (leached iron-rich tropical soils): soils which have been leached of iron and clay minerals with a horizon of accumulation at depth which slows drainage.

Granulometry studies performed during this project on samples from Kaolack (Gaye, 1990) confirm that the upper 3.5 m contain between 20-30% clay minerals (<50 μm) but fine grained sands (125-160 μm) form the main component (site KK2) but below this the clay content decreased. No data were available for KK1 but in KK3 and KK4 showed a fine grain content which was more consistent with depth.

3.4.2 Vegetation

Three distinct vegetation zones have been distinguished by Adams et al. (1965) which are directly related to rainfall - 1) Sahelian, 2) Sudanian, 3) Guinean, but only the first two are relevant to this study. The boundary between the two zones lay (in the 1960s) approximately E-W through Dakar, but in the two following two decades have been displaced to the south.

The Sahelian Zone, covering most of northern Senegal lies between 250-700 mm isohyets. It is characterised by the rainy season prairies, dotted with ephemeral trees and small spring bushes.

The Sudanian Zone, between 700-1500 mm rainfall, is a wooded savannah, with dry land forest in the north giving way to closed canopy forest in the south.

In the Louga area which has been well cultivated, the original vegetation has practically disappeared due to deforestation for firewood and cultivation. Fields of millet and groundnuts are interspersed with trees every 8-10 m (or much less as observed at the present time). Towards the north Acacia radiana is dominant with Acacia albida mixed in with it in the central region and which completely replaces it in the south. Other species include Balanites, Ficus platiphylla, Acacia milotica adamsonii, Aphania senegalensis, Parinari macrophilla. In the rainy season the carpet of vegetation may be quite dense, with annual grasses forming an ephemeral prairie steppe with Maytenus senegalensis, Andropogon gayanus and Aritida longifloria.

In the Kaolack region, the trees are interspersed also with cultivated fields (agro-forestry). The principal trees are Cordyla africana with Parkia biglobosa and numerus Ficus, all of which have edible fruits. During the jachères (alternate years of non-cultivation) the fields may be invaded by Pennisetum pedicellatum and Andropogon pseudapricus as well as small trees such as Guiera senegalensis and Combretum glutinosum. Other vegetation may become established such as Andropogon gayanus, Hyparrhenia. Schizachyrium and Combopogon giganteus.

3.5 Palaeoclimate

Groundwater recharge and available resources depend to a large extent on the antecedent climatic conditions extending over scales of time ranging from decades (10') to millennia 10^3 years). A consistent picture is now emerging for the climatic history, notably for periods of wetter or drier years based on careful multidisciplinary studies of the faunal record (diatoms, shells and other palaeoecological indicators), the archaeological record, sedimentological record (notably offshore sediments since accumulations on land are sparse) the geochemical record (radiocarbon and stable isotope data) and the historical record (from early chronicles and the records of explorers and settlers).

At the scale of millennia the palaeoclimatic history may be elegantly summarised by the diatom and sedimentation record of Lake Chad (Servant and Servant-Vildary, 1980) for which lake levels have been reconstructed over a period of 4×10^4 years. This is probably the most complete record for northern Africa and may be used to derive a palaeohydrological record expressed as P/E in Figure 3.9. Wet phases in order of decreasing importance are recorded between 9,000-8,000, at 6,000, 3,000-3,500, 11,000 and from 40,000 to 20,000 B.P. - the intervening periods being arid or hyperarid including the period from 3,000 B.P. to the present, during historic times, which has been an extended period of relative aridity.

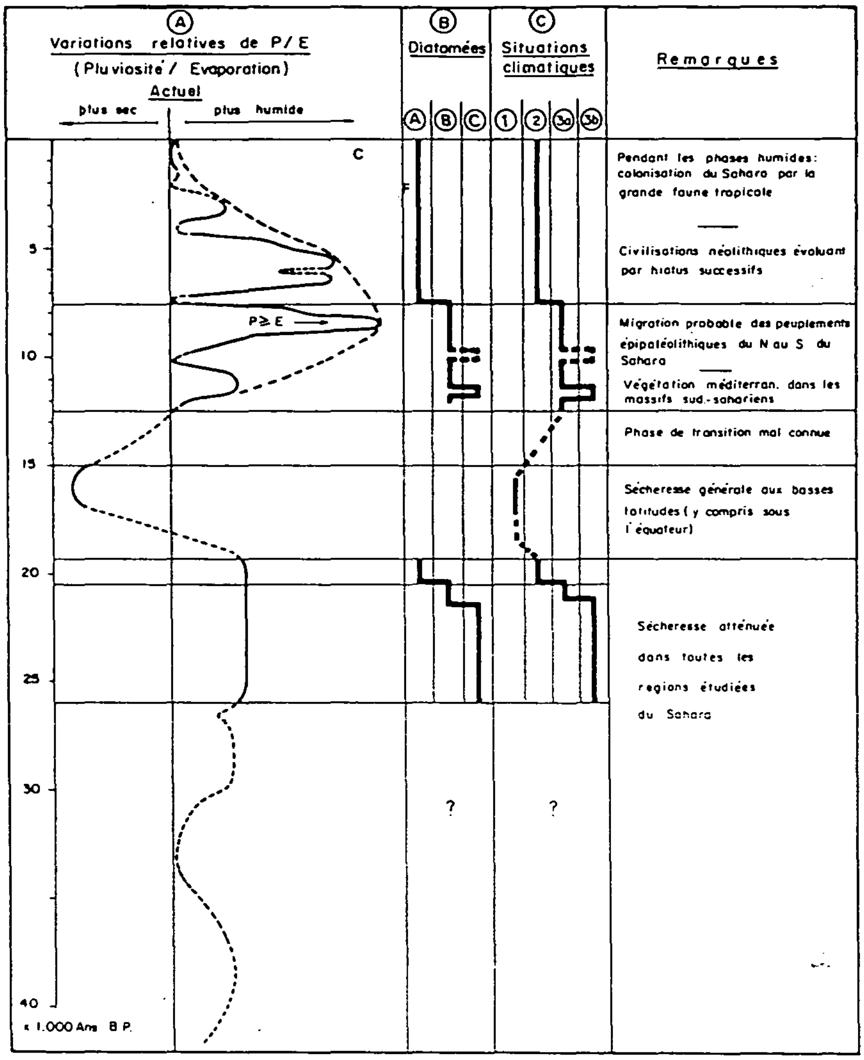


Figure 6.9 Evolution paléoclimatique du bassin du Tchad depuis 40 000 ans B.P.

A. Variation de P/E vers 14°N (d'après Servant 1973).

B. Evolution des associations de diatomées d'après Servant-Vildary (1977); A. espèces tropicales; B. espèces préférentielles des eaux froides associées à de rares espèces des hautes et moyennes latitudes et à de très rares espèces tropicales; C. espèces des hautes et moyennes latitudes, pas de formes tropicales.

C. Hypothèse sur les modifications des circulations atmosphériques. 1. Phase hyperaride. Circulation d'Est avec vents violents du NE en surface (puissants anticyclones subtropicaux décalés vers le Sud par rapport à leur position actuelle?). 2. Advections d'air polaire exceptionnelles ou rares aux basses latitudes. Climats tropicaux à pluies saisonnières et orageuses au Tchad. Zonation des isohyètes du Sud au Nord. 3a et 3b. Fréquentes advections d'air polaire aux latitudes du Tchad. Climats sans équivalents actuels dans les régions tropicales du continent africain.

Figure 3.9 Evolution of the Chad Basin over the past 40 000 years - a summary of likely wetter and drier episodes.

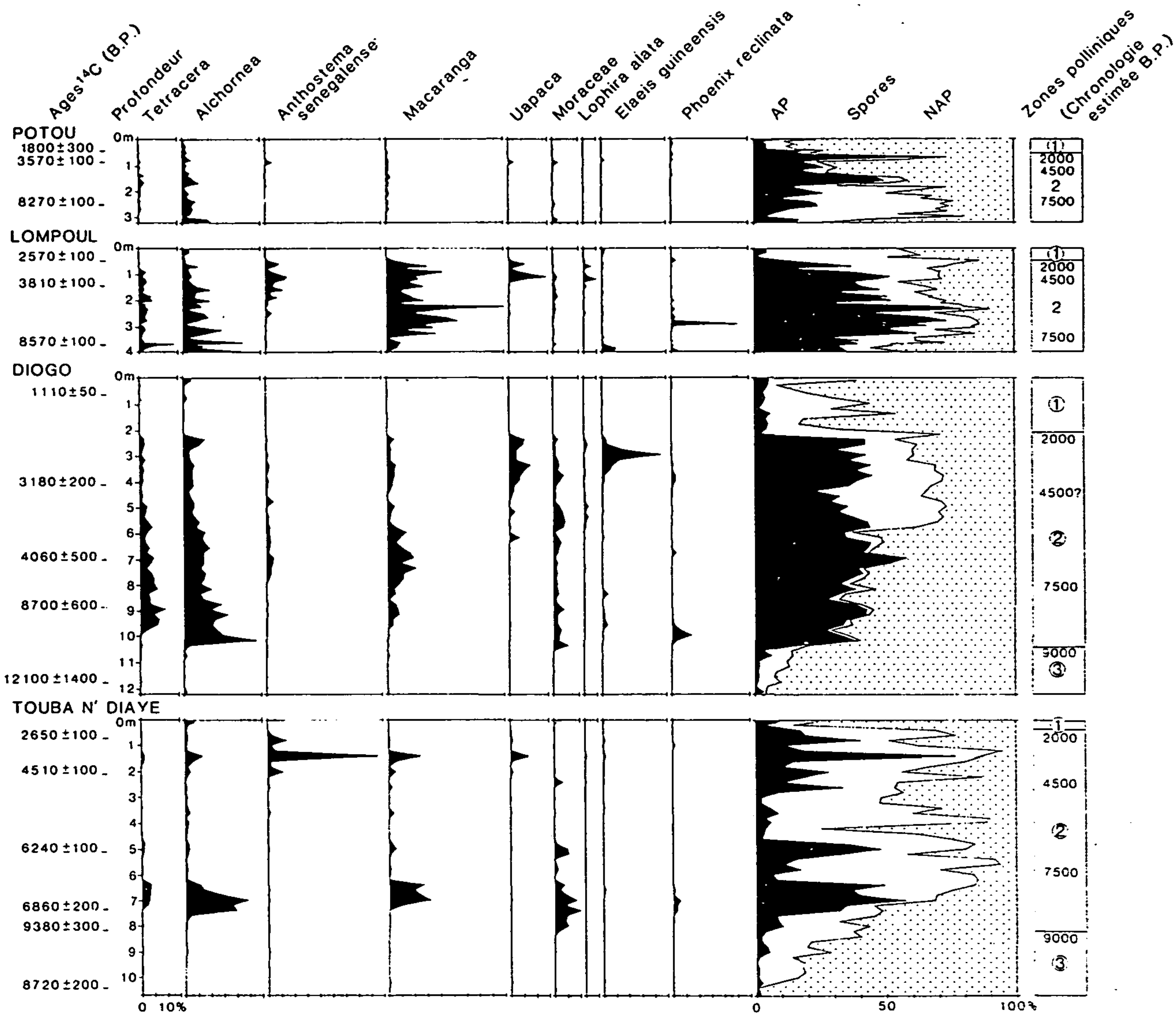


Figure 3.10 Pollen diagrams from Touba N'Diaye, Diogo, Lompoul and Potou showing on the left: radiocarbon ages, depth from surface and frequencies of the most important taxa of mesophilous forest; on the right a synthetic diagram with the total arboreal pollen, ferns and non-arboreal pollen, the pollen zones and estimated chronology (after Lezine, 1988).

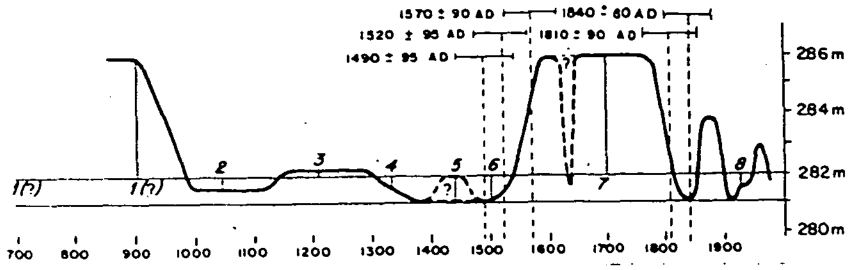


Figure 3.11 Variations in the level of Lake Chad during the last millennium (after Maley, 1973).

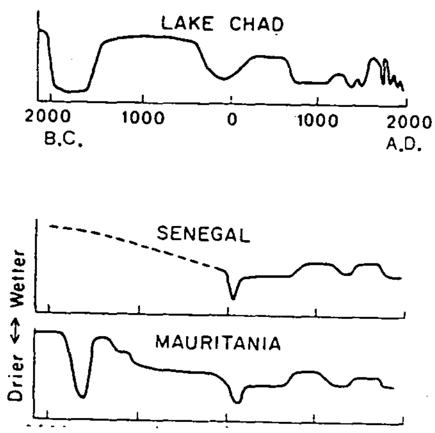


Figure 3.12 Fluctuations in lake levels and climate in Africa during the past 2000 years (after Nicholson, 1980).

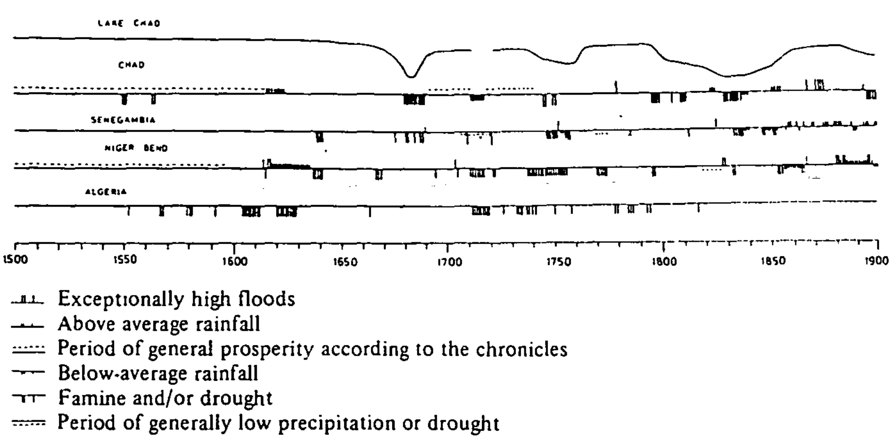
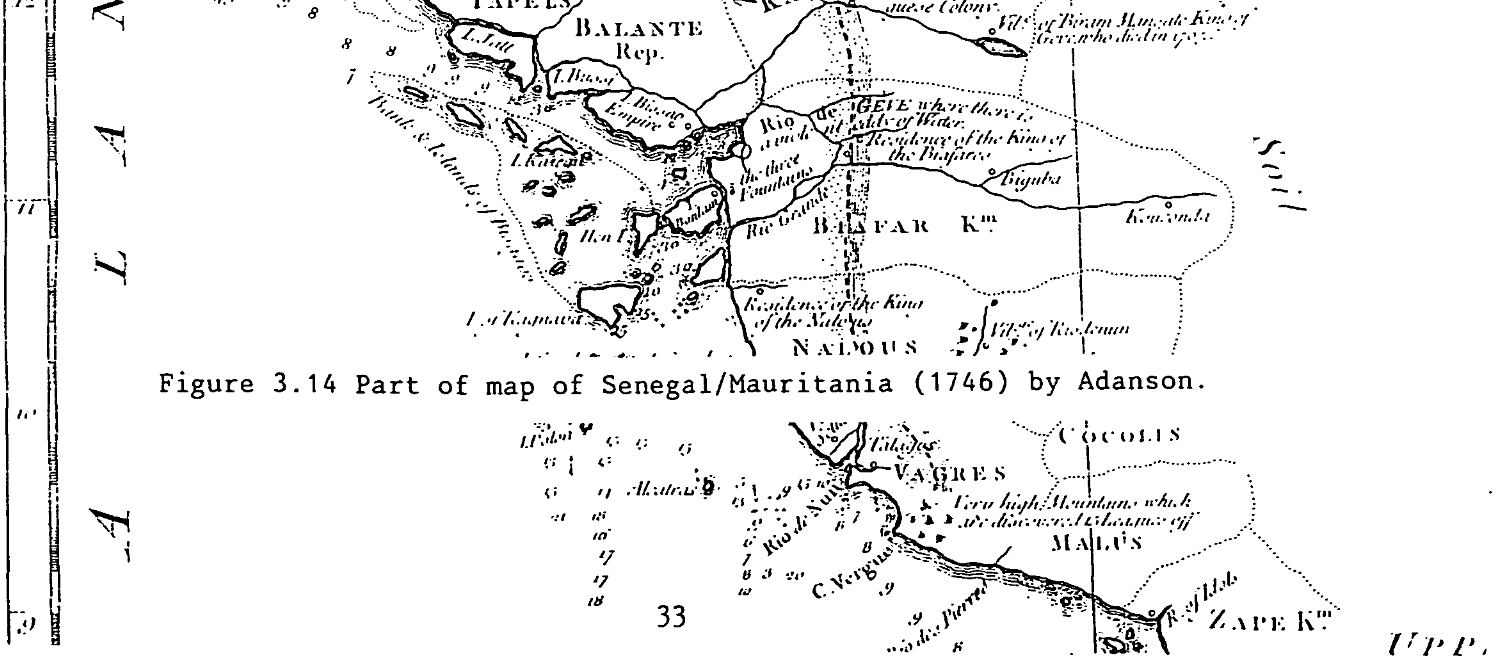


Figure 3.13 Chronology of famine and drought in Senegal, Chad, Niger Bend and northern Algeria, 1500 to 1900 (after Nicholson, 1980).

Figure 3.14 Part of map of Senegal/Mauritania (1746) by Adanson.



Flow of Senegal River at Bakel

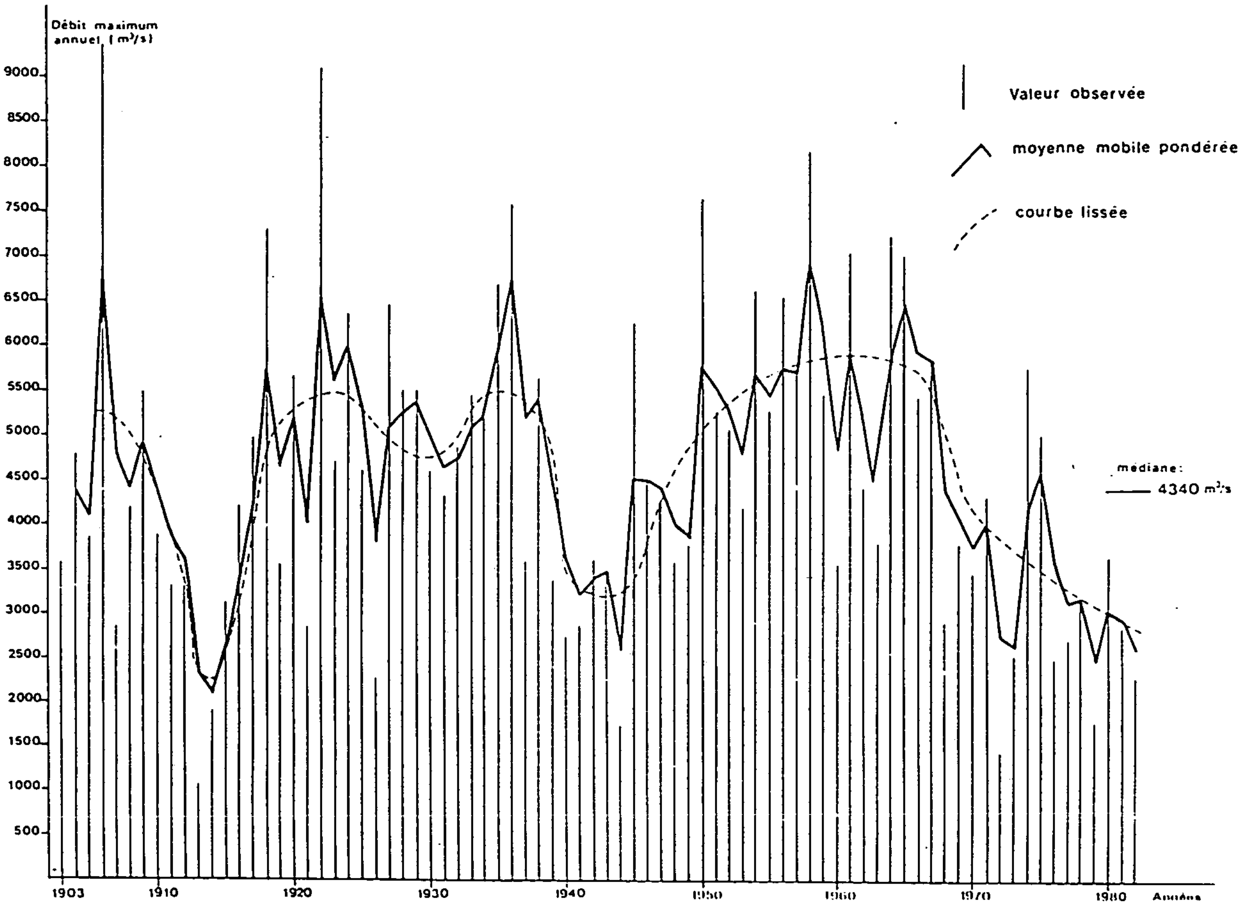


Figure 3.15 Maximum annual flows and mobile annual average flows for the Senegal River at Bakel (after Olivry, 1982).

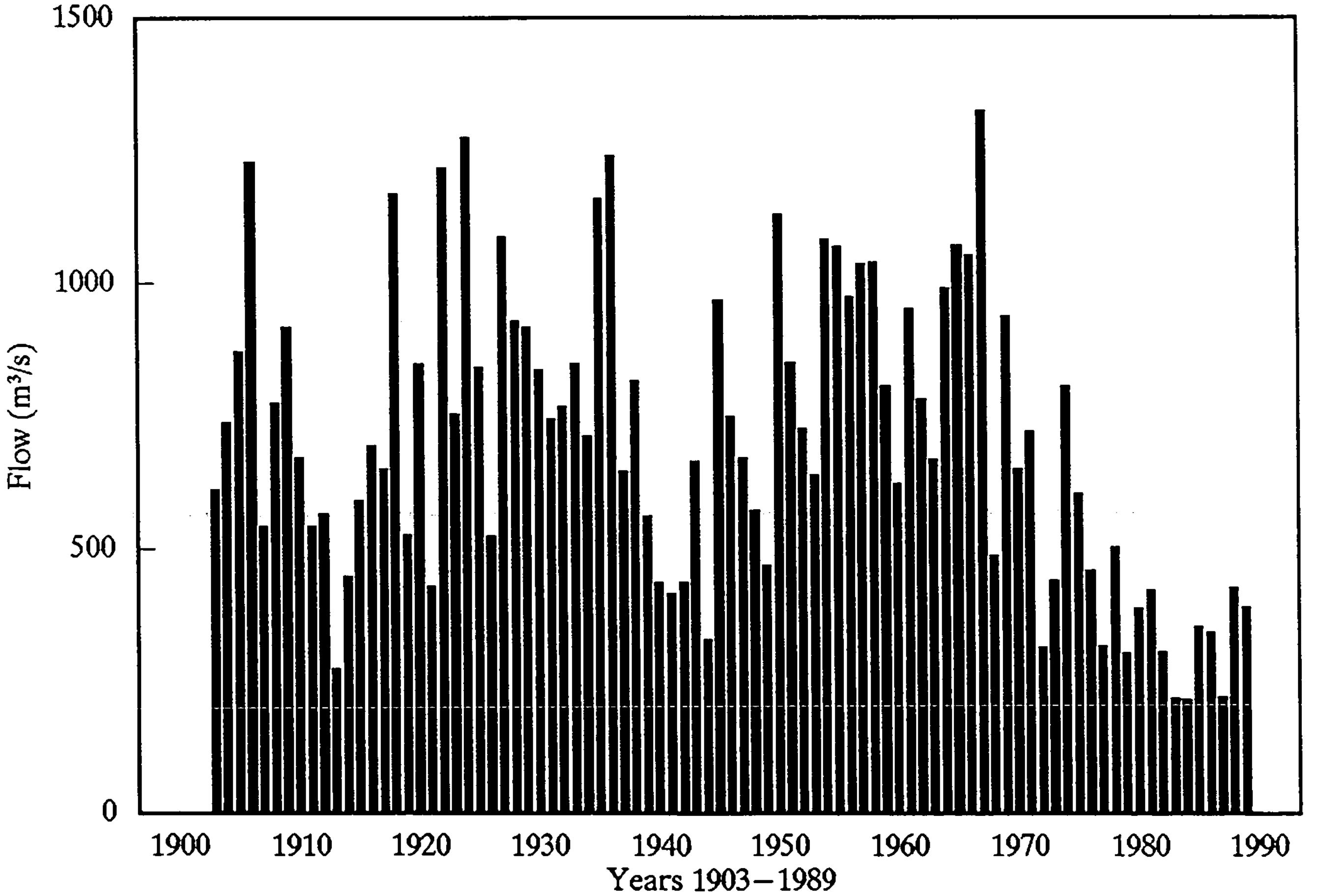


Figure 3.16 Mean flow of the Senegal River at Bakel based on data from Gac et al. (1990).

These late Quaternary and Holocene climatic fluctuations are considered either due to incursions of polar air to lower latitudes or conversely of the movement of the ITCZ further north over the Sahara. For the Central Sahara, tropical depressions are considered the likely source of rain up to the early Holocene (6,500 B.P.) and with monsoon rains the likely source up to 4,400 B.P. (Maley, 1977; Fabré and Petit-Maire, 1988). Evidence of the shift in climatic belts is also clearly demonstrated by the existence of stable late-Pleistocene sand dunes in areas now receiving 600-800 mm rainfall, e.g. in the Dakar area (Faure and Williams, 1977). An important factor in the palaeoenvironment of Senegal during the late Pleistocene/Holocene has been the lower sea level (minimum of -100 m around 18,000 B.P.) rising to near present day levels at 7,000 B.P. (Lezine, 1986). Important evidence linking climatic change and groundwater levels is provided by the evidence from the zone of niayes in coastal Senegal. The 'mayes' are interdunal peat-bogs maintained by the regional groundwater levels which fluctuate during wet and dry seasons and cycles of seasons. Lezine (1988, 1989) has shown using palynological evidence that vegetation changes are closely linked with rainfall and that the niayes which are closely linked with fluctuating groundwater levels, record these changes (Figure 3.10). The results from Touba and nearby are sufficiently close to the present area as to be directly relevant to the recharge history of the region. Two humid periods are recorded - from 9000-7500 BP and 4000-2000 BP. In the early Holocene (before 9000 BP) the regional vegetation was of pseudo-steppe, semi-desert type. During the next 1500 years or so, Guinean vegetation replaced former xerophytic vegetation types and this represented an increase in rainfall of at least 300 mm/year above the present. Sudano-Guinean swamp forest developed in the niayes in the intervening period with Sudanian dry forest and savanna developed in the hinterland. During the period from 4000 BP, a further migration of Guinean-type vegetation occurred with the expansion also of the area of the niayes in line with the higher water-table. Thus 4000-2000 BP is found to be the last major wet phase in the Sahel on the basis of palynological evidence, since which the present semi-arid environment has been more-or-less predominant.

At the scale of centuries and especially during the past 1000 years, Lake Chad (Figure 3.11) again offers the most complete climatic record (Maley, 1973; Servant and Servant-Vildary, 1980). Evidence from Senegal and Mauritania has also been compiled by Nicholson (1980) from various authors and is compared against the Lake Chad record in Figure 3.12. The lake acts as a 'rain gauge'. A major dry period is recorded around 1750 BC in west Africa and a dry period is also found for Senegal around 200 AD which is confirmed in the other two records. The variations during the past millennium have been built up from sedimentological and palynological records from superficial deposits and show that the period from 1600-1800 AD was much more humid than the present day and for the previous years of the millennium.

The record for the past 200-300 years has been constructed from archives, chronicles and colonial reports (Nicholson, 1980) and summarised in Figure 3.12. In Senegal and Gambia the chronology prior to 1850 has been built on the work of Curtin (1968). No famines or droughts are mentioned before 1640. However, Curtin does confirm that the 16th Century was characterised by increased rainfall relative to the present in Senegal and southern Mauritania. In the 17th Century this climatic situation persisted with the significant exception of a drought in c. 1640.

During the 16th and 18th Centuries, Michel (1969) describes the period as the last 'pluvial' in Senegal. Mangrove stands were recorded along the banks of the Senegal River and a more humid climate extended at least as far as southern Mauritania. Adanson's description of Senegal in 1749-1755 suggests that humid conditions lasted until this time (Adanson, 1759). He records that the island of Sor, near the mouth of the Senegal river was bordered by a very thick wood and thorny bushes. He describes forests on the river banks near Podor including tamarisks, redgum and thorny acacias, plus thriving imported citrus fruits. His maps (Figure 3.14) show certain lakes in northern Senegal and southern Mauritania which have since dried up, plus a forest in southern Mauritania to 18°N where precipitation today is below 200 mm. He mentions the great drought of c. 1749, a time which corresponds to the extremely severe Sahel drought of 1736-1758. He qualifies his statement by stating that the area near Saint-Louis and Podor had been rainless from December to June or July - a situation that is normal today. These descriptions imply both that the ITCZ advances more rapidly northward to produce an earlier summer rainy season and that there was a more frequent occurrence of the 'heug' rains. Up to 500 ancient maps of the Senegal River are in existence (J Y Gac, pers. comm.) and a further study of these might yield other information on the recent climatic/ vegetation history.

The scientific records of climate history are also very good for Senegal and Gambia and are based upon the measurements of rainfall at Saint-Louis, Banjul plus the flow of the Senegal River at Bakel, data which have been summarised by Olivry (1982), and Gac et al. (1990).

The Senegal River basin covers an area of some 218,000 km^2 and records of its flow have been obtained since 1903. The maximum flow of the river at Bakel from 1903-1982 is summarised in Figure 3.15, where the weighted mobile mean value is also given, taking account of the variability between adjacent years. In Figure 3.16 the mean river flow at Bakel is plotted from the data of Gac et al. (1990) as a histogram. Two distinct periods of low flow are noticed around 1913 and 1943 in addition to the prolonged period of drought from ca. 1970.

Rainfall records for Saint-Louis are the longest for West Africa, dating from 1854, although interrupted around 1880 due to yellow fever epidemic. Reliable data are summarised in Figure 1.3 for the period 1893-1990; for the years 1854-1892 it seems the period was generally wetter with a mean rainfall of around 400 mm yr^{-1}. 1863 (141 mm) and 1872 (188 mm) were the two minima of the period. The fluctuations of rainfall differ significantly from the records for the Senegal river, although there are some correlations such as the wetter period of the 1920s and 1930s. The high flow period of the 1950-60s does not appear in the Saint-Louis rainfall record.

The periods of low rainfall in the 20th Century were those of 1913-1914 and 1941-1942, and both of these are accentuated on a regional scale by the record of the Senegal River. A clear correspondence does, however, exist in the major drought period 1968-1982 (or probably 1986). The long-term mean of 356 mm contrasts markedly with the 1968-1986 mean of 223 mm which is a decrease of 37% on the long-term average from 1893-1986.

3.6 Water Use and Water Requirements

In the Louga area studied here, the predominant method for extraction of water is from traditional hand dug wells and so far there has been little or no development of groundwater from deeper tube wells, except at Louga, although further east towards Coki this becomes a more common means of abstraction as the water table gets deeper and yields are poorer. A detailed study of the water resources and water requirements for each village of <5000 inhabitants was conducted in northern Senegal in 1982 (Couté and Mauroux, 1982), a total of 4700 villages and 700 hamlets. Water was recognised as the limiting factor in development and therefore actual water needs were estimated for the domestic and non-domestic needs of the population. The main statistics for the Louga administrative region were documented at that time (Tables 3.1, 3.2).

Table 3.1 Details of the Louga region, 1982

Population	:	579,100
Population density	:	19.8 km^{-2}
Villages	:	2,584
Average population	:	221
Animals	:	1,046,200
Rainfall (1969-82)	:	279.5
Villages without water	:	1,285
Villages with one water point	:	903
Villages with more than one water point	:	396
Villages with satisfactory supply	:	636
Villages without satisfactory supply	:	1,948

Table 3.2 Types of well, borehole in Louga region (1982)

Total number of wells	:	2,379
Number in use	:	81%
Traditional hand dug wells	:	2,176 (92%)
Modern 'caisson' well	:	59 (2%)
Combined well/borehole	:	144 (6%)

The abstraction of water is by bucket or bag on a rope/pulley, which is regarded as unhygienic since the rope lies on the ground between lifts, dragging in the sand frequented also by animals.

A minimum water use of 20 litres/day^{-1} per person was recorded with 35 for cattle, 50 for horses, 40 for camels, and 5 for fowl, considered as average quantities. The Ministry of Hydraulics (Journées de l'eau) considers 40 litres/day to be a recommended target figure. Using the former figures the overall water use in 1982 was estimated at 239,000 m^3 day^{-1} or 8.7 Mm^3 yr^{-1}. This represents a layer of water 0.11 mm equivalent to 0.03% of the annual rainfall (400 mm).

4. METHODS

4.1 Background

Conventional methods of measuring recharge have limitations when applied to semi-arid and arid regions. A common indirect method of measurement involves consideration of the difference between rainfall and estimates of evapotranspiration, taking into account surface runoff and vegetation cover. Recharge estimates using this water balance approach rely on small differences between two large numbers (rainfall and evaporation), both of which present severe measurement problems in the semi-arid and arid zones. Other methods based on physical measurements including evaluating piezometric levels and soil moisture methods have been reviewed by Simmers (1988); many of these techniques are labour-intensive and need long-term monitoring and analysis.

Geochemical and isotopic methods have been applied to the estimation of recharge in the past 20 years. The use of environmental (thermonuclear) tritium to investigate recharge rates has been widely and fairly successfully used in temperate zones (Smith et al. 1970) and has also been applied successfully in semi-arid and arid zones, e.g. in Australia (Allison and Hughes, 1974), India (Sukhija and Shah, 1975), Saudi Arabia (Dincer et al., 1974), Libya (Allemoz and Olive, 1980), Cyprus (Edmunds and Walton, 1980). Although a proven tool for recharge estimation, tritium suffers from several disadvantages:

(i) tritium is not conservative in behaviour and is lost from the system by evaporation and transpiration;
(ii) the relatively short half life (12.3 yr) has limited the long-term usefulness of the method, especially since 1980;
(iii) vulnerability to contamination during sampling and processing, a factor which is enhanced in remote areas and at low total moisture levels;
(iv) analysis is highly specialised and costly;
(v) quantitative studies are difficult to achieve since it is difficult to determine a tritium mass balance;
(vi) there are not many tritium measurements of pre-1970 rainfall and so the input of tritium is rather poorly defined (especially when taken in conjunction with (i) above).

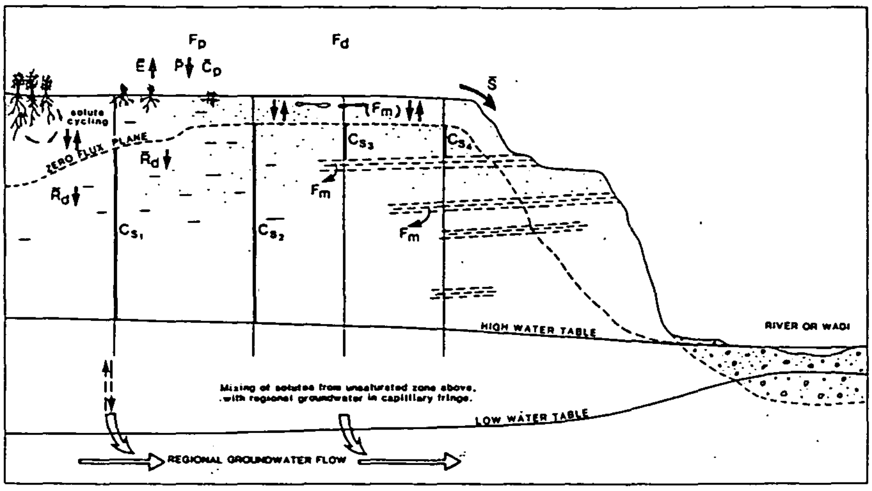


Figure 4.1a Schematic representation of solute movement and recharge via the unsaturated zone.

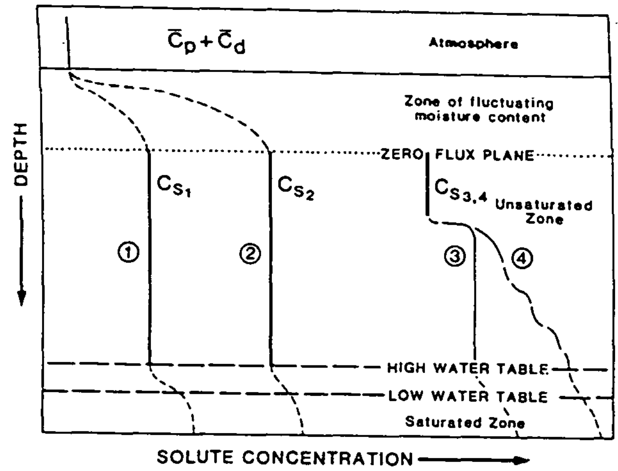


Figure 4.1b Idealised solute concentrations developed during percolation in profiles C_S $_{1-4}$ in Figure 4.1a.

Therefore alternative techniques are desirable which can be used to overcome these difficulties. Solute profiles offer one possible approach.

4.2 Use of Chloride to Estimate Recharge

Unlike tritium, chloride and possibly some other solutes, behave in a conservative manner during hydrological processes. Whereas the water vapour is lost, the chloride input from deposition is retained and accumulates.

The use of chloride mass balance in recharge estimation was demonstrated by Eriksson (1976) in India using regional groundwater samples. This technique is excellent for providing a minimum estimate of recharge but additions of solutes from various non-atmospheric sources may take place, limiting its usefulness. The use of unsaturated zone solute profiles in recharge estimation has been developed by Allison and Hughes (1978), Allison et al. (1985), Sharma and Hughes (1985) in Australia and by Kitching et al. (1980) and Edmunds and Walton (1980) in Cyprus. The basis of the technique has been described in Edmunds et al. (1987), and the zone used to evaluate the direct component of recharge is illustrated in Figure 1.

The input of solutes to the aquifer depends initially on the total atmospheric fallout per unit time, made up of rainfall (F_p) and the net dry deposition (F_d) fluxes. Both the rainfall amount (P) and local composition of the total deposition ($F_p + F_d$) may be determined for a given site, although the regional variation in both quantities must be considered if recharge estimation is required for large areas.

Solutes will be deposited on and transported through the upper soil during the rainy season at rates depending on the rainfall intensity. These solutes will undergo concentration as a result of evapotranspiration (E). Solutes may be removed from solution by plant uptake, by mineral precipitation, or by adsorption. Similarly solutes may be released by decay of dead plant material, by mineral dissolution or by desorption. In the absence of a knowledge of these ancillary fluxes, only those constituents for which there is no net release or storage by the soil or rock matrix may be used. Chloride is the solute that most frequently and most conveniently meets these requirements.

Nutrient cycling by plants may affect solute movement (including that of chloride) on an annual basis, but, in stable landscapes, the amounts removed annually by plant uptake are balanced by the amounts released by plant decomposition, i.e. a steady state should have been achieved. This assumes that there are no additions of the solute in fertilisers or permanent removal by crop harvesting (including the export of grazing animals).

The solute concentrations in the soil or in the upper unsaturated zone will vary seasonally or annually depending upon the intensity of the moisture flux due to the incident rainfall and evapotranspiration. Complex movement of solutes both upwards and downwards may take place in response to water movement, which in turn depend upon the prevailing water potential gradients. A 'zero flux plane' (ZFP) exists (Wellings and Bell, 1980) which effectively separates moisture and solutes moving upwards (evapotranspiration) from that moving downwards (drainage). The position of the ZFP will shift seasonally between the surface and a depth of several metres and may, in some places at certain times, be coincident with the water table in which case discharge may occur. Its position will also vary spatially in response to root development. However complex the soil moisture distribution might be in the soil zone, therefore, the transfer of moisture/solutes at depth will be a relatively straightforward process. Under conditions of recharge a maximum depth can thus be defined at which a net, steady state, moisture and solute transfer should take place towards the water table. The amount of solute crossing the ZFP would be expected to vary in relation to antecedent rainfall over one or more seasons and some oscillation in the solute profile would then occur. A detailed discussion of the transmission of solutes across the ZFP is given in Wellings and Bell (1980). The average composition of interstitial water in this profile (C_s) will, under steady state conditions, be proportional to the concentration factor, P/(P-E), assuming no loss of solute to minerals and that the water and 'inert' solutes are transported at the same rate.

In the steady state, the water balance equation can therefore be given by:

$$\bar{R}_d = \bar{P} - \bar{E} - \bar{S} \qquad (1)$$

where $\bar{R}_d$ is the direct recharge flux and $\bar{S}$ is the surface runoff flux; the bars indicate time- and space-averaged quantities. Providing surface runoff is negligible ($\bar{S} \sim 0$), this leads to:

$$\bar{R}_d = \bar{P} - \bar{E} \tag{2}$$

Similarly the solute balance is given by

$$\bar{F}_p + \bar{F}_d = \bar{F}_s + \bar{F}_m \tag{3}$$

where $\bar{F}_p$ and $\bar{F}_d$ are the average precipitation and net dry deposition fluxes (= input), respectively, and $\bar{F}_s$ and $\bar{F}_m$ are the net steady state output fluxes in the drainage water and the net flux of solute precipitated or adsorbed by minerals (dissolution and deposition give a negative flux), respectively. $\bar{F}_s$ is given by the output water flux multiplied by the solute concentration (appropriately averaged), i.e.

$$\bar{F}_s = \bar{R}_d \bar{C}_s$$

where $\bar{C}_s$ is the average concentration of the reference solute in the below-ZFP water. If we assume $\bar{F}_m = 0$, then Equations (3) and (4) combine to give:

$$\bar{F}_p + \bar{F}_d - \bar{R}_d \bar{C}_s \tag{5}$$

or on rearranging:

$$R_d = \frac{(\bar{F}_p + \bar{F}_d)}{\bar{C}_s} = \frac{(\bar{P}\bar{C}_p + F_d)}{\bar{C}_s} \tag{6}$$

Hence the amount of direct recharge can be estimated from a knowledge of the volume-averaged concentration of the reference solute in the rainfall ($\bar{C}_p$) and in the deep interstitial water ($\bar{C}_s$), the long-term average annual

precipitation ($\bar{P}$), and the net dry deposition flux of the reference solute ($\bar{F}_d$). Note that if F_d - 0, then the fraction of the rainfall contributing to direct recharge is simply given by the ratio $\bar{C}_p/\bar{C}_s$.
To recapitulate, the steady state model is subject to certain assumptions:

(1) since there is a time lag (Δt) in solute input to the unsaturated zone and its output to the saturated zone, it must be assumed that no major climatic change has occurred over this period;

(2) that there have been no external, e.g. fertiliser, additions nor recent changes in atmospheric pollution;

(3) that there is no <u>net</u> change in storage of the 'reference' solute above or below the ZFP, either by (a) plants or animals; or (b) by mineral precipitation/dissolution or adsorption/desorption. In the first instance this assumption should be valid if there have been no significant natural vegetation changes or changes in agricultural practices.

In principle, it may be possible to use as a reference any solute that is not released by weathering or removed by precipitation; even interacting solutes, e.g. cations or clays, in theory, may be able to be used since the quantity of exchangeable ions are often effectively constant and need not lead to a net change in storage. In practice the most inert solutes are likely to prove the most reliable and for this reason chloride has been used here for the recharge calculation although SO_4, NO_3 and SEC_{25} (specific electrical conductance at 25°C) have also been considered. It is possible that only a restricted portion of the unsaturated zone profile may be usable for recharge estimation (Figure 1). For example, the presence of certain lithologies, e.g residual marine bands, may release chloride. The possible development of solute profiles is summarised in Figure 2. Profiles 1 and 2 represent steady state drainage under different vegetation/soil conditions where evapotranspiration rates differ. Profiles 3 and 4 represent two possible cases where solute compositions have been modified by reaction and/or changes in storage. Only the upper part of profiles 3 and 4 would be of value in recharge calculations and, in certain reactive lithologies, no steady state profile may be developed at all.

The drainage compositions, C_{s1-2}, would be expected to be similar to those encountered at the surface of the water table. However the composition of the saturated flow will have been modified by the incoming lateral flow with higher salinity.

Therefore, water table samples taken from shallow wells are unlikely to be reliable for accurate recharge estimates. However, since chloride is not lost during drainage and saturated flow, the shallow groundwater chemistry, or river baseflow, can always be used in areas of active recharge to derive a minimum figure for total recharge (Eriksson, 1976) and could be more widely used in regional water balance studies.

4.3 Sampling Procedures in Senegal

Various techniques have been used in the past for sampling the unsaturated zone (Edmunds et al., 1987) including dry percussion drilling using wireline and claycutter, U4 coring, power augering and dug wells. Experience has shown that simple techniques relying on low technology can produce the most reliable results. In this project only two methods have been used: 1) hand dug or machine-aided dug wells; 2) hand augering.

At the beginning of the project, enquiries were made of government agencies, notably the Brigages des Puits (BP) in the Louga, Cap Vert and Kaolack regions, for news of any forthcoming well construction programmes. In addition non-governmental organisations (NGO) were contacted. As a result, two wells in the Nioro region and one nearer to Kaolack were constructed by the Norwegian Aid organisation and Kaolack BP respectively. Samples were taken by these teams, following instruction from our project personnel; at 1 m intervals, or at the end of each shift, material was collected at the level of working.

The majority of samples were obtained by hand auger. The auger used was made by Dormer Engineering, Australia, and consisted of a lightweight aluminium drill string with a hollow shell cutter tool. This assembly proved highly successful and profiles of up to 35 m were obtained in 3 days. To achieve this a labour force of 4 people was needed. Each round trip produced about 10 cm of material (160 cc) and samples were usually homogenised and bulked over each 25 cm.

For each method of sampling, material was collected into 500 ml glass Kilner jars (fruit bottling jars with a rubber seal). These samples were transported to Dakar for moisture content and conductivity measurements. They were then airfreighted (using the RAF) to UK for moisture extraction and analysis at Wallingford.

4.4 Moisture Extraction

Moisture content was determined gravimetrically on all samples. The interstitial waters were extracted either by elutriation or centrifugation for chemical analysis and by distillation or direct reduction with zinc for isotopic analysis.

4.4.1 Elutriation

A 50 gm sample of sand was weighed into a 100 ml beaker and 30 ml of distilled deionised water added. The slurry was stirred for about 1 minute and left to stand for 30 minutes when it was stirred again. After one hour, the supernatant solution was decanted with fine suspended material into a Sterilin 30 ml polycarbonate bottle. Next day this solution was filtered through 0.45 μm membrane filters and stored for analysis. A variation on this technique was to centrifuge the tubes and to take off the supernatant directly for filtration; this was possible in the laboratory but not in the field. The samples were used for the analysis of chloride, bromide and nitrate.

4.4.2 Centrifugation

The sand samples contained variable amounts of soil moisture and in this study attempts were made to recover interstitial water direction by centrifugation rather than by elutriation which was used in previous studies. The method used has been developed for UK studies by BGS (Kinniburgh and Miles, 1983) and is based upon displacement of the water by immiscible liquid, in this case 'Arklone', a widely used industrial solvent. Some 180 gm moist sand are placed in a teflon or polypropylene centrifuge bottle and covered with the immiscible liquid, total weight about 320 gm. The sample bottle, or groups of bottles, are then centrifuged at 13500 rpm for about 1 hr, after which a meniscus of displaced water droplets is found on the surface of the immiscible liquid.

Table 4.1 Direct reduction and vacuum distillation techniques compared on a sand profile from Senegal (Louga 8).

Depth range (m)	Moisture content (%)	Direct reduction δ^2H (‰)	Vacuum dist. δ^2H (‰)
0.5-1.0	1.9	-10.2	- 6.0
1.0-1.5	2.2	-19.4	-22.6
1.5-2.0	1.0	-19.3	-21.4
2.0-2.5	2.8	-32.2	-32.4
2.5-3.0	2.4	-38.1	-35.8
3.0-3.5	1.9	-41.0	-35.8
3.5-4.0	2.5	-39.6	-40.5
4.0-4.5	3.0	-41.4	-39.6
4.5-5.0	2.5	-41.1	-40.0
5.0-5.5	3.8	-42.3	-42.4
5.5-5.8	3.6	-32.8	-34.3
5.8-6.0	1.5	-36.9	-33.2
6.0-6.5	3.3	-38.8	-37.2
6.5-7.0	3.0	-35.7	-35.9
7.0-7.5	3.2	-38.8	-34.4
7.5-8.0	2.7	-37.2	-35.0
8.0-8.2	2.1	-31.8	-33.2
8.2-8.5	3.0	-34.9	-33.2
8.5-9.0	3.0	-32.7	-34.2
9.0-9.5	2.4	-30.0	-32.6
9.5-10.0	2.4	-27.7	-29.3
10.0-10.5	3.5	-31.2	-33.7
10.5-11.0	2.4	-28.2	-31.9
11.0-11.5	3.2	-28.8	-30.6
11.5-12.0	4.0	-28.1	-30.6
12.0-12.5	9.7	-27.0	-28.5
12.5-13.0	11.5	-29.1	-31.1
13.0-13.5	16.9	-28.9	-30.7

This sample is collected by syringe and filtered prior to analysis. Typically only 1 ml of water was obtained in each run, so 4 or 6 bottles may have been required for each vertical interval. In some cases where yields were low, the samples were diluted for analysis to make a volume of at least 5 ml. In some instances the samples were too dry (e.g. >2% moisture content) to yield water by this technique.

4.4.3 Vacuum distillation

Vacuum distillation was used as one method for obtaining water samples for isotopic measurement ($\delta^{18}O$ and $\delta^{2}H$) in addition to centrifugation and direct reduction (see below). This method has been described by Darling and Talbot (1989). The sample of sand is heated at 150°C and the water vapour collected in a cryogenic trap.

4.4.4 Direct reduction

This method has also been described by Darling and Talbot (1989) and has proved highly effective for obtaining isotopic profiles for $\delta^{2}H$ (but not of course $\delta^{18}O$). Very small samples of sand (sufficient to contain 10-15 mg of moisture) are heated above zinc shot for about 60 minutes which reduces the water to hydrogen for direct measurement of the hydrogen ratio. Results are shown for Louga 10 (Table 4.1) for a comparison between this and the vacuum distillation method and in general an excellent agreement is obtained.

4.5 Chemical analysis

Specific electrical conductance at 25°C was measured on all elutriate samples both in Dakar and Wallingford, using a standard conductivity bridge.

Chloride was measured at Wallingford using automated colorimetry (Technicon AA-11) using mercuric thiocyanate which is capable of measurement to 0.5 mg l^{-1}. Nitrate and bromide was also measured by autoanalyser method. Analyses of all other cations and ions were measured by ICP-optical emission spectrometry.

4.6 Comparison of results

Good agreement between the elutriate and centrifuge methods for chloride has been obtained and these results are compared and discussed below.

5. RESULTS

5.1 Rainfall

The chemistry of rainfall is an important component of geochemical recharge estimation. Ideally, long-term records are needed since we are relating results from unsaturated zone profiles extending over decades. Measurements of rainfall chemistry for Africa are few indeed but a study from Senegal (Travi et al., 1987) provides a valuable basis for this work. Monthly data were obtained by these authors for eight stations in Senegal during 1981 at which major ion chemistry and stable isotope compositions ($\delta^{18}O$ and δD) were measured (Figure 5.1). This study emphasizes the differences between the vapour providing the rains and the source of solutes which are supplied by marine aerosols.

In the present study, rainfall sampling was initiated at Dakar Airport (Hann) and at Louga and Leona near the main research site. Chemical data were obtained for Dakar from 1986-1989. Rainfall samples were collected daily from these sites by local people, usually meteorological workers although collection was sometimes intermittent. Chloride was measured on all rainfall samples (Tables 5.1-5.5) and weighted mean averages were calculated which are summarised in Table 5.6. In addition, samples from Louga (1988) were analysed for major and minor elements and Louga and Leona (1989) plus Dakar (1987) for isotope ratios.

The rainfall chemistry was measured on two adjacent raingauges at Louga to check on measurement precision (Table 5.1). For 1989 the correspondence between results for chloride from adjacent raingauges is good (weighted mean values 1.17 and 1.18 mg l^{-1} Cl respectively). In addition, the results have been considered as separate rainfall events to investigate chemistry as a function of rainfall intensity (Figure 5.2). It can be seen that the heaviest rains generally contain the lowest concentrations of chloride. For the present study (as in previous work in Sudan for example), the dry deposition outside of the rainy season has been ignored on the basis that a steady state exists with deposition of dust (aerosols being matched by erosion. In other words, the effective deposition for solute balance is the total deposition of aerosol plus the rain. Some very light rains at the beginning of the season show high chloride concentrations which implies the raining out of accumulated dust. The role of dry deposition on an annual basis does, however, need to be realistically studied so that this important assumption can be validated or challenged.

The rainfall chemistry (as well as amount) is found to vary significantly from site to site. Most notable is the coastal effect. The chloride concentrations at Leona (Table 5.3) are systematically higher than those at Louga (e.g. 1.63 mg l^{-1} Cl as against 1.14 mg l^{-1} Cl for the 1988 season). At Dakar (Tables 5.4 & 5.5) the rainfall chemistry, collected on the Cap Vert peninsula is much higher again (5.33 mg l^{-1} Cl for the 1988 season), and it would appear that there is an exponential solute decrease away from the coast (this is a generally well established finding in temperate maritime regions). It is also of interest that the mean concentration of chloride varies from year to year <u>at the same site</u>; this is of key importance to the recharge estimation. Thus at Louga the successive concentrations from 1988-1990 are 1.14, 5.95 and 1.43 respectively (Table 5.6).

The significance of these data is that despite the general movement of the monsoon air mass from the south, the variations in solutes including chloride reflect the extent of maritime aerosol derived from the ocean, as shown in Figure 5.3; west and north-west prevailing winds generally characterise the rainy season (Brigaud, 1965). If the trajectories of storms vary by small degrees of azimuth the solute deposition is changed considerably. This appears to have been the situation for example in 1989 as compared with 1988 and 1990, although meteorological data are not yet available to confirm this. For precise recharge calculations therefore it is important that runs of data are available over several years; in this study the mean of three years is used.

5.1.1 Rainfall chemistry

The chemistry of one season's rain (1988) is given for Louga in Table 5.7 and these results are discussed collectively below.

5.1.2 Stable isotope results

Rainfall measured on individual storms at Dakar (1987) and at Louga (1990) was measured for stable isotope content and ratios of $\delta^{18}O$ vs. $\delta^{2}H$ are plotted in Figure 5.4. There is a wide range in composition from positive $\delta^{18}O$ values to values more negative that -9.0. The Dakar (and Louga) samples have a linear relation $\delta^2H = 7.64\ \delta^{18}O + 5.51$ which is very slightly more enriched in $\delta^{18}O$ than the World Meteoric Line and the meteoric line determined in fewer (monthly) samples by Travi et al. (1987). The wide range along the meteoric line is characteristic of the evolution within a saturated tropical air mass, where fractionation of isotopes of water can take place. Some slight evaporation may have occurred during precipitation to produce some of the more positive values in Figure 5.4. In general it is concluded with Travi et al. (1987) that the air mass of the monsoon deriving from the south does not give rise to significant salinity increase and that this is most likely due to entrainment of aerosols over the sea.

5.2 Unsaturated Zone

Profiles from the unsaturated zone have been obtained from the three areas of Senegal (Figure 3.1). The principal results are from the main study area at Louga (Figure 5.5) where 19 profiles were taken, 11 from one locality west of the town (Figure 5.6) and the remainder further north as far as M'pal (Figure 5.7). Four profiles were taken from Sikatroune and Nioro du Rip (Figure 5.8), south of Kaolack in an area of higher rainfall. A series of five dug wells and one auger profile was also obtained from Niague (Figure 5.9) in the coastal zone north of Dakar. A summary of all site information is included in Table 5.8.

5.2.1 Louga Area

The main research site, situated near the Louga-Leona road some 3 km from Louga was chosen to be in a typical zone of the Quaternary aquifer. The topography is gently undulating reflecting the surfaces of the former dunes, and sampling was possible therefore both on the dunes and in the interdune areas. These were considered to be the two extremes of recharge possibilities for this terrain. The soils are sandy and even on gentle slopes there is little or no evidence of surface run-off. The vegetation is sparse and is now covered with shrubs, occasional acacia trees and low plants. The area is sometimes planted with groundnuts for rainfed cultivation. The area was formerly much more densely vegetated and human activity has resulted in an increasing de-vegetation. Some fenced-off

LOUGA 1

DATE	RAIN(mm)	CL(mg/l)
11/06/89	0.6	
16/06/89	11.9	
17/06/89	18.1	
27/06/89	8.6	20.8
30/06/89	0.1	
01/07/89	1.7	
07/07/89	13.5	14.4
11/07/89	50.6	6.18
16/07/89	34.7	1.42
17/07/89	20.9	2.44
01/08/89	0.7	39.4
02/08/89	3.2	
10/08/89	2.7	
11/08/89	90.3	1.66
13/08/89	0.5	6.82
14/08/89	15.6	
15/08/89	0.5	
16/08/89	27.1	1.76
21/08/89	5.2	15.8
22/08/89	23.4	6.22
23/08/89	37	
24/08/89	7.6	
25/08/89	7.4	
26/08/89	5.5	
28/08/89	10	
01/09/89	8.4	
05/09/89	16.2	4.76
13/09/89	13.9	12.5
20/09/89	7.6	
24/09/89	5.3	
19/10/89	17.9	24.6

LOUGA 2

DATE	RAIN(mm)	CL(mg/l)
27/06/89	8.6	
30/06/89	0.1	
01/07/89	1.7	
07/07/89	13.5	19.2
11/07/89	50.6	3.06
16/07/89	34.7	1.96
17/07/89	20.9	3.22
01/08/89	0.7	
02/08/89	3.2	
10/08/89	2.7	
11/08/89	90.3	1.26
13/08/89	0.5	6
14/08/89	15.6	
15/08/89	0.5	
16/08/89	27.1	3.16
21/08/89	5.2	13.4
22/08/89	23.4	2.92
23/08/89	37	0.32
24/08/89	7.6	
25/08/89	7.4	
26/08/89	5.5	
28/08/89	10	
01/09/89	8.4	
05/09/89	16.2	5.04
13/09/89	13.9	9.58
20/09/89	7.6	
24/09/89	5.3	
19/10/89	17.9	53.8

LEONA

DATE	RAIN(mm)	CL(mg/l)
12/06/89	0.9	
16/06/89	22.2	
17/06/89	21.7	
27/06/89	20.2	12.2
30/06/89	4.5	1.48
01/07/89	1.8	
07/07/89	11.2	15.1
12/07/89	3.8	
15/07/89	13	14.7
16/07/89	13.4	
18/07/89	26	8
25/07/89	7	9.2
01/08/89	5.8	32.9
02/08/89	7.9	15.4
11/08/89	10	15.4
11/08/89	18.2	4.68
13/08/89	17.1	6.52
15/08/89	17.2	4
16/08/89	8.7	5.18
21/08/89	7.2	18.1
22/08/89	31.2	3.94
24/08/89	25.2	5.6
01/09/89	16.4	8.88
06/09/89	31.2	1
24/09/89	11.2	27.4
07/10/89	14.7	21.5
09/10/89	15	7.16
19/10/89	8.7	

DAKAR

DATE	RAIN(mm)	CL(mg/l)
13/06/89	0.52	19
17/06/89	12.6	12.2
27/06/89	14.96	10.7
01/07/89	18.88	3.64
07/07/89	1.6	1.84
12/07/89	2.85	11
13/07/89	4.04	5.1
16/07/89	24.16	7.86
18/07/89	30.8	2.9
21/07/89	0.96	14
23/07/89	0.44	8.96
01/08/89	64.04	3.32
03/08/89	0.08	47
11/08/89	30.04	2.24
13/08/89	2.12	6.52
14/08/89	2.84	4.6
15/08/89	15.52	1.62
16/08/89	21.2	1.76
21/08/89	0.24	63
23/08/89	0.6	12.6
24/08/89	26.56	2.42
25/08/89	129.04	1.06
26/08/89	10.36	1.96
27/08/89	7.64	1.16
01/09/89	14.12	4.68
03/09/89	3.24	4.66
06/09/89	11.12	2.12
09/09/89	25.4	2.26

DAKAR

DATE	RAIN(mm)	CL(mg/l)
11/09/89	0.52	11.1
12/09/89	0.4	22.1
14/09/89	54.04	2.68
24/09/89	0.08	
03/10/89	0.88	
07/10/89	9.64	10.4

Table 5.1 to 5.4 Rainfall and rainfall chemistry at Louga 1 and 2 sites (1989), Leona (1989) and Dakar (1989).

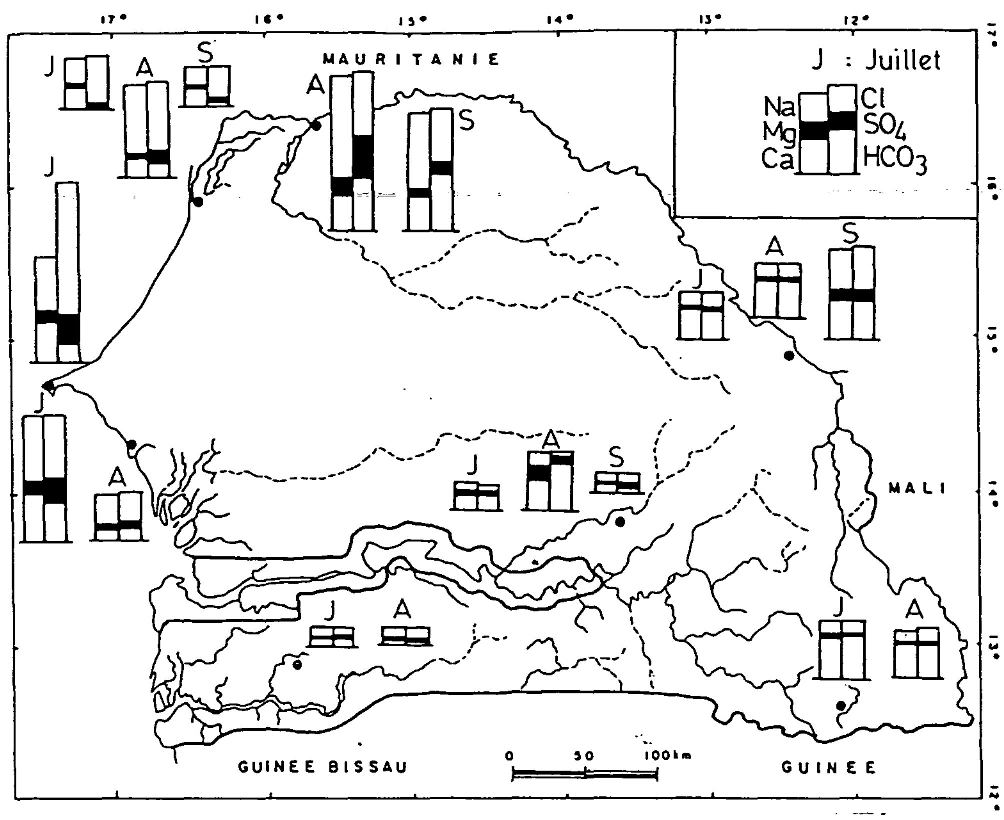


Figure 5.1 Monthly distribution of ionic concentration in rain (Travi et al, 1987).

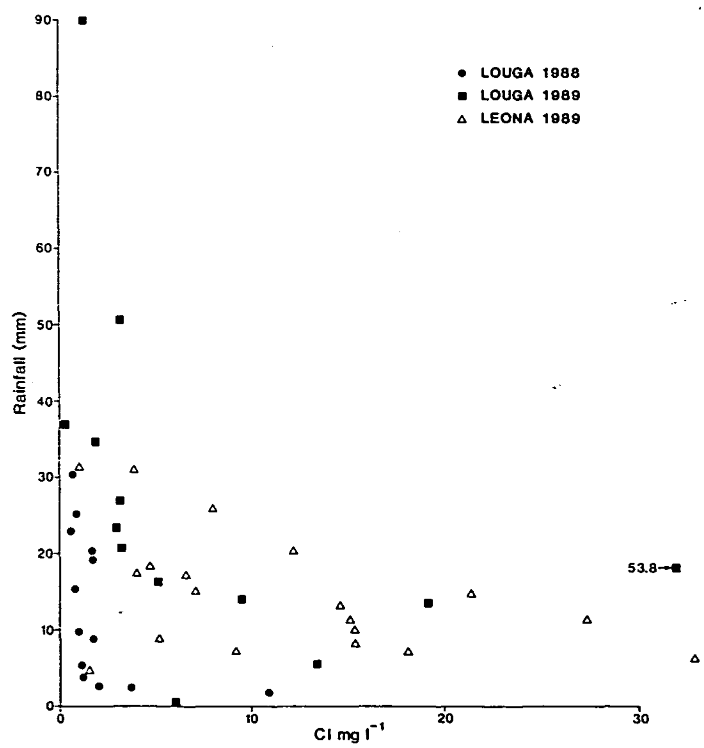


Figure 5.2 Chloride in rain as a function of rainfall intensity - Louga and Leona.

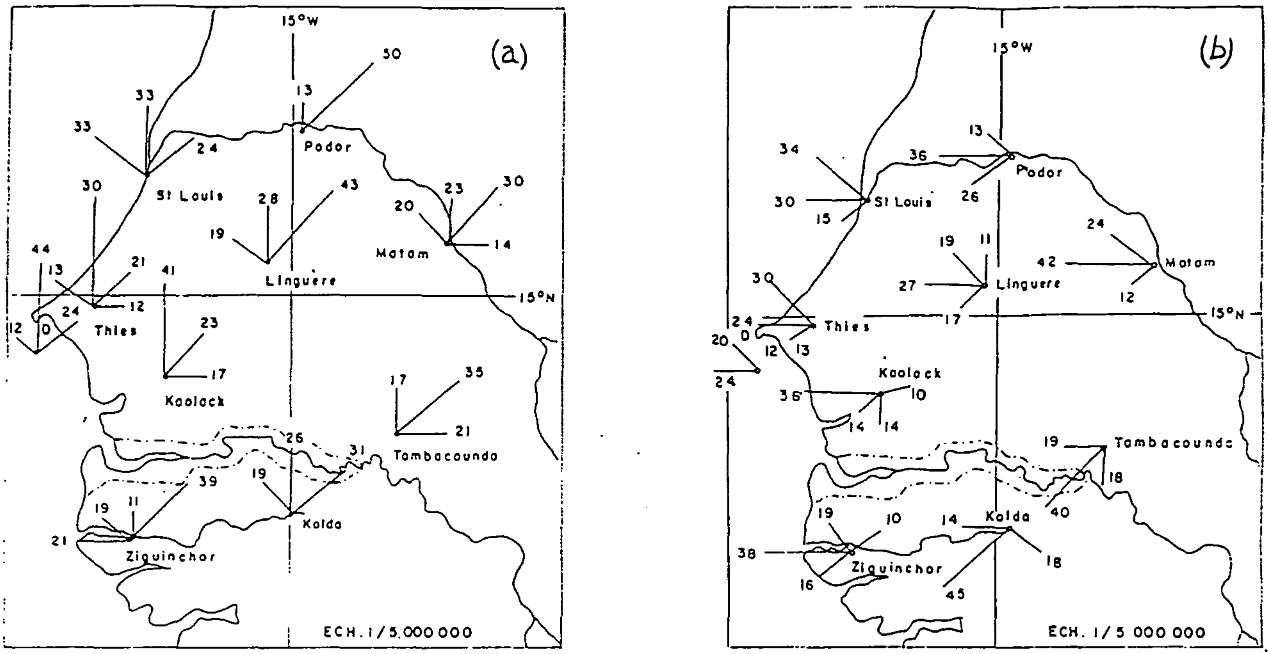


Figure 5.3 Direction of winds in Senegal (Brigaud, 1965); a) dry season, b) rainy season - frequency >10%.

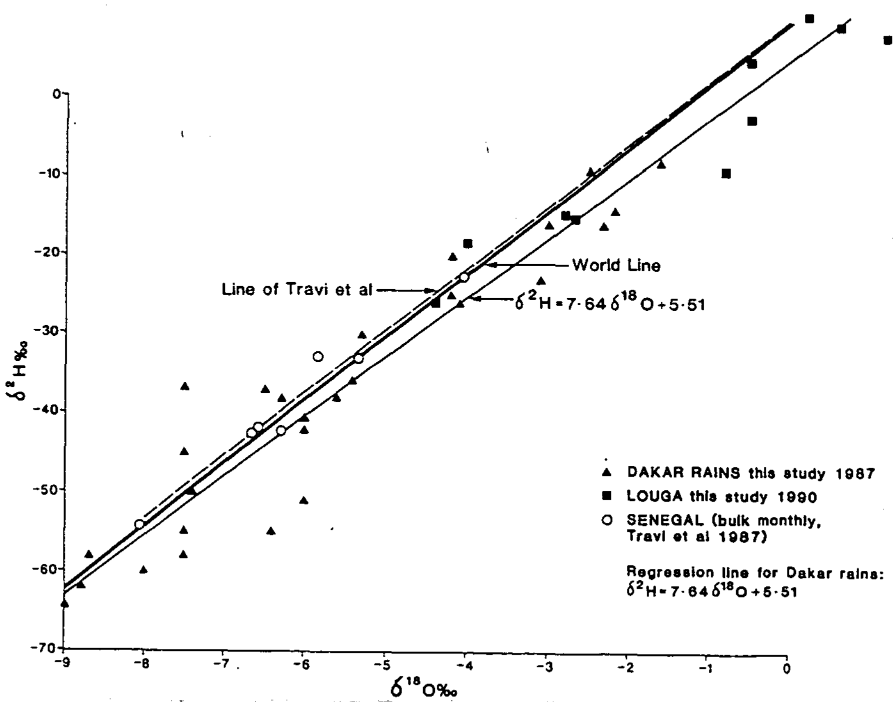


Figure 5.4 Oxygen and hydrogen isotopic compositions for rains from Senegal.

TABLE 5.6 Summary of rainfall amounts and weighted mean chloride concentrations used for recharge calculation.

	Year	Total rainfall (mm) (P)	Weighted mean chloride (C_p) (mg l)
DAKAR	1986	389.8	(8.54)*
	1987	443.0	6.58
	1988	440.1	5.33
	1989	n.a.	3.31
LOUGA	1988	443.2	1.14
	1989	436.1	5.95
	1990	255	1.43**
LEONA	1988	302	1.63
	1989	-	9.30

Values used for recharge calculation

		$\overline{P}$	$\overline{C_p}$
LOUGA REGION	1893-1968	356	2.8
	1969-1986	223	2.84
DAKAR REGION	1921-1988	489	4.2
KADLACK REGION	1921-1988	545	3.4

* mid-July to mid-August only
** mid-August to October only

Table 5.7 Chemistry of rain from Louga 1 (1988).

DATE	RAIN (mm	Na	K	Ca	Mg	SO4	Cl	Sr	Ba	B	Si	Br
01/08/88	2.2	6.86	2.8	12.4	1.69	12.8	12.3	0.065	0.048	0.017	1.3	0.059
02/08/88	0.2	8.19	3.6	14	1.72	12.3	12.9	0.074	0.047	0.027	1.5	0.085
03/08/88	33.8	0.62	-0.81	2	0.31	1.3	0.8	0.009	0.009	-0.015	0.7	0.007
14/08/88	25.3	0.59	-0.5	1.55	0.22	0.81	1.1	0.006	0.007	-0.015	0.44	0.005
15/08/88	1.8	2.41	-0.5	2.43	0.35	2.01	4.1	0.011	0.012	-0.015	0.46	0.017
17/08/88	12.1	0.45	-0.5	1.52	0.17	-0.66	0.8	0.006	0.005	-0.015	0.3	0.005
22/08/88	11.5	1.67	0.76	1.41	0.15	0.95	2.7	0.005	0.007	-0.015	0.27	0.011
26/08/88	21.4	0.82	-0.5	1.6	0.17	1.05	1.3	0.007	0.007	-0.015	0.27	0.006
28/08/88	3.1	1.47	-0.5	2.2	0.24	1.05	2.2	0.009	0.009	-0.015	0.36	0.012
30/08/88	16.1	0.74	-0.5	2.01	0.27	0.98	1.1	0.017	0.008	0.02	0.34	0.008
01/09/88	3.7	0.73	-0.5	1.42	0.23	0.53	1.1	0.01	0.007	0.017	0.4	0.007
04/09/88	8	0.7	-0.5	1.49	0.19	0.83	1.4	0.008	0.006	-0.015	0.25	0.008
06/09/88	5.3	0.85	-0.5	1.45	0.14	-0.69	1.6	0.007	0.005	-0.015	0.3	0.007
16/08/88	53.8	0.23	-0.5	0.9	0.08	0.48	0.5	0.004	0.003	-0.015	0.26	0.004
21/09/88	36	0.3	-0.5	1.02	0.08	-0.43	0.7	0.004	0.003	-0.015	0.17	0.005

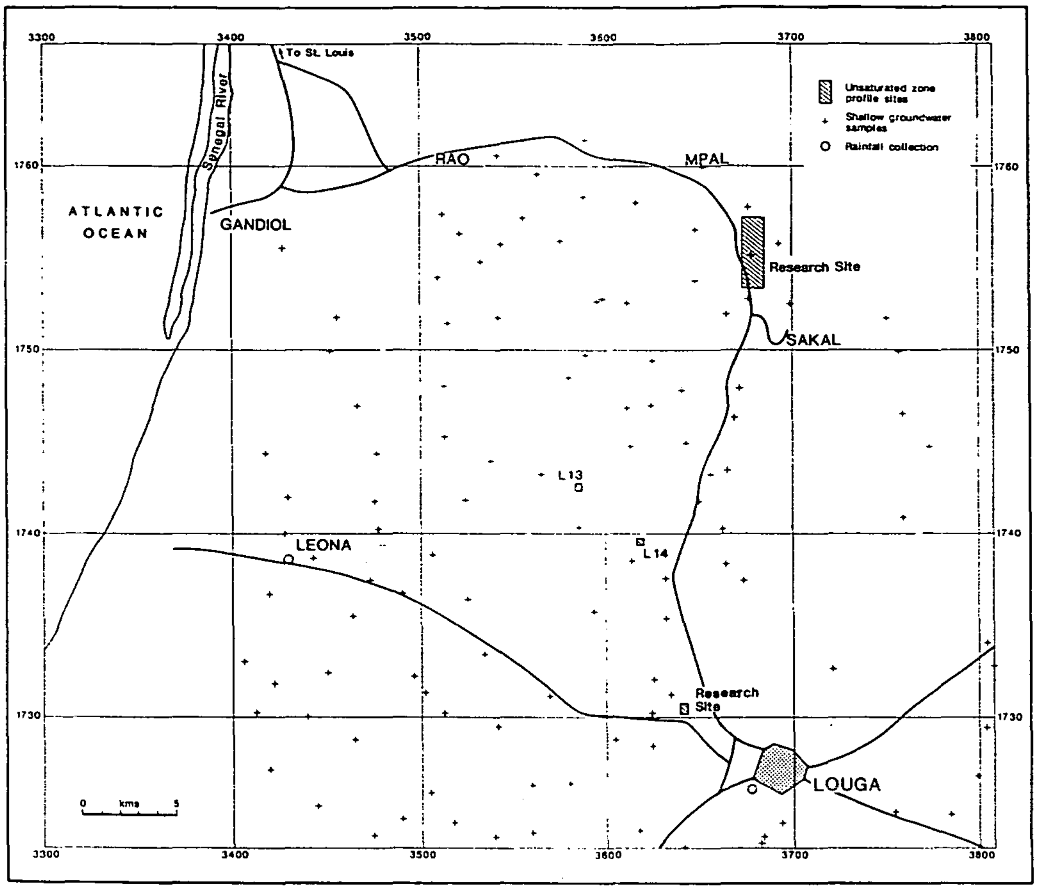
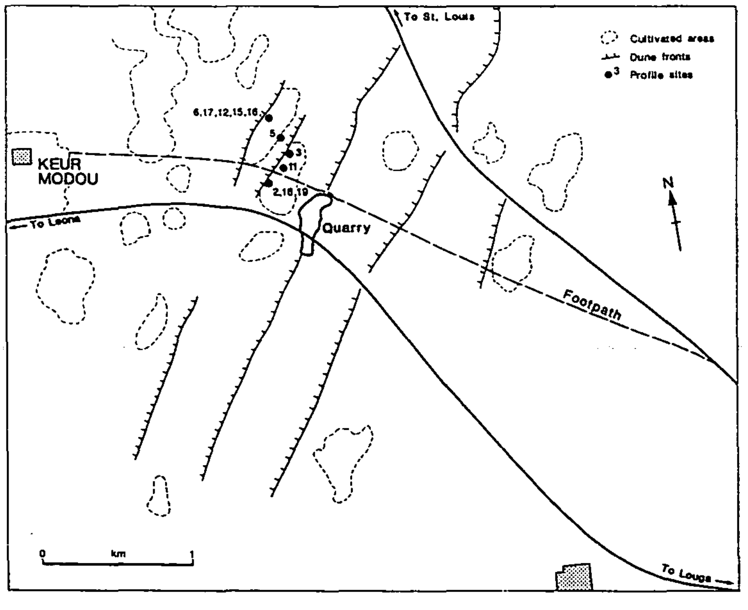


Figure 5.5 Site map of Louga area with locations of the main research sites and sample points for the shallow aquifer.



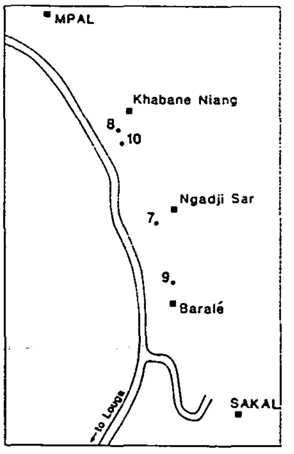


Figure 5.6 Sketch map of the main research site west of Louga showing profiles.

Figure 5.7 Sketch map of profile locations in the M'pal area.

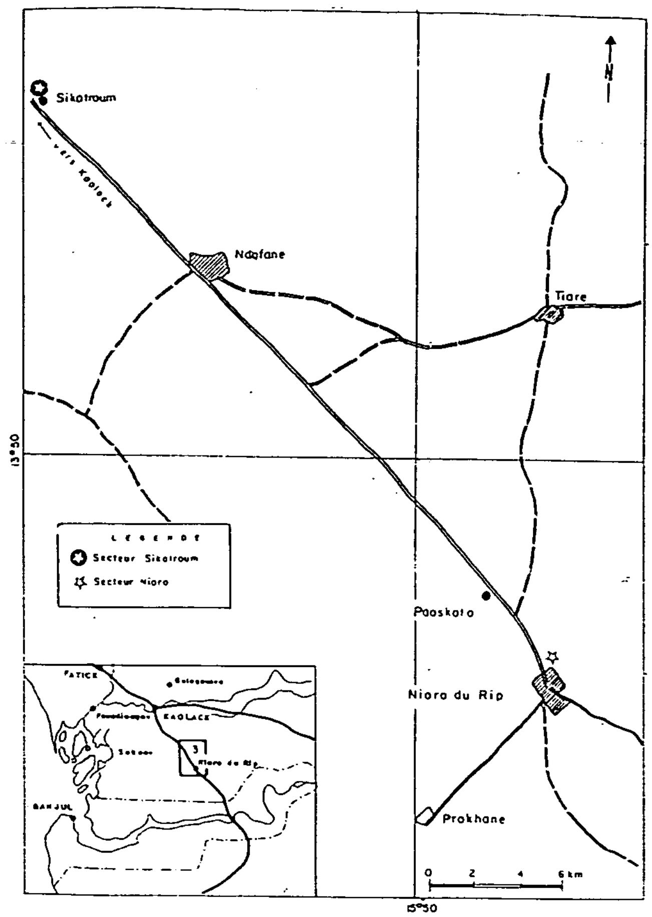


Figure 5.8 Location of profiles in the Nioro/Kaolack area.

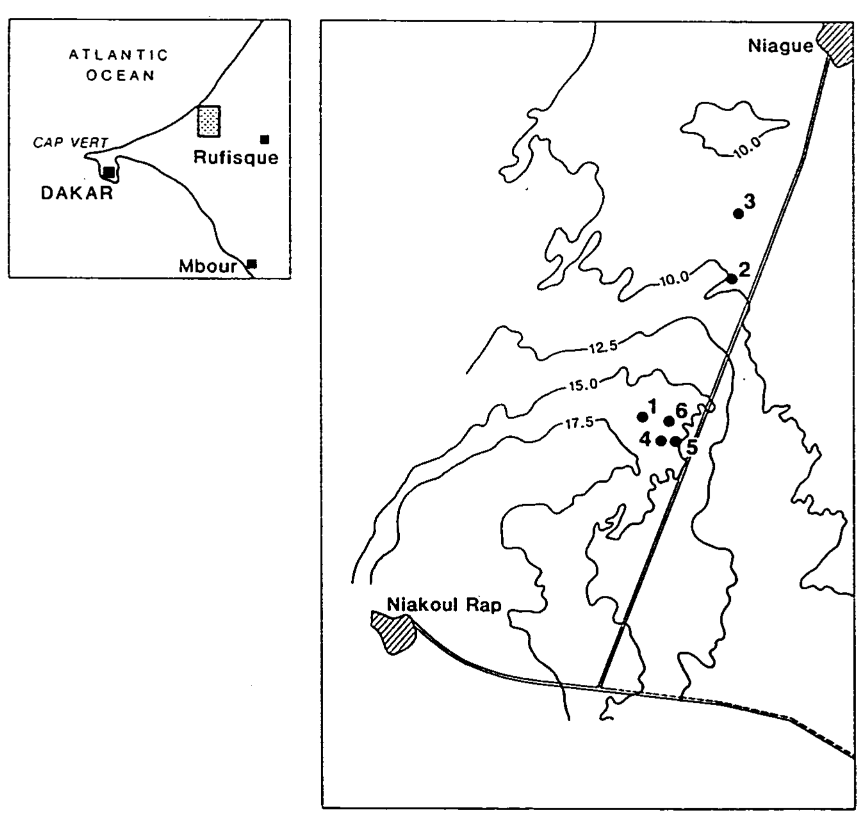


Figure 5.9 Location of profiles in the Niague area.

TABLE 5.8

AREA	LOCATION	PROFILE	DATE	METHOD	TOTAL DEPTH	WATER TABLE	DATA
		NG1	02/86	Dug well	9.45	No	
		NG4	04/87	Dug well	12.00	Yes	
NIAGUE		NG5	05-09/78	Dug well	8.00	No	
		NG6	06/87	Auger	6.00	NO	
		NG2	03-04/86	Dug well	7.00	Yes	
		NG3	04-05/86	Dug well	6.60	Yes	
		KK1	03-06/86	Dug well	19.50	Yes	
	Sikatroune	KK3	24/11/87	Auger	9.50	No	
KAOLACK		KK4	25/11/87	Auger	17.50	No	
	Nioro du Rip	KK2	29/11.87	Auger	16.40	No	
	Main	LG2	04/10/87	Auger	16.00	No	
	Research	LG3	16/10/87	Auger	25.00	No	
	Site	LG5	06/05/88	Auger	12.00	No	
		LG6	07/03/88	Auger	13.50	No	
		LG11	17/07/88	Auger	16.50	No	
		LG12	20/07/88	Auger	13.75	No	
		LG15	11/12/88	Auger	9.00	No	
		LG16	13/12/88	Auger	14.00	No	
LOUGA		LG17	16/12/88	Auger	13.00	No	
		LG18	07/03/89	Auger	35.50	Yes	
		LG19	29/03/89	Auger	20.00	No	
		LG7	26/05/88	Auger	7.00	No	
		LG8	28/05/88	Auger	12.50	Yes	
		LG9	17/06/88	Auger	13.25	Yes	
		LG10	18/06/88	Auger	11.50	No	
		LG13	21/07/88	Auger	7.00	No	
	M'Pal area	LG14	22/07/88	Auger	9.50	No	
		LG20	03/03/89	Auger	11.50	Yes	
		LG21	31/03/89	Auger	12.60	Yes	

areas with re-afforestation demonstrate the extent of natural vegetation which is possible if allowed to reestablish.

The relative disposition of the auger hole sites is shown in Figure 5.7. There is a quarry within 400 m of the research area which enables a good cross-section of the aquifer to be obtained. The section is almost pure sand with occasional fine material (loess?) which permits a higher water retention. In general the moisture content of the profiles below the top few metres can be used as a guide to lithology - drier profiles reflecting a high sand content, wetter profiles having more clay.

The lithology of some of the profiles has been examined by Tandia (1990) and the relationship between moisture content and the percentage of fine grained (clay size) material. The effect of increased clay material is well illustrated for profile Louga 3 (see below) at the main research site, where up to 23% fine material is found at 25 m with a moisture content of around 7%. Slightly relatively higher moisture contents are found in parts of the upper profile resulting from a pulse of percolating water which has not equilibrated evenly within the profile.

The second area (M'pal) is located near the Louga-St Louis road (Figure 5.7) between Baralé and M'pal within a 4 km radius. This area was selected because there was evidence here of a more saline groundwater (1400-1800 $\mu S\ cm^{-1}$ compared with 400 $\mu S\ cm^{-1}$ at Louga). Two other profiles were also drilled in-between the Louga and M'pal sites near Dabaye and Yerwaye west of the St Louis road (Figure 5.5) to provide a third region typical of this area of dune sand aquifer.

The main research area is shown (Figure 5.8) on a Landsat 4 satellite image of northern Senegal, taken at 09.30 on 9.2.86 where the resolution is considered to be 30 m. The false colour image depicts clearly the town of Louga and the lower lying vegetated coastal strip in red, adjacent to the Senegal River. Cultivated areas around each village stand out clearly as white areas which contrast with areas of more natural vegetation in green - the density of green being roughly proportional to the density of vegetation.

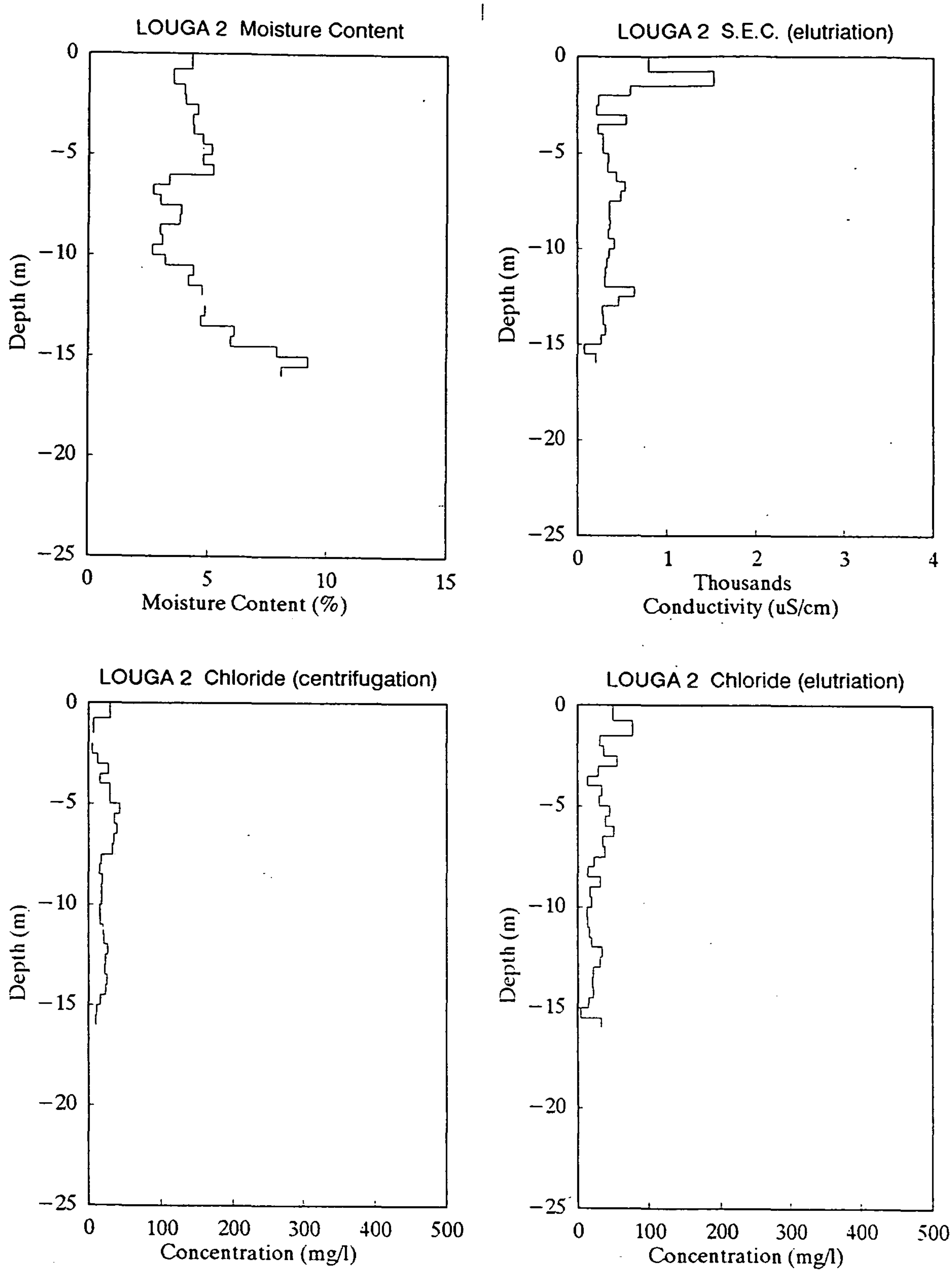


Figure 5.10 Profiles of moisture content, SEC, chloride (centrifugation), chloride (elutriation) - Louga 2.

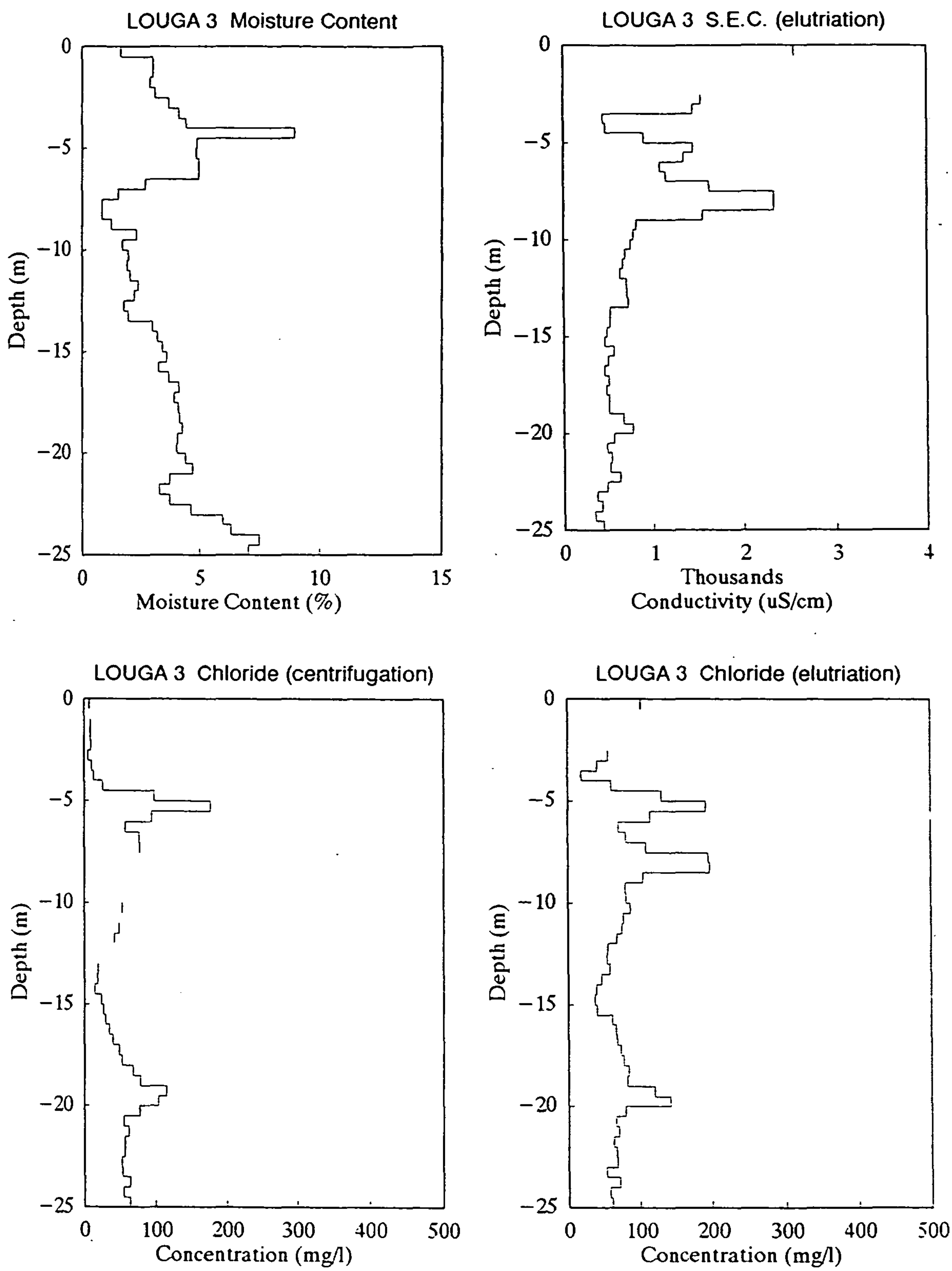


Figure 5.11 Profiles of moisture content, SEC, chloride (centrifugation), chloride (elutriation) - Louga 3.

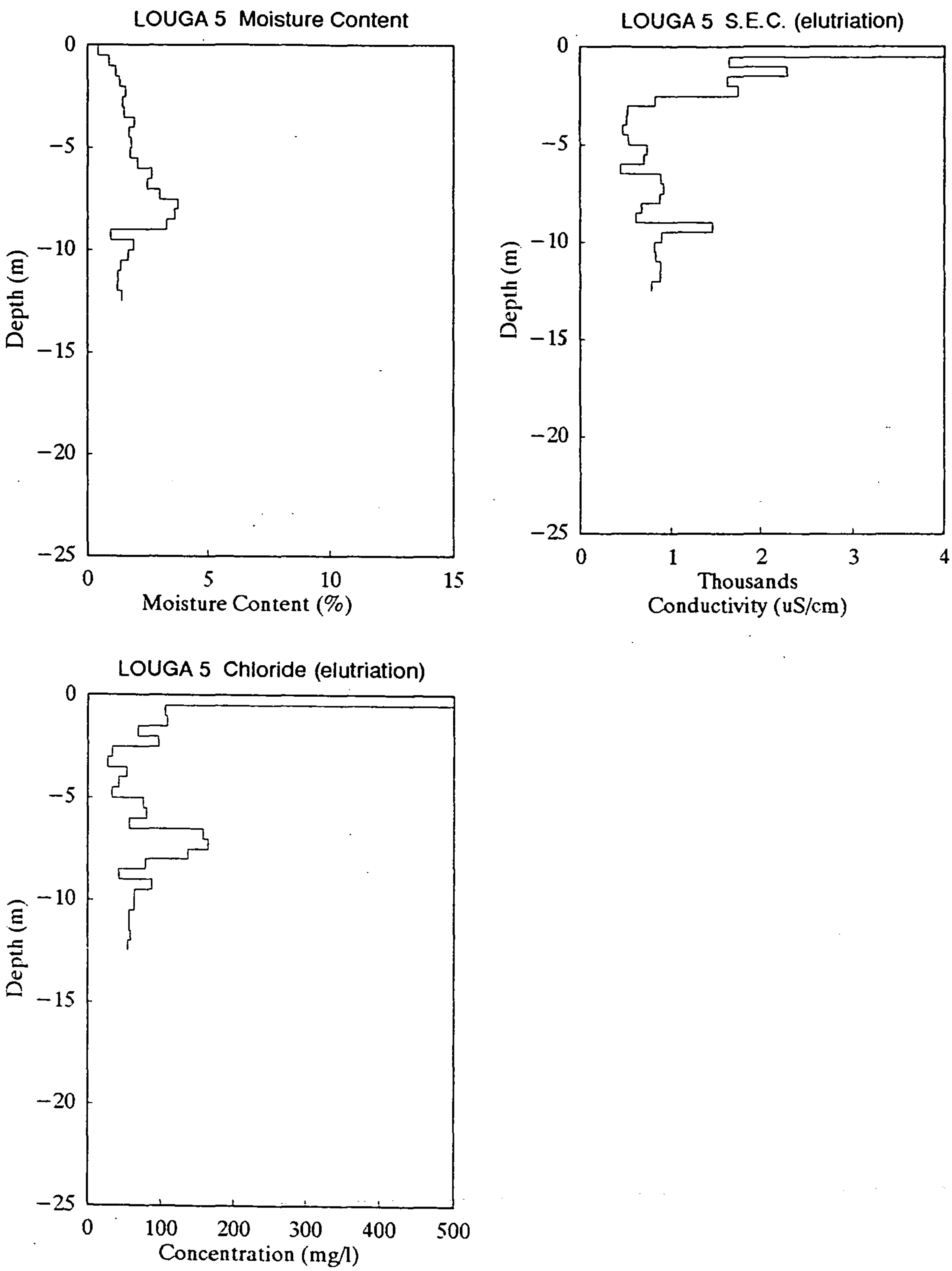


Figure 5.12 Profiles of moisture content, SEC and chloride (elutriation) - Louga 5.

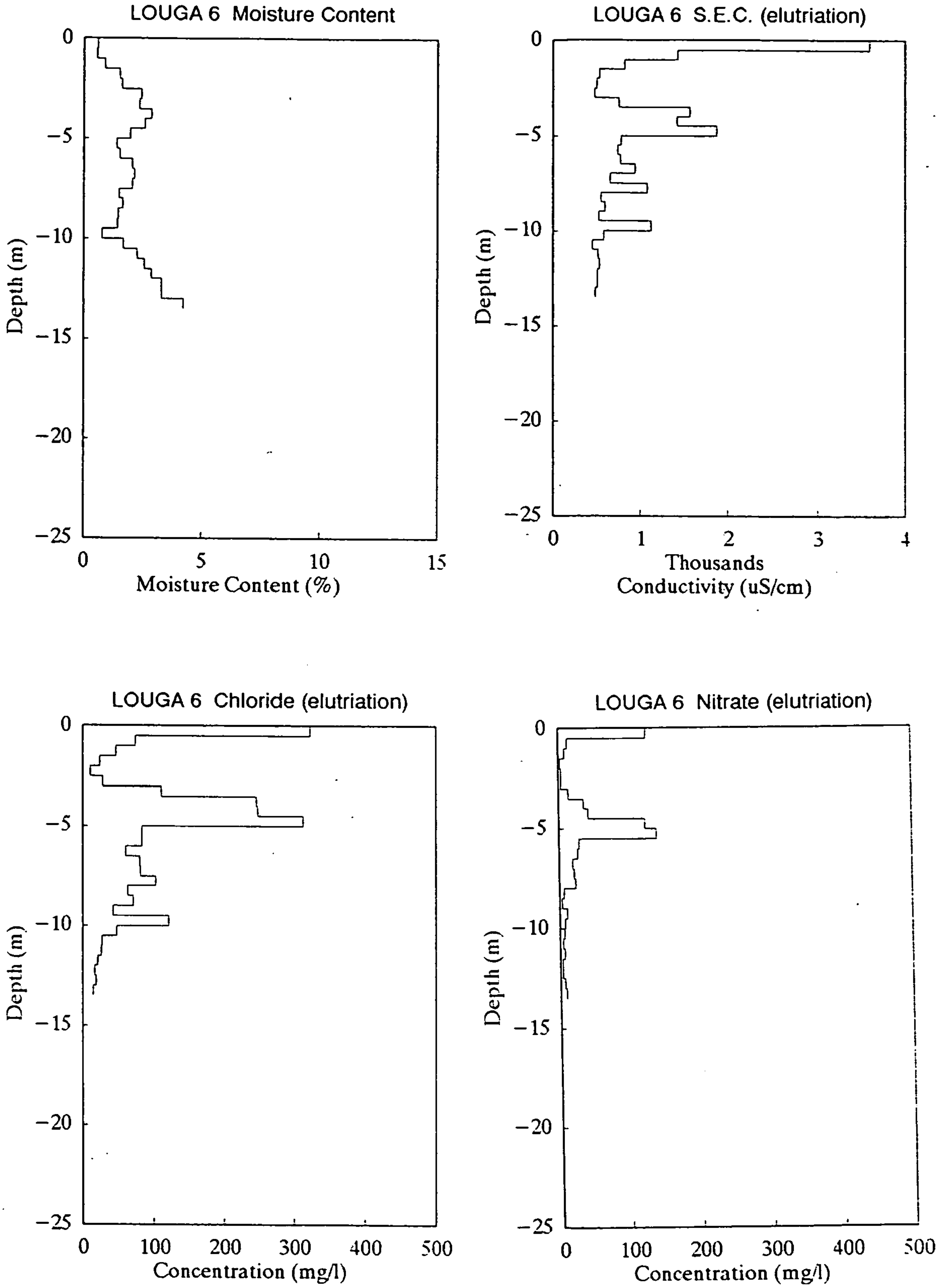


Figure 5.13 Profiles of moisture content, SEC, chloride (elutriation) and nitrate - Louga 6.

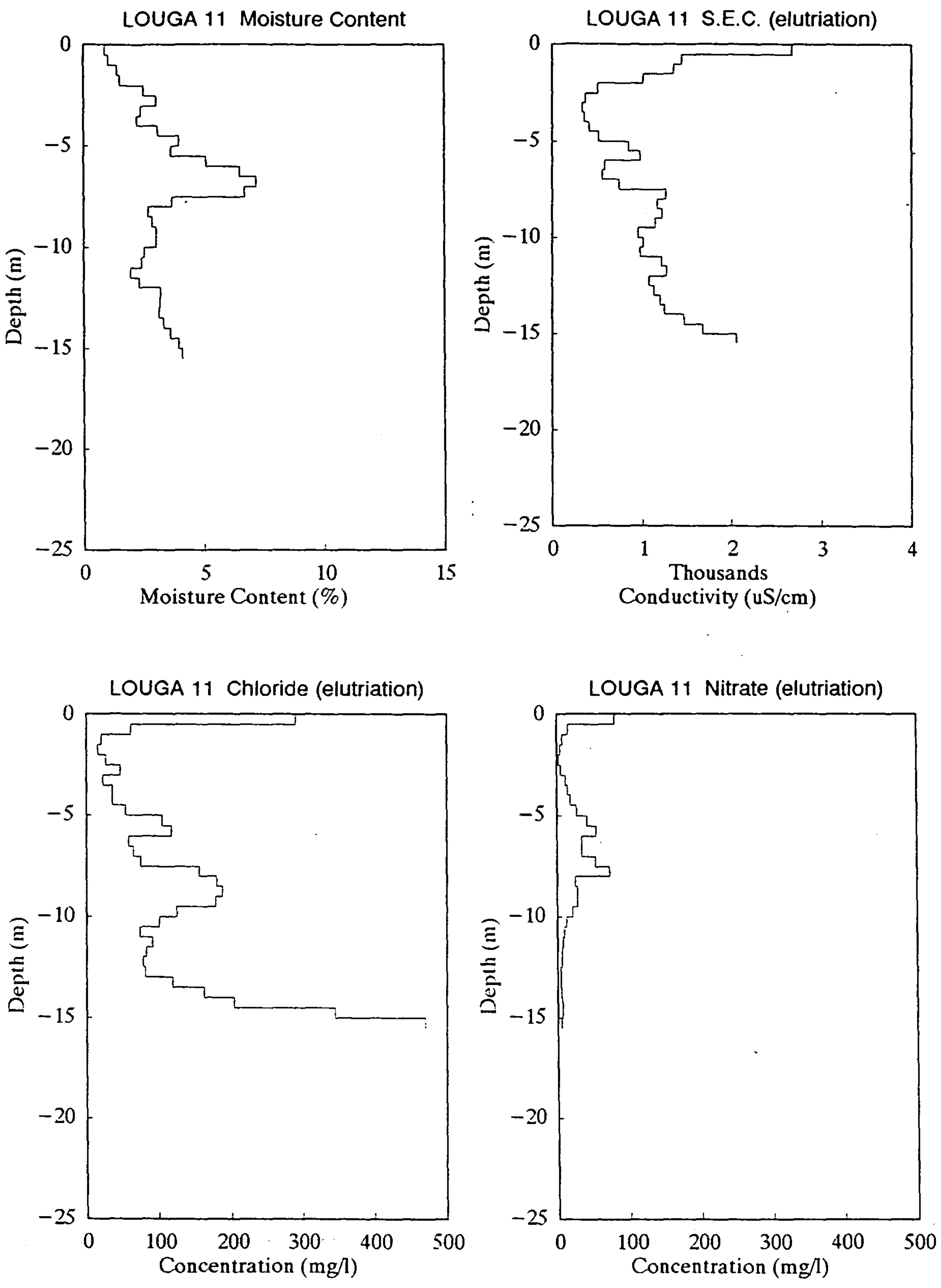


Figure 5.14 Profiles of moisture content, SEC, chloride (elutriation) and nitrate - Louga 11.

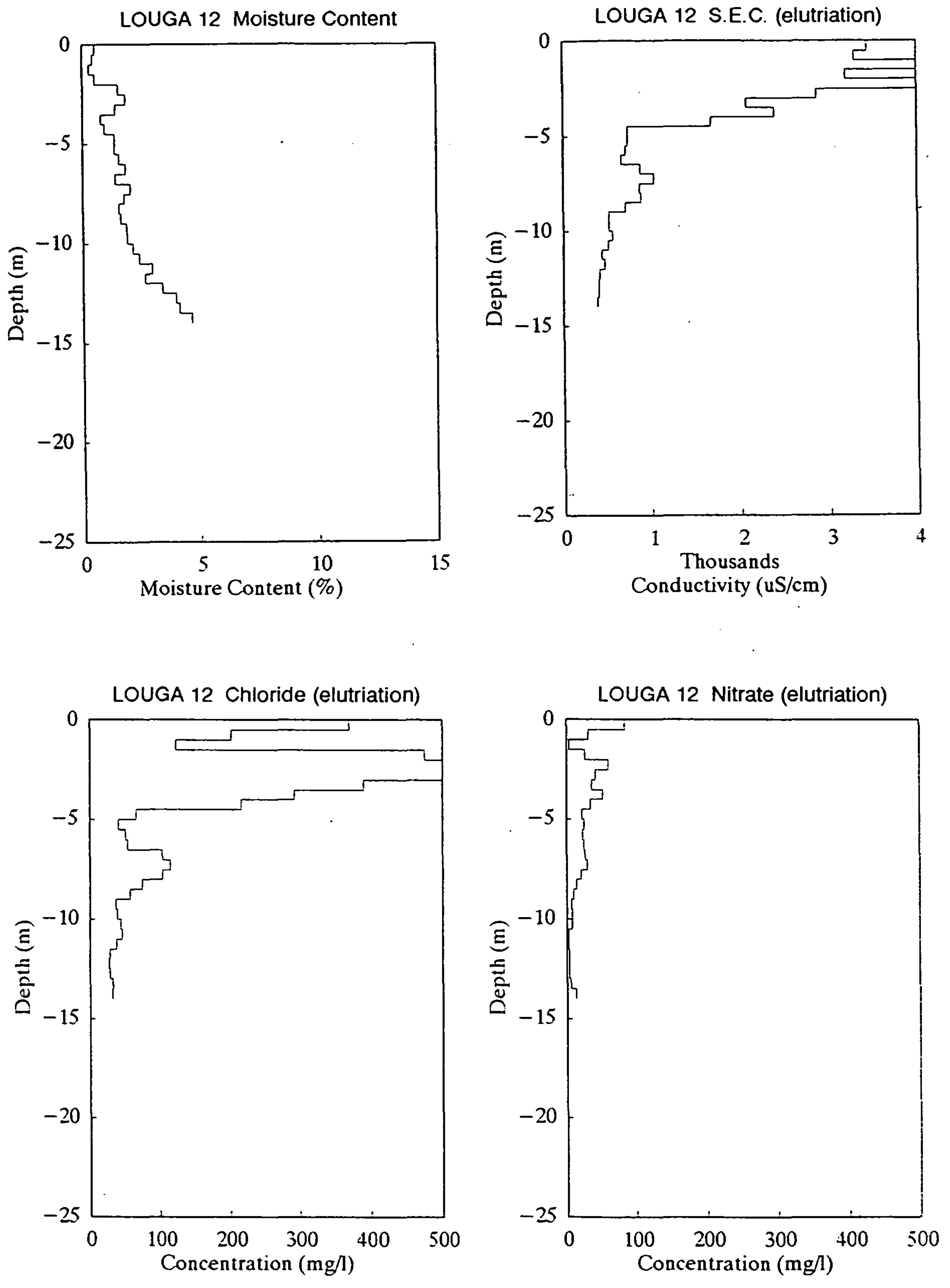


Figure 5.15 Profiles of moisture content, SEC, chloride (elutriation) and nitrate - Louga 12.

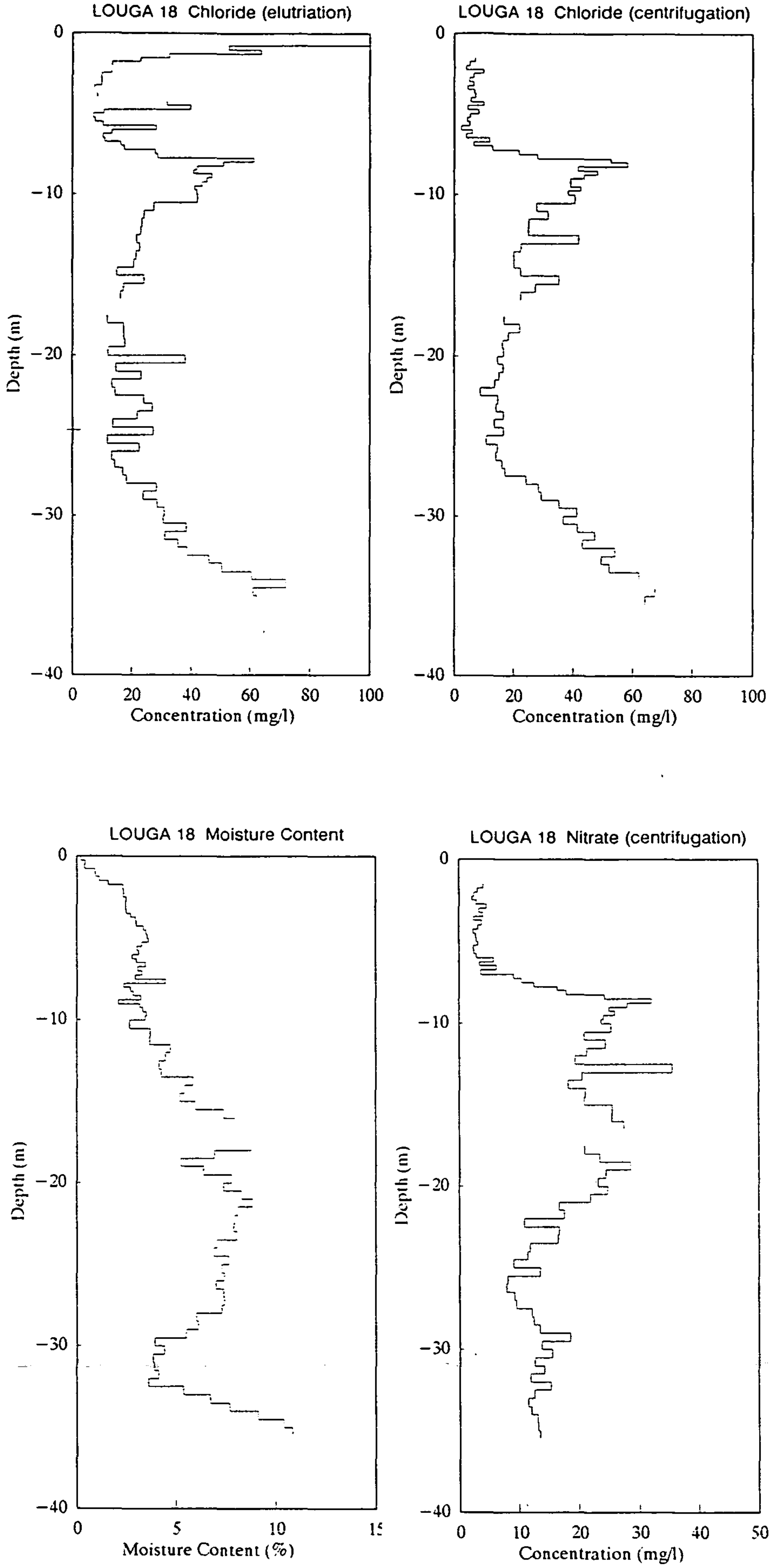


Figure 5.16 Profiles of moisture content, SEC, chloride centrifugation, chloride (elutriation) and nitrate - Louga 1º.

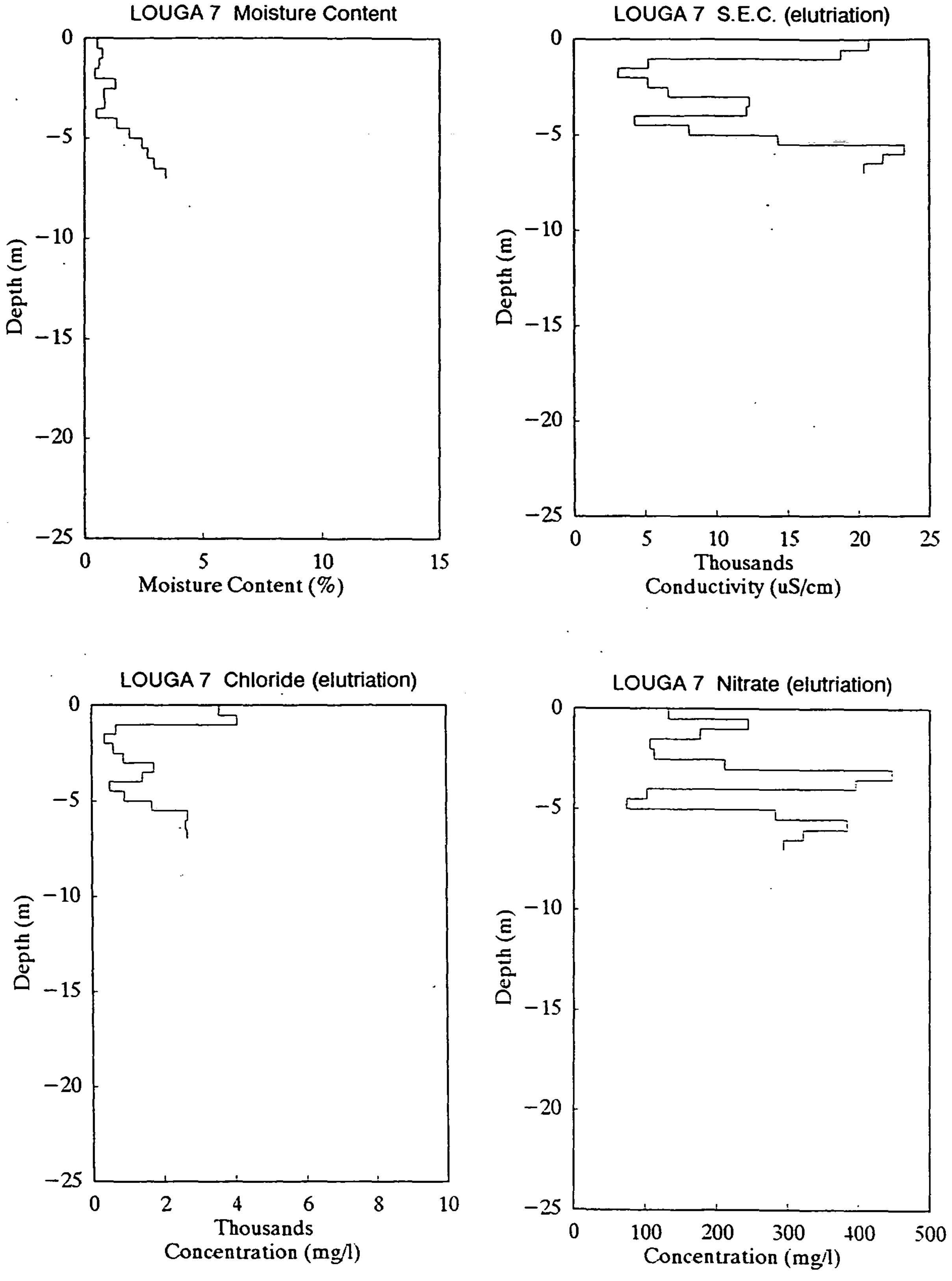


Figure 5.17 Profiles of moisture content, SEC, chloride centrifugation, chloride (elutriation) and nitrate - Louga 7.

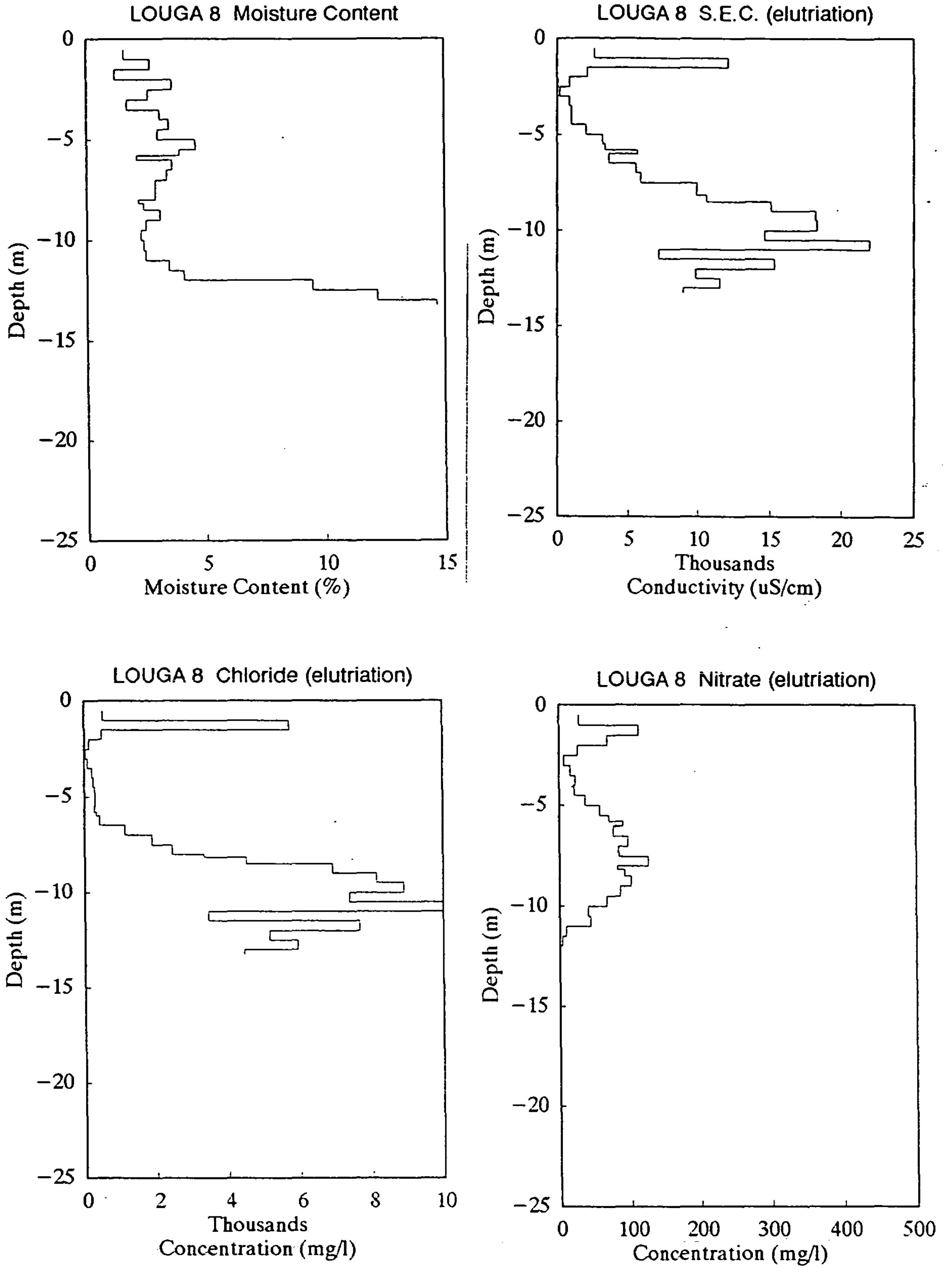


Figure 5.18 Profiles of moisture content, SEC, chloride centrifugation, chloride (elutriation) and nitrate - Louga 8.

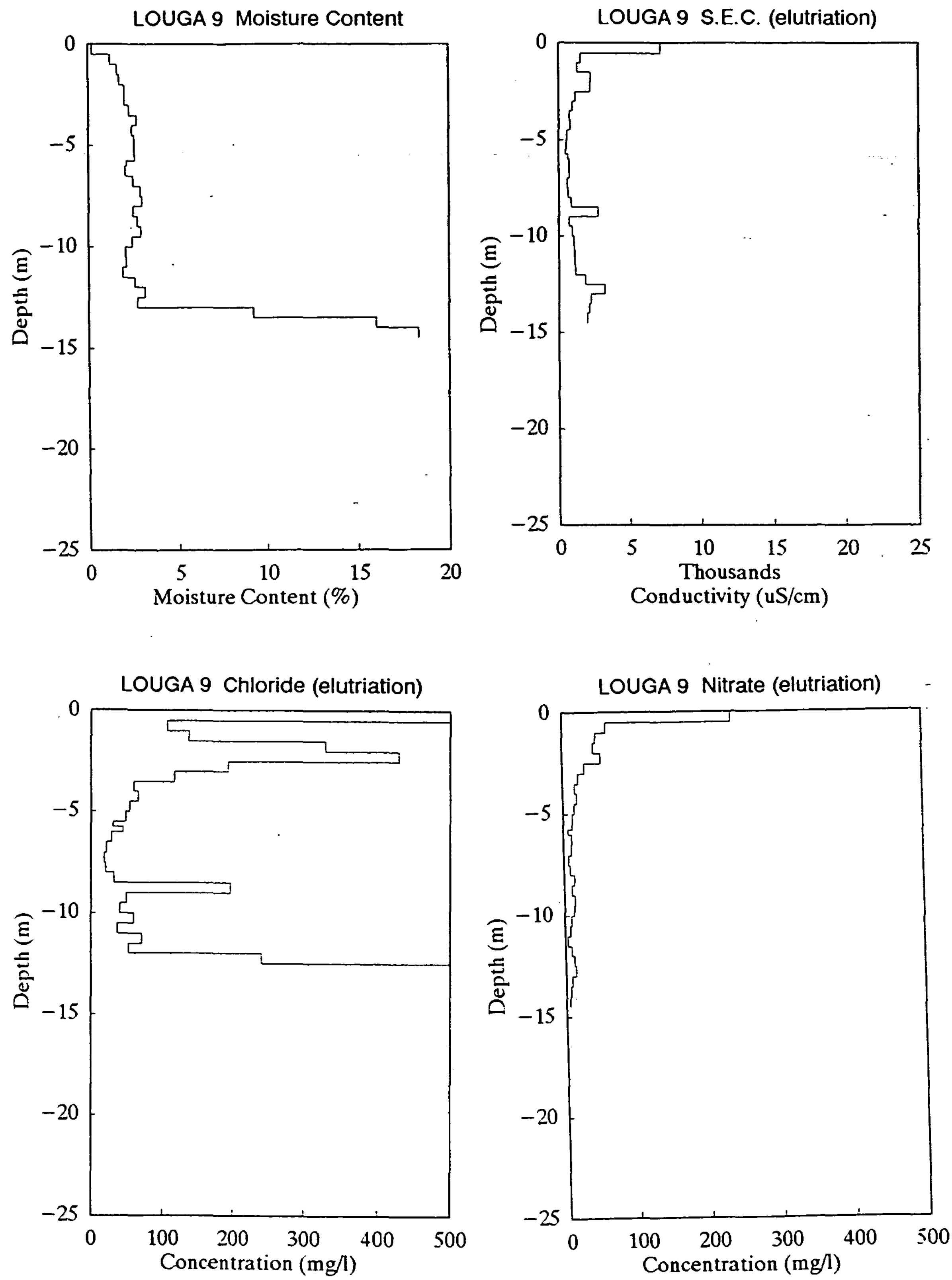


Figure 5.19 Profiles of moisture content, SEC, chloride centrifugation, chloride (elutriation) and nitrate - Louga 9.

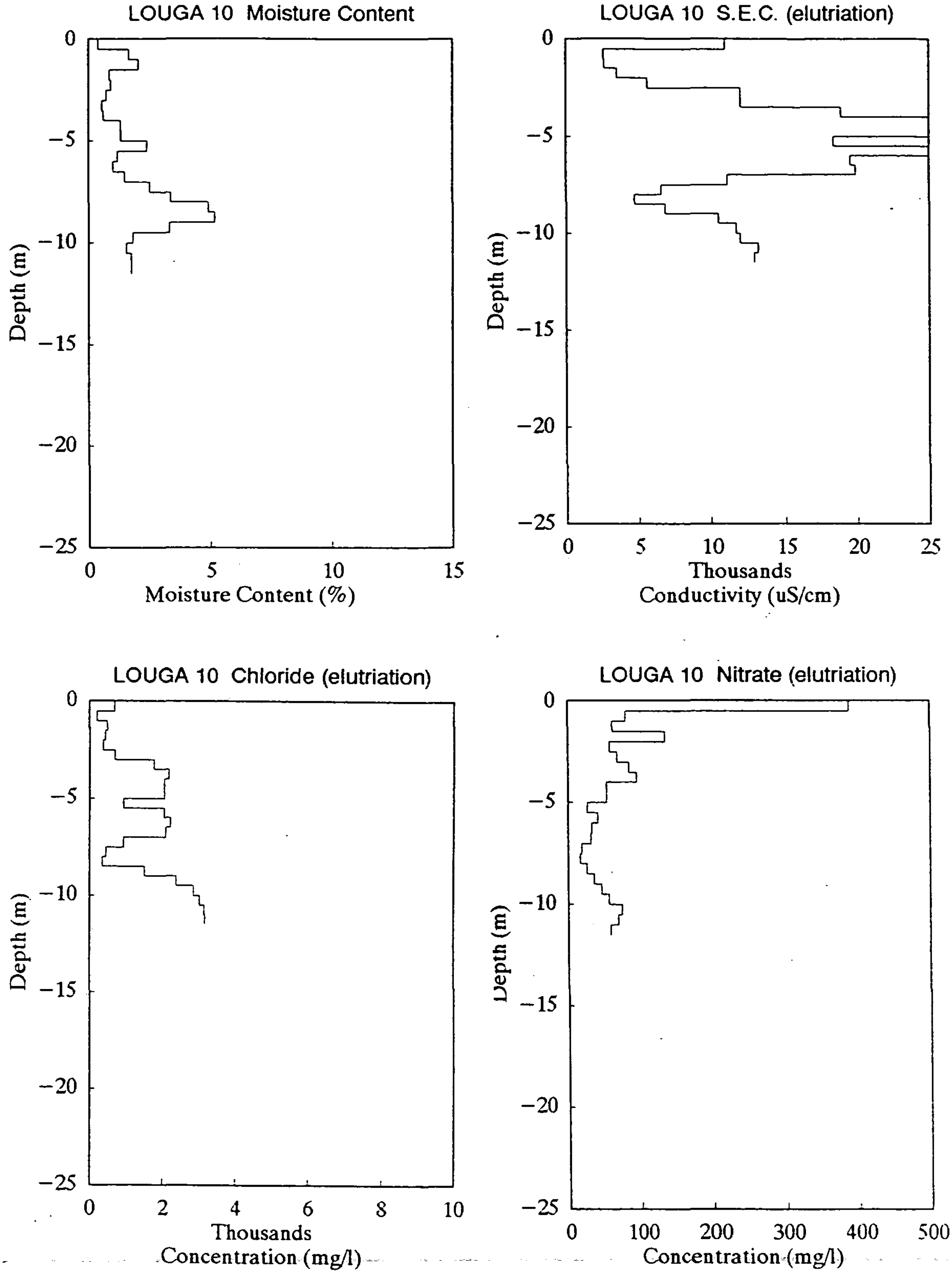


Figure 5.20 Profiles of moisture content, SEC, chloride centrifugation, chloride (elutriation) and nitrate - Louga 10.

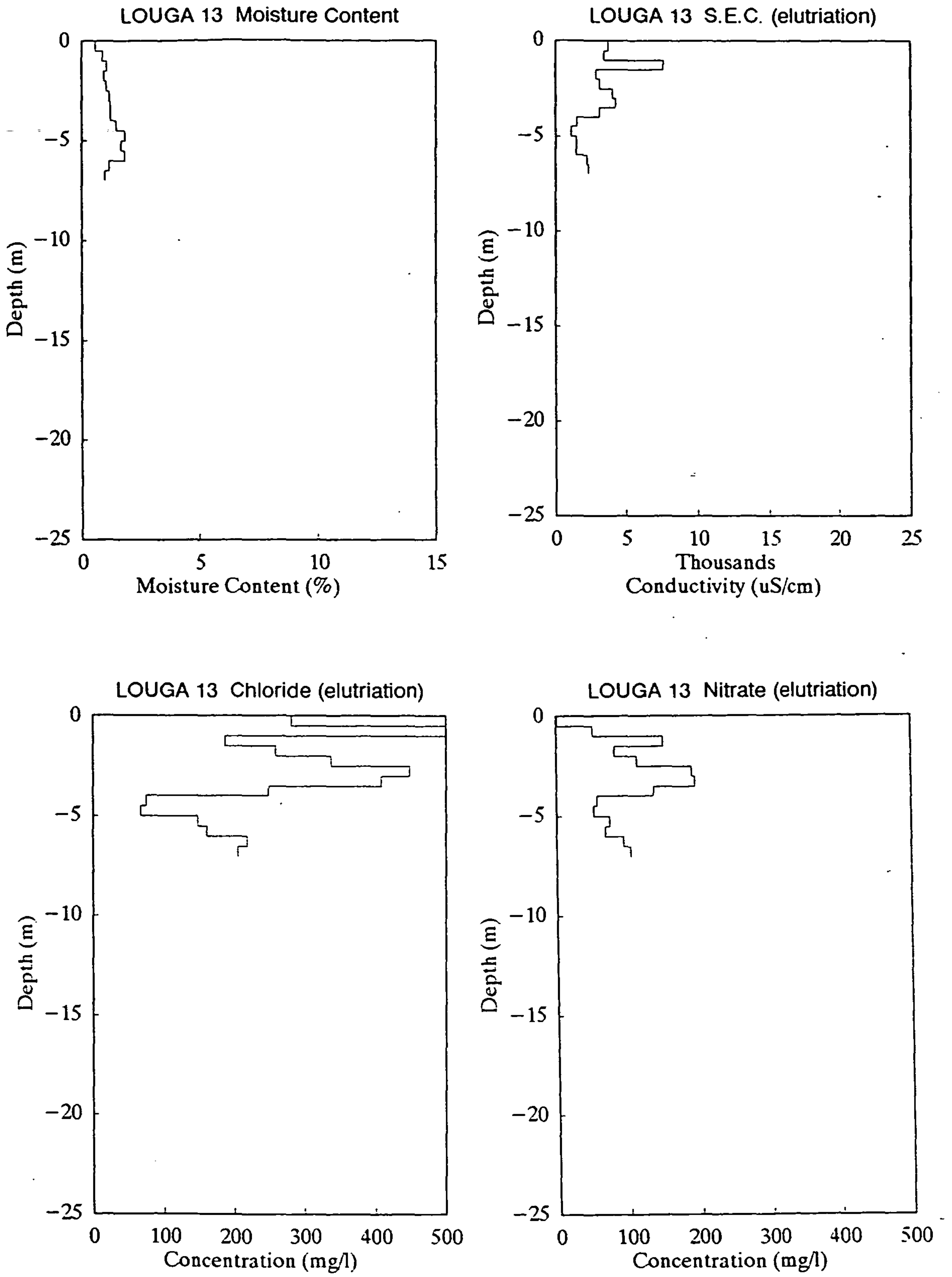


Figure 5.21 Profiles of moisture content, SEC, chloride (centrifugation), chloride (elutriation) and nitrate - Louga 13.

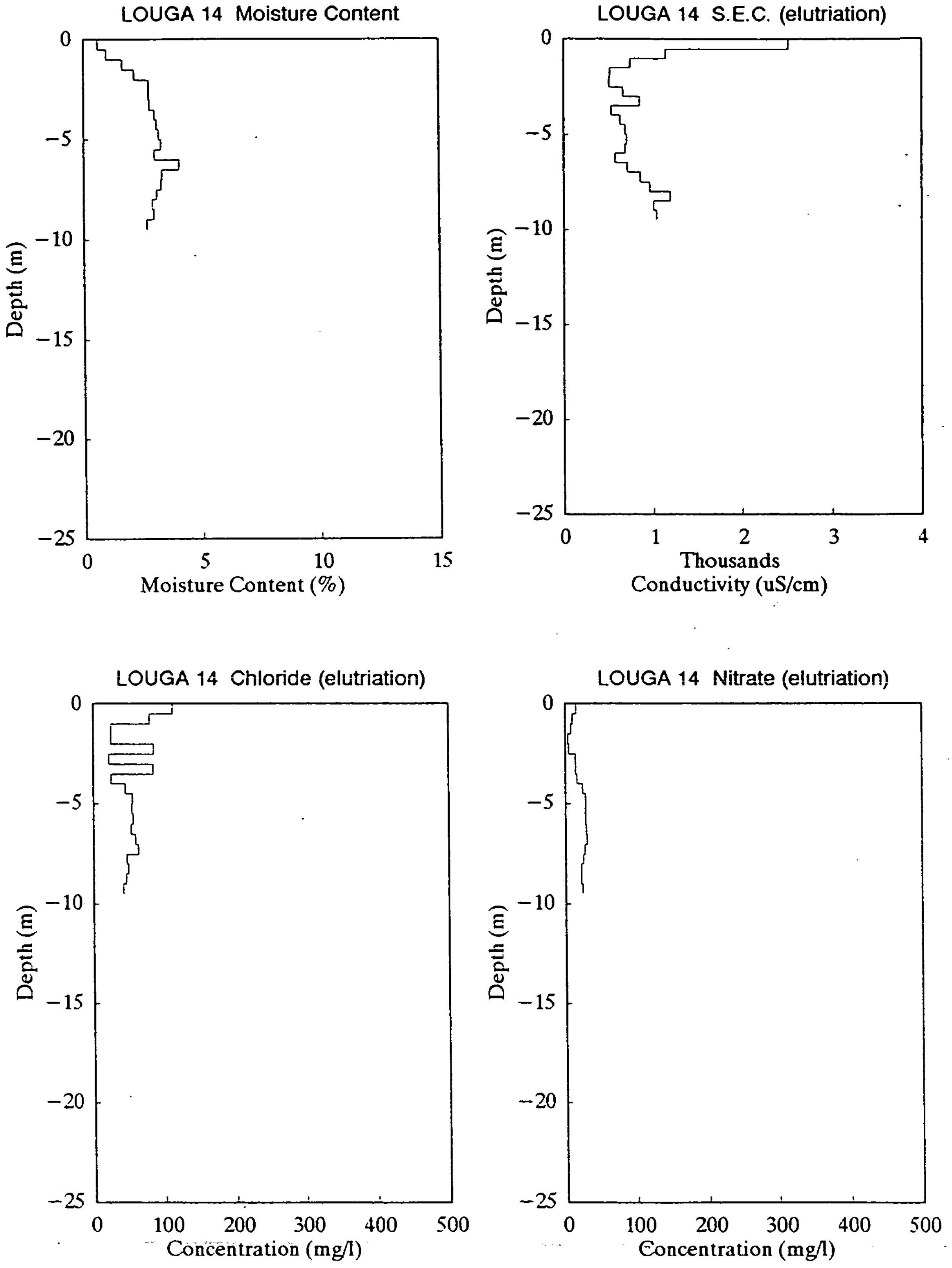


Figure 5.22 Profiles of moisture content, SEC, chloride (centrifugation), chloride (elutriation) and nitrate - Louga 14.

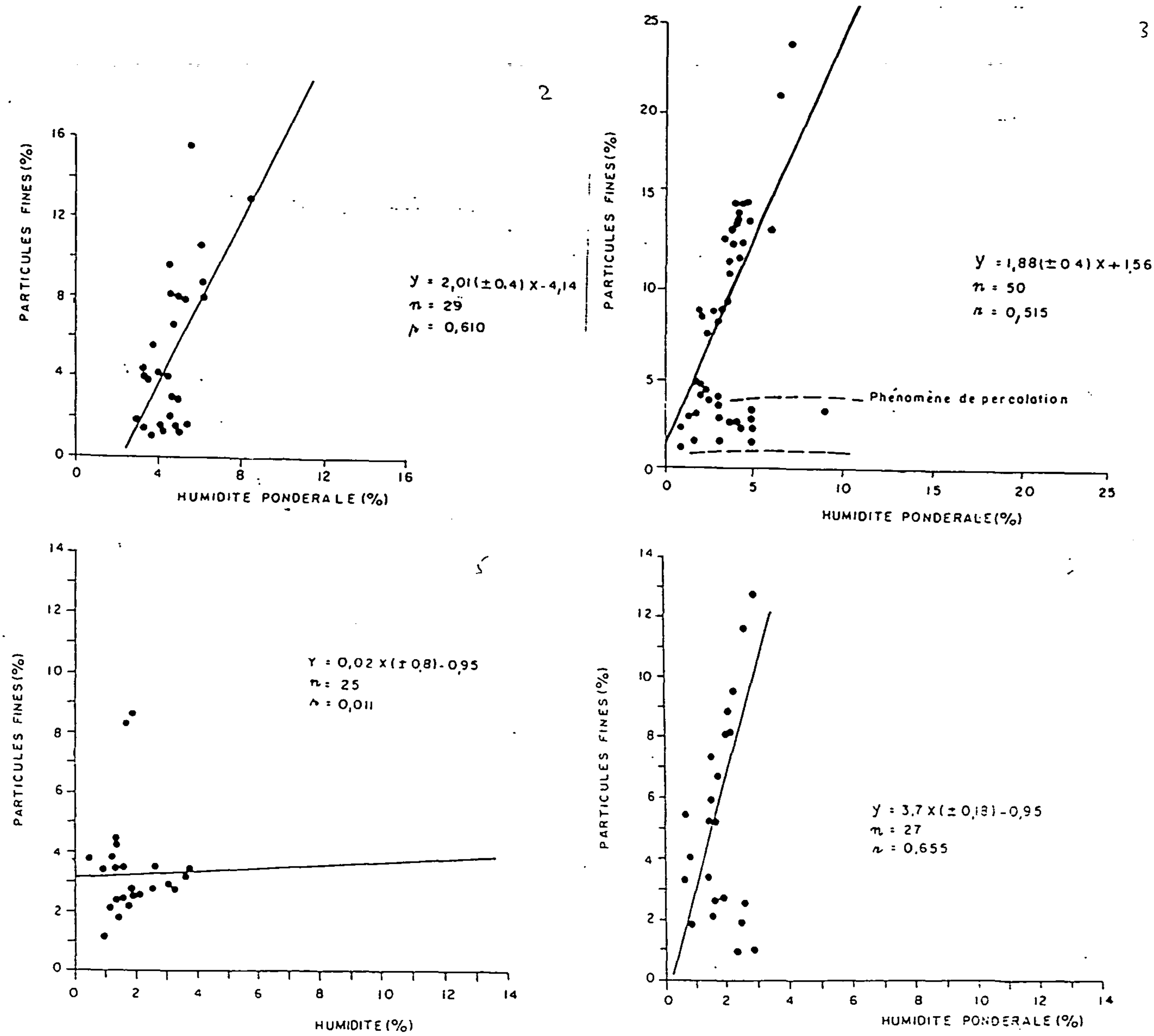


Figure 5.23 Relationship between gravimetric moisture content and content of fine particulate material (<50 µm) for profiles 2, 3, 5 and 6.

5.2.1.1 Moisture profiles

The moisture content is shown for those profiles at the main research site in Figures 5.10 to 5.16, for M'Pal sites in Figures 5.17 to 5.20 and Louga 13, 14 in Figures 5.21 and 5.22 respectively.

The moisture contents vary considerably within each profile mainly in response to lithology. This is demonstrated (Tandia, 1990) for profiles Louga 2, 3, 5, 6 (Figure 5.23). The correlation coefficient lies in the range 0.52 to 0.66 for three profiles but for Louga 5 there is no correlation. Within the upper sections of certain profiles, e.g. Louga 3, high moisture contents are found independent of lithology which are not in equilibrium and must represent a pulse of water not yet homogenised by grain size effects. In the lower parts of the profiles the correlation is usually good. The moisture balance in the upper 2 m (approx) of each profile will lie above the zero flux plane the depth of which is variable depending on seasonal and vegetational variations. Profiles were obtained at various seasons (Table 5.8) and those collected in spring (e.g. Louga 6) have a drier profile in the upper 2 m (approx) than, for example, Louga 2. Louga 18 (drilled in March) was the only profile to reach the water table and this provides a summary of the main characteristics of the moisture content. The upper 'dry' zone can be seen followed by a zone with moisture content below 5% then increasing to near 10% in relation to lithology (Figure 5.16). The capillary fringe commences at 33.0 m and moisture content rises to 11% to the maximum depth drilled (35.5 m) which is just below saturation; the static water table is probably around 1-2 m below this depth.

The profiles from M'pal region have low and relatively constant moisture contents, in general, between 2 and 4%. Louga 8 and 9 reach the water table as shown clearly by the capillary fringe. Profiles Louga 13 and 14 are also low in moisture content, typical of the sand aquifer of the region and neither reaches the water table.

5.2.1.2 Chloride and SEC profiles

The chloride content of the interstitial water is likely to be derived exclusively from atmospheric inputs, as described above, and its determination for recharge estimation is the main goal of this study. The

SEC (Specific Electrical Conductance at 25°C) on the other hand represents the total solute concentration in the interstitial water, including solutes derived from reactions between the rock and the percolating water. The SEC will also include the contribution from other rain-derived solutes, especially sulphate, sodium and calcium, which should be concentrated in proportion to chloride. Once the saturation with any mineral such as calcite or gypsum is reached there is the possibility that precipitation of these minerals near the surface may occur, thus lowering the SEC. This may only be a temporary phenomenon however since re-solution may take place during the rainy season.

The shapes of chloride and SEC peaks are generally rather similar (c.f. Louga 6, Figure 5.13) which suggests that atmospheric inputs dominate the solute chemistry.

From visual observation it is clear that the chloride concentrations of the Cl profile are different even at the same site. Louga 2 has a lower interstitial water chloride composition for instance than Louga 3 which indicates a higher overall recharge rate in the former site, as discussed below. Another feature of the profiles is the presence of several peaks and/or troughs in the chloride concentration. These are most likely to be related to a change in input, i.e. recharge rate either as a result of climatic changes, vegetation changes, or man-made influences. Thus, the profiles contain not only a record of the mean recharge rate but also a record of the recharge history as discussed below.

The remaining profiles are generally self-explanatory. However in Louga 8 very high chloride is found at depth which is considered to represent the uptake from evaporating minerals or residual saline water (see below). Clearly only the upper sections of these profiles can be used for recharge estimation.

5.2.1.3 Nitrate profiles

The nitrate profiles have been measured for several reasons. Nitrate is introduced into the profile from precipitation, from nitrogen fixation by plants and from the activities of man (notably chemical fertilisers). From rainfall it may be concentrated by evapotranspiration in the same manner as chloride from a mean input value of around 0.1 mg l^{-1} (Travi et al. 1987).

Once in the profile nitrate should remain stable in the presence of dissolved oxygen and should reflect the input values plus any nitrate from biological prediction by leguminous plants or other sources. Only once the oxygen has been consumed by oxidation of minerals (e.g. pyrite) or organic matter will nitrate reduction occur to any significant extent. It is clear that a significant fixation of nitrogen is taking place in the soil and the NO_3/Cl may reach 1 whereas the ratios in rain water are some 2 orders of magnitude lower than this.

The presence of very low or zero nitrate water must therefore mark an oxidation-reduction boundary in the profile or in the aquifer. In this study NO_3 is mainly investigated as an aid to interpreting the chloride profiles and recharge phenomena and to this end, NO_3/Cl profiles have been drawn (Figure 24, 25). Using Louga 12 as an example it is found that low NO_3/Cl peaks coincide almost exactly with high chloride, which suggests that nitrate depletion is occurring as a byproduct of the chloride enrichment. This would indicate either uptake by vegetation or lack of production of nitrate as a probable source of the variation and as having an influence on the chloride peaks in some profiles. The areas chosen for profiling were not heavily vegetated. However the profiles retain a history of several decades of input and trees/shrubs or other vegetation might have died or been felled for fuel. The profiles therefore may contain a history of these activities which need to be considered in the recharge model. It is also possible that during times of drought nitrate demand as well as water demand is higher (or nitrate production is lower) so that the observed lower NO_3/Cl ratios at high Cl are reflecting both phenomena. Louga 12 was drilled several metres from a large acacia tree and its root system may have extended to the site of the profile.

The total nitrate (NO_3-N) in the profiles also needs to be considered. Usually the nitrate concentrations are very high compared to rainfall inputs and the molar NO_3/Cl ratio may be as high as 1 especially where chloride concentrations are low (e.g. Louga 18). This suggests that the biological productivity is an important source of nitrate and its production is independent of the recharge rate. This topic will be discussed in more detail in a later section.

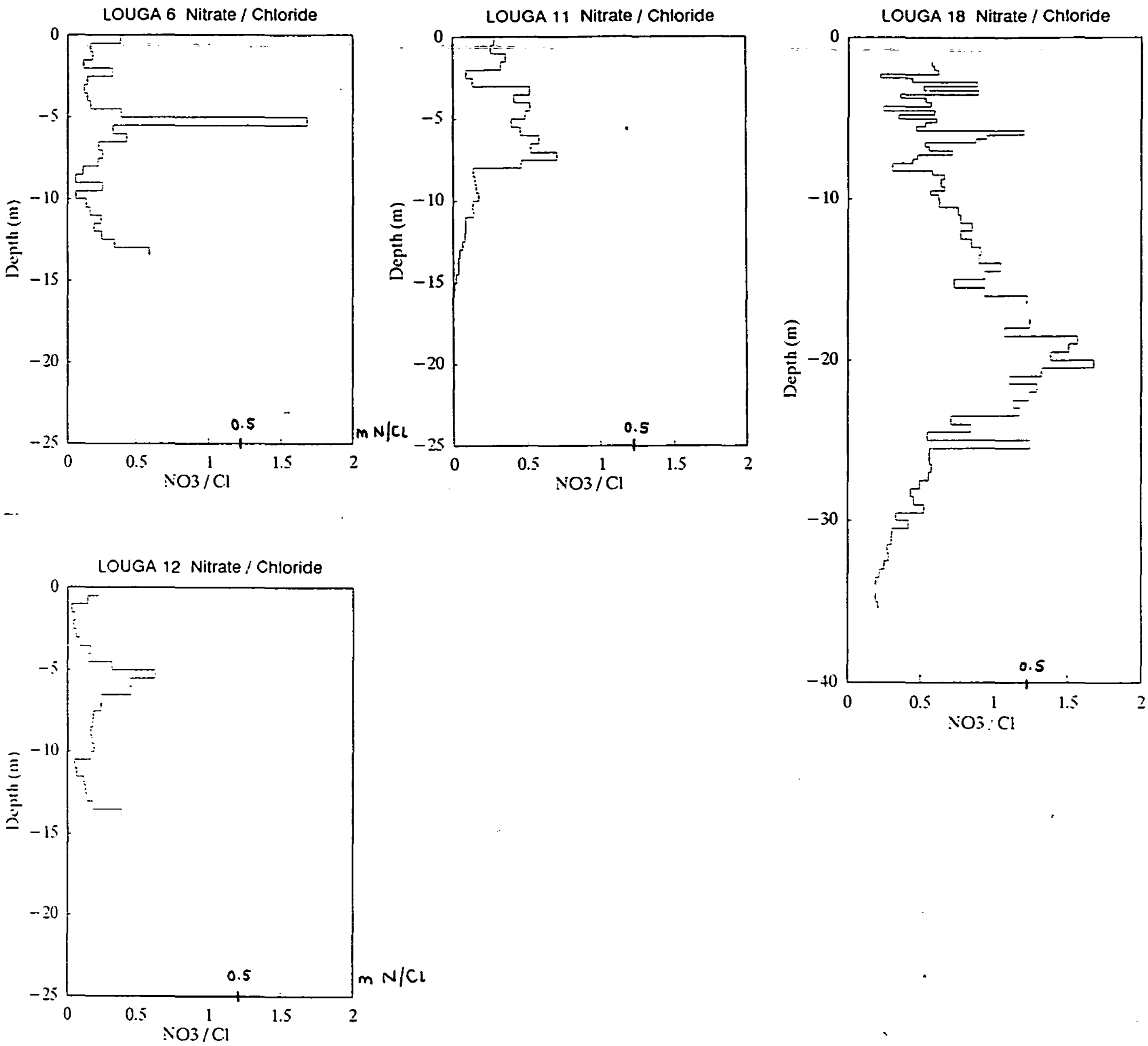


Figure 5.24 NO_3/Cl ratio for profiles at main Louga research area sites.

5.2.2 Kaolack area

Four profiles (Table 5.8) were obtained from southern Senegal in an area of higher rainfall at the sites at Sikatroune and Nioro du Rip south of Kaolack (Figure 5.8). Profile KK1 was made by sampling from a new dug well during construction by the Brigàde des Puits at Kaolack. The other three holes, one at Nioro and the other two in the same area of Sikatroune were made by hand auger. Only KK1 reached the water table at 19.5 m. Results for moisture content, chloride, SEC and nitrate are shown for each profile in Figures 5.26-5.29 (KK1-KK4 respectively).

5.2.2.1 Moisture content

The moisture contents in profiles in the Kaolack region are generally high, much higher than Louga, and reflect the increased clay mineral contents of these soils and underlying Continental Terminal sediments (see 3.4). In Kaolack 4, for example, there is a mean moisture content of around 7% and the same moisture content is to be seen in KK2 which is some 26 km further south. In the latter profile there is a marked increased in moisture content below 12 m to above 15% and this must represent the capillary fringe since the moisture content is similar to that in KK1 where water was encountered. KK1 also has a similar moisture content to the other profiles, characteristic of this facies of the Continental Terminal.

The upper 5 m of the profiles are different in each case. The profiles KK2, KK3 and KK4 were obtained in November 1987, some two months after the end of the rainy season. Their moisture contents are quite high, probably at or above field, capacity and contrast with KK1 which was commenced in March (and finished in June 1986). KK1 has a dry zone to 5 m which is considered most likely due to the drying of a relatively deep zone in the clay soil to this depth during the dry season; this would represent an effective zero flux plane of >5 m influenced possibly by vegetation. There are two other alternatives, discussed further below: 1) that there are two recharge layers, one rapid via cracks, and the other slower via a clay-rich soil matrix. 2) there may have been some drying of the upper 5 m sample. Despite precautions taken, this cannot categorically be ruled out.

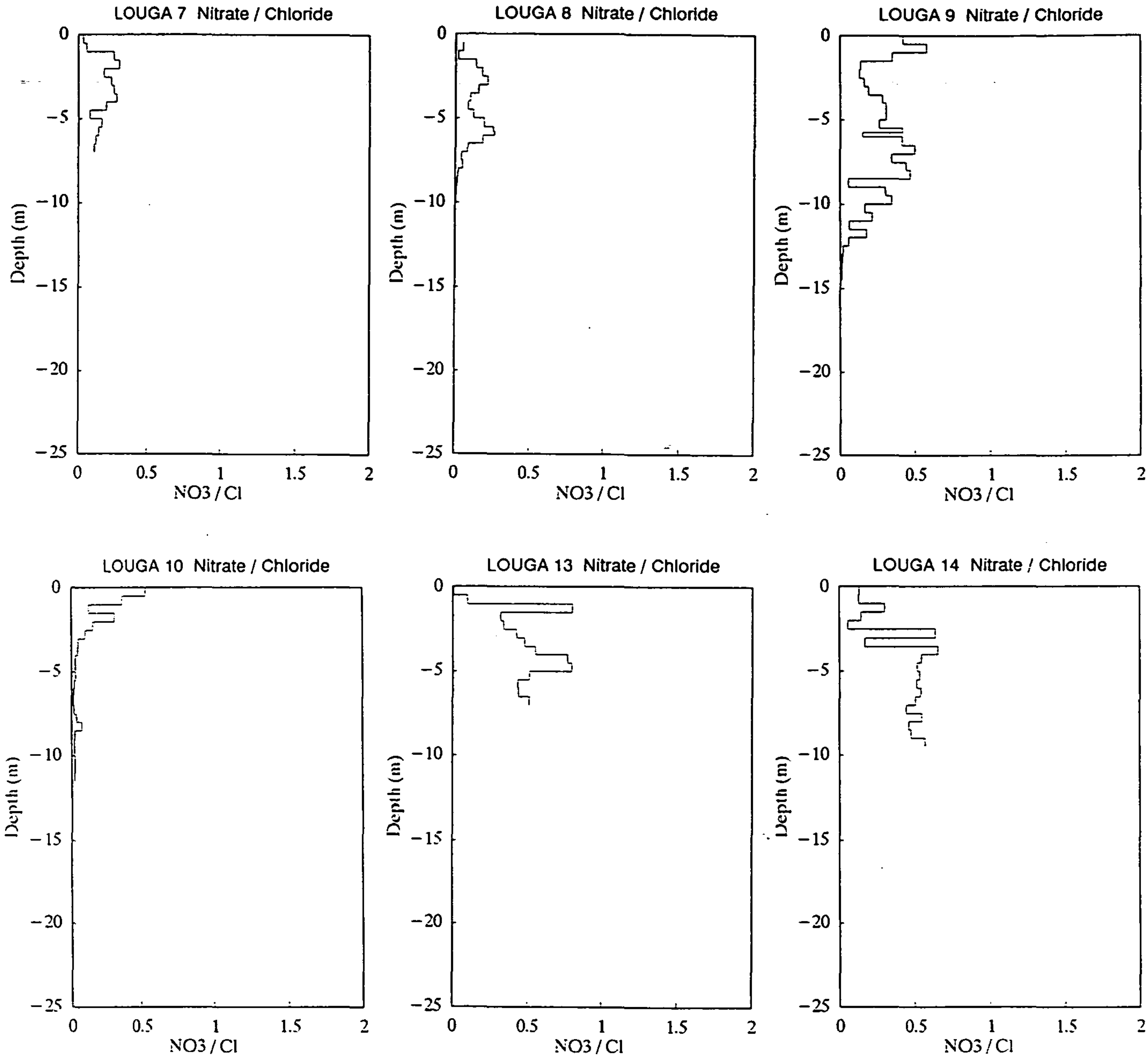


Figure 5.25 NO_3/Cl ratio for other Louga area sites.

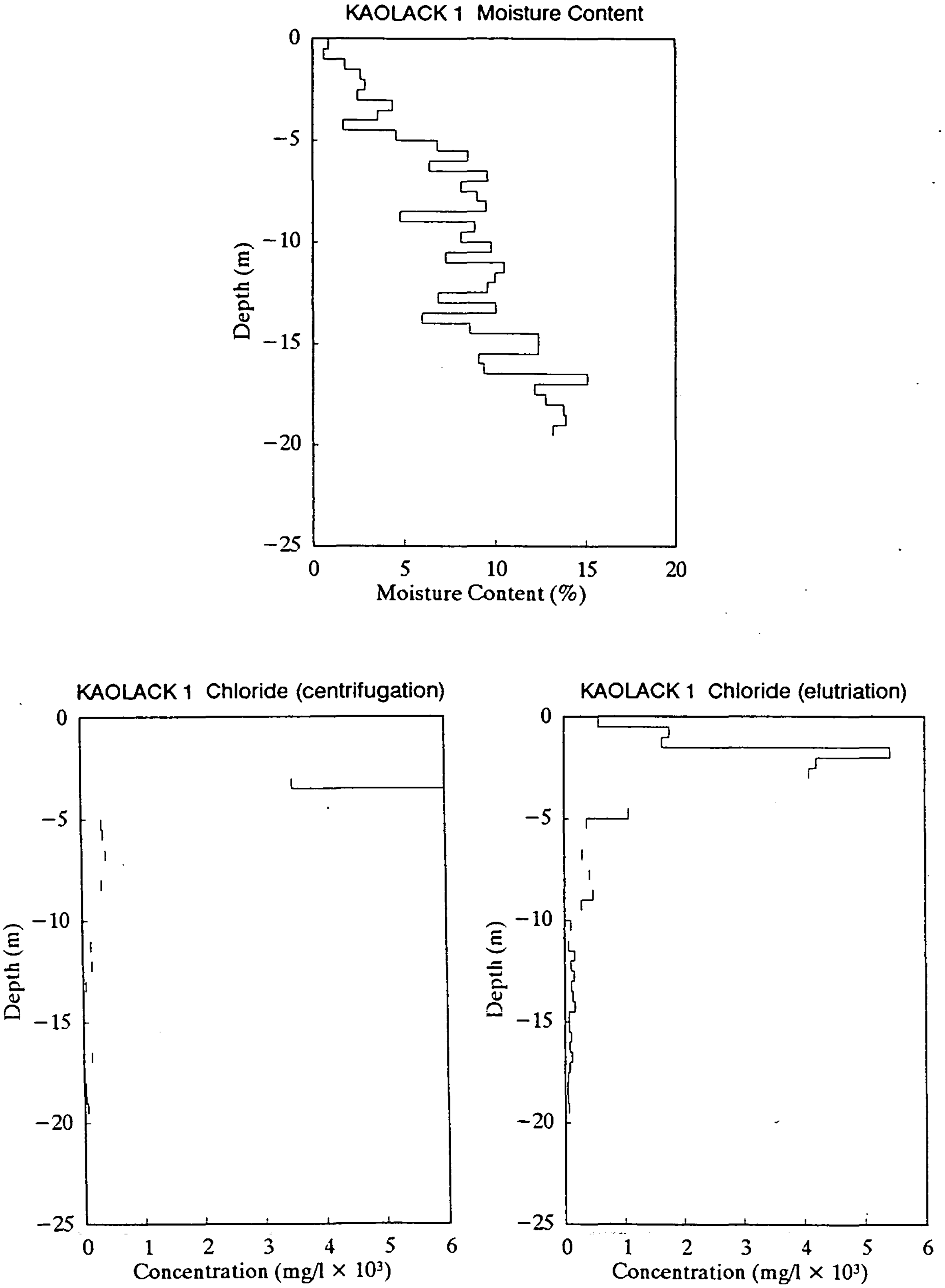


Figure 5.26 Profiles of moisture content, chloride (centrifugation), chloride (elutriation) and nitrate - Kaolack 1.

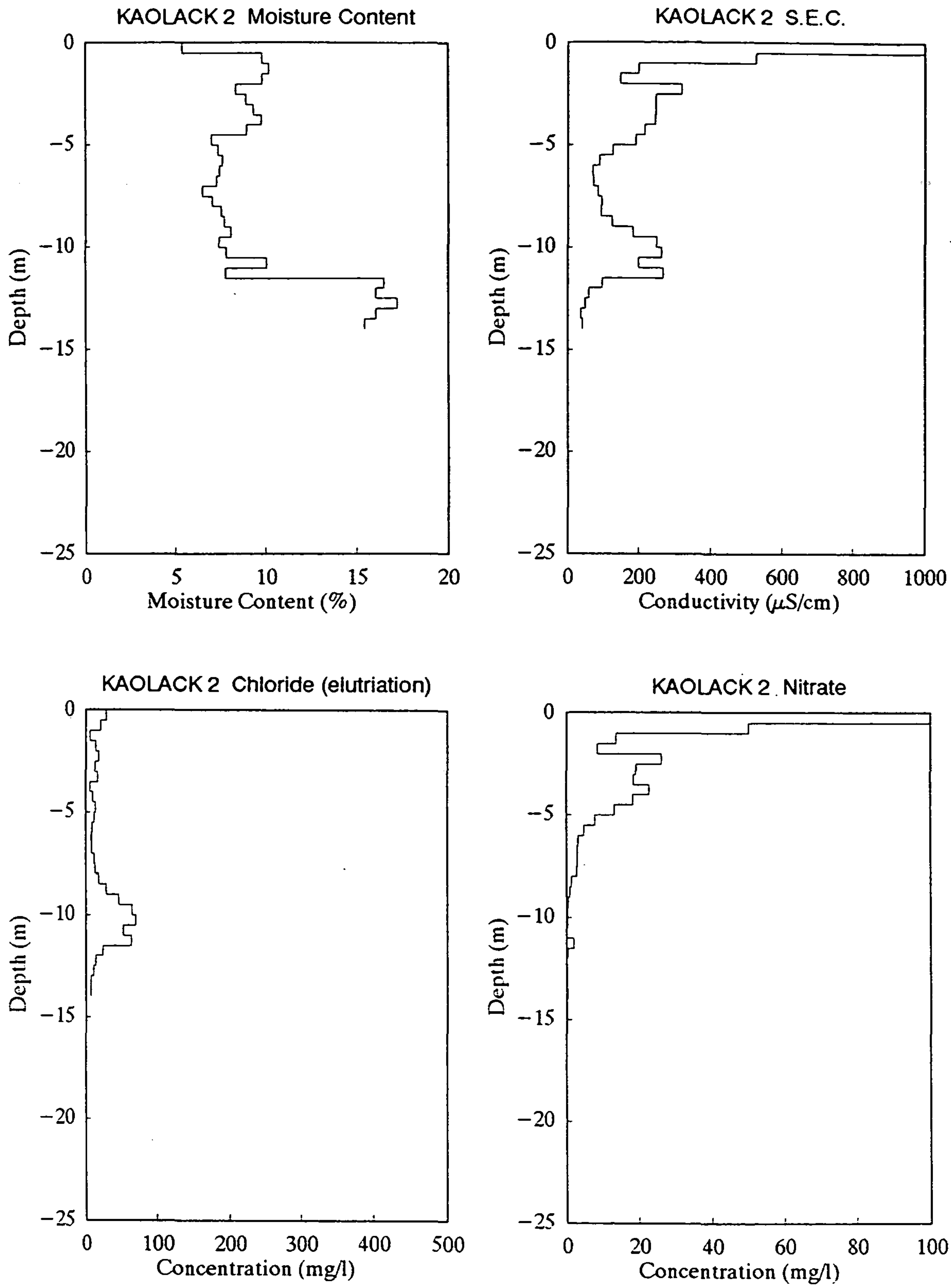


Figure 5.27 Profiles of moisture content, SEC, chloride (elutriation) and nitrate - Kaolack 2.

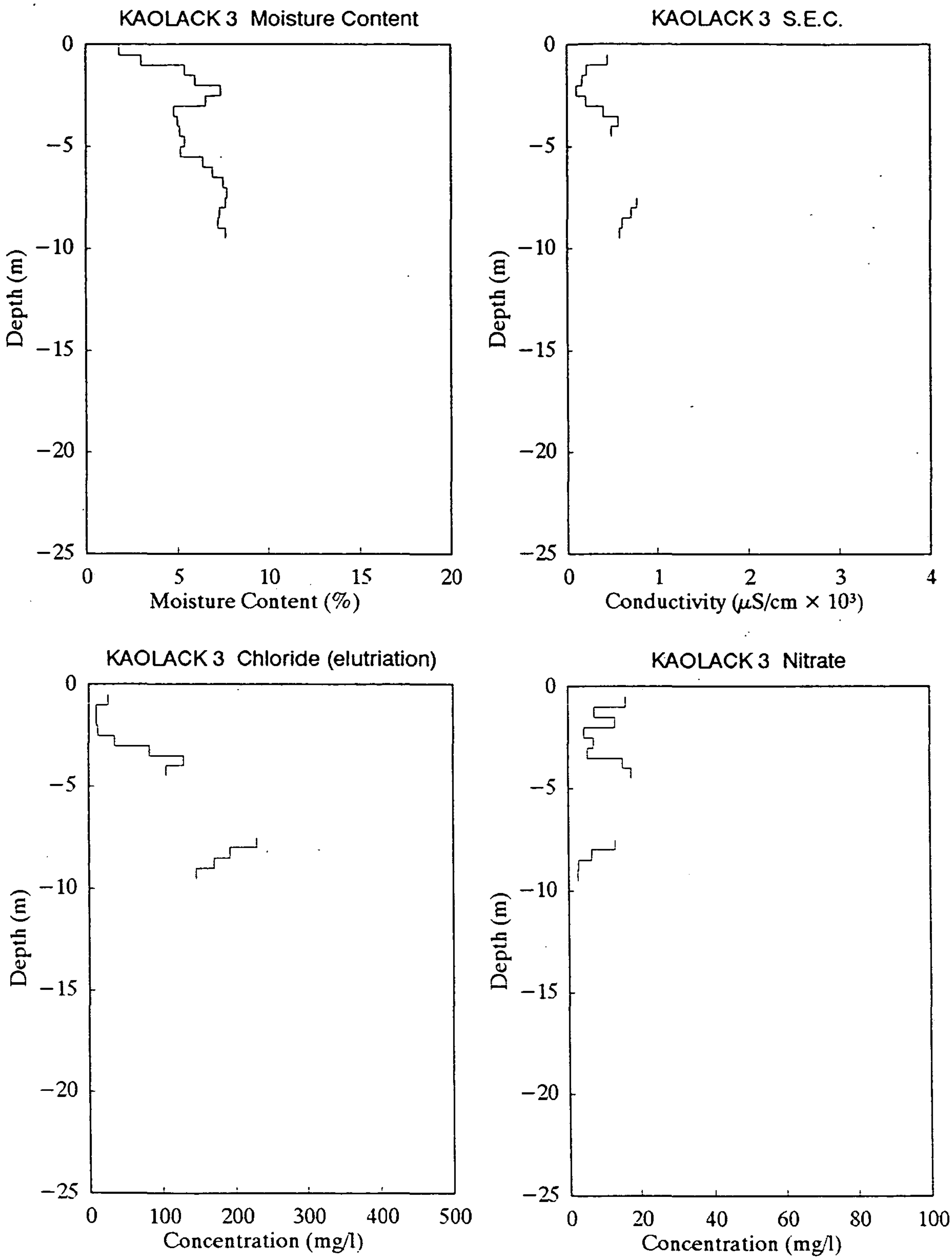


Figure 5.28 Profiles of moisture content, SEC, chloride (elutriation) and nitrate - Kaolack 3.

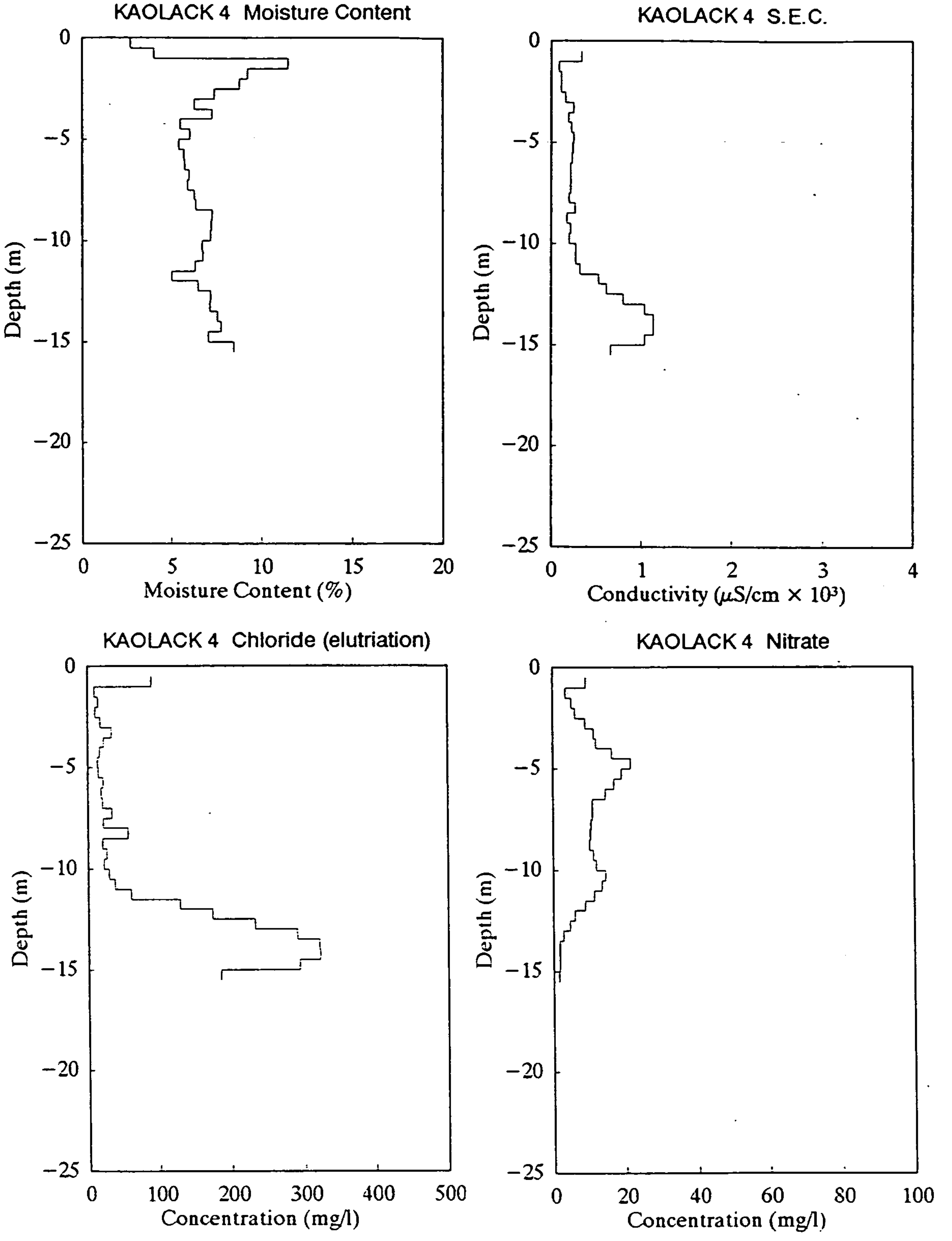


Figure 5.29 Profiles of moisture content, SEC, chloride (elutriation) and nitrate - Kaolack 4.

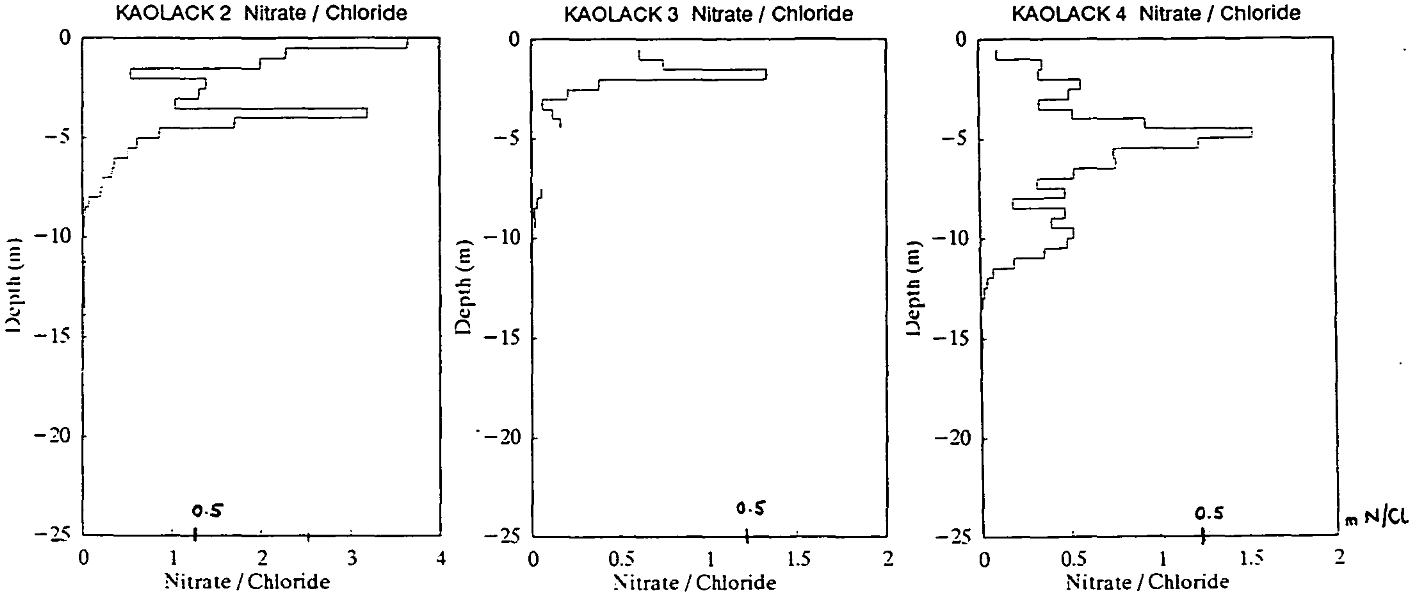


Figure 5.30 NO_3/Cl ratios for profiles from Kaolack area.

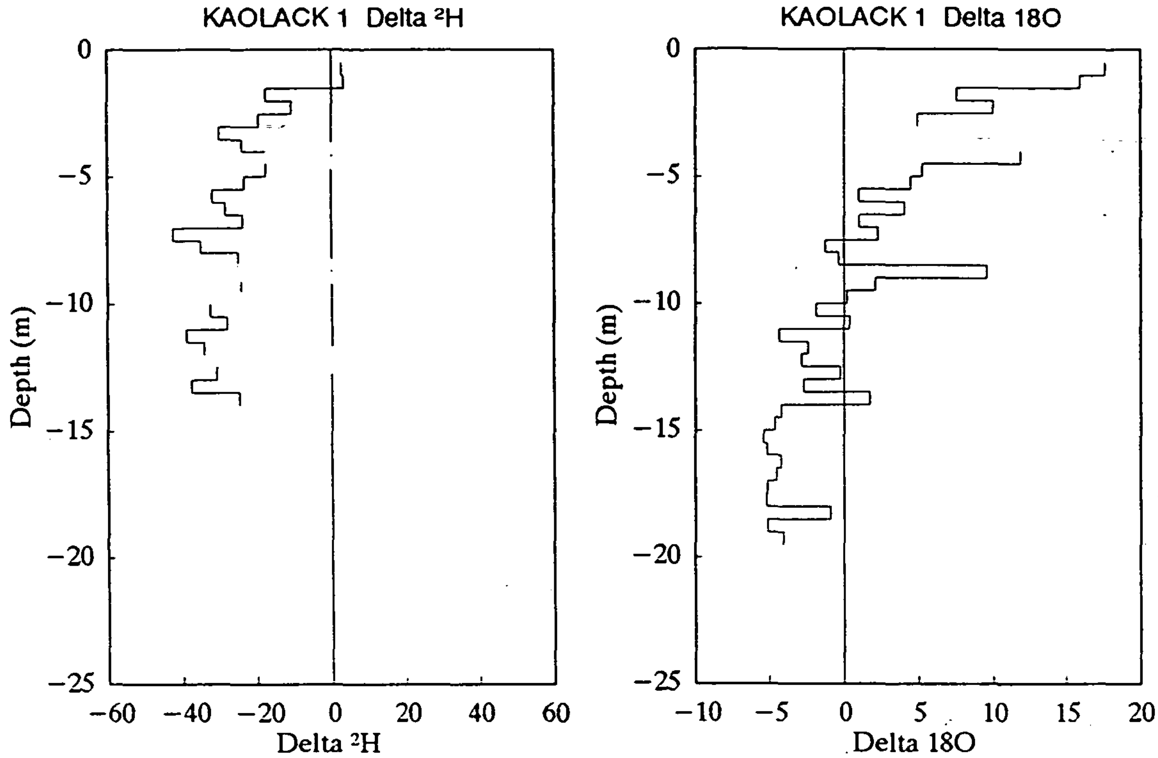


Figure 5.31 Isotope profiles ($\delta^{18}O$, $\delta^{2}H$) for Kaolack 1.

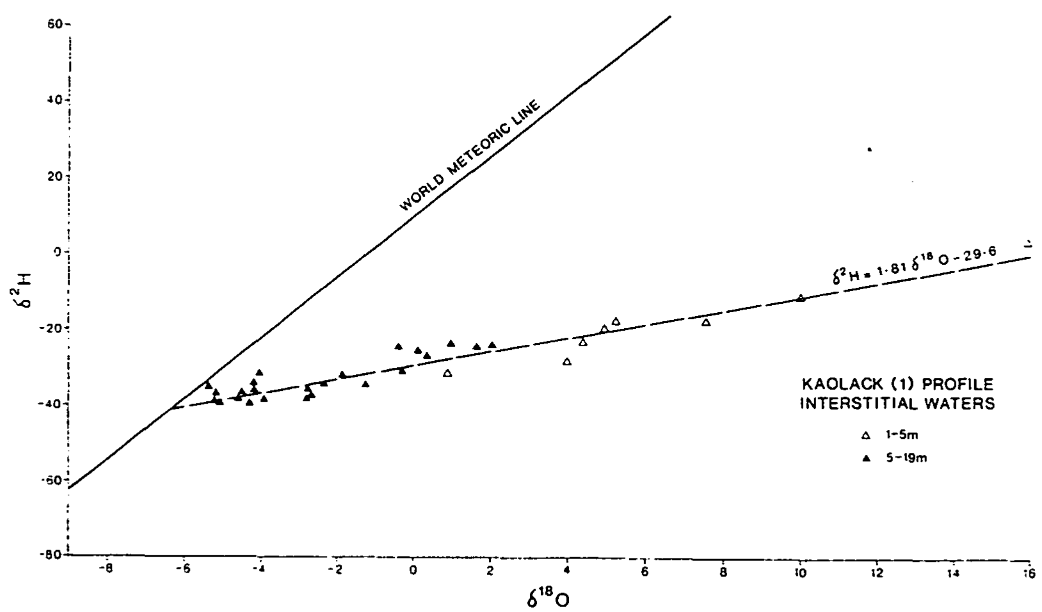


Figure 5.32 δ-diagram ($\delta^{18}O$, $\delta^{2}H$) for Kaolack 1.

5.2.2.2 **Chloride and SEC profiles**

The upper sections of profiles 2, 3 and 4 all have relatively low concentrations of chloride (23, 102 and 26 mg l^{-1} respectively). Each of these profiles can be interpreted assuming simple piston displacement but with chloride variations related to environmental factors (climate and/or vegetation). A distinct chloride peak is found in KK4 around 13 m, independent of moisture content and thus unrelated to the water table.

A problem exists with the interpretation of KK1. The lower section of this profile, 5-20 m, is similar in interstitial water concentration to the other three profiles. In contrast, there is a distinct peak over the top 5 m which clearly represents a zone of strong evaporation, as confirmed by stable isotope data. It is difficult to interpret how this peak can be a component of an active piston flow recharge system, since many decades of recharge is represented in this interval. Nitrate results (see below) were not available for this profile; these might have helped to resolve the origin of the high salinity.

5.2.2.3 **Nitrate profiles**

Nitrate profiles were only measured on profiles KK2, KK3 and KK4 (Figures 5.27-5.29). Interstitial water concentrations of nitrate are often as high as 20 mg l^{-1} NO_3-N, but in KK2 soil zone nitrate concentrations exceed 100 mg l^{-1} NO_3. There is often an inverse relationship between NO_3 and Cl and this is explored further using NO_3-N/Cl plots.

In the KK2 profile the m/NO_3-N/Cl ratio approaches 1 above 5.0 m and is interpreted as a zone of production of nitrate-nitrogen. If the production rate were constant and the NO_3 related to physical processes alone such as evaporation then the ratios should be near constant in an oxidising environment. This is clearly not the case. There are strong changes in the NO_3/Cl ratios which must relate to biological activity and, possibly at depth, to denitrification (see lower section of KK2 where there is an exponential decrease of NO_3). An alternative explanation of KK2 at depth might be that high Cl combined with low NO_3 might be an indicator of recharge during a period of drought where NO_3 production is low (see Louga results).

5.2.2.4 **Isotope profiles**

Data are only available from one profile, KK1 (Figure 5.31). The results show a strong enrichment in heavy isotopes near the surface with $\delta^{18}O$ values of +10 or even more positive. The results lie on a uniform evaporation line with a slope of 1.97 (Figure 5.32). The degree of enrichment of many waters below 5 m is not much above local rain or shallow groundwater and must represent an active recharge environment. The most likely explanation of the isotope data taken with the Cl and NO_3 results is that the upper 5 m represent a low permeability zone which is isolated from the main recharge route, which by-passes this zone.

5.2.3 **Niague area**

The Niague area is located near to Dakar (Figure 5.9) and was the area first investigated during the current studies. It lies in the area of 'Niayes' - alternate areas of fixed dunes and inter-dune depressions. This is an area of intensive cultivation for market-gardening close to the capital, and where seasonal irrigation is practised. Six profiles were made adjacent to the small road leading to Niague. As far as possible the area chosen represents a natural situation where rainfed agriculture was practised. However, at the time of this study the area was being cleared of scrub vegetation and several dug wells were being constructed for an irrigation network. A mixture of auger profiles and dug wells was therefore available (Table 5.8). The samples were obtained from an upper and a lower zone. In the former the water table was at around 12 m and in the lower zone around 5-6 m. The geological section of the site showed some 6 m of fine sands over sandy clays (NG2, NG3) but in NG4, for example, altered volcanic tuffs formed the main aquifer.

5.2.3.1 **Moisture contents**

Profile NG4 is the only one to have reached the water table at a depth of around 14 m (although the capillary fringe is not seen in these samples). Results are illustrated here only for NG2, NG3 and NG4 (Figures 5.33, 5.34 and 5.35) where relatively complete profiles were obtained. The average moisture contents in NG4 are around 10% and must indicate a significant clay component. Several zones with higher moisture contents (up to 20% or

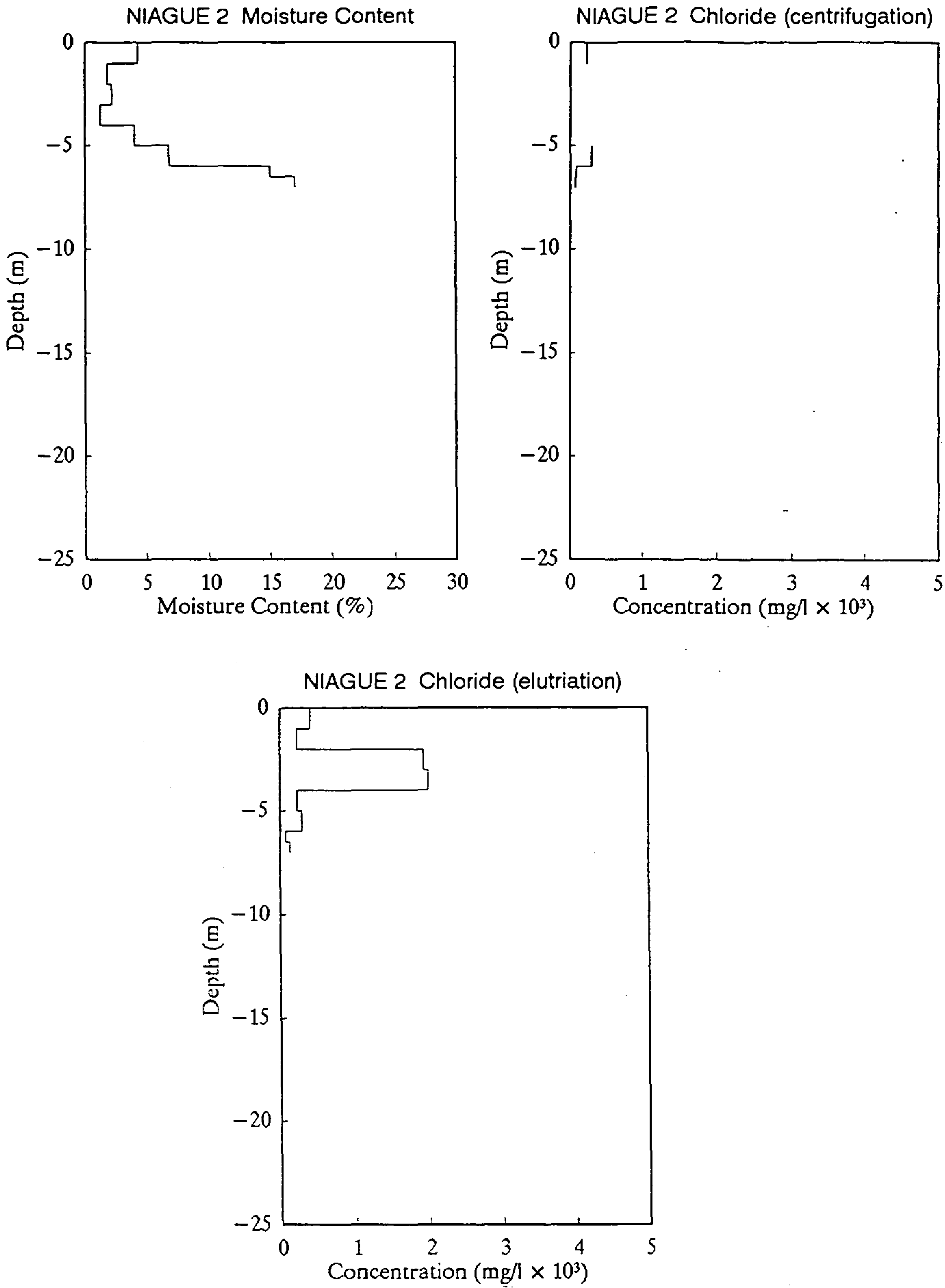


Figure 5.33 Moisture content, SEC, chloride profiles for Niague 2.

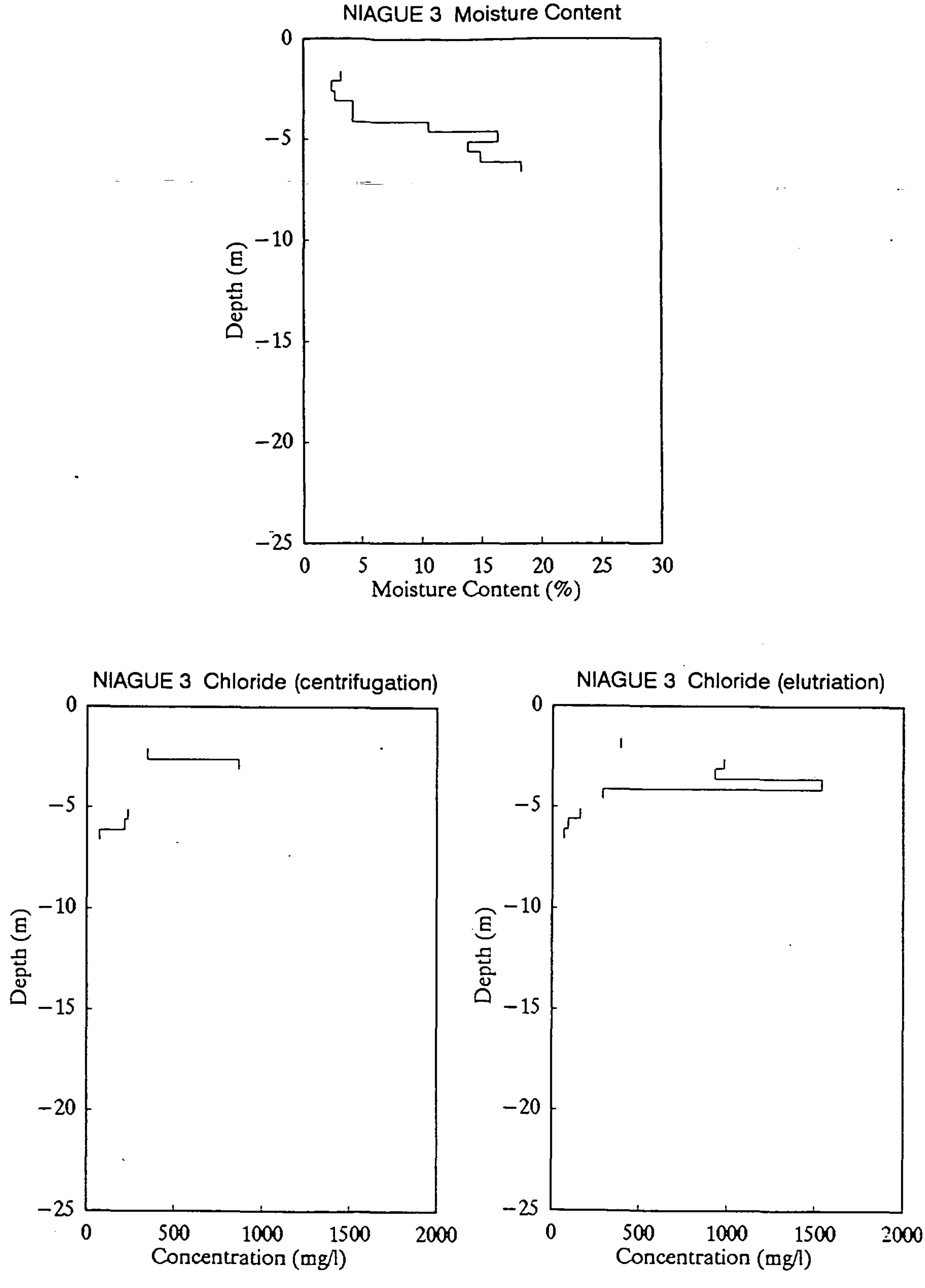


Figure 5.34 Moisture content, SEC, chloride profiles for Niague 3.

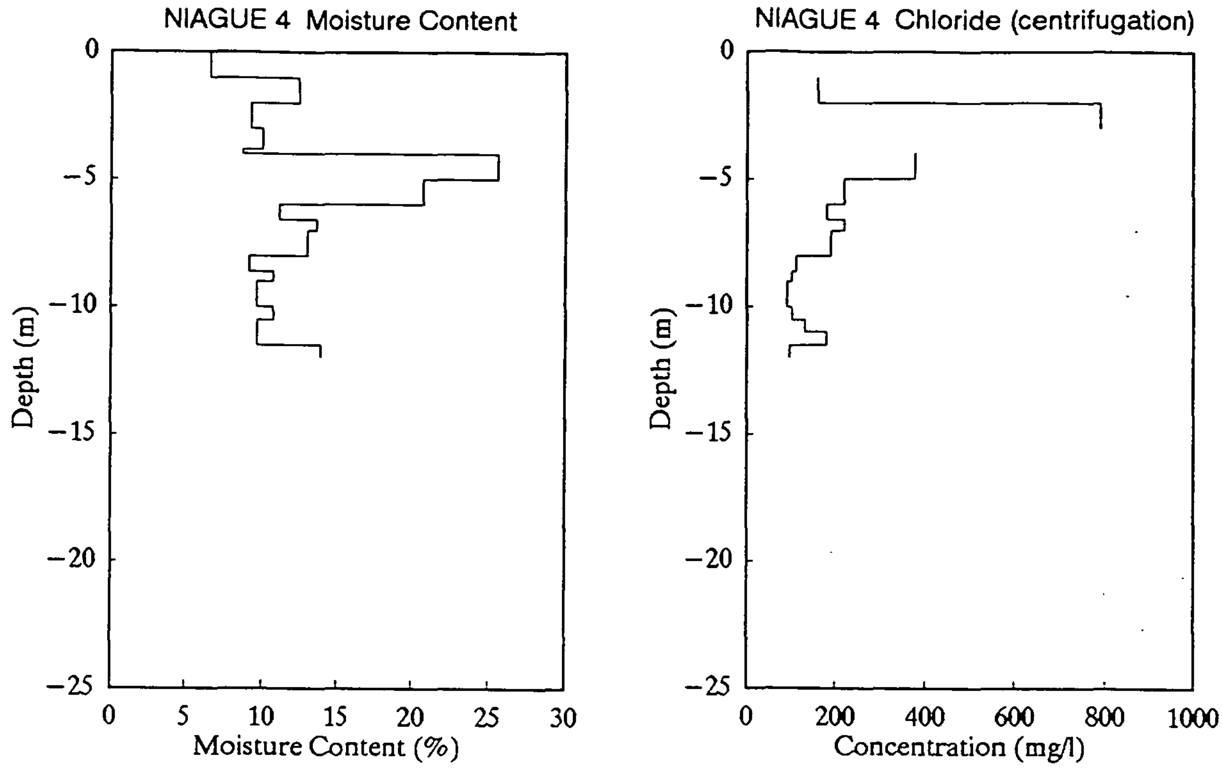


Figure 5.35 Moisture content, SEC, chloride profiles for Niague 4.

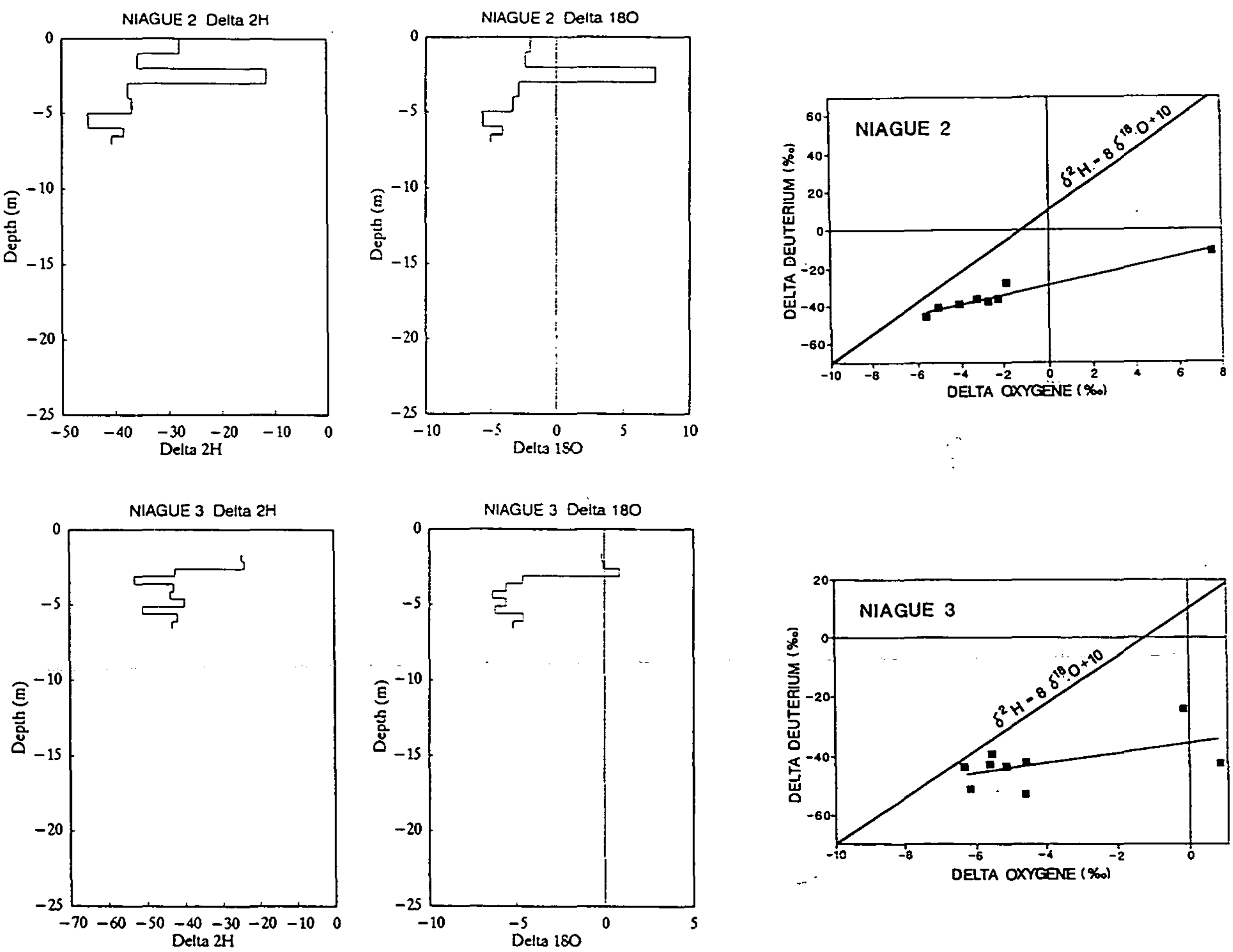


Figure 5.36 Relationship between oxygen-18 and deuterium in interstitial waters from Niague 2 and 3 profiles.

more) indicate perched water tables as in NG4 at 6 m, and NG2 and 3 at the same depths.

5.2.3.2 Chloride profiles

The concentrations of chloride in interstitial waters are rather variable. In NG4 the mean chloride concentration is only 38 mg l^{-1} indicating significant recharge. The higher Cl zone around 5 m may be a zone of lower recharge related to the 1970-1986 drought. In NG2 and NG3, zones of much higher chloride occur, which are thought to be related to former vegetation; this site was being cleared at the time of sampling so the profiles will reflect the natural rather than the cleared site conditions.

5.2.3.3 Isotope profiles

Stable isotope profiles for NG2 and NG3 (Figure 5.37) show a typical evaporative trend with slopes of around 2.3.

5.3 Regional Water Quality - Louga Area

The region between Louga and the Atlantic coast has been studied in some detail to provide not only information which can assist in regional recharge estimation, but also an indication of water quality in general.

The area has been described above (5.2.1) in relation to the main research site near Louga. The terrain is relatively uniform to the north, west and south of this site and by sampling the groundwater a three dimensional picture of the water quality distribution can be obtained. The area of Pleistocene dune sands gives way to a zone of 'niayes' adjacent to the coast beyond which is a barrier of active dunes. To the east of Louga the dune cover becomes much thinner and clays and limestones are never far from the surface.

The regional topography and land use are well seen in the Landsat 4 photographs (Figure 5.37). The main settlements stand out in red and so do areas of irrigation - note the irrigated farm east of Louga using pivot irrigation. The coastal zone with niayes and low lying areas with evapotranspiration also stand out red. The main area of interest is green. The darker areas indicate zones of natural vegetation and after checking in

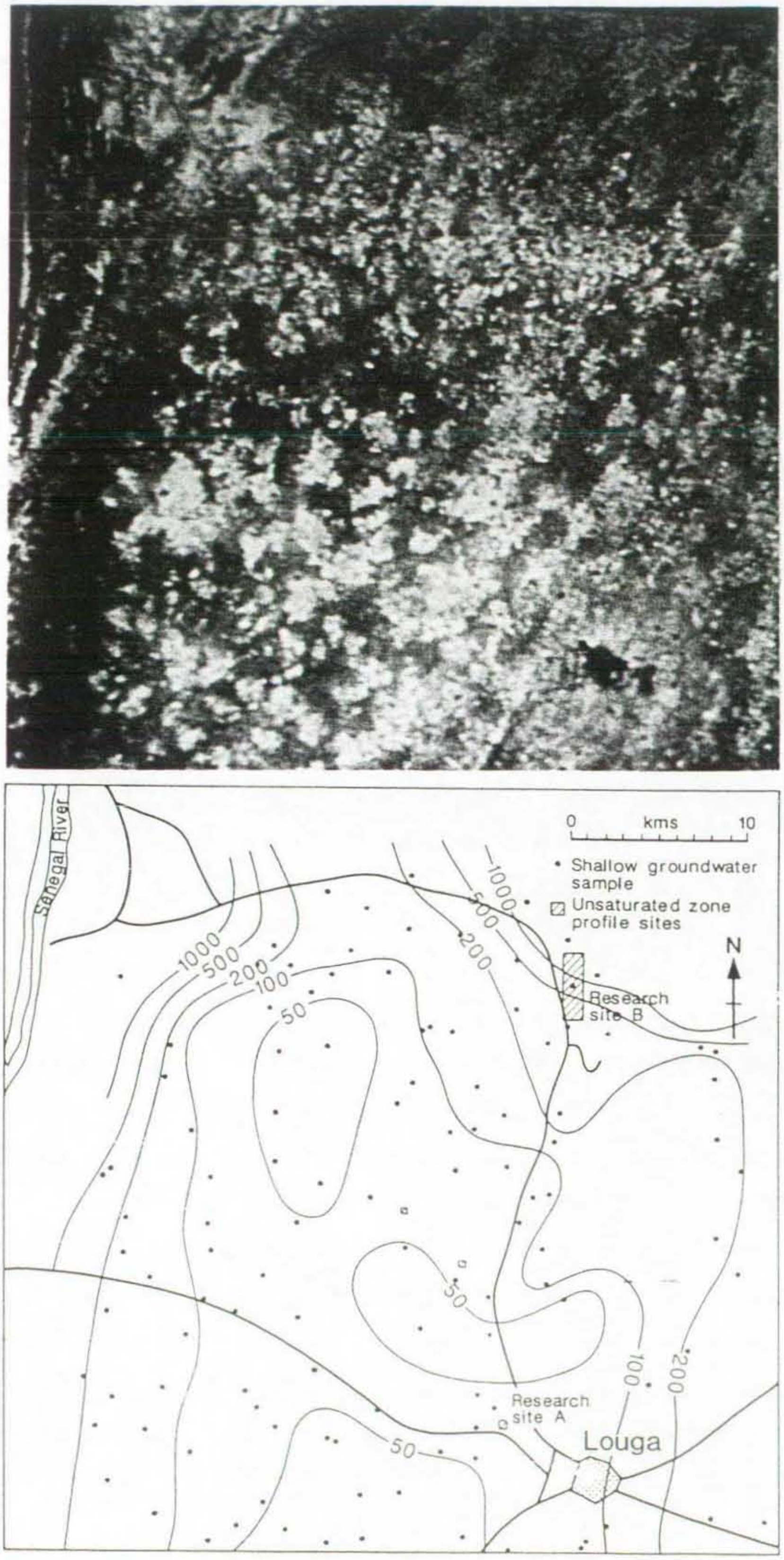


Figure 5.37 Landsat 4 photograph (9.2.86) of NW Senegal and the region sampled in the water quality and recharge study. Cultivated areas stand out in white around villages in contrast with the natural vegetation (green). Louga is situated in the bottom right of the photograph.

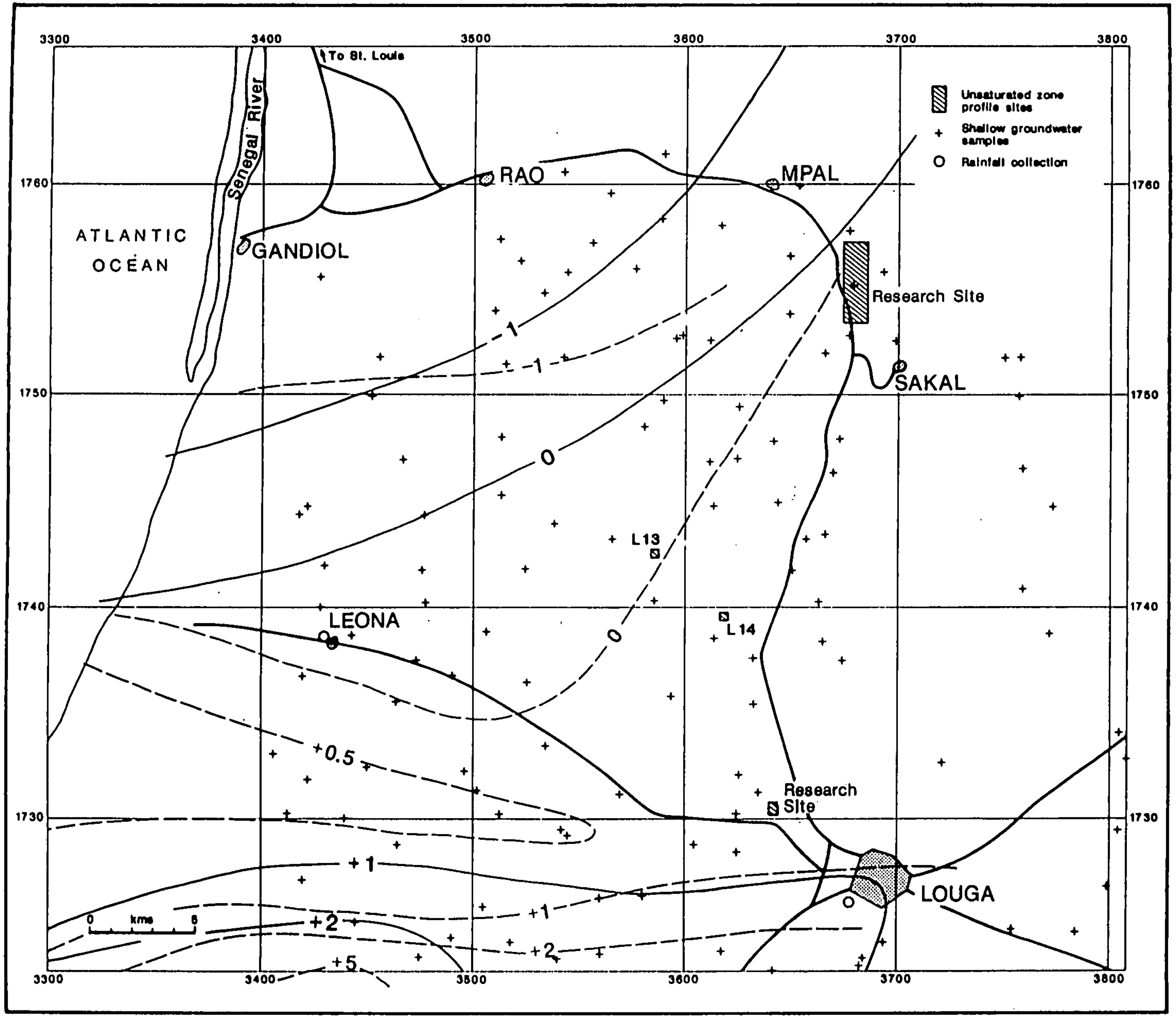


Figure 5.38

PIEZOMETRIC SURFACE OF THE PHREATIC AQUIFER LOUGA REGION

- - +1- - Water level (m) 1985

——+1—— Water level (m) 1990

(Data from Ministry of Hydraulics)

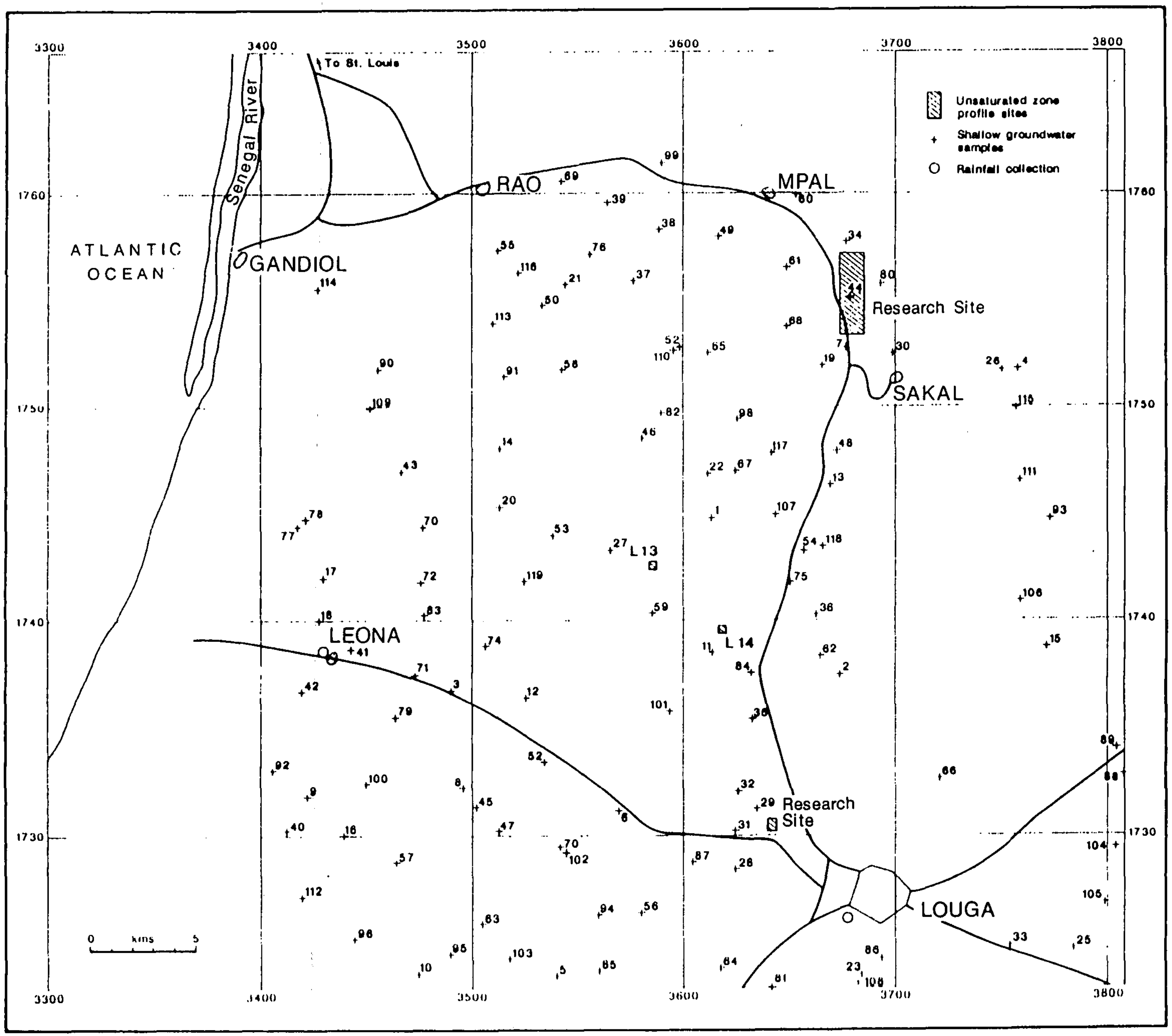


Figure 5.39

LOCATIONS OF DUG WELLS SAMPLED IN PRESENT SURVEY OF LOUGA AREA

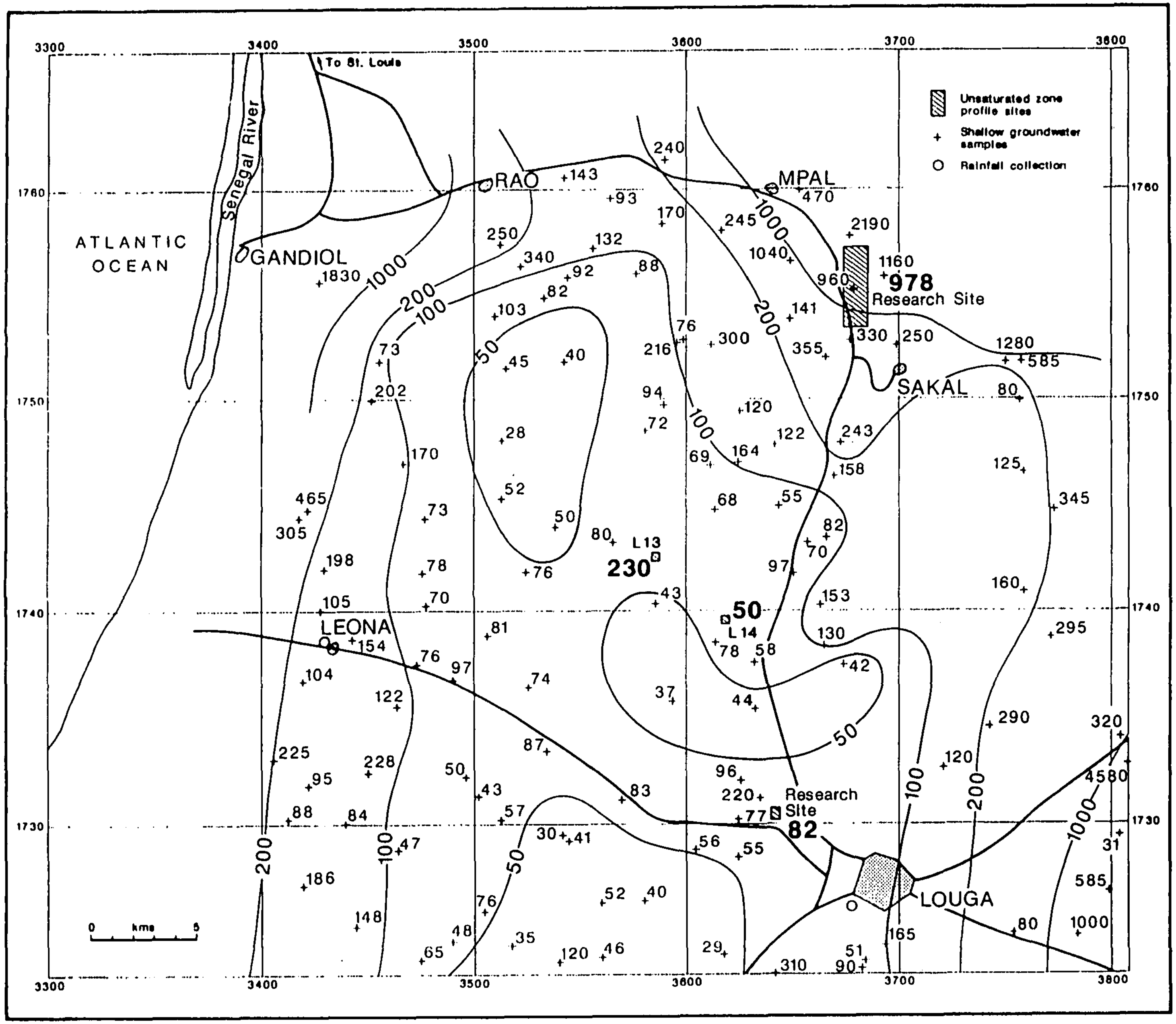


Figure 5.40

HYDROCHEMICAL DISTRIBUTION OF CHLORIDE - LOUGA AREA

+345 Cl in mg l^{-1}

—100— Isochlors

230 Mean value of chloride for the unsaturated zone

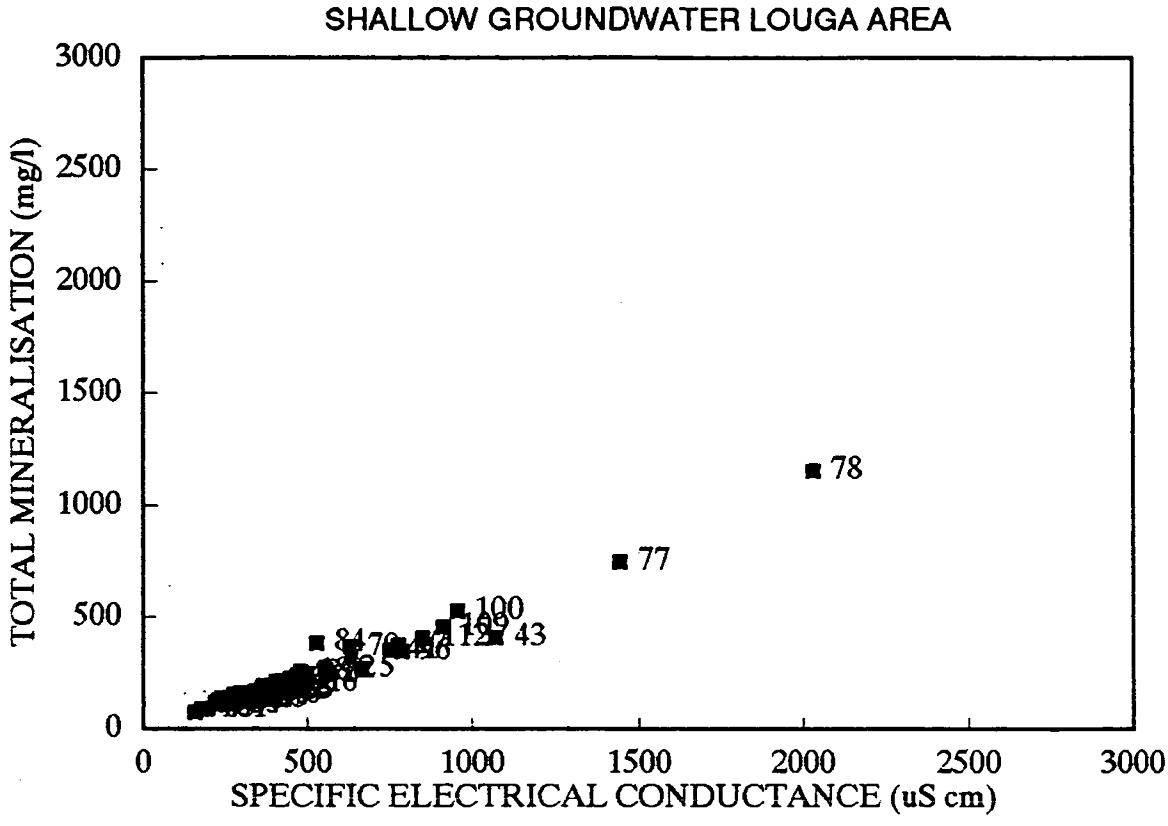


Figure 5.41 Correlation between SEC and total mineralisation for shallow groundwaters (Louga).

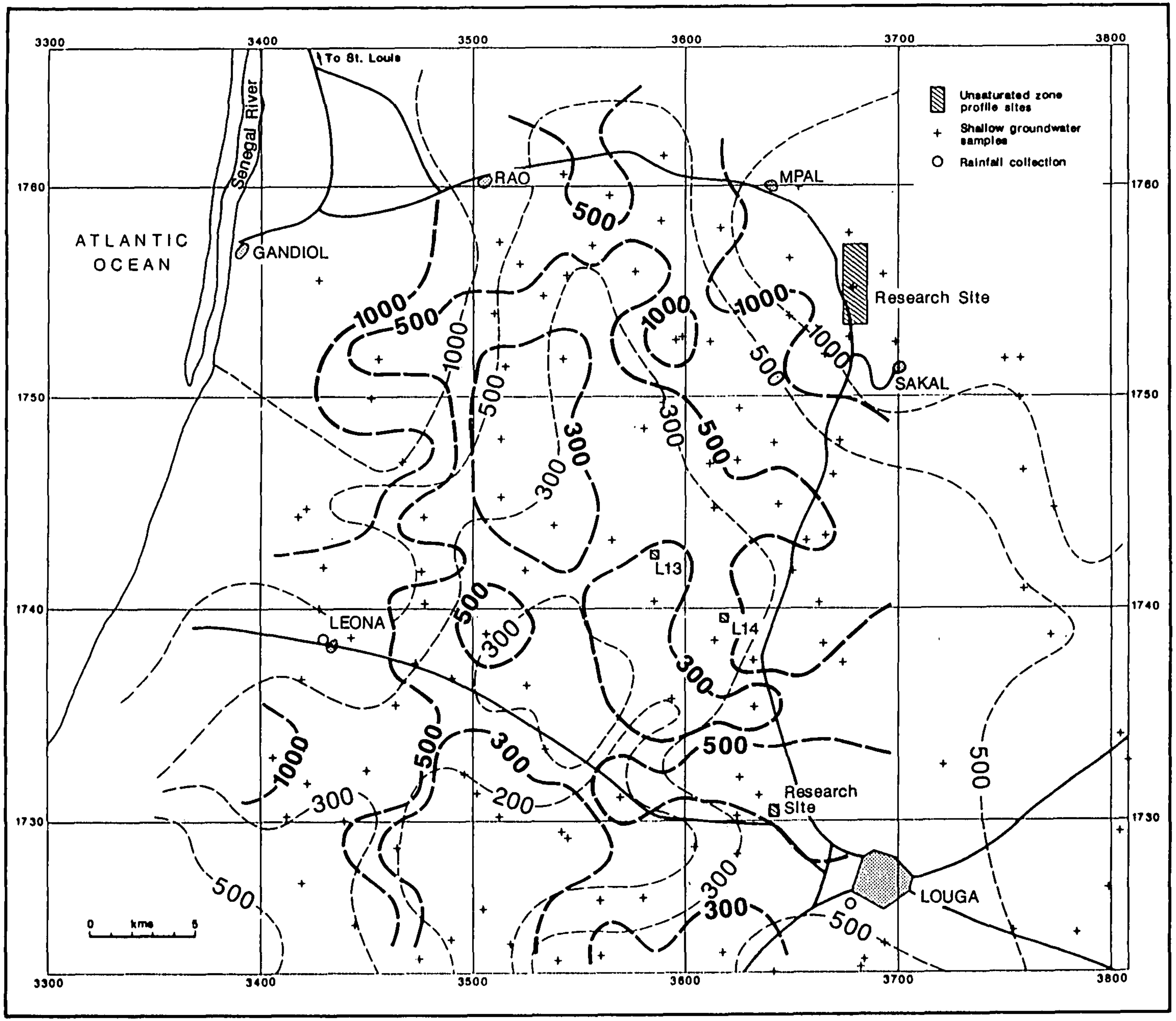


Figure 5.42

SPECIFIC ELECTRICAL CONDUCTANCE (SEC) IN SHALLOW GROUNDWATERS OF LOUGA AREA
$\mu S\ cm^{-1}$ (25°)

--200-- 1973 data

--500-- this study

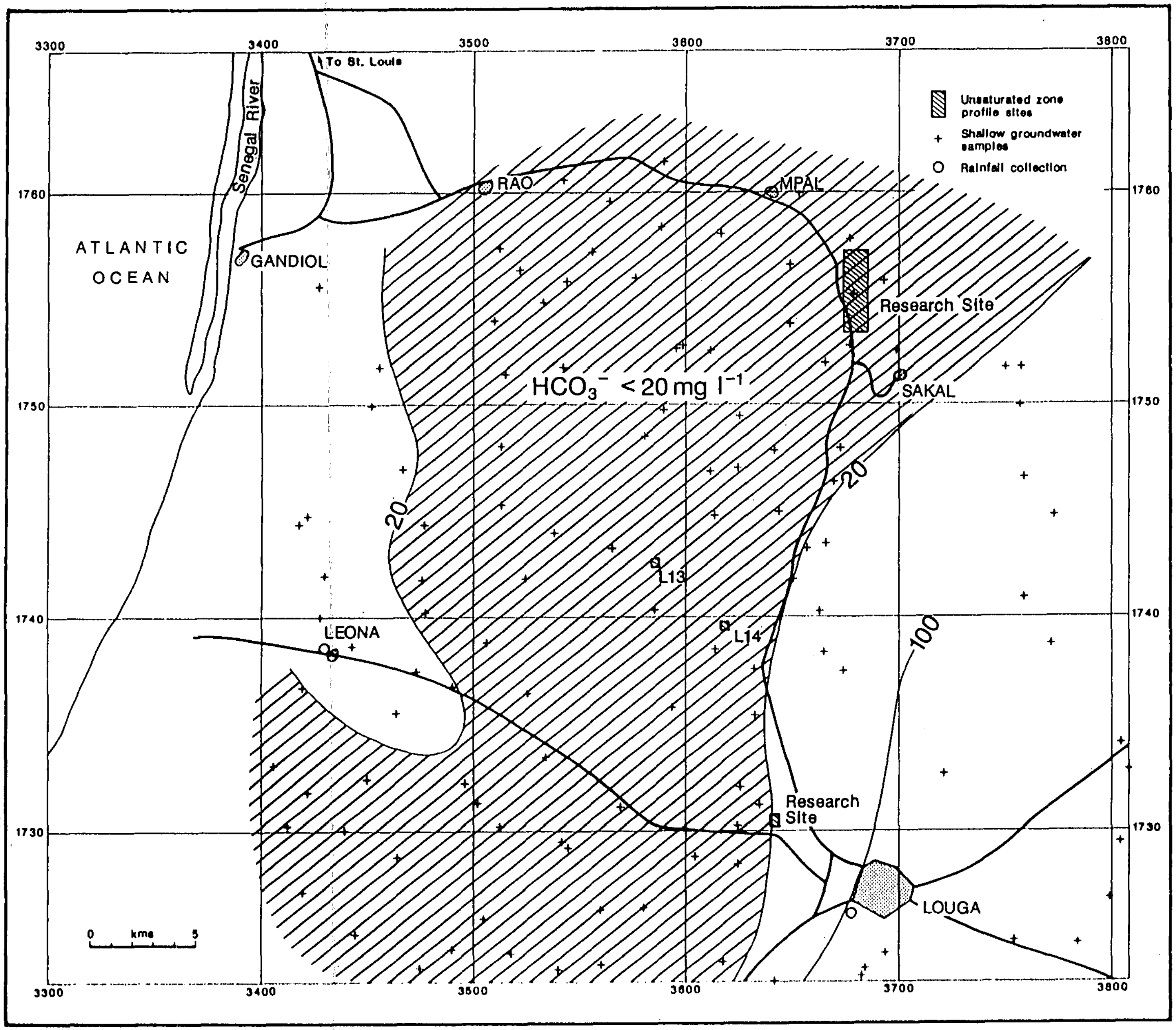


Figure 5.43

ALKALINITY (HCO_3^-) OF GROUNDWATERS IN LOUGA AREA

—20— Concentration of HCO_3^- in mg l^{-1}

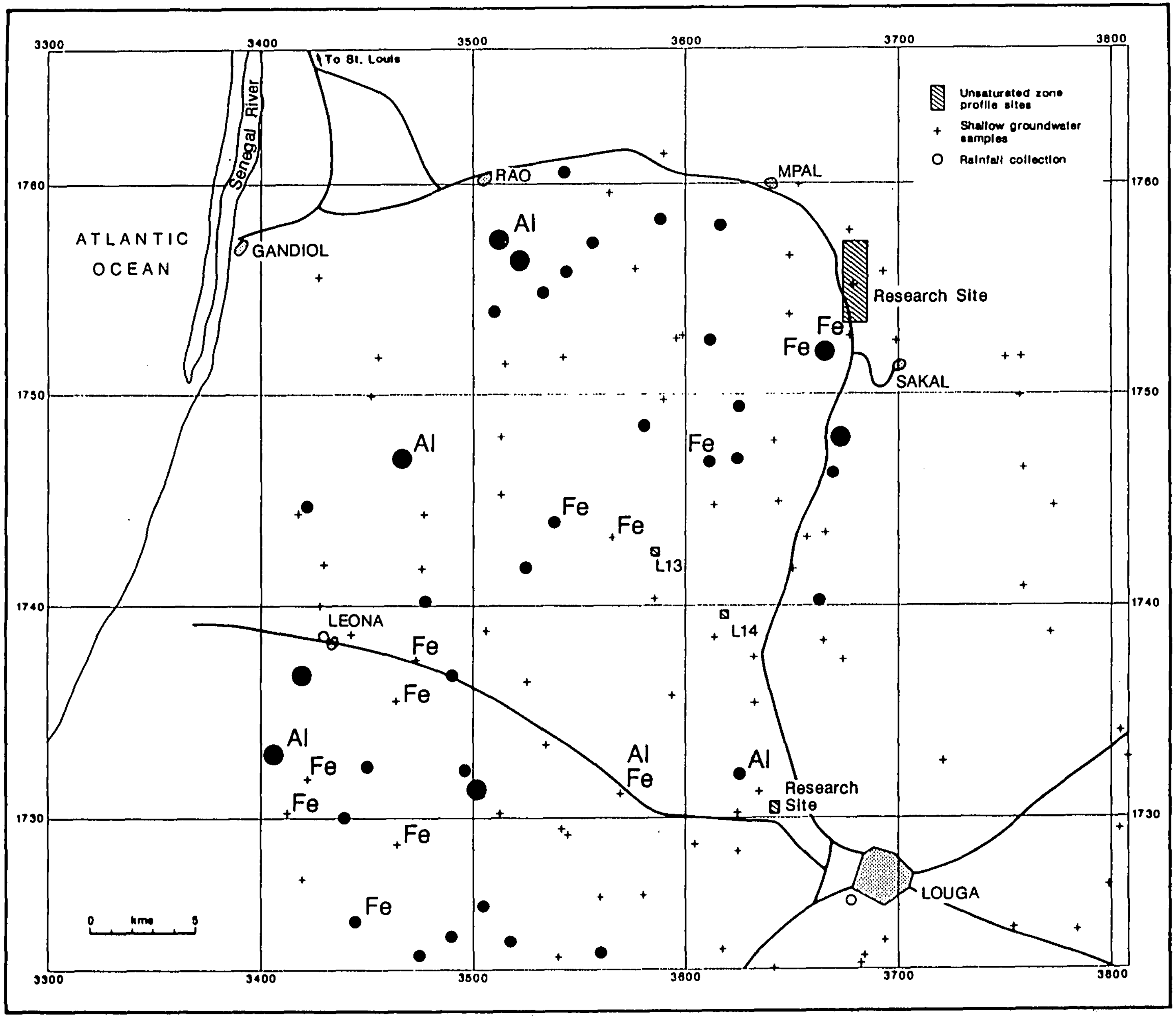


Figure 5.44

pH, IRON AND ALUMINIUM IN SHALLOW GROUNDWATERS FROM THE LOUGA AREA

● pH < 5·0

• pH 5·0 – 6·0

+ pH > 6·0

Al Aluminium > 0·4 mg l^{-1}

Fe Iron > 0·5 mg l^{-1}

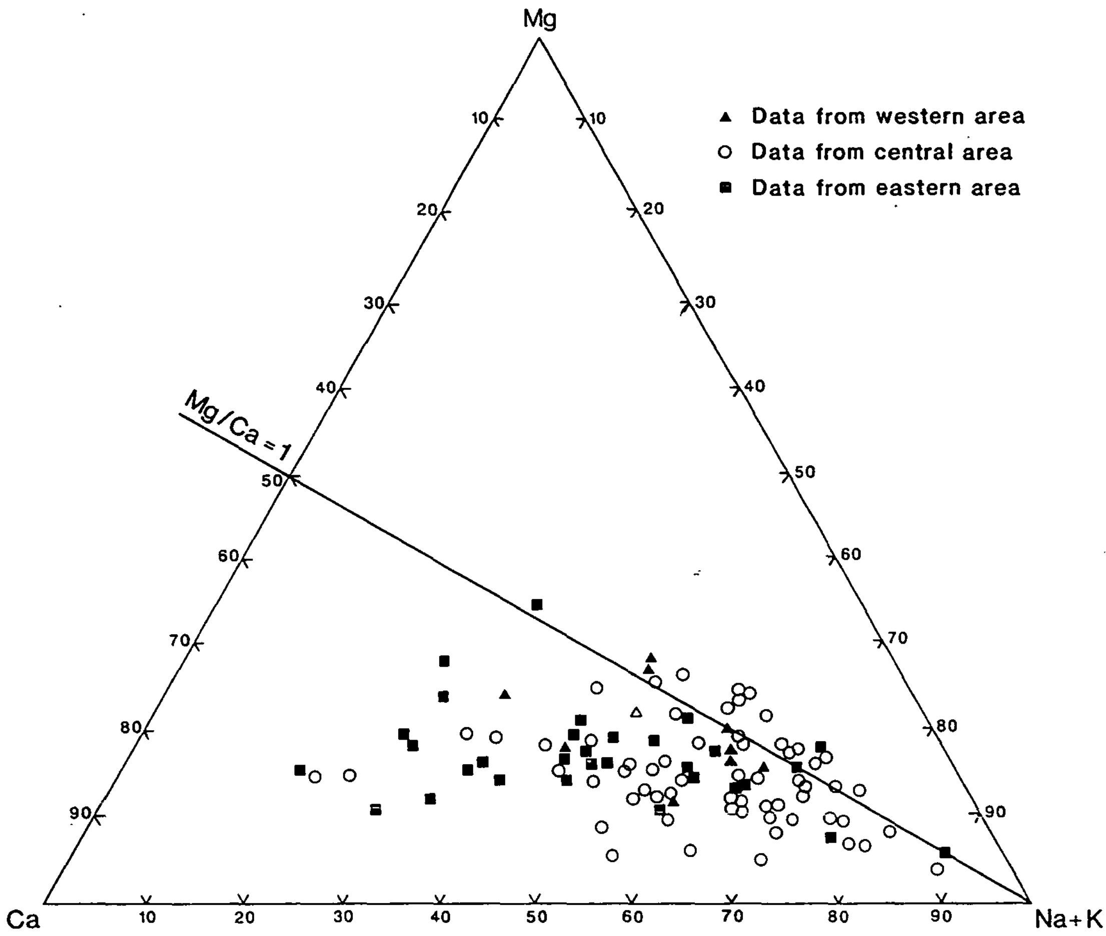


Figure 5.45 Trilinear diagram of cation compositions in groundwaters from the Louga region.

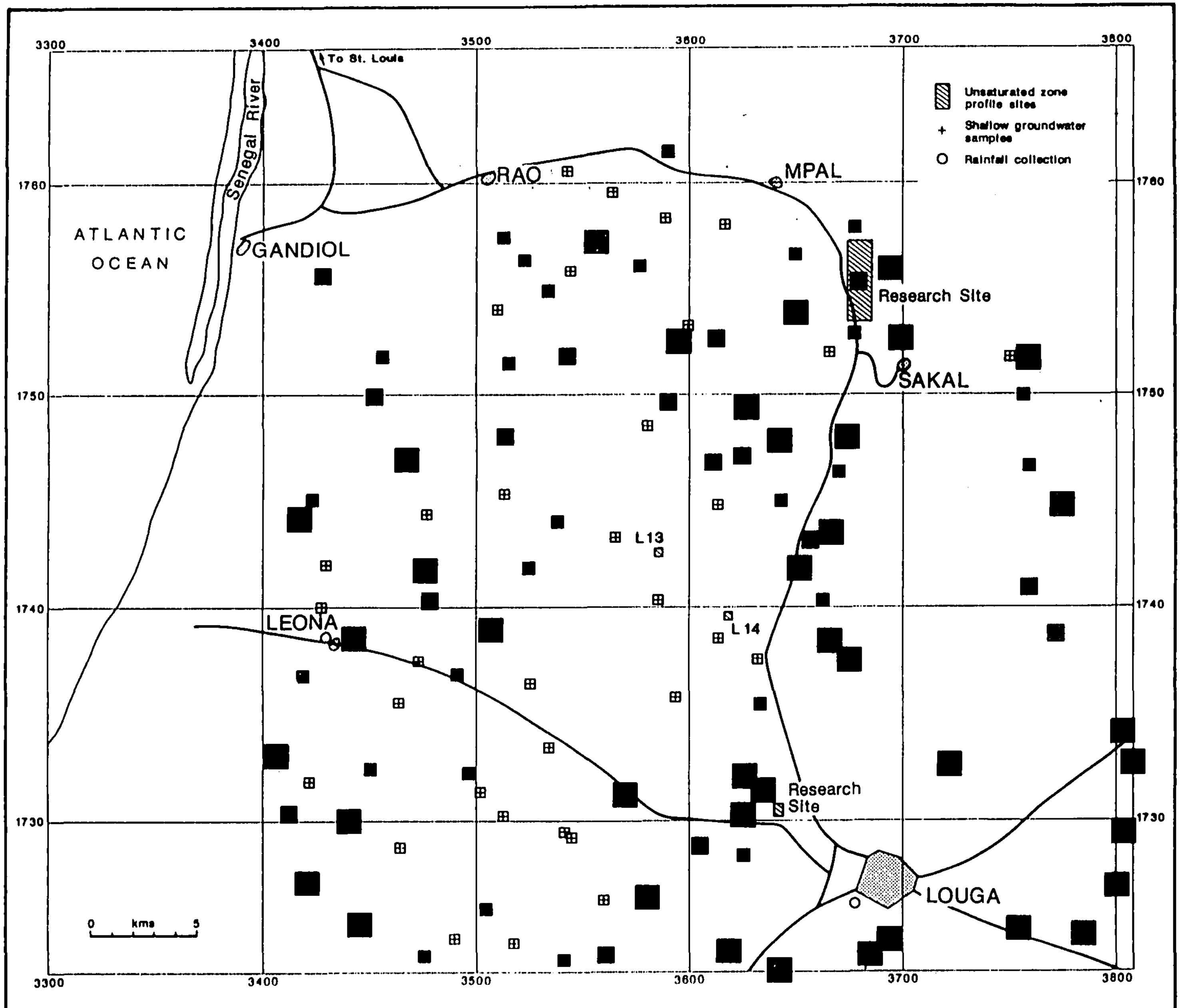


Figure 5.46

HYDROCHEMICAL DISTRIBUTION OF NITRATE (NO_3-N) IN THE LOUGA AREA

- < 1
- 1-5
- 5-10
- > 10

the field the intensity of green is approximately proportional to the amount of vegetation cover. The villages also stand out as 'red' centres surrounded by paler ares representing rain-fed cultivated areas. The main NNE-SSW or N-S trends of the Pleistocene dunes can also be seen.

The piezometric surface is drawn for 1985 and 1990 (Ministère d'Hydraulique, 1985, 1990) for the area (Figure 5.38) and it is seen that the levels are close to sea level over much of the region. There is also evidence of slight decline over the 5 year period. In general the water table lies between 25-35 m below ground level.

The area contains numerous traditional dug well with one or two usually to be found in each village or on the perimeter. The locations of 119 wells sampled in this survey are shown in Figure 5.39 and the site details plus isotopic and chemical data are shown in Table 5.9. Most of the wells have been deepened or reconstructed in recent years and the age refers to this.

5.3.1 **The regional distribution of chloride**

Individual values for chloride are shown in Figure 5.41 in which contours are also drawn for the whole area. A relatively homogeneous pattern emerges for the chemistry of the shallow groundwater, samples from within 1-2 m of the water table, which probably represent the most recent infiltrated water. The lowest chloride concentrations are found in the central zone where dune sands are thickest but towards the margins of the dune areas the water quality deteriorates.

The mean concentrations of chloride from the unsaturated zone are also shown and these correspond well (except L13) with the unsaturated zone values.

In the present case therefore it is considered that chloride measured regionally in the traditional wells may be used to provide regional estimates of recharge. The sole source of chloride is considered to be atmospheric rather than a residual marine/lacustrine source for example. Thus, the more saline groundwaters mainly reflect areas of lower recharge and the less saline waters are the most favoured areas for recharge. There is, however, the possibility that some higher salinities in the extreme west and north-east may be related to relict depositional salinity dating

Table 5.9 Chemical analyses of, and site information for, groundwater from traditional dug wells from the Louga area.

N°	LOCALITY	X	Y	AGE	DEPTH	PH	TEMP	SEC	D2H	180
1	Afé DIOP	361.3	1744.8	1985	21.92	5.09	29.5	330		
2	Baïnak	367.3	1737.4	1974	36.76	7.13	30.1	345		
3	Baïty GUEYE	349.0	1736.7	1982	26.24	5.80	28.3	465	-39	-4.4
4	Bakhdad MBENG	375.7	1751.7	1985	20.29	6.86			-37	-5.2
5	Bakhdar PEUL	354.0	1723.4	1982	34.27	7.06	29.0	665	-39	-4.9
6	Bangadji SAMB	356.9	1731.1	1987	38.01	6.35		560	-33	-4.5
7	Baralé	367.6	1752.8	1980	16.72			1428	-35	-5.0
8	Bayakh GAYE	349.6	1732.2	1974	31.15	5.64		239	-40	-5.3
9	Beut LAMINE	342.2	1731.8	1986	24.70	6.54	27.1	367	-37	-4.4
10	Boukoul	347.5	1723.5		33.05	5.56	28.3	271	-41	-4.7
11	Dabaye SAR	361.3	1738.5	1986	26.00			480		-5.0
12	Darou NDIAYE	352.5	1736.3	1984	33.37	6.02	28.7	358	-33	-4.7
13	Darou SALAM	366.9	1746.4	1972	21.67	5.32	29.4	536		-6.0
14	Deuk BOUREY	351.3	1748.1	1978	19.29	6.80		237	-35	-3.6
15	Diakhaslène	377.1	1738.7		29.63	6.94			-39	-5.2
16	Diama BEYE	344.0	1730.0	1981	29.16	5.53	29.3	500	-40	-4.8
17	Diamaguène PEUL	343.0	1742.0	1986	19.47	6.68	26.1	774	-38	-4.5
18	Gabane	342.8	1740.0	1986	23.65	6.76	27.5	476	-39	-4.5
19	Gad DEMBA	366.5	1752.0	1986	15.32	3.43	29.0	1134		
20	Gati 2	351.3	1745.3	1986	20.55	6.04		270	-38	-4.3
21	Iba SAR	354.4	1755.8	1980	14.32	5.40	27.5	308		
22	Kadiar PEUL	361.1	1746.9	1970	17.90	5.33		404	-36	-4.8
23	Kalassane NDIAYE	368.3	1723.3	1973	36.67	5.96	29.6	349	-33	-4.6
24	Kébé NDEUKT	373.8	1734.7	1978	31.75	6.99			-38	-4.8
25	Keur Ibra MARAM	378.3	1724.7	1975	32.65	6.77				
26	Keur Ibra NIANG	374.9	1751.8	1981	16.78	6.00			-36	-4.8
27	Keur MAFAL	356.5	1743.2	1986	32.57	6.04		314	-35	-4.7
28	Keur Mbarick PEUL 1	362.4	1728.4	1983	31.78			316	-34	-5.2
29	Keur Mbarick PEUL 2	363.4	1731.2		31.35			980		
30	Keur Meïssa GAYE	369.8	1752.6	1982	11.09			1580	-32	-3.5
31	Keur Modou II	362.4	1730.2	1981	37.05			442		
32	Keur Modou KHARY	362.5	1732.0	1962	34.70			665		
33	Keur Seni DIENG	375.3	1724.8	1983	32.53	6.89				
34	Khabane NIANG	367.6	1757.8	1987	16.72			7355	-32	-4.6
35	Khambala FAL	363.2	1735.3	1986	31.31	6.70	33.9	277		
36	Khanadji	366.2	1740.2	1979	25.93	5.63	28.6	568		
37	Khatali	357.6	1756.0	1970	11.50	6.13	28.9	384		-7.0
38	Khatet GAYE	358.8	1758.4	1985	9.43	5.16	27.3	672		
39	Kheilkom DIOP	356.4	1759.6	1984	11.52	6.40	26.9	396		
40	Kogne KOGNE	341.3	1730.2	1968	25.39	4.52	27.8	387	-38	-5.0
41	Léona	344.3	1738.6	1986	26.68	6.60		748	-37	-4.6
42	Longor	342.0	1736.6	1986	27.10	4.82	27.9	414	-30	-4.7
43	Madayana	346.7	1747.0	1987	22.34	4.60	26.8	1070	-38	-4.2
44	Maka Kale FAL	367.8	1755.2	1979	16.09			3320	-34	-4.1
45	Maka NDIAYE	350.2	1731.3	1974	30.55	4.88		190	-30	-3.2
46	Maraye DIAGNE	358.0	1748.6	1986	14.69	5.48		339	-36	-4.0
47	Maraye SECK	351.3	1730.1	1986	34.55	6.14		271	-40	-4.9
48	Massar DIOP 1	367.2	1748.0	1980	27.06	4.85	29.4	949		
49	Mbakhas	361.6	1758.1	1987	13.15	5.34	27.8	796		
50	Mbatias DIEYE	353.3	1754.8	1985	16.60	5.83		358	-36	-4.5
51	Mbaye Mbaye 1	359.8	1752.8	1983	13.66	5.65	28.5			
52	Mbaye Mbaye 2	353.4	1733.4	1969	33.21			337	-35	-6.0
53	Mbayène DIOP	353.8	1744.0	1962	24.53	5.85		260	-33	-3.8
54	Mboubène MBATAR	365.6	1743.2	1986	31.79	7.37	29.2	480		
55	Mboundi	351.2	1757.4	1987	12.17	4.18		858	-34	-4.8
56	Mbout SOW	358.0	1726.3	1978	34.92			330	-33	-4.9
57	Mérina DAKHAR	346.5	1728.7	1973	32.15	6.14	29.2	227	-39	-5.2
58	Mérina FAL	354.2	1751.8	1983	17.57	5.29		273	-39	-4.9
59	Mérina PEUL	358.5	1740.3	1974	24.05	6.23		217	-38	-4.8
60	Mpal	365.2	1760.0	1985	14.36			1832	-31	-4.7

N°	LOCALITY	X	Y	AGE	DEPTH	PH	TEMP	SEC	D2H	180
61	Ndabé TAL	364.8	1756.6	1982	14.93			3653	-30	-4.3
62	Ndam	366.4	1738.3	1940	30.11	7.14	30.5	672		
63	Ndam NDAM	350.5	1725.8	1976	37.15	5.48	28.9	303	-39	-5.0
64	Ndame NGOT	361.7	1723.8	1979	37.95	6.26	29.0	265	-31	-4.9
65	Ndawas DIAGNE	361.1	1752.6	1983	20.56	5.46	29.6	971		
66	Ndeukt GUEYE	372.0	1732.6	1950	34.30	6.95			-35	-4.7
67	Ndiader PEUL	362.4	1747.1	1980	17.73	5.44	28.9	621		
68	Ndiaguène	364.8	1753.8	1986	13.31			693	-31	-4.8
69	Ndiakhip	354.2	1760.6		14.78	5.32	28.2	501		
70	Ndialakhar	347.7	1744.4	1979	22.93	6.48	27.2	400	-31	-5.1
71	Ndiambou FAL	347.3	1737.4	1982	25.19	6.17		362	-39	-5.0
72	Ndiayène	347.6	1741.8	1987	29.10	6.70	26.5	552	-38	-4.9
73	Ndiéye BA	354.2	1729.4	1982	30.75			196	-37	-5.2
74	Ndiobène	350.6	1738.8	1984	30.49	6.80	29.8	636	-38	-4.5
75	Ndiok SAL	365.1	1741.8	1950	28.54	7.28	30.6	700		
76	Ndious	355.6	1757.2	1984	14.00	5.37	28.3	560		
77	Ndop CEANE	341.8	1744.4		2.50	5.91	25.1	1440	-40	-5.1
78	Ndop PUITS	342.2	1744.8	1986	8.00	6.86	24.0	2030	-38	-4.5
79	Ndoun	346.4	1735.4	1978	27.70	6.82	28.1	628	-38	-4.9
80	Ngadji SAR	369.2	1755.8	1983	14.25			4952	-33	-4.6
81	Nganiakh DIENG	364.1	1722.9	1950	31.73	6.61				
82	Ngomène	358.9	1749.8	1986	18.49	6.25		496	-36	-4.5
83	Ngoufat	347.8	1740.2	1986	24.60	5.80	26.9	379	-36	-4.8
84	Ngueun SAR	363.1	1737.5	1974				525	-33	-4.6
85	Ngueyène	356.0	1723.6	1979	36.50	5.68	29.8	265	-40	-4.7
86	Nguidilé	369.3	1724.2	1951	32.61	7.19				
87	Niakhal	360.4	1728.7	1983	36.12			426	-38	-5.3
88	Niomré 1	380.8	1732.9	1950	30.08	6.86				
89	Niomré 2	380.4	1734.0		28.40	6.98				
90	Pelour	345.6	1751.8	1983	6.05	6.64	25.5	322	-40	-4.5
91	Rakhmane SAL	351.5	1751.5	1983	17.50	6.65		290	-35	-4.2
92	Rayet	340.6	1733.0	1967	15.58	3.80	28.0	1330	-40	-5.3
93	Roye DIEYE	377.2	1744.8	1979	29.00	6.76			-38	-5.1
94	Salim SARR	356.0	1726.2	1987	35.81			323	-35	-5.3
95	Santhiou MBENGUENE	349.0	1724.4	1983	33.56	5.56	29.2	217	-37	-5.1
96	Santhiou MEISSA	344.5	1725.1	1961	30.80	6.14	28.6	784	-40	-5.0
97	Santiou BAITI	355.0	1766.5		29.84			251	-27	-5.0
98	Santiou Mérina	362.5	1749.5	1954	12.02	5.20	29.1	514		
99	Sémél	358.9	1761.4	1983	11.28	6.07	26.7	783		
100	Sér	345.0	1732.4	1986	37.15	5.63		952	-36	-4.4
101	Sine WADD	359.3	1735.7	1980	28.82	6.15		172	-38	-5.1
102	Taïba	354.5	1729.2	1974	32.62			164	-34	-5.4
103	Taïba NDIOUGA	351.8	1724.2	1976	33.10	5.70	29.0	154	-41	-4.8
104	Tako	380.3	1729.4	1988	34.05	6.46				
105	Tanim	379.8	1726.8	1983	28.70	7.64				
106	Thialla KEBE	375.8	1741.0	1983	27.70	7.11			-37	-5.0
107	Thiéckène	364.3	1745.0	1953	23.23		30.2	322		
108	Thiéle	368.2	1722.8	1950	33.95	7.03				
109	Tiarène	345.2	1750.0	1966	13.43	6.62	26.9	909	-40	-3.8
110	Tiéle DIAGNE	359.5	1752.7	1986	20.53	6.30	28.6	1065		
111	Togueul	375.8	1746.6	1936	26.90	6.82			-34	-4.7
112	Toro BEYE	342.0	1727.1	1984	29.20	5.80	28.1	849	-37	-4.9
113	Touba GUENE	351.0	1754.0	1983	22.49	5.14		373	-30	-2.9
114	Toug	342.8	1755.5	1987	5.80	7.36	23.7	6250	-32	-3.5
115	Yaddulahi	375.6	1749.9	1986	25.82	6.34			-37	-5.2
116	Yamane SOGG	352.2	1756.4	1983	13.51	4.62		1208	-27	-3.3
117	Yamane (SEk) 2	364.1	1747.9	1986	22.08	6.20	28.7	571		
118	Yermandé DIENG	366.5	1743.5	1985	27.28	6.45	28.6			
119	Yerwaye	352.4	1741.8	1986	26.80	5.69		308	-37	-4.7

N°	LOCALITY	NA	K	CA	MG	HCO3	SO4	CL	NO3
1	Afé DIOP	39.2	4.6	7.9	1.8		37.0	68	-0.8
2	Baïnak	28.5	3.1	33.8	5.5		1.9	42	15.9
3	Baïty GUEYE	48.4	4.4	20.0	8.7	18.9	39.0	97	3.7
4	Bakhdad MBENG	246.0	3.1	177.0	42.9	170.7	47.0	585	38.5
5	Bakhdar PEUL	51.0	2.3	65.0	6.0	6.1	16.0	120	3.3
6	Bangadji SAMB	53.1	6.2	28.3	14.1	34.1	-0.8	83	32.6
7	Baralé	138.0	2.6	89.4	24.9		54.4	330	2.5
8	Bayakh GAYE	29.1	3.7	6.7	2.9	12.2	11.7	50	1.2
9	Beut LAMINE	42.2	4.1	11.0	2.9	17.8	12.0	95	-0.5
10	Boukoul	26.9	2.4	12.0	3.6	12.7	3.0	65	1.1
11	Dabaye SAR	50.6	3.8	34.6	6.9		49.6	78	0.9
12	Darou NDIAYE	47.8	2.2	8.0	4.7	22.3	27.0	74	-0.5
13	Darou SALAM	70.8	5.8	23.8	8.1		19.9	158	3.0
14	Deuk BOUREY	18.5	5.3	14.1	4.8	45.1	17.6	28	5.2
15	Diakhaslène	147.0	1.9	103.0	29.2		19.0	295	7.2
16	Diama BEYE	57.6	4.9	11.0	11.2	8.5	3.0	84	23.2
17	Diamaguène PEUL	48.9	3.1	54.0	19.3	40.4	12.0	198	-0.5
18	Gabane	45.4	3.3	24.0	10.8	61.1	6.0	105	-0.5
19	Gad DEMBA	113.0	5.3	48.4	15.6		6.2	355	-0.8
20	Gati 2	25.9	3.4	14.0	4.6	9.8	18.2	52	0.5
21	Iba SAR	35.5	6.4	9.2	5.9		3.2	92	-0.8
22	Kadiar PEUL	45.9	3.0	11.7	6.3	3.7	30.0	69	9.5
23	Kalassane NDIAYE	39.7	2.8	13.0	4.9	6.8	0.0	51	16.2
24	Kébé NDEUKT	97.5	4.9	148.0	20.7	232.9	15.0	290	4.8
25	Keur Ibra MARAM	399.0	4.9	299.0	99.6	213.4	196.0	1000	57.5
26	Keur Ibra NIANG	471.0	5.5	184.0	106.0	57.3	7.0	1280	-0.1
27	Keur MAFAL	33.4	3.4	12.1	3.5	9.8	4.2	80	0.9
28	Keur Mbarick PEUL 1	37.5	2.8	5.8	1.7		-0.8	55	4.8
29	Keur Mbarick PEUL 2	57.7	4.6	79.4	19.8		3.1	220	13.7
30	Keur Meïssa GAYE	140.0	1.7	110.0	24.4		52.5	250	14.1
31	Keur Modou II	41.3	6.3	12.2	9.3		0.8	77	12.5
32	Keur Modou KHARY	57.5	11.4	15.1	12.0		1.0	96	29.0
33	Keur Seni DIENG	37.0	3.1	107.0	10.9	193.9	10.0	80	14.5
34	Khabane NIANG	1120.0	7.5	232.0	55.2		193.0	2190	3.8
35	Khambala FAL	27.8	5.4	20.6	2.9		31.2	44	1.3
36	Khanadji	68.0	4.3	30.1	8.7		39.8	153	1.4
37	Khatali	48.0	3.4	14.8	8.2		13.8	88	1.7
38	Khatet GAYE	89.0	16.9	27.3	7.9		75.5	170	-0.8
39	Kheilkom DIOP	43.8	4.9	19.6	10.2		18.0	93	0.8
40	Kogne KOGNE	29.3	4.5	15.0	3.3	0.0	5.0	88	5.2
41	Léona	47.7	11.3	54.5	24.5	23.2	9.2	154	29.1
42	Longor	38.5	8.3	14.0	6.8	1.2	9.0	104	2.7
43	Madayana	99.0	13.9	30.0	36.8	0.0	4.0	170	54.0
44	Maka Kale FAL	316.0	5.0	188.0	69.2		14.7	960	6.6
45	Maka NDIAYE	21.2	3.0	6.4	2.0	0.0	12.3	43	-0.5
46	Maraye DIAGNE	38.2	4.2	12.8	5.2	9.8	29.8	72	-0.5
47	Maraye SECK	30.1	3.0	14.8	3.0	31.7	12.7	57	1.7
48	Massar DIOP 1	137.0	11.0	33.0	19.9		36.6	243	27.5
49	Mbakhas	114.0	6.0	24.9	16.2		31.2	245	0.8
50	Mbatias DIEYE	40.0	5.5	19.4	2.6		6.2	82	2.5
51	Mbaye Mbaye 1	36.8	3.6	7.6	5.8		1.4	76	3.6
52	Mbaye Mbaye 2	62.2	3.3	6.9	3.7		35.7	87	0.9
53	Mbayène DIOP	29.6	2.9	10.3	3.2	12.2	20.0	50	1.5
54	Mboubène MBATAR	47.4	2.6	61.3	12.2		25.8	70	6.8
55	Mboundi	104.0	12.6	24.9	10.3		11.0	250	1.3
56	Mbout SOW	32.2	3.4	10.1	5.2		1.7	40	15.0
57	Mérina DAKHAR	29.1	2.4	6.0	2.1	24.1	16.0	46	0.2
58	Mérina FAL	29.1	7.1	6.6	4.5	17.1	2.2	43	12.5
59	Mérina PEUL	33.0	2.8	3.3	1.6	19.5	14.9	40	0.8
60	Mpal	89.7	8.4	140.0	43.2		7.1	470	10.5

N°	LOCALITY	NA	K	CA	MG	HCO3	SO4	CL	NO3
61	Ndabé TAL	315.0	17.1	207.0	98.5		5.3	1040	1.4
62	Ndam	59.0	3.5	71.0	13.3		5.3	130	16.0
63	Ndam NDAM	39.0	3.2	7.0	2.6	5.5	0.0	76	2.8
64	Ndame NGOT	19.9	3.0	15.0	3.2	25.4	1.0	29	13.0
65	Ndawas DIAGNE	114.0	8.6	31.7	27.1		4.8	300	8.0
66	Ndeukt GUEYE	31.5	3.3	144.0	17.5	125.6	2.0	120	55.3
67	Ndiader PEUL	94.8	3.8	13.4	9.2		18.3	164	9.0
68	Ndiaguène	84.9	4.3	15.0	10.6		10.6	141	13.0
69	Ndiakhip	62.9	5.8	22.0	6.0		12.7	143	-0.8
70	Ndialakhar	36.5	6.1	23.0	5.7	39.0	31.0	73	0.6
71	Ndiambou FAL	46.6	4.3	12.0	3.4	35.4	16.9	76	0.8
72	Ndiayène	63.8	5.1	23.0	8.2	54.9	13.0	78	20.7
73	Ndiéye BA	19.0	2.9	12.8	0.8		2.4	30	0.3
74	Ndiobène	47.1	13.5	47.0	13.0		47.0	81	13.0
75	Ndiok SAL	45.0	4.0	79.0	15.7		14.3	97	28.9
76	Ndious	63.0	7.9	19.4	13.8		8.8	132	15.7
77	Ndop CEANE	169.0	16.1	61.0	28.8	22.1	137.0	305	10.3
78	Ndop PUITS	224.0	90.5	75.0	35.3	103.0	162.0	465	3.3
79	Ndoun	66.6	5.6	36.0	9.3	69.3	59.0	122	-0.5
80	Ngadji SAR	500.0	12.8	392.0	100.0		198.0	1160	100.0
81	Nganiakh DIENG	92.8	4.5	292.0	37.7	170.7	35.0	310	111.0
82	Ngomène	53.7	3.3	20.8	9.2	24.4	30.7	94	8.3
83	Ngoufat	48.2	3.8	11.0	5.8	3.7	25.0	70	7.0
84	Ngueun SAR	28.1	2.0	69.1	10.2	158.5	61.3	58	<0.5
85	Ngueyène	28.4	11.5	7.0	1.9	4.5	0.0	46	9.3
86	Nguidilé	40.3	3.4	126.0	160 .0	197.5	9.0	165	14.1
87	Niakhal	27.6	2.4	32.5	7.7		3.5	56	5.8
88	Niomré 1	2781.0	10.0	440.0	367.0	375.5	1811.0	4580	21.6
89	Niomré 2	258.0	4.2	186.0	67.1	185.3	125.0	320	82.0
90	Pelour	37.9	2.6	11.0	4.6	17.7	10.0	73	2.0
91	Rakhmane SAL	22.3	13.3	16.8	4.7	26.8	32.4	45	1.0
92	Rayet	100.6	12.8	50.0	29.7		114.0	225	27.0
93	Roye DIEYE	96.0	2.4	172.0	36.2		33.0	345	16.9
94	Salim SARR	32.8	3.5	15.9	3.5		6.1	52	0.2
95	Santhiou MBENGUENE	24.3	3.1	9.0	2.2	14.5	8.0	47	0.3
96	Santhiou MEISSA	69.0	3.6	33.0	22.3	22.4	26.0	148	21.0
97	Santiou BAITI	18.7	2.8	16.0	3.6		6.1	40	0.2
98	Santiou Mérina	72.4	3.7	13.4	9.0		16.2	120	11.8
99	Sémél	88.0	9.4	44.5	14.5		19.0	240	1.5
100	Sér	118.0	8.0	39.3	19.1	20.7	92.0	228	3.2
101	Sine WADD	19.8	2.8	7.2	0.9	17.1	1.4	37	0.9
102	Taïba	23.5	2.0	7.0	1.5		3.1	41	0.1
103	Taïba NDIOUGA	15.2	1.9	8.0	1.8	13.8	0.0	35	-0.5
104	Tako	51.4	2.3	25.0	9.8	42.7	15.0	31	16.1
105	Tanim	656.0	1.1	44.0	21.9	601.1	245.0	585	23.9
106	Thialla KEBE	60.2	2.6	95.0	34.4	229.2	18.0	160	5.2
107	Thiéckène	38.7	1.5	21.5	4.8		22.3	55	1.3
108	Thiéle	31.6	3.4	103.0	14.2	225.6	5.0	90	6.3
109	Tiarène	111.0	3.2	35.0	14.4	34.7	49.0	202	6.8
110	Tiéle DIAGNE	98.5	28.9	54.4	31.9		85.4	216	27.5
111	Togueul	52.8	3.4	103.0	10.1	224.3	14.0	125	3.0
112	Toro BEYE	70.2	3.8	55.0	15.6	19.8	45.0	186	14.0
113	Touba GUENE	39.7	4.6	10.8	8.6	4.9	-0.8	103	0.5
114	Toug	886.0	46[illegible].0	272.0	90.6	91.4	245.0	1830	8.5
115	Yaddulahi	31.0	5.4	29.0	20.1	101.2	11.0	80	4.0
116	Yamane SOGG	117.0	8.7	44.8	35.5		10.0	340	1.2
117	Yamane (SEk) 2	78.4	5.8	22.7	7.2		13.8	122	21.0
118	Yermandé DIENG	61.6	2.3	30.5	6.2		28.0	82	10.0
119	Yerwaye	47.2	4.9	4.1	0.9	11.0	1.2	76	1.1

N°	LOCALITY	SR	BA	B	SI	LI	FE_TOTAL	MN
1	Afé DIOP	0.119	0.054	-0.030	16.0	0.013	0.045	0.553
2	Baïnak	0.160	0.111	0.030	15.5	-0.007	-0.015	-0.003
3	Baïty GUEYE	0.168	0.092	0.013	8.6	0.002	0.080	0.379
4	Bakhdad MBENG	0.841	0.305	0.019	21.2	-0.001	0.022	0.022
5	Bakhdar PEUL	0.231	0.331	0.032		-0.001	0.258	0.187
6	Bangadji SAMB	0.356	0.439	-0.030	10.3	0.007	1.360	0.908
7	Baralé	0.424	0.314	0.060	12.3	-0.010	2.100	0.070
8	Bayakh GAYE	0.102	0.113	-0.030	11.7	0.009	0.250	0.200
9	Beut LAMINE	0.168	0.097	0.021	13.4	0.003	10.650	0.143
10	Boukoul	0.088	0.100	0.013	10.1	0.001	0.263	0.351
11	Dabaye SAR	0.338	0.879	0.045	9.7	-0.007	-0.015	0.007
12	Darou NDIAYE	0.092	0.152	0.025	8.7	0.002	0.099	0.400
13	Darou SALAM	0.158	0.101	0.044	15.7	0.018	0.019	0.196
14	Deuk BOUREY	0.254	0.128	0.060	8.8	0.015	0.021	0.017
15	Diakhaslène	0.661	0.286	0.100	23.5	0.003	0.022	0.014
16	Diama BEYE	0.189	0.496	0.025	10.4	0.023	0.022	0.387
17	Diamaguène PEUL	0.418	0.527	0.062	27.0	0.002	0.016	2.183
18	Gabane	0.266	0.205	0.041	23.7	0.007	0.011	0.289
19	Gad DEMBA	0.294	0.658	0.043	18.6	0.047	19.700	2.380
20	Gati 2	0.021	0.083	0.037	13.1	-0.007	0.145	0.227
21	Iba SAR	0.150	0.170	0.030	8.7	0.017	-0.015	0.263
22	Kadiar PEUL	0.108	0.187	0.041	15.3	0.014	7.500	0.349
23	Kalassane NDIAYE	0.110	0.112	0.012	10.5	0.002	0.056	0.384
24	Kébé NDEUKT	0.511	0.268	0.050	18.5	0.086	0.051	0.040
25	Keur Ibra MARAM	3.158	0.077	0.105	29.0	0.021	0.032	0.005
26	Keur Ibra NIANG	1.405	1.289	0.025	14.6	0.037	0.031	6.392
27	Keur MAFAL	0.210	0.221	-0.030	12.2	0.010	11.000	0.843
28	Keur Mbarick PEUL 1	0.098	0.255	-0.060	12.1	0.001	0.037	0.740
29	Keur Mbarick PEUL 2	0.584	0.496	-0.060	11.9	-0.010	-0.015	0.014
30	Keur Meïssa GAYE	0.381	0.363	0.190	15.9	-0.010	-0.015	0.065
31	Keur Modou II	0.121	0.208	-0.060	12.4	-0.010	-0.015	0.570
32	Keur Modou KHARY	0.159	0.474	0.060	20.2	0.058	0.990	0.470
33	Keur Seni DIENG	0.230	0.074	0.022	19.2	0.023	0.011	0.011
34	Khabane NIANG	0.800	0.152	-0.060	13.6	-0.010	0.038	0.208
35	Khambala FAL	0.259	0.087	0.070	11.1	-0.007	0.021	0.014
36	Khanadji	0.289	0.157	0.045	15.9	0.011	-0.015	0.353
37	Khatali	0.105	0.169	0.058	8.1	-0.007	0.015	0.150
38	Khatet GAYE	0.189	0.075	0.052	22.6	0.042	-0.015	0.402
39	Kheilkom DIOP	0.170	0.344	0.045	8.8	-0.007	-0.015	0.145
40	Kogne KOGNE	0.302	0.092	0.020	11.1	0.008	9.300	0.185
41	Léona	0.518	0.600	0.036	15.3	0.019	0.093	0.078
42	Longor	0.214	0.273	0.028	19.4	0.092	0.849	0.542
43	Madayana	0.435	1.376	0.041	16.6	0.191	0.060	0.919
44	Maka Kale FAL	1.070	0.662	-0.060	13.1	0.017	0.017	2.000
45	Maka NDIAYE	0.096	0.122	-0.030	10.5	-0.007	1.070	0.151
46	Maraye DIAGNE	0.134	0.123	0.037	12.3	0.008	0.034	0.290
47	Maraye SECK	0.266	0.096	-0.030	11.7	-0.007	-0.015	0.047
48	Massar DIOP 1	0.329	0.336	0.050	13.6	0.025	-0.015	1.350
49	Mbakhas	0.308	0.296	0.030	16.5	0.025	-0.015	0.318
50	Mbatias DIEYE	0.187	0.088	0.037	10.5	0.014	0.089	0.186
51	Mbaye Mbaye 1	0.081	0.131	0.037	9.7	0.012	0.017	0.071
52	Mbaye Mbaye 2	0.112	0.414	-0.060	7.9	-0.010	0.023	0.600
53	Mbayène DIOP	0.100	0.059	0.031	9.1	-0.007	0.509	0.299
54	Mboubène MBATAR	0.241	0.120	0.080	15.6	-0.007	0.028	-0.003
55	Mboundi	0.219	0.443	0.050	8.2	0.042	0.394	0.366
56	Mbout SOW	0.122	0.109	-0.060	9.2	-0.010	0.019	0.023
57	Mérina DAKHAR	0.063	0.070	0.024	10.0	0.002	4.770	0.132
58	Mérina FAL	0.093	0.267	0.048	7.9	0.021	0.028	0.914
59	Mérina PEUL	0.044	0.049	0.037	12.4	0.013	0.081	0.086
60	Mpal	0.406	0.688	0.065	21.7	0.014	0.031	0.026

N°	LOCALITY	SR	BA	B	SI	LI	FE_TOTAL	MN
61	Ndabé TAL	1.370	1.500	-0.060	17.9	-0.010	0.026	0.580
62	Ndam	0.217	0.138	0.035	11.7	-0.007	-0.015	-0.003
63	Ndam NDAM	0.071	0.125	0.013	9.8	0.010	0.058	0.287
64	Ndame NGOT	0.237	0.140	0.015	13.9	-0.007	0.089	0.011
65	Ndawas DIAGNE	0.287	0.436	-0.030	10.1	0.008	-0.015	1.390
66	Ndeukt GUEYE	0.410	0.104	0.028	18.8	0.007	0.036	0.002
67	Ndiader PEUL	0.221	0.253	0.034	22.8	0.022	-0.015	0.304
68	Ndiaguène	0.218	0.720	0.073	16.0	0.026	-0.015	0.750
69	Ndiakhip	0.145	0.152	-0.030	12.6	0.028	0.075	0.221
70	Ndialakhar	0.188	0.113	0.047	16.1	0.011	0.002	0.327
71	Ndiambou FAL	0.135	0.101	0.051	14.6	-0.007	15.100	0.000
72	Ndiayène	0.313	0.217	0.005	12.8	0.003	0.007	0.061
73	Ndiéye BA	0.159	0.036	-0.060	7.6	-0.010	0.045	0.003
74	Ndiobène	0.323	0.094	0.024	9.2	0.009	0.050	0.126
75	Ndiok SAL	0.331	0.149	0.056	13.2	-0.007	-0.015	-0.003
76	Ndious	0.259	0.909	0.043	10.6	0.042	0.021	0.417
77	Ndop CEANE	0.384	0.114	0.073	9.7	0.007	0.033	0.450
78	Ndop PUITS	0.558	0.242	0.199	8.6	0.001	0.014	0.364
79	Ndoun	0.205	0.143	0.052	16.3	0.000	6.547	0.118
80	Ngadji SAR	1.840	0.098	-0.060	10.7	-0.010		0.007
81	Nganiakh DIENG	0.686	0.344	0.027	20.6	0.031	0.021	0.003
82	Ngomène	0.249	0.116	0.051	13.6	0.009	0.032	0.122
83	Ngoufat	0.129	0.178	0.025	10.2	0.006	0.064	0.155
84	Ngueun SAR	0.186	0.275	0.038	14.0	-0.007	0.017	0.020
85	Ngueyène	0.114	0.421	0.032	17.0	0.021	0.036	2.172
86	Nguidilé	0.345	0.188	0.032	17.2	0.002	0.017	0.003
87	Niakhal	0.207	0.143	-0.060	8.9	-0.010	0.012	0.016
88	Niomré 1	6.579	0.052	1.890	25.7	42.500	0.075	0.029
89	Niomré 2	2.181	0.177	0.176	26.1	0.002	0.029	0.017
90	Pelour	0.105	0.051	0.033	8.2	0.018	0.041	0.016
91	Rakhmane SAL	0.212	0.164	0.062	15.8	0.025	0.212	0.139
92	Rayet	0.509	0.199	0.060	16.7	0.045	32.900	1.160
93	Roye DIEYE	0.679	0.302	0.040	21.2	0.007	0.026	0.097
94	Salim SARR	0.198	0.096	0.060	12.5	-0.010	0.030	0.202
95	Santhiou MBENGUENE	0.017	0.080	0.019	10.5	0.003	0.077	0.094
96	Santhiou MEISSA	0.364	0.253	0.029	10.4	0.006	0.460	0.699
97	Santiou BAITI	0.118	0.091	-0.060	10.8	-0.010	-0.015	0.110
98	Santiou Mérina	0.131	0.214	0.063	25.2	0.033	0.018	0.270
99	Sémél	0.326	0.336	0.046	11.5	0.018	-0.015	0.323
100	Sér	0.435	0.072	0.039	14.3	0.016	0.078	1.010
101	Sine WADD	0.141	0.050	-0.030	13.6	0.009	0.017	0.012
102	Taïba	0.109	0.048	-0.060	10.3	-0.010	0.092	0.075
103	Taïba NDIOUGA	0.089	0.068	0.009	11.7	0.003	0.010	0.176
104	Tako	0.348	0.045	0.043	29.4	0.009	0.014	0.031
105	Tanim	0.466	0.084	0.308	28.9	0.022	0.019	0.002
106	Thialla KEBE	0.929	0.365	0.064	20.8	0.001	0.028	0.011
107	Thiéckène	0.081	0.055	0.036	13.0	-0.007	0.026	0.006
108	Thiéle	0.198	0.129	0.028	16.5	0.013	0.026	0.004
109	Tiarène	0.293	0.155	0.055	18.0	0.013	0.047	0.093
110	Tiéle DIAGNE	0.480	0.356	0.055	11.4	-0.007	-0.015	0.025
111	Togueul	0.185	0.248	0.029	22.6	0.007	0.076	0.028
112	Toro BEYE	0.421	0.114	0.021	11.6	0.004	0.260	0.000
113	Touba GUENE	0.171	0.591	-0.030	8.6	0.032	0.264	0.638
114	Toug	1.845	0.104	0.125	9.8	22.800	0.032	0.187
115	Yaddulahi	0.248	0.328	0.008	9.1	0.001	0.040	0.026
116	Yamane SOGG	0.462	1.570	0.038	8.1	0.049	0.025	3.950
117	Yamane (SEk) 2	0.245	0.205	0.048	13.1	-0.007	-0.015	0.040
118	Yermandé DIENG	0.213	0.072	0.035	9.7	-0.007	-0.015	0.003
119	Yerwaye	0.106	0.053	0.034	13.6	0.020	0.373	0.049

N°	LOCALITY	BR	P_TOTAL	AL	CO	V	ZN	F
1	Afé DIOP	0.030	-0.5	-0.100		-0.015	0.077	
2	Baïnak	0.140	-0.5	-0.100		-0.015	0.072	
3	Baïty GUEYE	0.200		-0.020	-0.001	0.001	0.025	
4	Bakhdad MBENG	1.480		0.022	-0.001	0.006	0.021	
5	Bakhdar PEUL	0.612		0.016	-0.001	0.002	0.010	
6	Bangadji SAMB		-0.5	1.060	0.030	0.028	0.118	
7	Baralé	1.100	-0.5	-0.100			-0.040	0.09
8	Bayakh GAYE		-0.5	-0.100		-0.015	0.054	
9	Beut LAMINE	0.190		-0.020	0.004	-0.001		
10	Boukoul	0.133		-0.020	0.001		0.027	
11	Dabaye SAR	-0.050	-0.5	-0.100		-0.015	-0.020	
12	Darou NDIAYE	0.165		-0.020	0.005	0.001	0.024	
13	Darou SALAM	0.330	-0.5	-0.100		-0.015	0.077	
14	Deuk BOUREY		-0.5	-0.100		-0.015	0.021	
15	Diakhaslène	1.040		-0.020	-0.001	0.006	0.010	
16	Diama BEYE	0.216		-0.020	0.025	0.004	0.062	
17	Diamaguène PEUL	0.400		0.029	0.007	0.002	0.013	
18	Gabane	0.685		-0.020	0.002	-0.001	0.019	
19	Gad DEMBA	1.500	-0.5	-0.100	0.020	-0.015	0.110	
20	Gati 2		-0.5	-0.100		-0.015	0.032	
21	Iba SAR	0.230	-0.5	-0.100		-0.015	0.052	
22	Kadiar PEUL		-0.5	-0.100	0.170	-0.015	0.049	
23	Kalassane NDIAYE	0.160	-0.5	0.019	0.013	0.000	0.048	
24	Kébé NDEUKT	0.795		-0.020	1.000	0.003	0.026	
25	Keur Ibra MARAM	3.000		0.066	-0.001	0.006	0.024	
26	Keur Ibra NIANG	4.600		0.026	0.099	0.039	0.019	
27	Keur MAFAL		-0.5	0.100		-0.015	0.036	
28	Keur Mbarick PEUL 1	0.120	-0.5	-0.100			-0.040	0.05
29	Keur Mbarick PEUL 2	0.650	-0.5	-0.100			0.040	0.08
30	Keur Meïssa GAYE	1.000	-0.5	-0.100			-0.040	0.17
31	Keur Modou II	0.230	-0.5	-0.100			-0.040	-0.05
32	Keur Modou KHARY	0.310	-0.5	0.700			0.160	0.05
33	Keur Seni DIENG	0.320		0.028		0.028	0.009	
34	Khabane NIANG	8.500	-0.5	-0.100			0.051	0.07
35	Khambala FAL	0.050	-0.5	-0.100		-0.015	0.090	
36	Khanadji	0.340	-0.5	-0.100		-0.015	0.126	
37	Khatali	0.330	-0.5	-0.100		0.015	0.033	
38	Khatet GAYE	0.680	-0.5	-0.100		-0.015	0.066	
39	Kheilkom DIOP	0.320	-0.5	-0.100		-0.015	0.028	
40	Kogne KOGNE	0.415		0.064	0.004	-0.001	0.118	
41	Léona		-0.5	-0.100		-0.015	0.229	
42	Longor	0.610		0.091	0.072	-0.001	0.142	
43	Madayana	0.500		0.587	0.055	0.002	0.184	
44	Maka Kale FAL	0.360	-0.5	-0.100			0.088	0.05
45	Maka NDIAYE		-0.5	-0.100		-0.015	0.033	
46	Maraye DIAGNE		-0.5	-0.100		-0.015	0.024	
47	Maraye SECK		-0.5	-0.100		-0.015	0.078	
48	Massar DIOP 1	0.840	-0.5	-0.100	0.040	-0.015	0.231	
49	Mbakhas	0.510	-0.5	-0.100		-0.015	0.033	
50	Mbatias DIEYE		-0.5	-0.100		-0.015	0.034	
51	Mbaye Mbaye 1	0.300	-0.5	-0.100		-0.015	0.054	
52	Mbaye Mbaye 2	0.190	-0.5	-0.100			0.042	-0.05
53	Mbayène DIOP		-0.5	-0.100		-0.015	0.547	
54	Mboubène MBATAR	0.200	-0.5	-0.100		0.032	0.046	
55	Mboundi		-0.5	0.340		-0.015	0.063	
56	Mbout SOW	0.160		-0.100			-0.040	-0.05
57	Mérina DAKHAR	0.108		-0.020	-0.001	-0.001	0.020	
58	Mérina FAL		-0.5	-0.100		-0.015	0.065	
59	Mérina PEUL		-0.5	-0.100		-0.015	0.026	
60	Mpal	1.900	-0.5	-0.100			-0.040	0.06

N°	LOCALITY	BR	P_TOTAL	AL	CO	V	ZN	F
61	Ndabé TAL	0.410	-0.5	-0.100			-0.040	0.09
62	Ndam	0.440	-0.5	-0.100		-0.015	0.052	
63	Ndam NDAM	0.148		-0.020	0.008	-0.001	0.109	
64	Ndame NGOT	0.146		0.055			0.033	
65	Ndawas DIAGNE	3.000	-0.5	-0.100	0.020	-0.015	0.074	
66	Ndeukt GUEYE	0.348		0.035	-0.001	0.006	0.130	
67	Ndiader PEUL	0.520	-0.5	-0.100		-0.015	0.024	
68	Ndiaguène	0.630		-0.100			-0.040	0.06
69	Ndiakhip	1.200	-0.5	-0.100		-0.015	0.057	
70	Ndialakhar	0.220		-0.020	0.002	-0.001	0.010	
71	Ndiambou FAL	0.232	-0.5	0.290		-0.015	0.090	
72	Ndiayène	0.264		-0.020	-0.001	0.002	0.011	
73	Ndiéye BA	0.080	-0.5	-0.100			-0.040	0.07
74	Ndiobène	0.200		-0.020	0.002	0.005	0.021	
75	Ndiok SAL	0.330	-0.5	-0.100		-0.015	0.033	
76	Ndious	0.370	-0.5	-0.100	0.035	-0.015	0.152	
77	Ndop CEANE	0.720		-0.020	0.013	0.010	0.019	
78	Ndop PUITS	1.300		-0.020	0.004	0.023	0.027	
79	Ndoun	0.269		-0.020	-0.001	0.002	0.023	
80	Ngadji SAR	0.460	-0.5	-0.100			0.097	0.13
81	Nganiakh DIENG	1.160		0.031	-0.001	0.004	0.015	
82	Ngomène		-0.5	-0.100		0.024	0.029	
83	Ngoufat	0.221		0.035	0.032	0.001	0.028	
84	Ngueun SAR		-0.5	-0.100		-0.015		
85	Ngueyène	0.113		-0.001	0.034	-0.001	0.063	
86	Nguidilé	0.510		-0.020	-0.001	0.003	0.010	
87	Niakhal	0.210	-0.5	-0.100			-0.040	0.08
88	Niomré 1	11.000		0.268	0.036	0.041	0.086	
89	Niomré 2	1.130		0.027	-0.001	0.065	0.031	
90	Pelour	0.196		0.085	0.002	0.026	0.007	
91	Rakhmane SAL		-0.5	0.100		-0.015	0.023	
92	Rayet	0.475		2.000	0.463	0.003	0.460	
93	Roye DIEYE	1.200		0.022	-0.001	0.006	0.013	
94	Salim SARR	0.160	-0.5	-0.100			0.041	0.09
95	Santhiou MBENGUENE	0.088		-0.020	-0.001	-0.001	0.063	
96	Santhiou MEISSA	0.255		-0.020	0.061	0.003	0.090	
97	Santiou BAITI	0.100	-0.5	-0.100			-0.040	0.10
98	Santiou Mérina	0.440	-0.5	-0.100	0.030	-0.015	0.092	
99	Sémél	0.720	-0.5	-0.100		-0.015	0.079	
100	Sér		-0.5	-0.100	0.040	-0.015	0.036	
101	Sine WADD		-0.5	-0.100		-0.015	-0.020	
102	Taïba	0.110	-0.5	-0.100			-0.040	-0.05
103	Taïba NDIOUGA	0.134		-0.010	-0.001	-0.002	0.024	
104	Tako	0.135		0.022	-0.001	0.006	0.010	
105	Tanim	1.500		-0.020	-0.001	0.020	0.008	
106	Thialla KEBE	0.536		0.045	-0.001	0.006	0.021	
107	Thiéckène	0.210	-0.5	-0.100		-0.015	0.050	
108	Thiéle	0.320		0.036	-0.001	0.004	0.011	
109	Tiarène	0.620		0.023	0.008	0.002	0.015	
110	Tiéle DIAGNE	0.740	-0.5	-0.100		0.200	-0.020	
111	Togueul	0.494		0.021	-0.001	0.005	0.012	
112	Toro BEYE	0.270		-0.020	0.016	0.014	0.050	
113	Touba GUENE		-0.5	0.120		-0.015	0.242	
114	Toug	6.600		0.023	0.001	0.043	0.018	
115	Yaddulahi	0.288		0.056		0.002	0.022	
116	Yamane SOGG		-0.5	0.120	0.160	-0.015	0.106	
117	Yamane (SEk) 2	0.530	-0.5	-0.100		0.029	0.099	
118	Yermandé DIENG	0.300	-0.5	-0.100		-0.015	0.020	
119	Yerwaye		-0.5	-0.100		-0.015	0.082	

TABLE 5.10 Trace element analyses of shallow groundwters from the Louga region - corresponding details are shown in Table 5.9. Analysis by ICP-MS with results in µg l^{-1}; ^{x} denotes analysis by ICP-OES and figures in parentheses indicate correspondinding ICP-OES analyses in Table 5.9)

		Li	Al	Be	Ce	Cd	Co	La	B	Ni	Pb	Rb	Tl	U	Y	Cs	Cu
3	BAITY GUEYE	2 (2)	7	<0.4	<0.1	<0.4	2.0	<0.1	19 (13)	6	1.3	17	0.1	<0.1	0.2	<0.2	1
16	DIAMA BEYE	20 (23)	13	3.2	<0.1	0.8	26	<0.1	34 (25)	50	1.2	24	0.3	1.4	0.4	<0.2	25
10	BOUKOUL	2 (2)	12	<0.4	<0.1	<0.4	24	<0.1	16 (13)	<3	1.1	3.2	<0.1	<0.1	0.2	<0.2	2
24	KEBE NDEUKT	10 (86)	41	<0.4	0.1	<0.4	0.6	<0.1	47 (50)	<3	1.5	4.2	<0.1	1.7	<0.1	<0.2	2
26	KEUR IBRA NIANG	30 (37)	26	<0.4	0.2	0.5	93	<0.1	23 (25)	42	1.7	15	<0.1	0.4	0.7	<0.2	4
40	KOGNE KOGNE	7 (8)	71	0.7	0.2	<0.4	5.7	<0.1	23 (90)	13	1.9	11	<0.1	0.2	0.7	<0.2	14
42	LONGOR	90 (92)	106	22	0.7	1.2	74	0.2	29 (28)	118	4.1	30	0.4	0.9	3.6	<0.2	25
43	MADAYANA	180 (191)	587^{x}	37	2.1	0.5	55	0.5	54 (41)	126	4.3	65	0.4	2.1	9.1	<0.2	68
63	NDAM NDAM	10 (10)	16	0.6	<0.1	<0.4	6.6	<0.1	13 (13)	8	1.3	10	<0.1	<0.1	0.2	<0.2	7
83	NGOUFAT	5 (6)	37	<0.4	<0.1	<0.4	3.8	<0.1	24 (25)	6	1.0	10	<0.1	<0.1	0.1	<0.2	2
92	RAYET	43 (45)	2000^{x}	38	16.7	2.9	436^{x}	2.5	56 (60)		4.7	27	0.2	9.9	68	<0.2	160
93	ROYE DIEYE	8 (7)	38	<0.4	<0.1	<0.4	0.6	<0.1	44 (40)	<3	2.5	1.9	<0.1	1.5	0.1	<0.2	1
103	TAIBA NDIOUGA	3 (3)	8	<0.4	<0.1	<0.4	1.0	<0.1	10 (9)	<3	0.8	2.6	<0.1	<0.1	0.1	<0.2	2
	LOUGA 18 (35 m)	6	4	<0.4	<0.1	<0.4	1.2	<0.1	46	20	0.4	9.1	<0.1	<0.1	0.6	<0.2	4

to early Holocene or late Pleistocene times, and this is discussed in Chapter 6 in relation to bromide results.

5.3.2 Hydrogeochemistry

The specific electrical conductance (SEC) may be used to provide a good indication of total mineralisation of groundwater. For those samples with full mineral analyses (i.e. including HCO_3) there is an excellent correlation ($r^2 = 0.99$) between sum of determined ions (cations and anions) and SEC (Figure 5.41). The total mineralisation is related to the SEC by a factor of 0.5. The close correlation between these parameters is a further check on the quality of the chemical analyses and also indicates that there are no major facies changes in the regional groundwater body, e.g. high sulphate waters, which would give rise to a different slope. The distribution of SEC is shown in Figure 5.42 and correlates quite closely with the Cl occurrence.

The main aquifer has low alkalinity with the majority of groundwaters having $HCO_3 < 20$ mg l^{-1} (Figure 5.43). This reflects the virtual absence of carbonate minerals in the continental dune sands where the low HCO_3 values are maintained by solution of silicate minerals. An exception is the area near Leona towards the coast where some slightly higher values may indicate the influence of marine sands at depth. Likewise the rise in alkalinity towards the east is related to the thinning of the sand aquifer over carbonates and other deposits of the Tertiary succession.

In association with the low alkalinities, the pH is commonly below 6.0. These sites are shown in Figure 5.44 where some sites with particularly acidic groundwater (<5.0) are also shown. The latter correspond with water having alkalinity of zero and in some of these high iron (>10 mg l^{-1}) or high aluminium (>0.4 mg l^{-1}) are to be found. The area south of Leona is particularly affected.

The overall cation chemistry is summarised in the trilinear diagram (Figure 5.45) where the shallow groundwater data have been subdivided into samples from the western, central and eastern zones of the region. It can be seen that there are no distinct differences between waters from any sector of the aquifer apart from the more Ca enriched waters found in the eastern area linked to the occurrence of carbonates.

One of the most important features of the region is the occurrence of high nitrate concentrations across the whole area (Figure 5.46). Many of the groundwaters contain nitrate in excess of 10 mg l^{-1} NO_3-N which exceed the WHO acceptable limits for drinking water. The shallow groundwater results compliment the results already given for the unsaturated zone and it is considered that these relate to natural production and are in no way connected with pollution.

5.3.2.1 **Trace element occurrence**

This study has provided the first opportunity to investigate a wide range of trace elements in groundwaters from the semi-arid zone. This has been undertaken as part of a wider interest in trace element geochemistry, but has relevance here in relation to the groundwater quality and health. The results (Tables 5.9 and 5.10) are reported here but are not interpreted in any detail, since they will be the subject of further study.

Some comments on trace element concentrations are reported here since they relate to water quality and potability in general. The higher abundance of dissolved metals is clearly related to those groundwaters with low pH and this group of waters if used for drinking clearly pose a significant risk to health. These trace element concentrations are likely to result from natural mobilisation under acidic conditions and are not likely to be related to pollution, except in very few cases. Thus well 43 (Madayana) has a pH of 4.6 and aluminium of 0.59 with associated Be = 37 $\mu g\ l^{-1}$, Co = 55 $\mu g\ l^{-1}$, Ni = 126 $\mu g\ l^{-1}$ and Cu = 68 $\mu g\ l^{-1}$. The same enrichments are found in other acidic groundwaters indicating the likelihood of a natural source.

Of the other trace elements, fluorine is deficient in all the waters analysed from the shallow aquifer with possible effect on dental health.

6. DISCUSSION AND CONCLUSIONS

The main objective of this study has been to develop and apply the solute profile technique for recharge estimation but in addition it has been possible to obtain information on recharge history over the 20th Century and also to investigate certain water quality problems of the shallow groundwater system by linking inputs via the unsaturated zone to the water table. The main results from each of these themes is discussed.

This project has shown that geochemical techniques provide a preferable alternative technique to conventional methods for recharge and related hydrogeological and environmental studies of semi-arid regions. By measuring a wide spectrum of chemical species (made possible by microchemical, multielement analysis) and stable isotope ratios there is the potential to perform simultaneously an investigation of physical phenomenon such as recharge, the types of geochemical processes that control water quality as well as environmental change. The extraction of interstitial waters from the unsaturated zone offers a powerful means of studying changes during infiltration/recharge with time. The isotope ratios of oxygen and hydrogen enable a study to be made of the water molecule and how it responds to physical processes such as evaporation. The measurement of chloride which is totally conserved in the infiltration process does, however, offer the best method for recharge estimation. This is a straightforward measurement and one that can be readily applied to remote terrains using simple equipment. Throughout this study the emphasis has been placed on development of simple methods, appropriate to developing countries. The use of the hand auger in particular provides a simple and inexpensive means of sampling over much of Senegal and in similar unconsolidated terrain in the Sahel belt. Information can also be obtained from hand-dug wells, thousands of which are constructed annually in semi-arid regions.

6.1 Estimation of recharge

In the Louga region of northern Senegal a number of profiles to depths ranging from 10 to 35 m have been obtained. In this region the rainfall during the period 1969-1987 was only 223 mm compared with a long-term average of 356 mm, representing a decline of 3%. A research site of 1 km^2 was established in a typical area of fixed dune sands overlying the main aquifer of the region. At this site direct recharge at individual sites was determined and in addition the spatial variability of recharge could be assessed. Seven profiles were completed at this site at which the mean concentrations of chloride in the interstitial solutions were determined (Table 6.1). As well as the mean recharge over the whole interval (underlined values), separate recharge values have been calculated for some profiles to indicate that higher or lower recharge may have occurred over certain periods of time.

The values for chloride range from 24 to 115 mg $^{-1}$ Cl with a global mean value of 81±48 mg l^{-1}. The direct recharge at each site is then calculated using the relationship given in Chapter 4. An average value of 290 mm for rainfall (P) has been chosen for these calculations which is an average for the past 60 years, and a value of 2.8 mg l^{-1} (Cp) for average rainfall chemistry (based only on the past three years of measurement). Substituting these values the range of recharge at the Louga site ranges from 4.6 to 34 mm yr^{-1} with a mean of 15.2 mm. Thus, it can be seen that as well as investigating the individual site, chloride profiles provide a means of deriving integrated recharge estimates taking account of spatial variability.

The reasons for the spatial variability at the Louga site are considered due mainly to slight variations in soil texture and to the amount of clays present in the top 50 cm, for example, which may have a profound effect on the amount of recharge that is possible. The other main variable is the vegetation. At the present time, the vegetation cover in this area is relatively sparse, since some clearance for rainfed agriculture (especially groundnuts) has occurred. The root system of many species of plant are quite extensive laterally however, and uptake of water to 1 m depth by plants will be an important and variable factor in recharge potential. The shape of chemical and isotopic profiles suggests that significant water loss from below 1 m is not taking place and thus the maximum depth of the 'zero flux plane' is likely to be around 2 m. Acacia and other trees will have the greatest effect on recharge both locally and over a long time-scale. Several zones of high chloride (and lower recharge) may relate to the lifespan of trees at a particular locality. Surface runoff in this region is considered to be zero. It is considered that the recharge estimates so obtained have taken account of these likely causes of spatial

TABLE 6.1. Mean annual recharge at Louga research site.

PROFILE NAME	INTERVAL i (m) i	MEAN RAINFALL p	MEAN CHLORIDE IN RAINFALL Cp	MEAN CONCN. OF CHLORIDE IN PROFILE Cs_i	MEAN ANNUAL RECHARGE Rd
LOUGA 2	1.5-16.0*	290	2.8	27.9	29.1
LOUGA 3	2.5-25.0*	290	2.8	81	10.1
	2.5-4.5	290	2.8	61	13.1
	4.5-9.0	290	2.8	134	6.1
	9.0-25.0	290	2.8	70	11.6
LOUGA 5	1.5-12.5*	290	2.8	73	11.1
LOUGA 6	1.0-13.5*	290	2.8	80	10.1
LOUGA 11	14.0-15.5	290	2.8	115	7.1
	1.0-14.0	290	2.8	89	9.1
	14.0-15.5	290	2.8	340	2.4
LOUGA 12	1.0-14.0*	290	2.8	175	4.6
	1.0-4.5	290	2.8	503	1.6
	4.5-14.0	290	2.8	54	15.0
LOUGA 18	1.5-35.5*	290	2.8	23.6	34.4
	1.5-6.3	290	2.8	6.1	133.0
	6.25-11.5	290	2.8	34.5	23.5
	11.5-18.5	290	2.8	25.1	32.4
	18.5-27.5	290	2.8	14.9	54.4
	27.5-31.5	290	2.8	42.7	19.0

TABLE 6.2 Mean annual recharge at outlying sites and M'pal, Louga area.

PROFILE NAME	INTERVAL i (m) i (m)	MEAN RAINFALL p (mm)	MEAN CHLORIDE IN RAINFALL Cp (mg l^{-1})	MEAN CONCN. OF CHLORIDE IN PROFILE Cs_i (mg l^{-1})	MEAN ANNUAL RECHARGE Rd (mm yr^{-1})
M'PAL AREA					
LOUGA 7	1.0-7.0	290	2.8	1403	0.59
LOUGA 8	1.5-7.0	290	2.8	752	1.08
LOUGA 9	1.0-12.0	290	2.8	95	8.6
LOUGA 10	1.5-12.0	290	2.8	1660	0.49
M'PAL AREA					
LOUGA 13	1.0-7.0	290	2.8	231	3.5
LOUGA 14	1.0-9.5	290	2.8	50	16.2

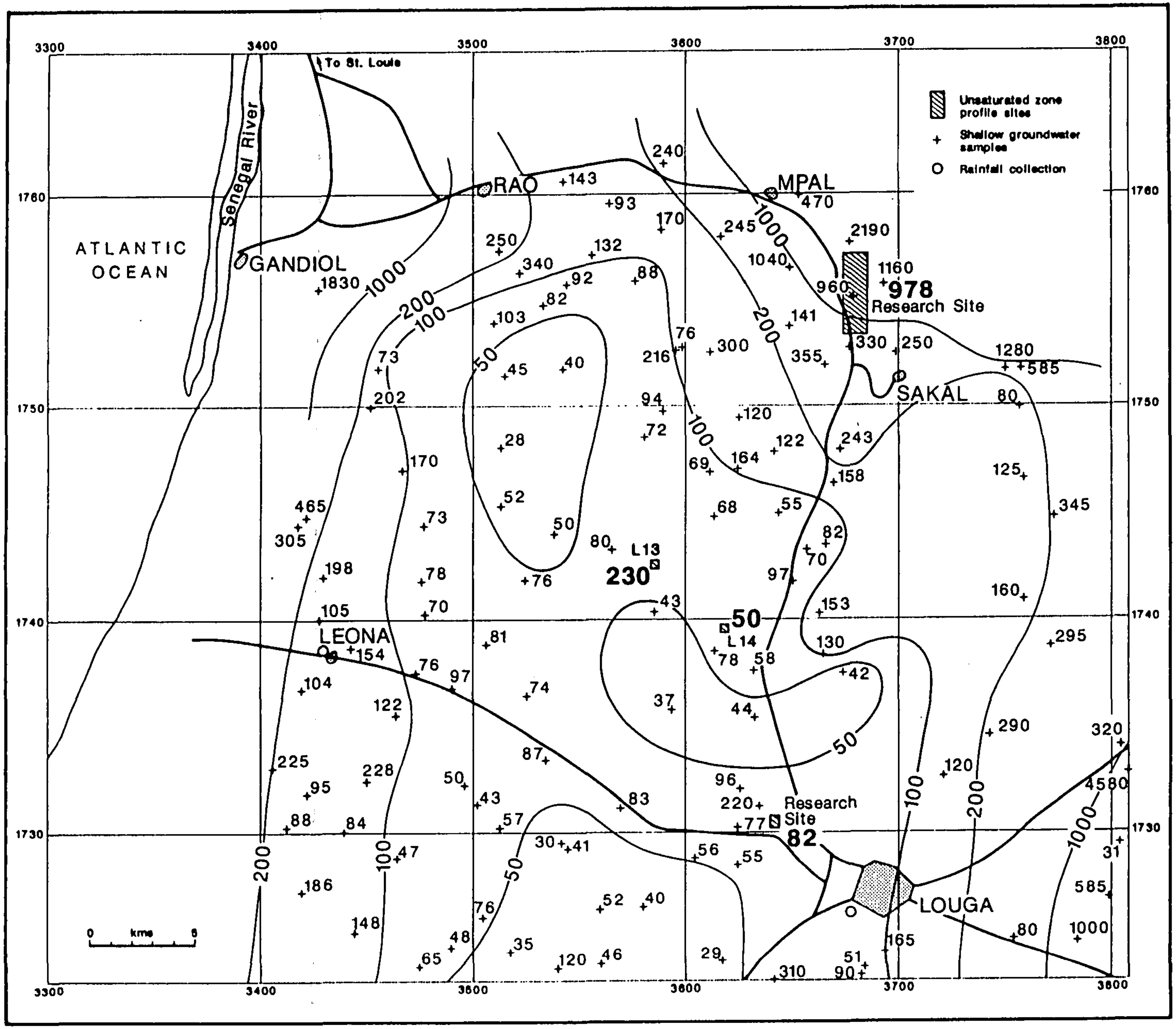


Figure 6.1

HYDROCHEMICAL DISTRIBUTION OF CHLORIDE - LOUGA AREA

+345 Cl in mg l^{-1}

—100— Isochlors

230 Mean value of chloride for the unsaturated zone

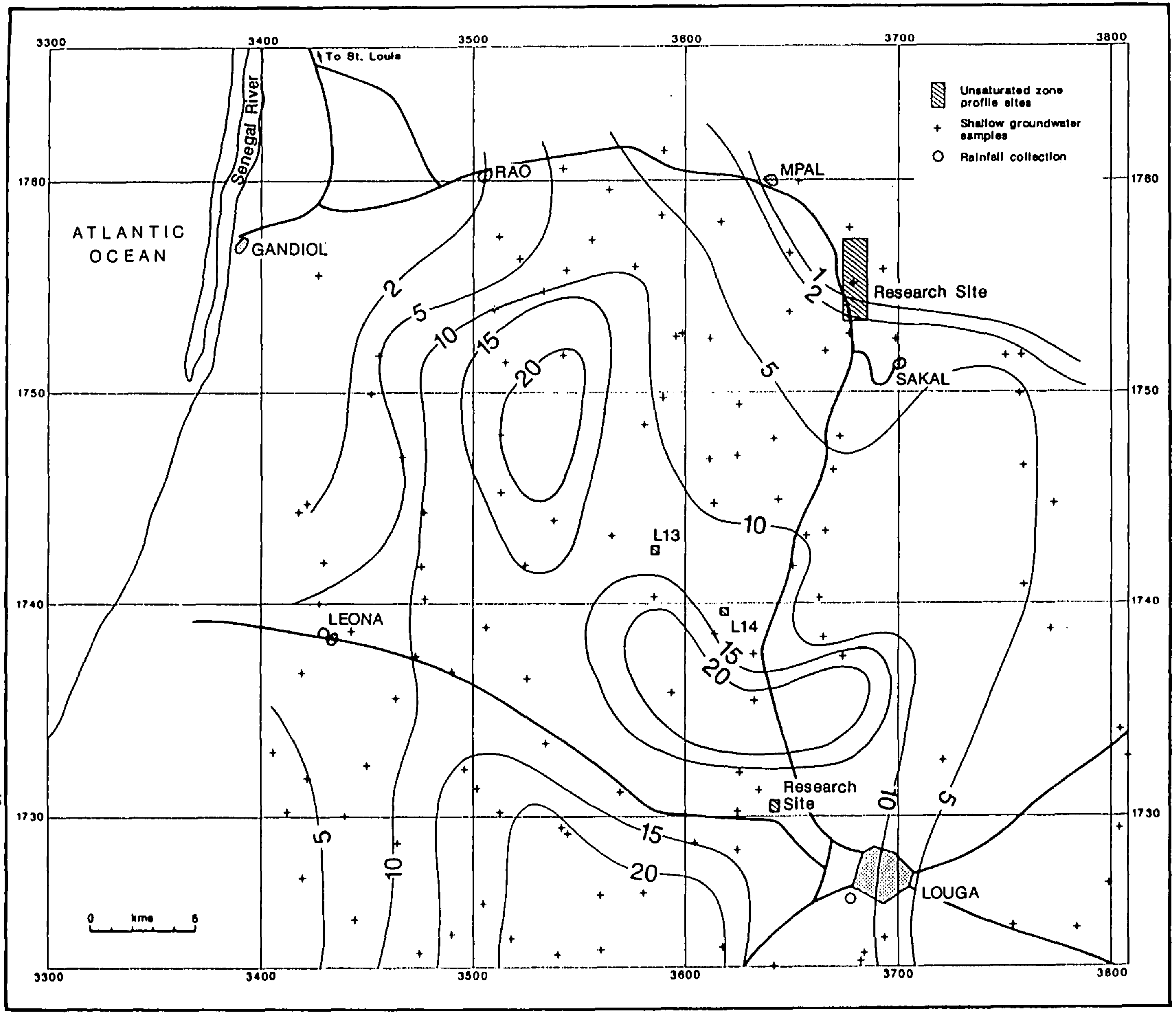


Figure 6.2

GROUNDWATER RECHARGE IN N.W. SENEGAL (LOUGA REGION) DERIVED FROM CHLORIDE

—20— Mean annual recharge (mm)

variability. The solute profile method highlights the wide differences in recharge rate even in a relatively homogeneous terrain.

It can be seen that, compared with traditional methods of recharge estimation, the solute profile (chloride) method has a further advantage. The mean concentration of chloride in each profile effectively provides the average recharge over a number of years whereas most traditional methods provide results only on a short-term basis. The chloride profile acts like a cumulative rain gauge over a period of decades in the case of northern Senegal.

Several other profiles constructed in the Louga region provide a better indication of recharge in the area. Two sites north-west of Louga gave mean chloride concentrations of 50 and 230 mg l^{-1} Cl corresponding respectively to recharge of 17 and 4.6 mm yr^{-1} (Table 6.1). Further north of M'pal much lower recharge is indicated from several profiles in which much higher chloride is found than at the main Louga research site (Table 6.2). These concentrations represent recharge of around 1 mm yr^{-1} which are the result of a better development of clay soils in this lower lying region.

In the Louga region as a whole, the results obtained from unsaturated zone profiles may be confirmed by comparison with chloride concentrations obtained from the unconfined aquifer. The water samples taken from the traditional wells of the region represent the water which has most recently arrived at the water table. A comparison is possible in most of this area, since no external or additional sources of chloride other than atmospheric are proposed. In Figure 6.1, the chloride results obtained from each source may be compared and, with the possible exception of L13 (single point measurement only), there is a good correlation. Thus, it is considered that the shallow groundwater chloride (backed up by the unsaturated zone evidence) may here be used to derive regional recharge estimates.

In Figure 6.2 the chloride data have been converted into regional estimates of recharge using the contours from Figure 5.41 and assuming that the unsaturated zone data and water table results form a continuum. These values may be used to estimate available replenishable resource; in the area bounded by the 20 mm/year contour this represents 20 000 m^3/year and in the area bounded by the 2 m contour only 2000 m^3/year of more brackish water. Overall, therefore, this is an area favourable to recharge. Natural recharge far exceeds domestic water used by traditional village methods (some 300 m^3/km^2/year) even during periods of drought when recharge rates may be half the above values.

The falling water tables in this region and elsewhere in Senegal are most likely to be due to the short-term low rate of recharge seen by the aquifer during the drought period, exacerbated by natural leakage or abstraction from deeper aquifers. The Louga area and much of the Quaternary aquifer acts as a probable recharge zone for much of the lower aquifer system exploited by deep wells and which in turn recharges the deeper aquifers of the Senegal Basin where water tables are often depressed (e.g. Ferlo). If the recharge rates to the east of the area studied are much lower due to unfavourable soil/bedrock characteristics, then the declining water table in an area designated as an abundant recharge area may be satisfactorily explained. A more precise water balance of the main aquifer system is therefore needed using the better recharge estimates derived here.

Estimates of recharge for the Kaolack and Niague regions are summarised in Table 6.3. With the exception of Kaolack 1, the whole profile has been used for recharge calculation. In Kaolack 1 the interval from 5.0-19.5 m only has been used since it is concluded that the upper 50 m represent a zone out of hydraulic continuity with the rest of the profile either temporarily because of active tree roots or permanently because of a clay band which is by-passed during the recharge process. These estimates, 11.7, 108, 18.1, 21.6 mm for KK1-4 respectively, are rather variable. It is considered that one of these (108 mm) represents an area of cleared vegetation and that the other values (average 17.1 mm) are representative of the region as a whole. This figure is comparable to that for the average for Louga (10.5 mm year) and indicates that the higher rainfall is almost compensated for by the increased, general vegetation cover. Clearance of vegetation, however, dramatically increases the recharge rate.

At Niague the recharge situation is similar to Kaolack. The estimates are rather provisional in view of the short interval of unsaturated zone available. The values for Niague 2 and 3 give recharge estimates of 11.6 and 13.3 respectively (Table 6.3) which are comparable to those from the other two areas; NG4 gives 60 mm which is more typical of a cleared area.

TABLE 6.3 Groundwater recharge in Kaolack and Niague areas calculated from chloride interstitial water concentrations over different intervals (i). The preferred mean annual recharge values are underlined.

PROFILE NAME	INTERVAL i (m)	MEAN RAINFALL	MEAN CHLORIDE IN RAINFALL	MEAN CONCN. OF CHLORIDE IN PROFILE	MEAN ANNUAL RECHARGE
	i	p	Cp	Cs_i	Rd
KAOLACK 1	0.5-19.5	545	3.4	747.4	2.5
	5.0-10.5		3.4	327.6	5.7
	5.0-19.5		3.4	158.0	11.7
	10.0-19.5		3.4	99.1	18.7
KAOLACK 2	1.5-14.0	730	3.4	23.0	108
KAOLACK 3	1.5-9.0	545	3.4	102.4	18.1
KAOLACK 4	1.5-11.5	545	3.4	25.7	72.1
	1.5015.5		3.4	85.8	21.6
	11.5-15.5		3.4	243.7	7.6
NIAGUE 2	4.0-7.0	487	4.2	177.8	11.6
NIAGUE 3	4.0-6.6	489	4.2	154.2	13.3
NIAGUE 4	4.0-12.0	489	4.2	34.1	60.2

As mentioned above this locality has been progressively cleared of vegetation during recent years.

In summary it is found that the chloride method provides a powerful method for recharge estimation and shows up clearly the wide differences that can exist from point to point depending upon soils and vegetation. Nevertheless, with sufficient point source data, combined with the regional information from shallow wells, the spatial variability can be accounted for to provide realistic estimates of long-term recharge. The main limitation in interpretation is in the measurement of Cp. In this study a three-year average is used; refinement of the recharge estimates can be made once a longer set of rainfall information can be obtained. Verification of the recharge estimates (unsaturated zone only) are being obtained using tritium on samples analysed by IAEA (Vienna). Preliminary data indicate that the 1963/64 peak is around 15 m in the L18 profile and confirms the recharge estimates given here.

6.2 Recharge and environmental history

It has been shown how chloride may be used to provide long-term estimates of recharge. It is also possible to use the chloride and other information contained in the interstitial waters to study the history of inputs over the time span represented by the waters traversing the unsaturated zone.

Using the recharge estimate calculated using chloride it is then possible to calibrate each profile, if the moisture content is known and to calculate the rate of movement v_w (in metres/yr):

$$v_w = \frac{Rd}{1000 \times \theta_w}$$

where θ_w, the volumetric moisture content, is given by:

$$\theta_w = \frac{bd \times mc}{\rho_w \times 1000} \quad , \quad \text{so } v_w = \frac{Rd}{bd \times mc}$$

where bd = bulk density of the dry sediment (assumed to be 1.5), mc = moisture content in g/kg of dry sand and ρ_w is the density of water. These values have been calculated for profiles (2, 3, 5, 6, 11, 12 and 18) at the main Louga site as well as 8, 9 and 10 at M'pal, and are given in Table 6.4 where several vertical intervals have been chosen, corresponding to representative chloride or moisture content; the rates of movement calculated are therefore averages for each interval. Finally, the residence time (t), represented by each interval, is shown. In these calculations the values for P are chosen to represent the most likely value for the time span in question, rather than the global average of 290 mm used in Table 6.1.

At the main Louga site the velocities of flow in the unsaturated zone range from 6 cm to 3.2 m yr^{-1} but with typical drainage rates of 0.2-0.4 m yr^{-1}. Up to 118 years record is contained in these profiles, so that current recharge in certain cases reflects input conditions of the 19th Century. Calibration of the profiles reflects both the variability of moisture content (grain size) and chloride concentrations, and some correlations can be seen. The most recent data chosen are far the year of the rainy season prior to sampling. In profiles 2, 3, 5, 6, 11 and 18 chloride peaks occur which correlate with the period of drought 1968-1986 (Figure 6.4). The peaks may be rather subdued in some profiles (e.g. 2) where recharge rates are higher but emphasised in other profiles, such as 3 and 6, where lower recharge rates are found. Thus, profiles showing records of the same climatic event may be quite different in appearance, occupying varying vertical intervals.

The Louga 3 profile is possibly the best model for the record in preceding years and this record is compared with climatic data in Figure 6.4. A major peak is found near to 1940 which is thought to reflect another episode of drought which is not so strongly shown in the St Louis record (Figure 2.3) but which is well documented on a regional scale in the flow of the Senegal river at Bakel (Figure 3.15, 3.16). Olivry (1983) noted this inconsistency but draws attention to the important periods of high rainfall in the 1950s and 1960s and also in the 1920s and 1930s reflected in both rainfall and river flow data. It may be that rainfall intensity also differed between the two drought periods so that the river reflects the lower recharge conditions better than the total rainfall. The period of the 1920s is shown by a zone of low chloride concentrations in the Louga 3 profile. The peak of Cl at 20 m may correspond to a period of low recharge during the decade around 1900. This is a period of low rainfall at St Louis (Figure 1.3) which corresponds also with a low flow period on

TABLE 6.4

PROFILE	INTERVAL i (m)	P (mm)	Rd (mm)	mc (g/kg)	θ_w	v_w (m/yr)	t (yr)
LOUGA RESEARCH SITE							
LOUGA 2	1.5-16.0	223	22.3	45.8	0.069	0.32	45
							Σ 45
LOUGA 3	2.5-4.5	290	18.0	52.8	0.079	0.23	8.7
	4.5-9.0	223	5.7	29.9	0.045	0.13	35.5
	9.0-17.0	356	15.8	26.6	0.040	0.40	20
	17.0-25.0	356	12.8	47.2	0.071	0.18	44
							Σ118
LOUGA 5	1.5-6.5	223	8.8	17.9	0.026	0.34	15
	6.5-8.0	223	4.0	30.8	0.046	0.09	17
	8.0-12.5	356	15.8	18.7	0.028	0.56	8.0
							Σ 40
LOUGA 6	1.5-2.5	290	45.6	15.8	0.024	1.9	<1
	2.5-5.0	223	3.3	24.5	0.036	0.09	28
	5.0-10.0	223	7.9	18.5	0.028	0.28	18
	10.0-13.5	356	39.7	28.8	0.043	0.92	Σ 50
LOUGA 11	1.5-5.0	290	23.5	26.8	0.040	0.59	6
	5.0-10.5	223	5.1	43.1	0.065	0.08	68
	10.5-13.5	356	11.3	27.1	0.041	0.28	11
	13.5-15.5	356	3.4	37.4	0.056	0.06	33
							Σ118
LOUGA 12	1.5-4.5	223	1.1	11.6	0.017	0.06	50
	4.5-14.0	356	18.5	23.6	0.035	0.53	18
							Σ 68
LOUGA 18	1.25-6.25	290	133	28.1	0.042	3.2	1.6
	6.25-11.5	223	18.1	31.6	0.047	0.38	13.8
	11.5-18.5	356	39.7	59.2	0.089	0.45	16
	18.5-27.5	356	67	74.4	0.112	0.60	15
	27.5-35.5	356	23.3	63	0.095	0.24	33
							Σ 74
M'PAL AREA							
LOUGA 9	1.5-3.5	223	2.3	20.0	0.030	0.08	25
	3.5-12.0	356	10.6	25.3	0.038	0.28	30
							Σ 55
LOUGA 8	1.0-1.5	290	0.14	27.0	0.041	0.003	166
	1.5-6.5	356	3.8	30.0	0.045	0.08	63
							Σ229
LOUGA 14	1.5-3.0	290	1.6	7.4	0.011	0.14	11
	3.0-7.0	356	0.52	12.5	0.019	0.03	133
	7.0-8.5	356	1.68	36.0	0.054	0.03	50
	8.5-11.5	356	0.37	25.8	0.039	0.009	333
							Σ527

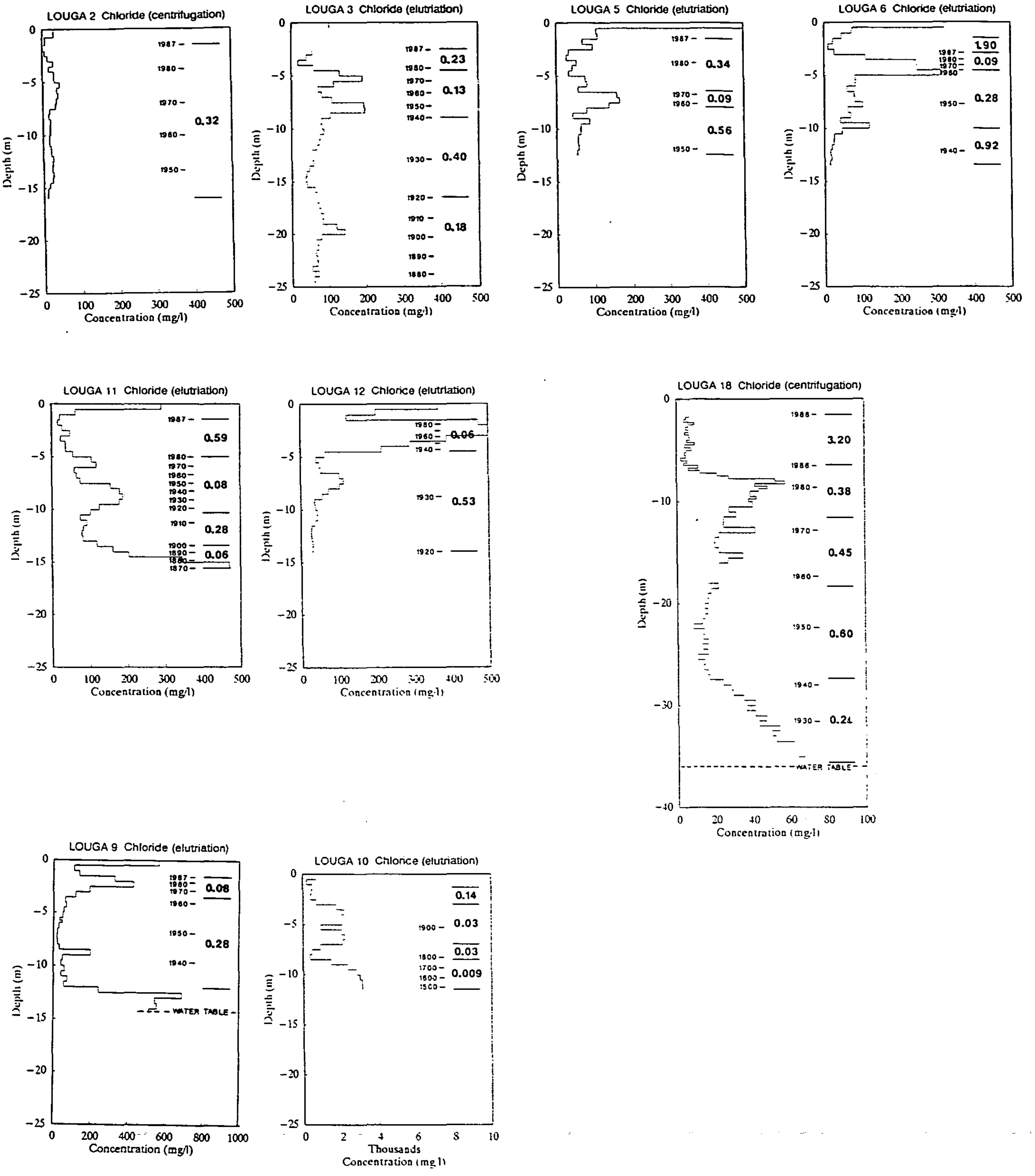


Figure 6.3 Chloride profiles for Louga sites calibrated chronologically as described in the text. The annual velocity of movement for the intervals chosen are shown in larger numbers.

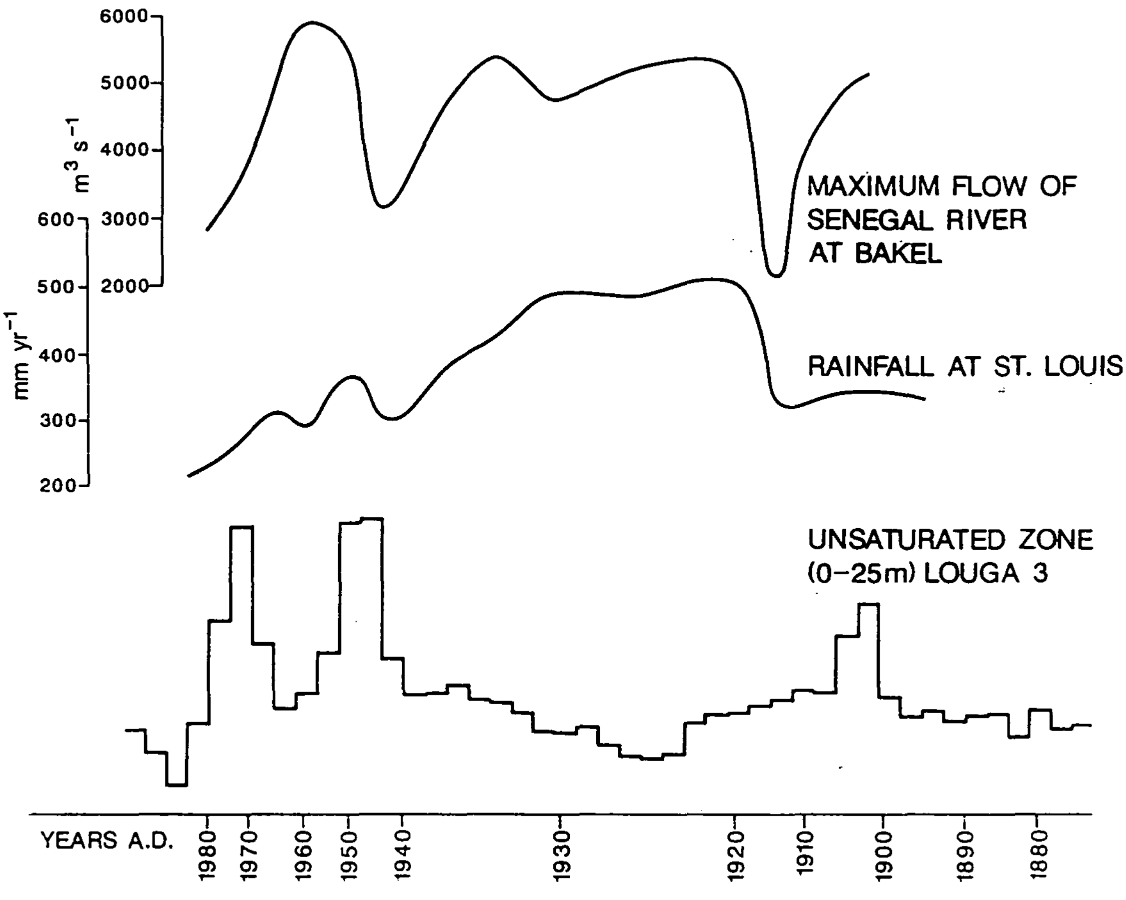


Figure 6.4 Comparison of the calibrated Louga 3 profile with the climatic record of the past century, based on St Louis rainfall and the flow of the Senegal River at Bakel.

the Senegal river in the first decade of this century. The likely correlation of the climatic history with the borehole record is summarised in Figure 6.4. The rise in chloride coincides with the end of the lower rainfall period about 1917.

Some dispersion of solute peaks is inevitable even during homogeneous piston flow and it should not be expected that exact correlation will occur. Changes in the vegetation at a particular site with time will also lead to non-linearity in the correspondence between solute and other climatic records. Some by-pass flow via root systems may also lead to smoothing or dislocation of some profiles.

Among some of the other profiles with long time intervals some correspondence with the earlier events can also be seen. In Louga 18, the low chloride of the 1950s/1960s and a rise in chloride towards 1940 coincide with the Louga 3 model. In Louga 12 the matching is not so good but a peak around the mid 1930s may be the offset 1940 drought response whilst the lower chloride below this interval correlates well with the higher recharge of the 1920s.

Some information may also be obtained from the M'pal area profiles where recharge rates are lower and hence profile residence times proportionally longer. At Louga 5, recharge characteristics are similar to those in the area west of Louga and both the 1970s and 1980s peaks plus a 1940s peak may be seen, before the profile terminates at the water table. The record of the Louga 8 profile is difficult to interpret; the high salinities at 8-10 m may be related to factors other than recharge (e.g. former saline lake levels and the saline zone may also indicate a fall in the water table). In Louga 10 the chloride profile would indicate a record of >500 years. It is difficult to interpret this profile except conjecturally; the distinct periods of lower salinity are most likely to correspond to wetter periods during the past half millennium but during drier episodes there is likely to have been some homogenisation due to diffusion. More data from the same area is needed to build on this hypothesis.

The oxygen and hydrogen isotope ratios provide additional information for the study of the recharge history. Various authors (e.g. Allison et al, 1984) have tried to use the isotope profile to measure recharge. The main value of the isotopic information is to provide qualitative information on the recharge process in support or otherwise of the chloride recharge model. During each season, following the rains, evaporation will lead to the enrichment in soil moisture of the heavier isotope (^{18}O) as the lighter isotope ^{16}O is preferentially lost as vapour. A characteristic 'front' is developed within the top metre of the profile separating two zones - an upper zone of vapour transfer and a lower zone of liquid transfer (Figure 6.5). In arid regions, this method may be used to quantify evaporative discharge (Barnes and Allison, 1983) since a steady-state isotope profile is established; this is particularly effective where the water table is close to the surface (e.g. near Sebkhas). In semi-arid regions where some annual recharge takes place, the 'front' is modified by the next season's incoming rain and some downward displacement of the isotopically heavier moisture will occur. Therefore, a difference is to be expected between alternating periods of wet years and dry years with more or less recharge.

The isotopic profiles (δ^2H only) obtained from Louga are shown in Figure 6.6 and it is seen that oscillations occur in the profiles between about -50 and -20‰ δ^2H. The profiles are compared with the time scale adopted from chloride measurements. Several instances may be found where more positive or more negative isotopic contents of interstitial waters correspond quite well with climatic indicators. Profile Louga 18 shows an enrichment in deuterium over the interval ca. 1968-1986 and this same feature is seen also in profiles 5, 6, 11 and 9. A zone of isotopically lighter water is seen in Louga 18 marking the years 1945-1965 and a similar interval is seen in Louga 5, 6 and 9. The 1940's drought period is markedly more positive (δ^2H) values in Louga 18 and this feature is seen probably in Louga 5, 6 (offset?) and possibly Louga 12. The wet phase of the 1920s and 1930s is best seen probably in Louga 11 and 12. It is tempting to interpret the long-term profile Louga 10 as recording the wet phase from 1600-1800 or later in comparison with the generally drier period pre-1600 and post-1900 (c.f. Figure 3.11) but more data are needed to attempt such correlations with more confidence.

The isotopic relationship is summarised in more detail for profile Louga 18 for which $\delta^{18}O$ as well as δ^2H have been measured (Figure 6.7).

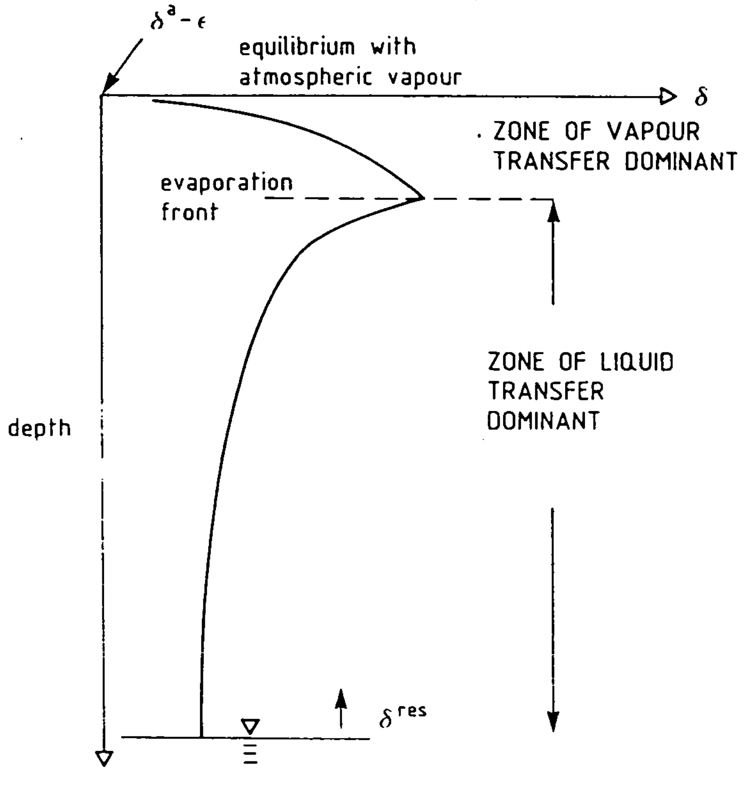


Figure 6.5

Theoretical curve of stable isotope contents in a soil profile under arid conditions. Near the surface, the stable isotope content of the soil water tends towards $\delta^a - \varepsilon$ (δ^a = heavy isotope content of the atmospheric moisture, ε = isotope enrichment factor between liquid and vapour). Adapted from Barnes and Allison, 1983

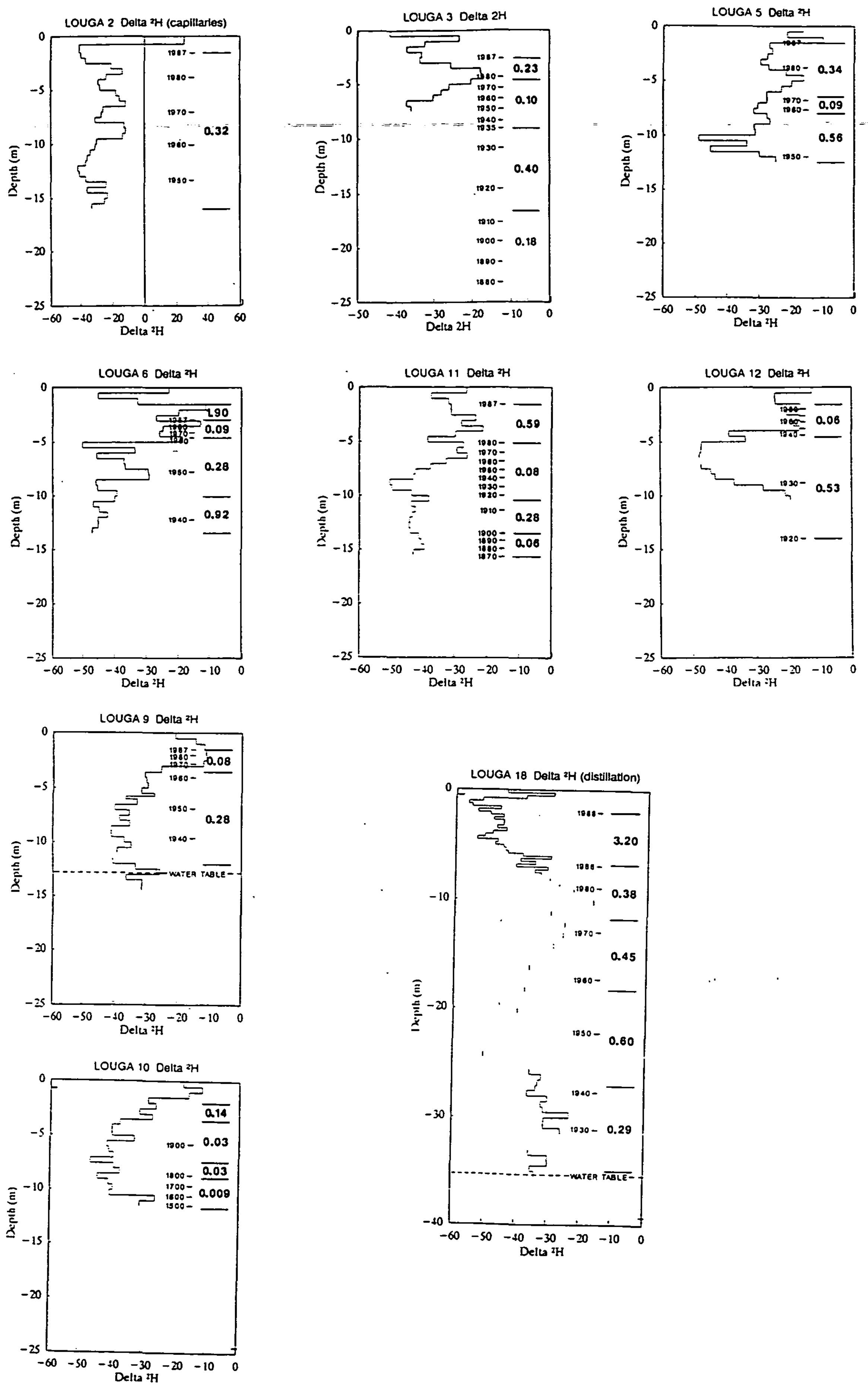


Figure 6.6 Stable isotope (δ^2H) profiles for the unsaturated zone at Louga sites, calibrated as for chloride above.

The Dakar rains fall on a line with characteristic slope (7.64). The interstitial waters from the top 10 m of the profile lie on a slope of 4.59 indicating some evaporation but intercepting the meteoric line at -8.5 $\delta^{18}O$, corresponding to the highest rains (Dakar, 1986). In contrast, waters from the lowest 10 m of the profile lie on a line with slope 1.49 indicating strong evaporation and intercepting the meteoric line near -5.5 $\delta^{18}O$. Moreover this line intercepts the line in the field of groundwaters at the water table of the same region. This is only one explanation of the data and it might be incorrect to draw only these two lines through the data; each year may, for example, have a characteristic line linking its recharge to the meteoric line and the rainfall of immediately preceding years. However, it may be that the groundwater at the top of the saturated zone may change its composition gradually as it receives incoming recharge from different climatic periods.

Bromide has been investigated in view of its possible use as a climatic or environmental indicator alongside chloride. In the first instance, the variations in the Br/Cl rainwater (Figure 6.7a & b), groundwater (Figure 6.7d) and the unsaturated zone (Figure 6.7) have been investigated to see their relationship to sea water (Br/Cl = 3.43×10^{3}). The rainfall Br/Cl ratios tend to be slightly enriched in Br compared with sea water and there is a slight tendency for this enrichment to be higher in the heaviest rains (from Louga, but not from Dakar). Bromide is generally enriched relative to chloride in rain over land as compared with sea water (Duce, 1965; Winchester and Duce, 1967) although marine aerosols close to the sea surface do not show any enrichment. An explanation of this phenomenon is that bromine is oxidised by the action of sunlight and the resultant bromine vapour then combines with the lighter aerosols as they move overland, thus enhancing the Br/Cl ratio. Rainfall from Plynlimon, Wales (1984-1989) has a mean Br/Cl of 4.4×10^{-3} (Neal pers. comm) with higher ratios being found generally in rains with lowest chloride, higher chloride rains showing a 'sea salt' effect having corresponding low Br/Cl. In Senegal the mean Br/Cl ratio value in rainfall is 4.87×10^{-3} (Louga) and 6.30×10^{-3} (Dakar) and there is a tendency for Br/Cl to be higher in heaviest rains. Shallow groundwaters have a Br/Cl ratio of 3.26×10^{-3} close to that of sea water (3.43×10^{-3}).

Significant enrichment in bromine is observed in interstitial waters from the unsaturated zone (L18) where Br/Cl ratios may be as high as 0.01.

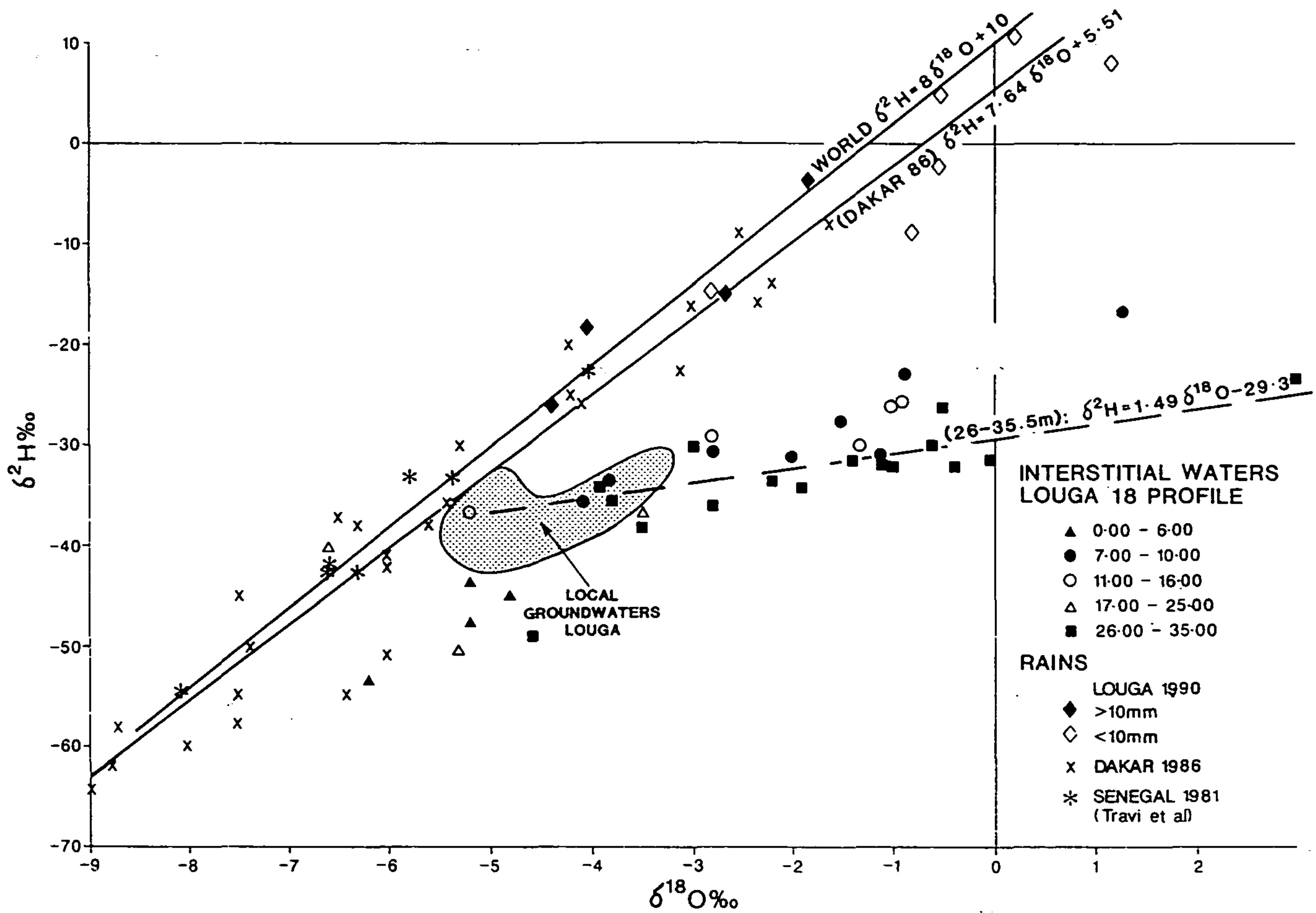


Figure 6.7 Plot of $\delta^{18}O$ vs. $\delta^{2}H$ for unsaturated zone interstitial waters from Louga 18; data are compared with rain and shallow groundwaters.

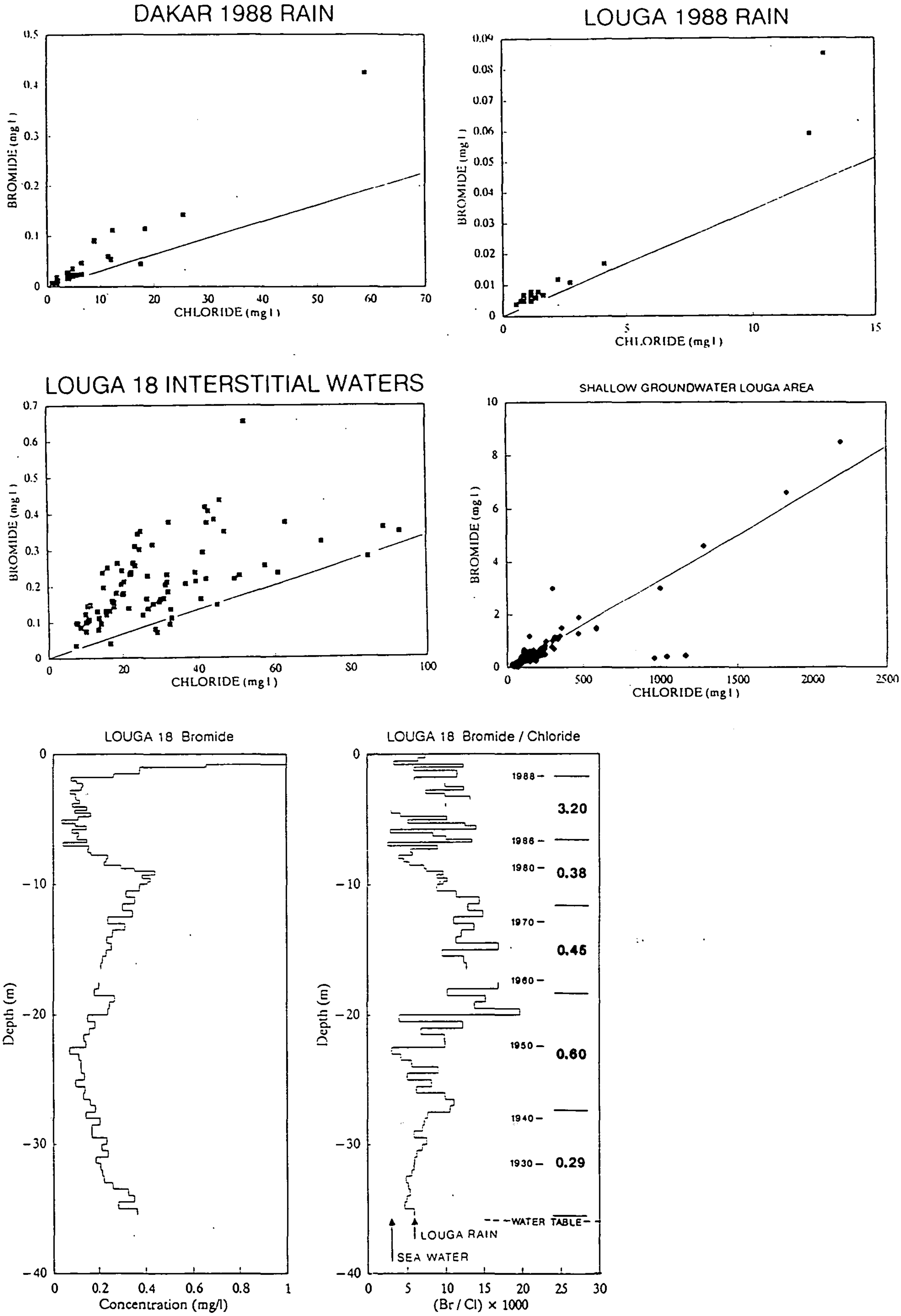


Figure 6.8 Bromide-chloride relationships in rain and groundwater: a) Dakar rain 1988; b) Louga rain 1988: c) shallow groundwaters Louga area; d) interstitial waters Louga 18; e) Louga 18 profile for Br; f) Louga 18 Br/Cl ratio, calibrated chronologically.

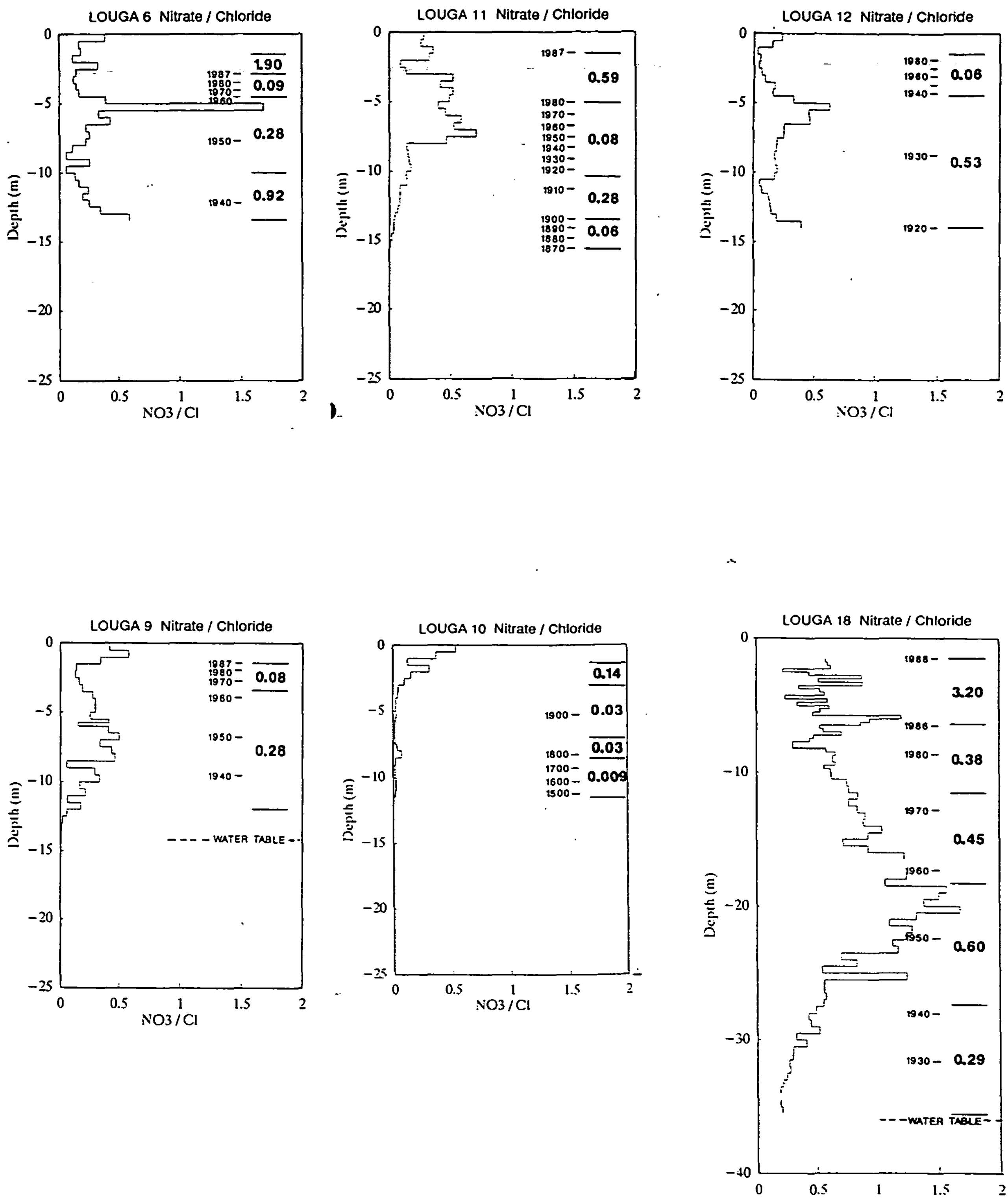


Figure 6.9 Nitrate-chloride ratios in interstitial waters

Systematic variations in Br/Cl are found with depth with Br/Cl varying inversely with chloride. The high Br/Cl ratios therefore correlate with periods with high than average rainfall and low ratios with episodes of drought. Thus bromine appears not to be conservative in its behaviour and the extent of enrichment may be useful as a tracer.

There are probably two main mechanisms whereby Br/Cl ratios may increase above marine levels - oxidation to bromine gas as described above, and concentration by organic matter. Upon decomposition of organic matter the Br^- may be preferentially released to the drainage water (Gerritse and George, 1988). From the present evidence it is clear that some enrichment in Br first occurs in the atmosphere and it may be that this enrichment is greater in semi-arid/tropical regions compared with temperate zones, should the model of Duce et al. apply, on account of greater solar radiation intensity. Coupled with this, there may also be an effect due to the air-mass trajectory of the solutes. Greater residence time in the atmosphere may lead to higher Br/Cl enrichment as compared with short transit from the ocean surface. Of course it is also possible to get a depletion in Br/Cl should halite be entrained as dust in the rainstorm. More information on wind directions and air-mass trajectory is needed to resolve the cause of apparent higher Br/Cl in rains in tropical regions. The enrichment in interstitial waters corresponding to times of higher rainfall is considered more likely to relate to an effect taking place in the soil zone and it is realistic to consider that a greater biomass production during wet-years and subsequent enhanced release of Br may account for the observations here. A further possibility might be that microbiological activity may also lead to some enrichment of Br, but this has not been reported.

The high concentrations of nitrate in the unsaturated zone are also of interest from the point of view of environmental change. It is clear that these concentrations, often well in excess of 10 mg l^{-1}, cannot be the result of pollution, except perhaps in isolated instances. In this region it is likely that the origin is from fixation of nitrate by leguminous plants. In Figure 6.9 the concentrations of nitrate expressed as NO_3-N/Cl are plotted together with residence times derived above using chloride. The NO_3-N/Cl ratio closely follows the pattern seen for bromide - higher values of the ratio coinciding with low chloride and hence wetter recharge periods. Nitrate is produced almost entirely in the soil zone rather than in the atmosphere but its enrichment may be related to that of Br. It seems likely that nitrate production is relatively high in wetter years which ties in with the higher activity of leguminous plants which tend to reduce nitrogen fixation during arid phases. An alternative or additional explanation could be that the generally higher growth and production of organic matter in wetter years leads to a corresponding decay of material releasing relatively more NO_3 (and Br).

The implications of this historical evidence from the water resources viewpoint is that estimates of the extremes of groundwater recharge can then be made. In the case of Louga 3 where the long-term average recharge is 10.1 mm yr, the lowest recharge during periods of drought must be 4 mm yr whilst at times of high rainfall, e.g. 1920s, it may be as high as 20 mm. Thus, the reduction in resources during times of drought may be proportionally much greater than the reduction in rainfall; the regional estimate of 15.2 mm therefore would become 6.0 mm - a reduction of 70% compared with rainfall reduced by only 36%.

This may help to explain the declining water tables in Senegal during the past two decades. It yet remains for these improved estimates of recharge to be compared against realistic abstraction rates and natural leakages to determine the overall impact of the climatic change.

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SEMINAIRE DE PRESENTATION DES RESULTATS DU PROJET DE RECHERCHE

LA REALIMENTATION DES NAPPES AU SENEGAL

Novotel Dakar 6 décembre

PROGRAMME

08.00 – 08.30	Accueil et inscription des participants	
08.30 – 09.00	Séance d'ouverture – Répresentant M. le Recteur de l'Université C.A. Diop – Son Excellence M. l'Ambassadeur de Grande Bretagne – Son Excellence M. Cheikh A.K. Cissoko, Ministre du Developpement Rurale et l'Hydraulique	
09.00 – 09.30	Pause café	
9.30 – 12.00	La réalimentation des nappes	
	Introduction au projet du BGS et de l'UCAD	W M Edmunds, British Geological Survey
	La réalimentation des nappes et la palaeorecharge dans les pays semi – arides	W M Edmunds
	Application des techniques géochimiques et isotopiques à l'évaluation des resources en eau de la bande sahélienne	J – Ch Fontes, Université Paris – Sud
	Le cadre du Sénégal dans la bande sahélienne, son hydrogéologie et les problèmes de la réalimentation des nappes aquifères	C.B. Gaye, Université C.A. Diop de Dakar
12.00 – 12.30	Discussion	
12.30 – 14.00	Déjeuner	
14.00 – 15.30	Résultats du projet du BGS et conclusions	W M Edmunds
	Contributions de l'Université Cheikh Anta Diop de Dakar et de l'Université Paris Sud	C B Gaye J – Ch Fontes
15.30 – 16.00	Pause café	
16.00 – 17.15	Projets liés	
	Utilisation des isotopes en hydrologie dans les pays du Sahel	J F Aranyossy, IAEA (PNUD), Dakar
	Les acacias et la zone non – saturée	B Dreyfus, ORSTOM (Dakar)
	Consommation prévisionelle et consommation réele en milieu rural au Sénégal	P G S Smith, Overseas Development Administration, British Embassy, Dakar
17.15 – 17.45	Discussion	
17.45 – 18.00	Séance de clôture	
18.30	Réception offerte par SEM l'Ambassadeur de Grande – Bretagne	

APPENDIX 1. Seminar on the results of the research project held in Dakar 6 December 1990.

APPENDIX 2. Outline procedure for recharge estimation.

1. TERRAIN. In Senegal much of the sandy lithology is suitable for recharge estimation, even where sands overlie clays, limestone and other rocks. A minimum of 6 m is needed for the profile, preferably 10 m. Sites should be almost level to eliminate surface runoff. A selection of representative soil/vegetation types is recommended so that a site average can be taken.

2. DRILLING. Any dry drilling method is suitable. We recommend use of a hand auger or power auger with hollow stem, <u>or</u> samples taken during traditional (1.5 m diam) well construction.

3. SAMPLING. Samples of moist sand etc (e.g. 500 gm) must be collected at minimum 0.5 m intervals, preferably bulking and sub-sampling the material over that depth. Avoid drying by sealing rapidly in water-tight containers - glass jars are best, with sealed lids.

4. PROCESSING. Elutriation of sands is the simplest procedure. First determine moisture content by drying at 110°C, e.g. 100 gm moist sand, recording the weight loss as % wet weight. Then taken 50 gm wet sand and add 30 ml distilled, deionised water in a glass beaker, stir and cover. Stir again after 30 minutes. Decant the supernatant liquid into a small stoppered tube (e.g. medical sample bottle). Next morning either decant or filter the supernatant solution into another tube ready for analysis.

5. ANALYSIS. The elutriate sample must be analysed for chloride using a method with detection limit around 0.5 mg l^{-1}. The result must then be corrected back to the interstitial water concentration, using the volume of water used for elutriation and the amount of moisture in the wet sand elutriated. If a good relationship between SEC and chloride can be established, the SEC can be measured on the elutriate and converted into chloride to give a reasonable but less accurate recharge estimate. Ensure that the distilled water used is chloride-free, if not suitable blanks must be subtracted.

6. INPUTS. The amount and chemistry of the rainfall over preceding years must be known for a nearby meteorological station.

7. CALCULATION. The direct recharge (Rd) is then simply calculated from:

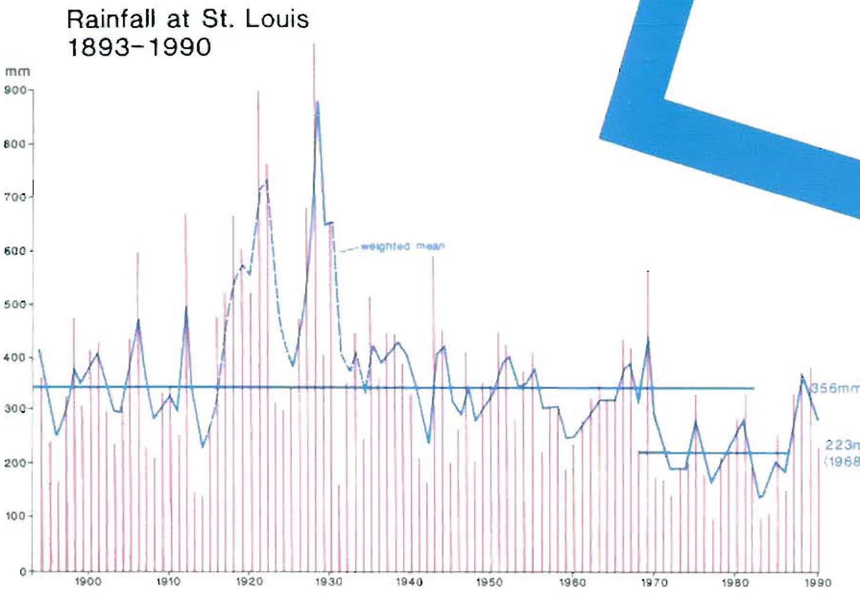
$$Rd = P. \frac{C_p}{C_s}$$

where P is the mean rainfall, C_p is the average chloride content of the rain and C_s is the mean interstitial water chloride concentration over the interval sampled.

APPENDIX 3. BGS information sheets in English and French dealing with the project.

BRITISH GEOLOGICAL SURVEY

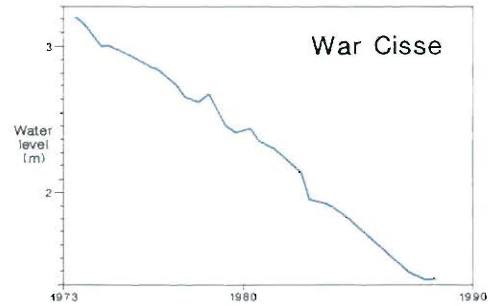
ESTIMATION OF RECHARGE TO AQUIFERS IN SENEGAL



Record of the Sahel drought (1968–86) in Senegal (left) and declining phreatic groundwater levels at Ware Cisse, northern Senegal

The Problem: lower rainfall — falling water tables.

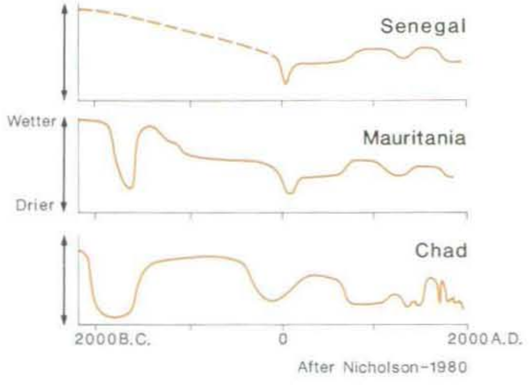
In semi-arid regions of the world groundwater is likely to be the only perennial source of water supply. Some aquifers may only have been recharged by rain falling during wetter climatic periods and groundwater is effectively being mined. Elsewhere present day rainfall may be too low under certain conditions to provide significant replenishment. What therefore is the amount of groundwater that can be safely and sustainably abstracted? Recent research in Senegal has developed a simple yet powerful geochemical technique for estimating both the current recharge and the recharge history. This makes use of the chemical and isotopic information contained in the water of the unsaturated zone.



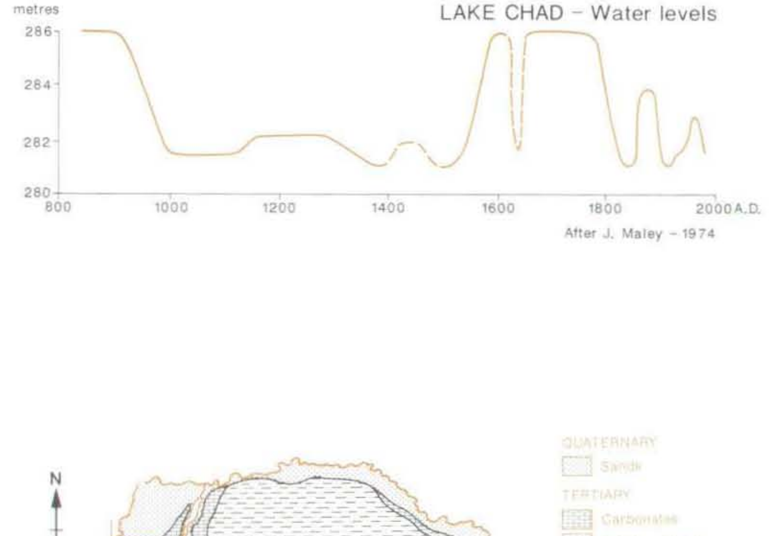
This project has been set against the recent catastrophic Sahel drought which in Senegal resulted in an 18-year period with a 36% fall in rainfall. At the same time there has been a steady decline in water levels, typically 0.1–0.2 metres per year. This has presented serious problems particularly to villagers who rely on water supplies from traditional wells.

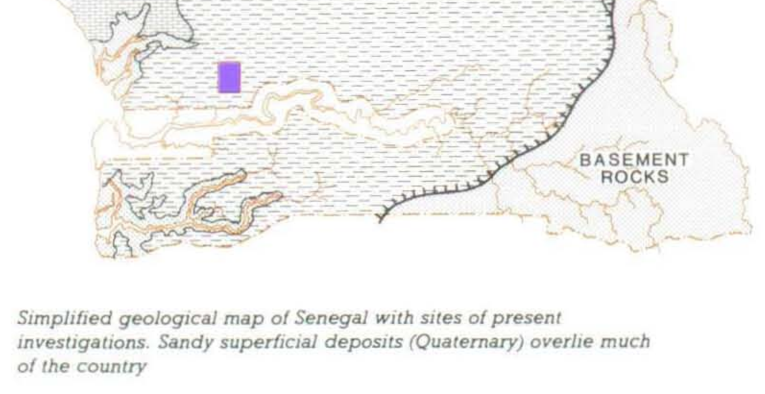
Climate history of West Africa in historic times

It has been possible to construct a history of climate change before rainfall records began by studies of the geological record. Careful study of lake and marine sediments, fauna (diatoms, shells etc) and archaeological records by various scientists has enabled the sequence of wetter and drier episodes of past millennia to be reconstructed. Wetter periods correspond to times of significant groundwater recharge.



Climatic changes in Senegal during the past four millennia set against the detailed record for Lake Chad, shown in more detail below





Simplified geological map of Senegal with sites of present investigations. Sandy superficial deposits (Quaternary) overlie much of the country

Senegal

Senegal has undergone important climatic changes in the past millennia and the excellent record of lake levels of Lake Chad may be used to supplement the relatively incomplete record for West Africa. The significantly wetter climate of the 17th and 18th centuries is confirmed from historical journals, in which mangrove swamps and former lakes are reported in the vicinity of the Senegal River. The geology of Senegal is dominated by a sedimentary basin. Many sandy sediments in the basin as well as overlying dune sands are ideal for sampling in the present investigations.

Sampling the unsaturated zone using hand-auger

Methods of investigation

Profiles of sand have been obtained by one of two methods 1) using a lightweight hand auger, 2) by sampling dug wells being constructed for water supply by government teams or non-governmental organisations. The auger technique is rapid and relatively cheap and profiles up to 35 m have been obtained, some to the water table. The water in these samples, taken at 25 or 50 centimetre intervals, is extracted by elutriation or centrifugation for chemical analysis, and by distillation for the investigation of stable isotope ratios (oxygen and hydrogen). Moisture contents were also recorded.

The small volumes of water obtained (5–10 millilitres) are sufficient for measurement not only of chloride but for a substantial range of other elements using ICP emission spectrometry, which provide information on geochemical evolution, past environments and recharge history.

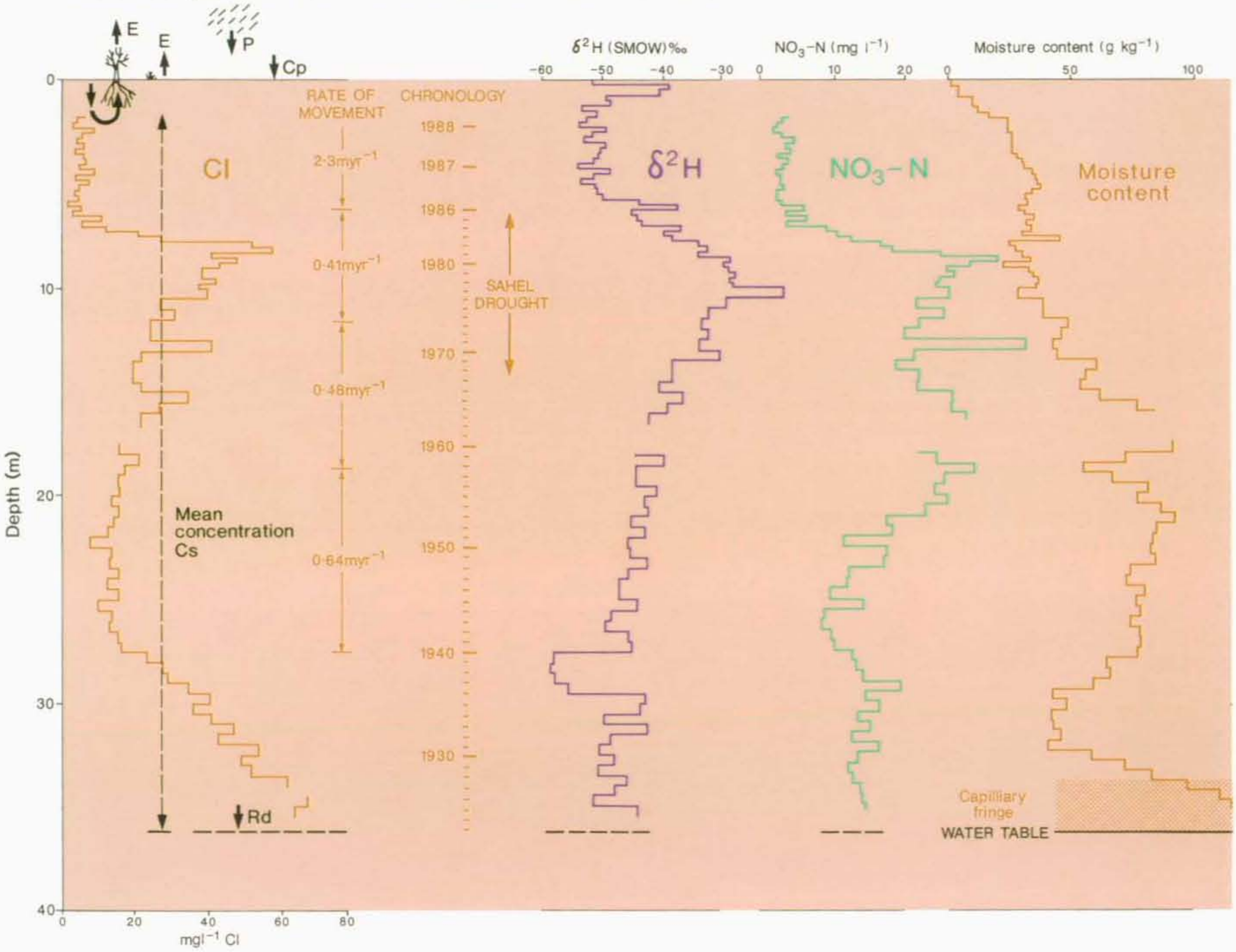
Water samples were also obtained from shallow wells in the vicinity of the research area. These provide a regional assessment of groundwater chemistry concentrations which enable improved estimates of recharge (using chloride) to be made as well as studying quality problems associated with the use of traditional wells.

Geochemical profiles in water in the unsaturated zone

Interpretation of profiles

The chemical information in the pore waters can be interpreted to give 1) recharge estimates, 2) recharge history, 3) water quality and potential pollution problems.

Chemical profiles of water in the unsaturated zone



Estimation of recharge

One of 13 profiles from the Louga area is used to illustrate the technique. This profile reached the water table at 36 m. The surface runoff in this sandy terrain is negligible and the direct recharge **R**d) may be calculated from the equation:

Rd = **PC**p/**C**s

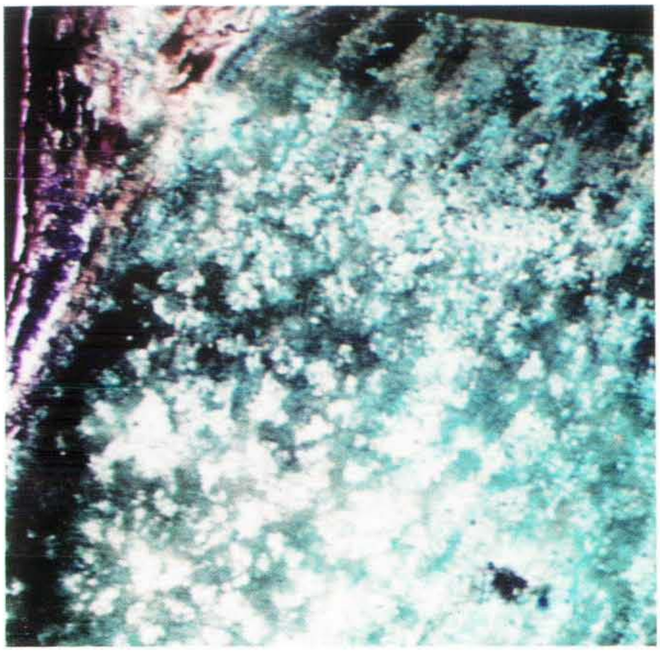
where **P** is the relevant mean annual precipitation, **C**p is the mean chloride in rainfall and **C**s is the mean chloride in the profile. In this example **R**d = 45 mm.

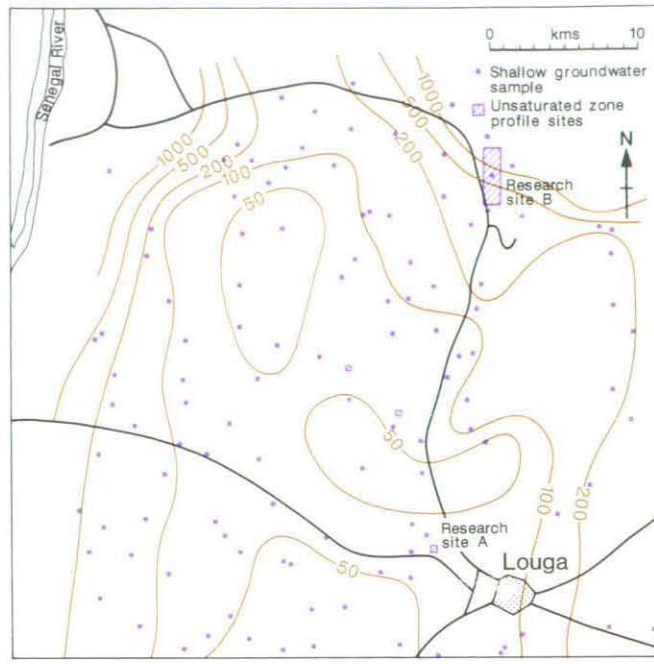
Recharge history

Using the moisture content it is then possible to calculate the rate of downward movement and thence the residence time. The recharge estimate derived above is an average for a 60 year period, i.e. the water now entering the aquifer fell as rain in about 1930. The oscillations of chloride show that the recharge rate has not been constant. The period of Sahel drought can be seen as a zone of high chloride concentrations. This is also emphasized by the less negative values for δ^2H which show that the water from this period is enriched in the heavy isotope, deuterium, as a result of greater evaporation during the drought. Other profiles with higher chloride concentrations and/or from greater depths may enable the recharge history over periods up to two thousand years (or more) to be determined.

Water quality

The chemical analyses provide further information on imputs to the aquifer (both natural and man-made). Of interest here are the high concentrations of nitrate. These values often in excess of 10 milligrams/litre NO_3-N, are unrelated to pollution but arise from natural fixation by plants or micro-organisms, with subsequent concentration by evaporation.





LANDSET 4 Photograph (9.2.86) of north-west Senegal and region sampled in the water quality and recharge study. Cultivated areas stand out white around villages in contrast with natural vegetation (green). On the map contours of chloride concentration (blue) in waters from shallow wells are used to compare with profile data and to estimate recharge at a regional scale. Research sites show in red

Recharge on a regional scale

The techniques developed here enable long-term recharge estimates to be made at one point on the map, Measuring recharge for an area is one of the most difficult problems in hydrogeology—not least as a result of spatial variability due to changes in vegetation, soil type and texture, slope etc. The geochemical techniques nevertheless enable a number of points within a region to be assessed and integrated. Within the one square kilometre control area A west of Louga, 7 profiles gave a mean **C**s of 82 milligrams per litre of chloride, corresponding to a long-term recharge of 13 mm per year. The variability as measured by the standard deviation (±42 milligrams per litre) is consistent with the present and recent vegetation contrasts within the sand dune areas.

Fortunately the regional recharge rates can be cross-checked using the chloride concentrations in water samples from below the water table, taken from traditional wells. The chloride map (above) suggests relatively high recharge in the central region, but much lower recharge in the north and east where changes to a less permeable lithology occur. Since chloride is only derived from atmospheric sources, the regional map can be used to produce areal estimates of recharge. For area A the recharge to groundwater is estimated at 13 000 cubic metres per square kilometre but in area B is considered to 1 100 cubic metres per square kilometre of more brackish water. Overall this area has very favourable recharge characteristics. Natural recharge far exceeds domestic water used by traditional village methods (some 300 m^3 per square kilometre per year), even during a drought when recharge may be halved. The falling water tables in Senegal are most likely to be due to the short-term low rate of recharge seen by the aquifer, exacerbated by natural leakage or abstraction from deeper aquifers; a more precise water balance is still required.

Reference

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This study has been carried out in collaberation with the Universite de Paris-Sud.

Funding for British Geological Survey (BGS) research into recharge estimation is provided by the Overseas Development Administration (ODA). BGS is a component body of the Natural Environment Research Council (NERC)

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